NaTech Risk in Production Plants in Regions Subjected to High Seismicity, Tornado or Flooding Hazard

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Abstract

Seismic phenomena and tornadoes are among the most relevant causes of damage on the built environment and their effect on industrial plants might not be limited to a mere structural damage. Under particular conditions, such as the presence of inflammable substances, e.g., hydrocarbons or other chemical products, earthquakes, flooding and tornadoes can trigger fires and the damages on the plant can cause the release of hazardous materials. Such scenarios are named as NaTech because of the combination of natural/technological hazard. Due to the technological aspects involved in such risk, the related costs are high in terms of damages to the environment and remediation activities on the damaged items. Chemical plants usually consist in tall industrial items (reactors, distillation columns,…) or large tanks, i.e., structures that are largely affected by seismic effects (in terms of large displacement and sloshing). For this reason, NaTech hazards have been already considered in the industrial risk analyses for those production plants settled in the developed countries, say in US and Europe (Italy, Greece), where the seismic or meteorological hazard is high. Despite the strict regulations in term of seismic safety, fire prevention and restrictions for hazardous substances, many criticalities have been already highlighted. Considering NaTech hazard in a Disaster Risk Reduction framework is fundamental, in particular in fast-developing areas such as Iran, China, Brazil and African countries where specific regulations in term of industrial safety are not detailed, say absent, and no seismic-resisting rules are considered in the design of the plants. To tackle NaTech hazard, a two stages risk analysis is proposed: a risk assessment based on the technological hazards is first performed in order to identify the critical items, then the seismic vulnerability is computed through quick-assessment procedures. The outcomes of the research can be useful for helping the countries in which NaTech risk cannot be avoided.

1. Introduction

The possibility of a production plant to be damaged by a natural hazardous event is well known among the industrial practitioners. The design of the structures that serve for the stability of the industrial items, such as, towers, saddles, supports, or foundations takes into account the ordinary loads that a building can experience throughout its design life, i.e., wind, snow, seismic action. Despite this care about natural hazards, many severe accidents in the process industries have been triggered by natural events, with the consequent release of hazardous substances (Lindell and Perry, 1996; Young et al., 2004; Cozzani, 2010).

The double composition of such kind of events, i.e., natural and technological, easily explains the term that is commonly used among technicians and experts: NaTech risk (Showalter and Myers, 1994). The public awareness towards such kind of danger certainly raised in the last decades after the large floodings that struck the central Europe and the effects of hurricanes Katrina and Rita on oil industry in the Central America (Salzano et al., 2009; Cruz and Krausmann, 2009). In addition to the well known many damages to the nuclear power plants on Japan’s East coast, say Fukushima, the 2011 Great East Japan earthquake caused a damage to the chemical industry estimated in US$210 billions (Krausmann and Cruz, 2013). The larges effects of NaTech events are the direct damages, i.e., the release of toxic substances, the presence of fires and combustion of hazardous materials, blast waves, that can affect the areas surrounding the industrial site. Following the detailed analyses performed by the previously referenced authors, common features can be identified in dealing with NaTech accidents (Cozzani, 2010): (i) the cause of the event does not depend on natural phenomena that originates within the industrial site, (ii) the natural event has a wide extension, in such a way that many items are simultaneously affected, (iii) emergency intervention can be delayed by the effects of the natural event.

In the last decades many researches focused on such kind of complex industrial hazards. The major attentions towards climate changes induced a large consideration towards NaTech events since one of the drawbacks of global warming is the increased severity of the natural events, such as flooding and strong winds, in terms of both intensity and frequency (Cruz and Krausmann, 2008; Krausmann et al., 2011). In addition to this general statement, further attention has to be paid at a regional scale. The regional hazards can largely vary in intensity and frequency or new hazards, i.e., phenomena that usually not affect an area, can appear. Besides, keeping the hazard fixed, the larger the amount of industrial settlements, the larger the risk. For example, it has been found that 1994 Northridge earthquake produced three times more NaTech events than 1989 Loma Pieta earthquake (Lindell and Perry, 1996; Cruz, 2005). A similar trend has been recorded by Showalter and Myers (1994) during the Eighties. Figure 1 shows the yearly number of industrial accidents comprised in the EM-DAT database (the data are not limited to NaTech events but also comprises accidents due to technological causes). The considered industrial accidents comprise: chemical and oil spill, gas leak, explosions and fire. In addition, the right-hand side vertical axis reports the number of people involved by the accidents (in terms of annual number of deaths). The total number of records is 2035 with a total number of deaths equal to 85403. It can be noted that the accidents increase in number starting from the Eighties; the number of involved people increases accordingly. It can be noted that in the few accidents that occurred in the first half of XX Century, the number of involved people was extremely high, while this trend reduced after the Second World War.

