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Risk-based Vulnerability Analysis of Chemical Facilities Affected by Flooding

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Flooding may affect chemical facilities leading to major accidents (fires, explosions, contamination), following damages to structures and equipment. This type of accident is indicated as a “natural-technological” (Natech) event and occurred in the past, often leading to severe accidental scenarios. Recent studies allowed developing a specific methodology aimed at including Natech scenarios triggered by flooding into Quantitative Risk Assessment (QRA) analyses for chemical facilities. The methodology relies on the use of specific fragility models for the evaluation of failure probability of process units affected by flooding. Despite these models consider different types of equipment geometries and flooding conditions, they do not account for the presence of safety barriers (e.g., fire-protection systems, bunds, blanketing system). In the present work, the previously developed QRA methodology is improved in order to provide a risk-based vulnerability analysis of Natech scenarios induced by severe flooding taking into account the presence of safety barriers. The methodology is improved by including the availability assessment of safety barriers based on the possibility the systems have been impacted by the flood. A tailored Failure Mode and Effect and Criticality Analysis (FMECA) is presented for assessing the damages to safety barriers resulting from flooding events. As an example, the analysis of an important safety barrier through the FMECA approach is presented. The study shows an example of both risk informed decision-making concerning protection systems and development of new criteria for the assessment of safety barrier failure in case of natural hazards.

1. Introduction

In recent years, the possibility of natural hazards affecting chemical and process facilities has become of great concern among both industry and academia (Showalter, Myers, 1994). The reasons of this growing interest are manifold. Chemical and process industries indeed handle significant quantities of hazardous substances, which can lead to dangerous outcomes in case of release. Natural events impacting on process facilities may cause both direct damages to assets and trigger technological scenarios involving chemical substances. These scenarios in technical literature are usually referred to as “natural-technological” (Natech) (Krausmann et al., 2017). Natech accidents are characterized by exacerbated consequences possibly caused by multiple simultaneous failures and by accident propagation to nearby structures, i.e., domino effect (Cozzani et al., 2014). For example, during the Tohoku Earthquake that hit Japan in 2011, a disastrous Natech accident involved a LPG (liquefied petroleum gas) storage farm: the structural collapse of a tank caused damages to nearby tanks, and the release of flammable material led to multiple massive explosions, which in turn triggered fires in adjacent petrochemical plants (Krausmann and Cruz, 2013). Floods constitute a potential trigger for multiple failures as well. During San Jacinto River flood, US 1994, several hydrocarbon pipelines ruptured and multiple severe spills were experienced in the affected area (NTSB, 1996). Operator intervention was hampered, and accessing manual interruption valves was impossible because of floodwater.

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Moreover, the frequency of such natural hazards (i.e., in particular floods and droughts) is expected to grow because of climate change and disaster related economic damages are reported to be increasing, thus the likelihood of high magnitude Natech scenarios is consequently expected to grow as well (Cruz et al., 2006).

A number of methodologies have been proposed for assessing the risk posed by Natech to process facilities. Among the others is worth mentioning the methodologies aimed at including Natech assessment into the framework of the well-established Quantitative Risk Assessment (QRA). The first attempts have been carried out by Antonioni et al. (2007, 2009), based on observational equipment fragility models. Physical models for equipment failure in case of flooding have been later developed for atmospheric tanks (Landucci et al., 2012) and pressurized vessels (Landucci et al., 2014) and included in the most recent QRA process (Cozzani et al., 2014). A common gap in current methodologies is that the assessment is usually carried out without considering the presence of safety barriers. Safety barriers are devices intended for the prevention or mitigation of accident scenarios. Safety barriers have the potential to play a key role in limiting accident probability and/or consequences. The aim of the present study is to include the role of safety barriers in assessing risk-based vulnerability of chemical and process plants impacted by flooding. The starting point was the QRA procedure extended to Natech scenarios caused by flooding proposed by Cozzani et al. (2014). As shown in Figure 1, the procedure was modified to include a step dedicated to the specific assessment of safety barriers in the presence of a natural event impacting on the facility.