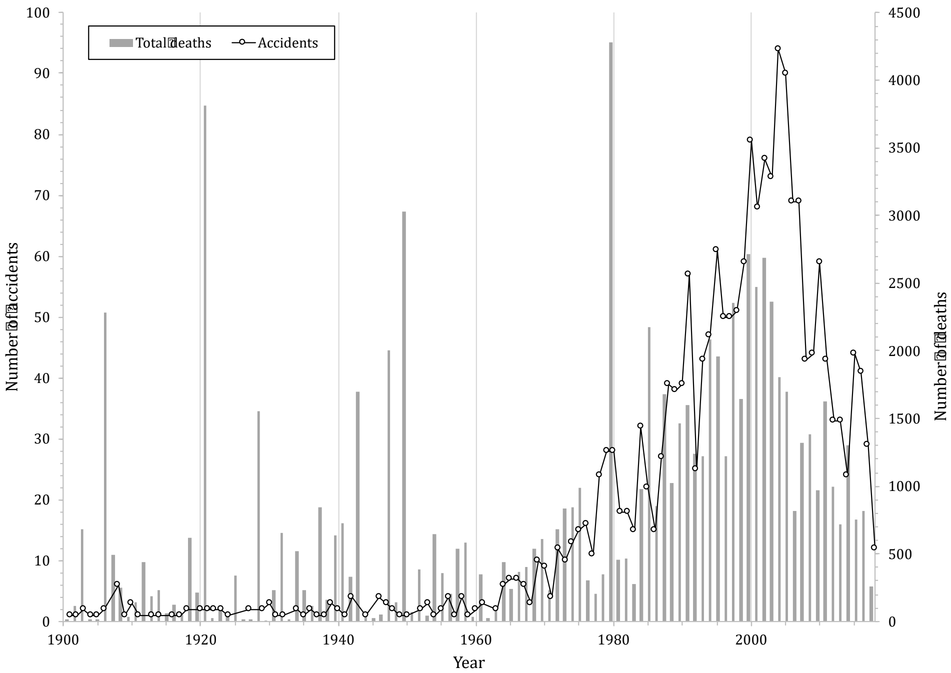


Figure 1: Annual number of industrial accidents (chemical and oil spill, gas leak, fire and explosions) and number of people involved (deaths) in the period 1900-2018. Source: own elaboration from EM-DAT database.

Figure 2 shows the number and the type of industrial accidents in the period 1900-2018, as found by the authors in the EM-DAT database. Despite the fact that the largest number of accidents (mainly fires and explosions) occurred in the developed countries, in which the majority of the industrial districts are located, there are evidences of criticalities also in the low incoming regions (such as Africa, Central or Southern Asia). It can be also noted that the effects of explosions, being limited in number, have the largest effects in terms of loss of lives.

Conversely, the direct effects on the populations of the lack of containment (involving the spills) are limited, while the impacts on the environments are large.

Earthquakes are among the strongest natural hazards that can strike the inhabited areas. This phenomenon produces ground accelerations which induce lateral forces into buildings and industrial items. Following the Probabilistic Seismic Hazard Analysis (PSHA) proposed by Cornell (1968), the seismic intensity is measured in terms of peak ground acceleration for a given return period (corresponding to a probability of occurrence during a time window). Figure 3 shows the value of the peak ground acceleration with a 10% exceedance probability in 50 years (corresponding to a return period of 475 years). It clearly emerges that the most hazardous areas are those located along tectonic plate boundaries, such as Americas' West coast, Indonesia, Japan, New Zealand, Southern Europe and Central Asia. Figure 3 also reports the location of the major crude oil refineries (2014 data), highlighting the fact that a large number of oil industries are located in zones with high seismicity. There are areas in which, although the hazard is high, a very limited number of dangerous installations is recorded: in these areas the NaTech risk is quasi-null. Conversely, the risk is extremely high in these areas in which the hazard is high and many oil industries are present. Southern Europe is among these last locations: recent researches conducted by the authors on 70 existing Italian tanks showed that 10% of these suffer potential failure if subjected to strong shaking (De Biagi et al., 2018). Despite the fact that Italy is worldwide recognized as an earthquake-prone country, the compulsory seismic design was imposed in 2008 Italian building codes, only. Thus, none of the examined tanks was designed using seismic provisions (De Biagi et al., 2018). Such evidence confirms the idea that NaTech risk is present both in industrialized and under development countries.

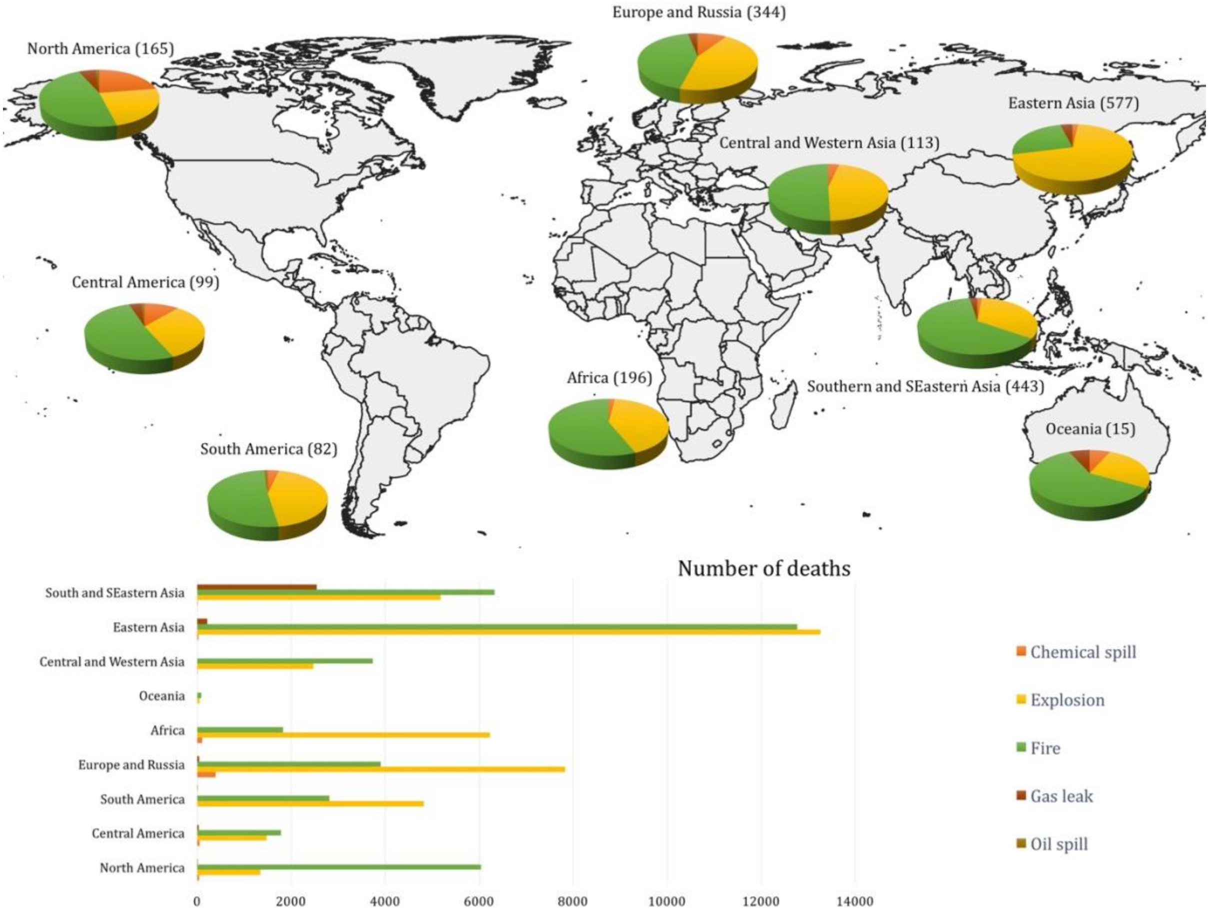


Figure 2: Industrial accidents (chemical and oil spills, gas leak, fire and explosions) and number of people involved (deaths) in the period 1900-2018 in various geographic areas. The colors of the pie and bar charts follow the key. Source: own elaboration from EM-DAT database.