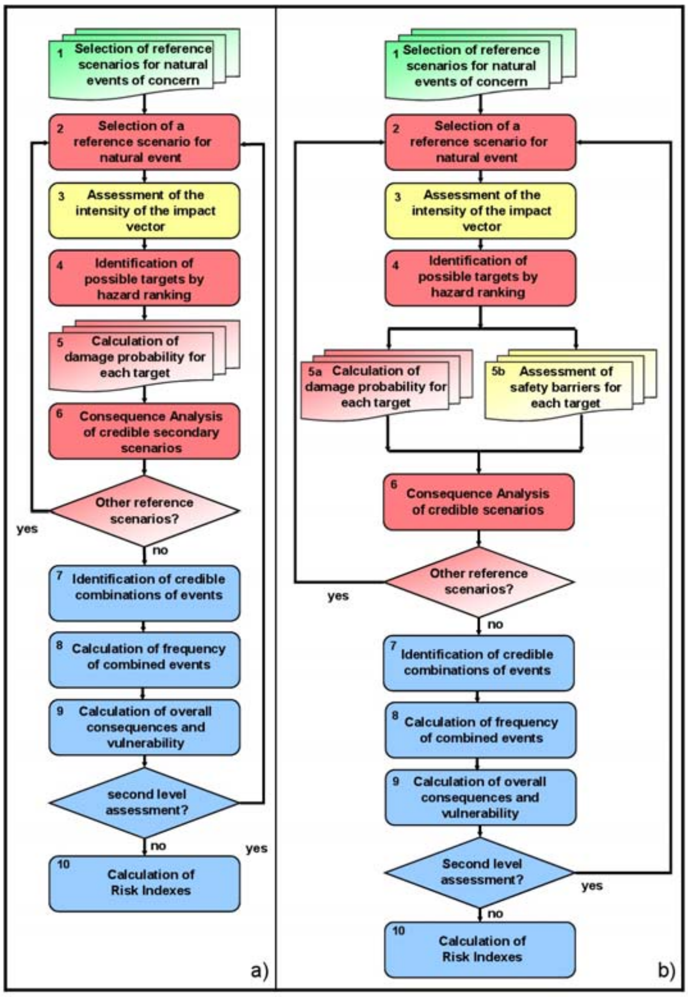

1 Selection of reference scenarios for natural events of concern
2 Selection of a reference scenario for natural event
3 Assessment of the intensity of the impact vector
4 Identification of possible targets by hazard ranking
5 Calculation of damage probability for each target
6 Consequence Analysis of credible secondary scenarios
Other reference scenarios?
yes
no
7 Identification of credible combinations of events
8 Calculation of frequency of combined events
9 Calculation of overall consequences and vulnerability
second level assessment?
no
yes
10 Calculation of Risk Indexes
a)
1 Selection of reference scenarios for natural events of concern
2 Selection of a reference scenario for natural event
3 Assessment of the intensity of the impact vector
4 Identification of possible targets by hazard ranking
5a Calculation of damage probability for each target
5b Assessment of safety barriers for each target
6 Consequence Analysis of credible scenarios
Other reference scenarios?
yes
no
7 Identification of credible combinations of events
8 Calculation of frequency of combined events
9 Calculation of overall consequences and vulnerability
Second level assessment?
yes
no
10 Calculation of Risk Indexes
b)

Figure 1: a) Procedure developed by Cozzani et al. (2014). b) Tailored procedure accounting for safety barriers. The barrier assessment is carried out in a dedicated parallel node (node 5b).

This step is needed since floods (as other natural hazards) may heavily affect safety systems and related structures, potentially leading to unavailability of protection and to an increased vulnerability of the critical equipment. The failure modes of safety barriers are determined by their architecture, their dependence on lifelines, as well as by natural hazard features. It is clear the availability assessment needs to account for specificities related to the site and to the flood scenario. This assessment can be carried out seeking the credible failure modes of subsystems composing the safety barrier, as will be described in the following sections.

2. Safety barriers

In this section concise definitions are provided on safety barriers and safety functions, according to the protection layer concept (CCPS, 2001; Delvosalle et al., 2001), in order to provide an unambiguous reference for the purposes of the present study. Safety functions are technical solutions to be achieved in order to avoid, prevent or mitigate defined events. Safety functions are directly served by physical engineered systems or procedures, which are referred to as safety barriers. This definition is quite general, and safety barriers embrace a broad set of solutions, from fire protection systems to authority intervention in case of accident. In Table 1, a commonly accepted classification is reported, together with some examples. The Failure Mode and Effect and Criticality Analysis (FMECA) shown in Section 4 is focused on passive and active barriers, because estimating the effect of natural disasters on emergency/procedural barriers would be more complex and should consider stress on emergency teams, which is likely to enhance human error during crisis scenarios (Steinberg and Cruz, 2004).

Table 1: Summary of safety barriers types adopted in process facilities.