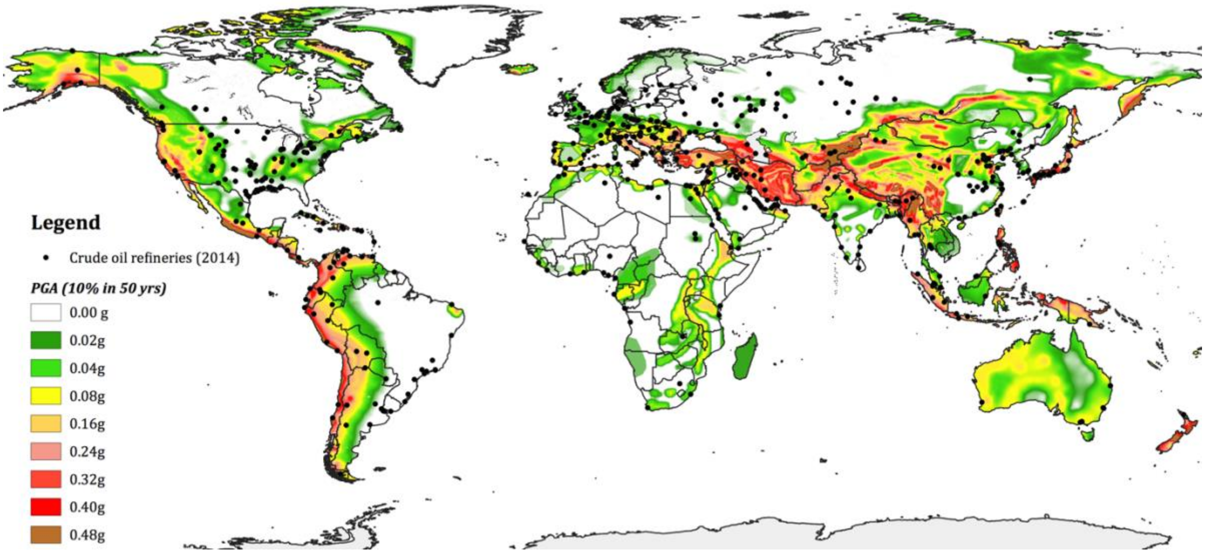


Figure 3: Worldwide peak ground acceleration (for a return period of 475 years) and location of the major oil industries. Source: own elaboration from Global Seismic Hazard Program data.

2. Assessing NaTech risk

Establishing a robust procedure for assessing the vulnerability of the items towards natural hazards and the extents of the potential damages are among the major issues for managing NaTech risks in the industrial districts. Krausmann et al. (2011) proposed a nine steps general approach which considers the characterization of the natural event (in terms of magnitude and frequency), the identification of the target equipment and its damage scenarios with a related damage probability, the evaluation of the consequences of a scenario and, finally, the calculation of the risk. The damage scenarios related to earthquakes, flooding or tornadoes largely differ. In order to understand the brief description that follows, the reader should be known about the fact that the supporting structures of the industrial items are usually designed in such a way to sustain downwards vertical forces (gravity forces) acting from the elevation to the foundation. Ground acceleration during an earthquake promotes the transverse vibration of the masses composing the industrial item resulting in strong horizontal forces (unusual for the design of the item). Similar effects can be recorded during strong winds (tornadoes) when dynamic pressures act on the lateral surfaces of the industrial items. During flooding two different phenomena can simultaneously occur: high water level induces buoyancy forces that let the tanks to pressurized vessels to float, hydrodynamic forces laterally pushes the items.

In this paper, a two steps expeditious procedure for assessing NaTech risk is described and discussed. As it can be observed in the flowchart sketched in Figure 4, the procedure consists in two main stages, into which the dual faces of NaTech risk are independently analyzed. Stage 1 deals with the evaluation of those items which failure can engender direct and indirect damages. The former are related to the release of toxic substances, containment, fires, explosions, while the latter, e.g., relate to delays in rescue operations. If the industrial risk is not relevant, i.e., independently from the natural hazard, no relevant technological effects subsist, the procedure finishes and it is assessed that NaTech risk is low, say absent. On the contrary, if there are evidences that the industrial risk cannot be ignored, a simplified structural analysis is performed in order to highlight the possibility of structural failure of the item, in case of which the technological hazard can be triggered. Step 2 of the expeditious procedure consists in simplified structural analyses. These presuppose the evaluation of the fundamental parameters of the natural hazard (say, the peak ground acceleration for the seismic hazard, wind velocity for tornado hazard, water depth and flow velocity for flooding hazard) and in the performance of structural calculations adopting simplified models able to catch the response and assess if the failure can take place (Frigo et al., 2017). The calculations are executed for seismic, flooding and tornado hazards and the worst condition, i.e., failure for at least one of these, is considered. If the structural collapse can occur, NaTech risk is considered as high and advanced calculations and quantitative risk assessment must be performed. In the following, details about each stage are provided.

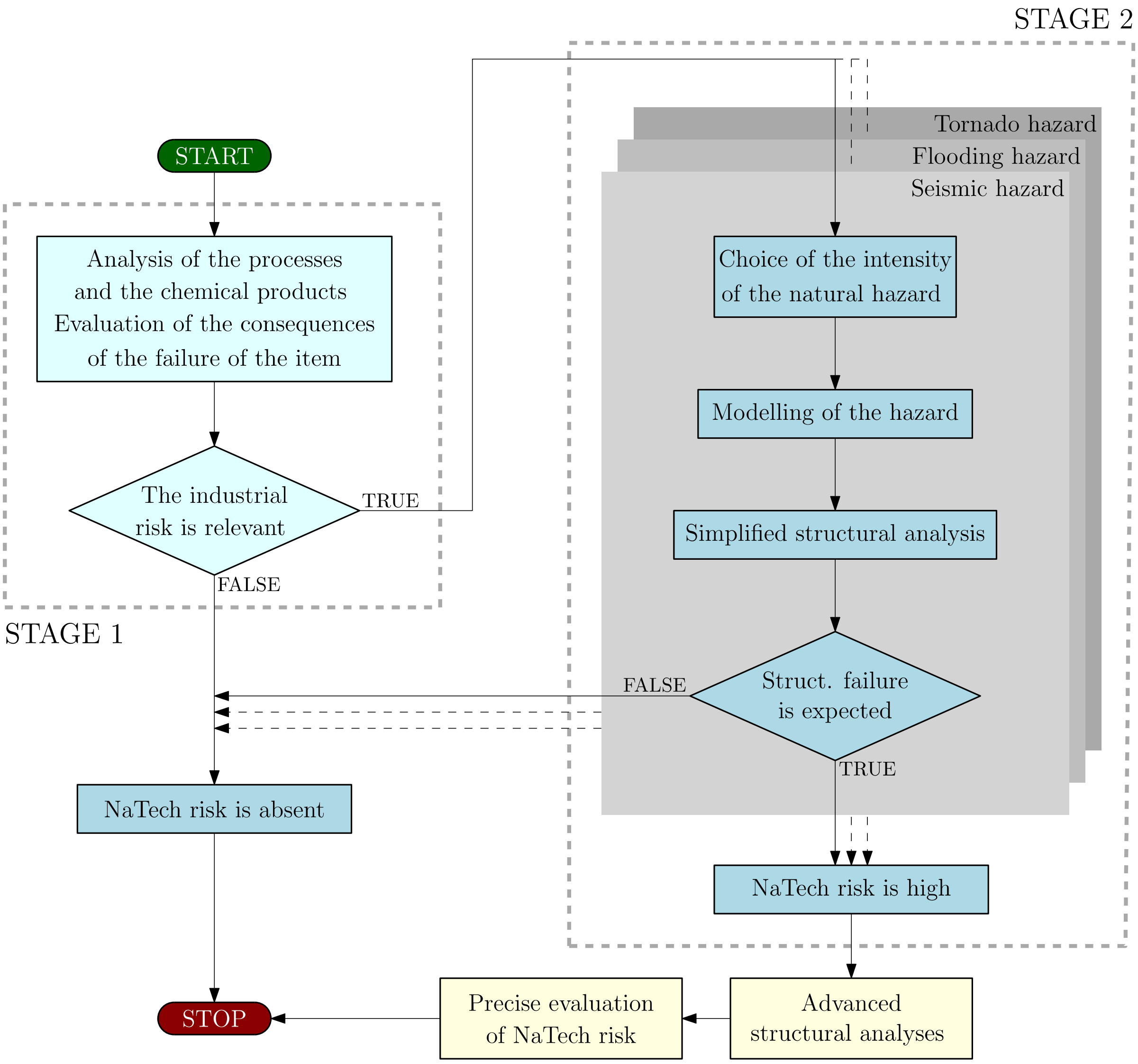


Figure 4: Flowchart of the NaTech risk analysis. Stage 1 and 2 corresponds to the expeditious methodology herein illustrated. The sketch is a multi-hazard enhanced version of the flowchart reported in Chiaia et al. (2016).