Classification	Description	Examples
Passive barriers	Activation not needed; usually physical barriers.	PSV, Fireproofing, Catch Basins, Dikes, Sumps, Mounds;
Active barriers	Activation is needed; complex systems usually composed of detection, treatment and actuation system.	Foam-water system, Firefighting water, Emergency Shutdown (ESD), Emergency Blowdown (EBD), Manual valves;
Emergency or Procedural barriers	Actuation of procedures and coordinate actions by personnel or externals	Internal or External Emergency Plan, Fire Brigades, Emergency Teams;

3. Case histories & lessons learned

From the analysis of past accidents (a selection of events of particular relevance is presented in Table 2) some key lessons on safety barrier failure in case of natural hazards can be inferred.

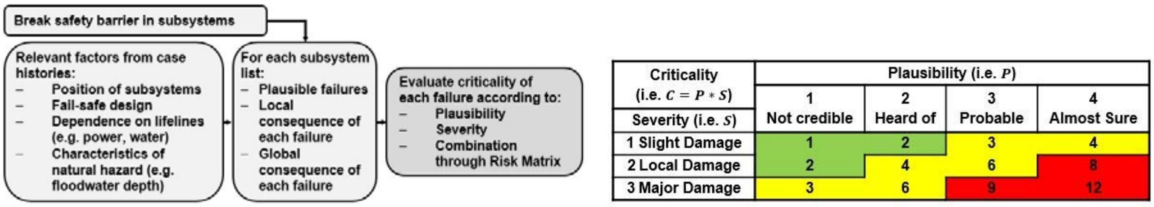
Table 2: Examples of case histories involving barrier failures

Natural Event	Barrier Failure	Short Description	Reference
Koaceli Earthquake, 1999	Firefighting water was not available; Foam-water system for vapour suppression unavailable;	Power outage: pumps could not be started. Water lifeline disruption caused by debris impact: water pressure loss, water supply unavailable.	(Steinberg and Cruz, 2004)
Koaceli Earthquake, 1999	Containment dikes failures;	Concrete dikes were damaged: liquid hazmat (acrylonitrile) spilt into the sea.	(Girgin, 2011)
Vltava River Flood, 2002	Emergency retention sumps were flooded	Liquid hazmat (chlorine) could not be retained and spilt in air and water.	(eMars)
Hurricane Harvey, 2017	Chemical storage refrigeration system unavailable; Backup generators flooded; Emergency intervention after days;	Power outage: loss of refrigeration to peroxide storage. Backup generators were flooded: violent explosions arose. Emergency teams were strongly hindered by floodwaters.	(Additives for Polymers, 2017)
San Jacinto River Flood, 1994	Manual interruption valves flooded and inaccessible;	Floodwater height hampered the intervention of operators not allowing them reaching manual valves.	(NTSB, 1996)
Tohoku Earthquake and Tsunami, 2011	Backup power generators flooded;	Backup power generators were located in a swamped area and were flooded during tsunami.	(Labib and Harris, 2015)

It is worth remarking that unless standard specific requirements, usually barriers are not designed to withstand extreme natural events. It is clear from Table 2 that one of the main causes of vulnerability of safety barriers is power outage. In a recent research, Karagiannis et al. (2017) reported power outage in the totality of analysed flooding events, and in most seismic events. Even backup power generation cannot be relied on, according to case histories analysis. Location of safety barrier subsystems is fundamental as well: for example, position of pumps or backup power generators with respect to floodwater depth may determine their availability.

4. Methodology

A methodology was developed to assess the performance of safety barriers in the presence of flood events, in order to assess the actual probability of the final scenarios considering the role of safety barriers, as shown in Figure 1b. The methodology was based on the combination of FMECA and of past accident analysis. FMECA is an equipment-oriented technique for the identification of failures affecting the system capability to operate (Lees, 1996). FMECA was chosen compared to other hazard identification tools because it requires more limited information, and barrier failure is described qualitatively in the case histories. A flowchart of the methodology is shown in Figure 2a, while a Risk Matrix for Criticality evaluation is reported in Figure 2b. Failure criticality depends on the plausibility of the scenario and on the severity of damage.