A theoretical approach on risk considers it as the product of hazard, vulnerability and exposure. Even if not explicitly mentioned, the three components of risk are present in the aforementioned approach, even if they are not identified singularly. In particular, the exposure is considered through the evaluation of the consequences of the failure of the item (in Stage 1 of Figure 4). As detailed in the following, in the present approach the exposure is evaluated in terms of the consequences of the failure of the item. Differently from other risk approaches, the exposure is evaluated as a binary variable, i.e., the consequences are acceptable, or not. The hazard and the vulnerability are considered in Stage 2. In particular, the structural response of the industrial item (that is, the vulnerability) under a given scenario in which the natural phenomenon has a predefined intensity, i.e., the hazard, which calculation is out of the scopes of the present paper, is computed. Thus, the potential failure of the item is evaluated.

3. Identification of the relevant items (Stage 1)

Stage 1 of the NaTech risk assessment consists in the evaluation of the consequences of the damage or the failure of a single industrial item. The major studies on the effects of NaTech of the industrial facilities are based on the observation of past real events on similar items. Fabbrocino et al. (2005) analyzed the possible degrees of damage of a tank and identified three levels of loss of containment: RS1 no loss; RS2 moderate loss; RS3 extensive loss of containment. A similar approach was adopted by Salzano and Cozzani (2007) who identified the following three levels of loss of containment (Krausmann et al., 2011): RS1 continuous release from a hole with an equivalent diameter of 10 mm; RS2 continuous release of the complete inventory (in more than 10 minutes); RS3 instantaneous release of the complete inventory (in less than 2 minutes) following severe structural damage.

In the present expeditious NaTech risk assessment, the identification of those industrial items which consequences of failure are relevant consists in evaluating the chemical properties and the physical state of the process materials contained in each item. For example, the presence of explosive vapors in the item needs more care than in case of inert gases. For this purpose, Antonioni et al. (2009) proposed a tool for establishing a preliminary ranking of the critical items in a refining industry. The weights to be attributed to each component, which are reported in Table 1, were evaluated following items' operating conditions and type and damage distances. For example, it results that the damage of pressurized liquefied gas vessel results in larger damage (thus, larger criticality) than in case of damage of a tank containing liquid at atmospheric pressure.

Table 1: Preliminary weights for establishing priorities for the ranking of critical equipment items (Antonioni et al., 2009).

	Storage vessels	Large diameter pipes	Columns	Reactor, heat exchangers
Pressurized liquefied gas	4	4	3	3
Overheated liquid	3	3	2	2
Gas (compressed)	3	2	2	1
Cryogenic liquid	2	2	2	1
Liquid	1	1	1	1

4. Simplified structural calculations (Stage 2)

Stage 2 of the NaTech risk assessment concerns the vulnerability evaluation of the items under various hazards. Before describing the possible simplified structural models, it is necessary to detail how a refining process is composed: (i) the raw material arrives in the production site and it is stored; then, (ii) the raw material is processed (distilled) and (iii) the various produced “fractions” are stored for further usages (sell, reuse in the plant,…). Tanks serve for the storage of fluid raw and refined products while vessels are used as containers of gas products. The separation processes need the so-called “distillation columns”, i.e., tall industrial items in which the vapors of the heated raw material condense (at different temperatures). The materials are transferred through piping systems, which are usually suspended from the main items or supported by independent frame systems. A large variety of structural types and construction materials is observed in the apparatuses of processes production plants.

Essentially, the following structural classes can be identified (Paolacci et al., 2012). Slim items (a) have one prevailing dimension and can be further classified depending on their orientation: vertical and horizontal. Process columns are vertical vessels partially filled by liquid fractions and anchored at their base or supported by a frame structure. Chimneys are hinged at their base and contain atmospheric pressure gas. Horizontal vessels usually serve for storing pressure gases and are supported by a couple of saddle.

Above-ground squat items (b) comprise large cylindrical tanks (with floating or fixed roof) with capacity up to 200 000 m^3. Squat items supported by columns (c) are characterized by heavy process items lying on multiple concrete or steel supports with bracing systems. Examples of such items comprise Horton spheres for liquefied gas or furnaces for raw material heating.

For each of the previously listed structural types, the effects of an earthquake, flooding and tornado can be evaluated through simplified modelling, as listed in Table 2.

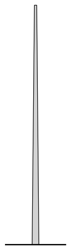
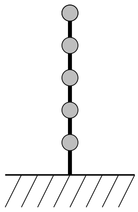
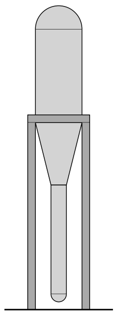
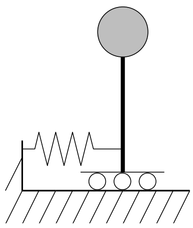
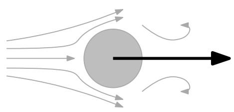
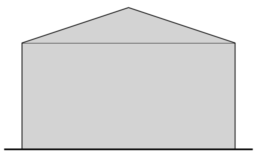
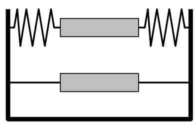
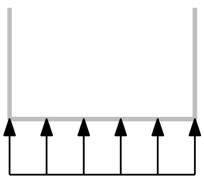
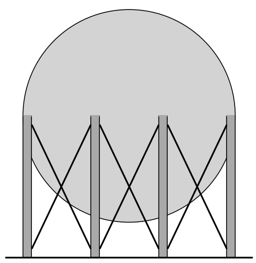
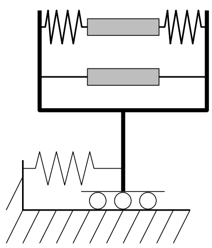
This consists in identifying the most relevant structural components (in term of stiffness and strength) and analyzing the mutual effects in order to formulate a structural model made of a limited number of elements (beams, rods, concentrated masses) to be subjected to loads (in case of flooding or tornado) or to base acceleration (in case of seismic hazard). For example, the simplified model to study the seismic response of an Horton sphere, i.e., a spherical pressure vessel supported by braced column (shown in the last row of Table 2) is represented by a vertical rigid element supported by rollers and connected to a fixed point by a spring (simulating the lateral stiffness of the braced columns). In order to take into account the sloshing behavior of the liquid contained in the sphere, the classical double masses approach (convective and impulsive masses) can be adopted. A sketch of the simplified model is reported in the fourth row/second column of Table 2. An example of simplified calculations on industrial items can be found in Chiaia et al. (2016).

5. Conclusions

The present paper illustrates a expeditious procedure for the assessment of NaTech hazards in industrial plant (chemical, oil,…). The procedure consists in two stages: identification and vulnerability calculation. The former consists in the evaluation of those items which failure consequences are relevant with respect to the loss of containment (environmental aspects, explosions,…) and the safety of the people working in the production plant (indirect damages). The latter presupposes that the vulnerability of the selected items is computed through simplified structural models onto which forces derived from independent natural hazard analyses are performed.

Very accurate (but complex) methodologies to perform quantitative NaTech risk analyses are present in the literature (say, Krausmann and Cruz, 2013). These presuppose a detailed study of the combination of the events in order to generate scenarios with a given probabilities of occurrence. The risk is the sum of the consequence times the expected frequencies of occurrences. Nevertheless, such detailed approaches need precise considerations about the vulnerability of the items. Due to the difficulty in getting the precise structural response of the item, fragility functions derived from previous generalized studies and observations are usually adopted.

Table 2: Simplified modelling schemes and actions for seismic, flooding and tornado hazards vulnerability analysis.

Structural type	Seismic hazard	Flooding hazard	Tornado hazard
a. Slim items			
	 Distributed mass	Lateral hydrodynamic forces	Vortex formation Aerodynamics effects
	 SDOF system	Lateral hydrodynamic forces 	Lateral pressure
b. Above-ground squat items			
	 Impulsive and convective masses	 Buoyancy forces	Tank toppling due to lateral and suction wind pressures
c. Squat items on columns			
	 SDOF system	Lateral hydrodynamic forces on supporting columns	Lateral wind pressure

The present approach, on the contrary, presupposes a single damage scenario (the loss of containment) but details the structural behavior of each item through simplified but realistic calculations. It has been highlighted that the majority of industrial accidents occur in those areas where many natural hazards are contemporary present. Due to its capacity in dealing with different structural types and construction materials, the outcomes of the present research can be implemented in such regions (e.g., Iran, China, Brazil) where specific regulations in term of industrial safety are not detailed, say absent, and no costly seismic-resisting rules are considered in the design of the plants. For a large screening in such areas located in developing countries, the present expeditious approach can be setup by expert engineers through a survey form into which the main features of each item are reported. Then, working with preselected structural models, the behavior of the item subjected to the effects of the natural hazard is evaluated and a preliminary NaTech assessment is performed. Detailed analyses are performed only on those items that result hazardous. An additional outcome of the present approach consists in the possibility of updating emergency response plans on the base of the increasing intensity of the meteorological natural phenomena, as suggested by Girgin, 2010.

References

Antonioni, G., S. Bonvicini, G. Spadoni, and V. Cozzani. 2009. Development of a framework for the risl assessment of Na-Tech accidental events. *Reliability Engineering and System Safety*, Vol.94: 1442-1450.

Campedel, M. 2008. *Analysis of major industrial accidents triggered by natural events reported in the principal available chemical accident databases*. Report EUR 23391 EN.

Chiaia, B., V. De Biagi, C. Zannini Quirini, L. Fiorentini, V. Rossini, and P.M. Carli. 2016. A framework for NaTech seismic risk assessment in industrial plants. *International Journal of Forensic Engineering*, Vol.3: 86-105.

Cornell, C.A. 1968. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, Vol.58: 1583-1606.

Cozzani, V. 2010. Towards the inclusion of external factors in quantitative risk assessment: the analysis of NaTech accident scenarios. Proceedings CISAP-4, Chem.Eng.Transactions, p. 1-6.

Cruz, A. 2005: NaTech disasters: a review of practices, lessons learned and future research needs. Paper presented at the 5th Annual IIASA-DPRI Forum, Integrated Disaster Risk Management: Innovations in Science and Policy, Beijing, China, 14-18 September 2005, 10 pp.

Cruz, A.M. and E. Krausmann. 2008. Damage to offshore oil and gas facilities following Hurricanes Katrina and Rita: An overview. *Journal of Loss Prevention*, Vol.21: 620-626.

Cruz, A.M., and E. Krausmann. 2009. Hazardous-materials releases from offshore oil and gas facilities and emergency response following hurricanes Katrina and Rita. *Journal of Loss Prevention in the Process Industries*, Vol.22: 59-65.

De Biagi, V., B. Chiaia, L. Fiorentini, and C. Zannini Quirini. 2018. Seismic vulnerability assessment of fuels storage tanks in Italy. *Journal of Pressure Vessels Technology*, accepted manuscript. doi:10.1115/1.4040313

EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium.

Fabbrocino, G., I. Iervolino, F. Orlando, and E. Salzano. 2005. Quantitative risk analysis of oil storage facilities in seismic areas. *Journal of Hazardous Materials A*, Vol.123: 61-69.

Girgin, S. 2011. The natech events during the 17 August 1999 Kocaeli earthquake: aftermath and lessons learned. *Natural Hazards and Earth System Sciences*, Vol.11: 1129-1140.

Krausmann, E. and A.M. Cruz. 2013. Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. *Natural Hazards*, Vol.67: 811-828.

Krausmann, E., V. Cozzani, E. Salzano and E. Renni. 2011. Industrial accidents triggered by natural hazards: an emerging risk issue. *Natural Hazards and Earth System Sciences*, Vol.11: 921-929.

Lindell, M.K. and R.W. Perry. 1996. Identifying and managing conjoint threats: Earthquake-induced hazardous materials releases in the US. *Journal of Hazardous Materials*, Vol.50: 31-46.

Lindell, M. K. and R. W. Perry. 2005. Addressing Gaps in Environmental Emergency Planning: Hazardous Materials Releases During Earthquakes. Journal of Environmental Planning and Management, Vol.39: 529-543.

Paolacci, R., R. Giannini and M. De Angelis (March 28th 2012). Analysis of the Seismic Risk of Major-Hazard Industrial Plants and Applicability of Innovative Seismic Protection Systems, Petrochemicals Vivek Patel, IntechOpen, DOI: 10.5772/38365.

Salzano, E. and V. Cozzani.. 2007. *Quantitative risk assessment of industrial processes: The path towards a global approach,* In: Focus on Hazardous Materials Research, edited by: Mason, L. G., Nova Science Publishers, New York.

Salzano, E., A. Basco, V. Busini, V. Cozzani, E. Marzo, R. Rota and G. Spadoni. 2013. Public Awareness Promoting New or Emerging Risk: Industrial Accidents. Journal of Risk Research, Vol.16: 469-485.

Showalter, P. S., and Myers, M.F. 1994. Natural Disasters in the United States as Release Agents of Oil, Chemicals, or Radiological Materials Between 1980-9: Analysis and Recommendations. *Risk Analysis*, Vol.14: 169-181.

Young, S., L. Balluz, and J. Malilay. 2004. Natural and technologic hazardous material releases during and after natural disasters: a review. *Science of the Total Environment*, Vol.322: 3-20.