Break safety barrier in subsystems
Relevant factors from case histories:
– Position of subsystems
– Fail-safe design
– Dependence on lifelines (e.g. power, water)
– Characteristics of natural hazard (e.g. floodwater depth)
For each subsystem list:
– Plausible failures
– Local consequence of each failure
– Global consequence of each failure
Evaluate criticality of each failure according to:
– Plausibility
– Severity
– Combination through Risk Matrix

Criticality (i.e. $C = P * S$)	Plausibility (i.e. P)			
Severity (i.e. S)	1 Not credible	2 Heard of	3 Probable	4 Almost Sure
1 Slight Damage	1	2	3	4
2 Local Damage	2	4	6	8
3 Major Damage	3	6	9	12

Figure 2: a) Flowchart for tailored FMECA; b) Risk Matrix for failure criticality assessment.

Considering lessons learnt from past accident analysis, relevant factors were identified for making judgments on the impact of natural hazards. A part of the list is reported in the bottom-left node in Figure 2a. Starting from the list, failure modes of each subsystem are analysed and assigned of criticality scores. From criticality scores it is possible to make risk-informed decision on the state of each barrier. The tailored FMECA is conceived for complex systems, but can easily be applied to simpler systems such as passive barriers as well.

5. Example of application: firefighting water network

The methodology has been applied to the firefighting water network, which provides water to sprinkler system for fire extinguishment, and to water deluge system (WDS) to ensure critical equipment protection from fire (e.g., LPG vessels). Figure 3 shows a reference scheme retrieved from the analysis of commercial solutions.

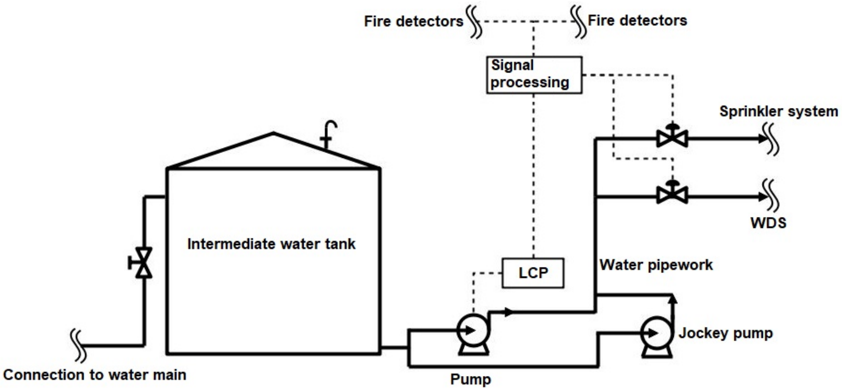


Figure 3: Reference scheme of firefighting water network. The system is connected to sprinklers and to WDS; LCP: local control panel.

The system is composed of a water main feed tank, which is connected to the firefighting water distribution pipework. A signal processing unit is provided for triggering the activation of water pump and opening of valves in water pipework in case of fire detection. A jockey pump (also called pressurization pump) is installed to keep water pipework always in pressure, to ensure appropriate water ejection when nozzles open. It is likely that multiple pumps and multiple jockey pumps are present in real systems. However, in the reference scheme redundancies are not considered, as a conservative choice. Part of the results obtained through FMECA is presented in Table 3. It is worth noting that a too detailed decomposition of the system in subsystems is not needed for the aim of the present analysis. For each subsystem, plausible failure modes and effects are analysed with relative criticality scores, considering a generic flooding event with possible presence of debris.

Table 3: A part of the table for firefighting water network obtained from FMECA. P = plausibility; S = severity; C = criticality.

Subsystem	Failure mode	Local effect	Global effect	P	S	C
Intermediate water tank	Displacement	Rupture of connections, water loss	System Unavailable	2	3	6
	Debris impact	Water loss, tank may remain empty	System potentially unavailable	2	2	4
Connection to water main	Damaged by water velocity	Failure of connection to tank, water loss, tank may remain empty	System potentially unavailable	1	3	3
	Debris impact	Failure of connection to tank, water loss, tank may remain empty	System potentially unavailable	2	2	4
Pump	Flooded	Pump not working (electric motor)	System Unavailable	3	3	9
	Power Outage	No power to pump motor	System Unavailable	4	3	12
Water pipework	Damaged by water velocity	Failure of connections, water pressure loss	System potentially unavailable	2	2	4
	Debris impact	Failure of connections, water pressure loss	System potentially unavailable	2	2	4
Local control panel (LCP)	Flooded	System not working, no signal to pump	System Unavailable	2	3	6
	Power Outage	System not working, no signal to pump	System Unavailable	4	3	12
Jockey pump	Flooded	Pump not working, water pressure loss	System potentially unavailable	3	2	6
	Power Outage	No power to pump motor, water pressure loss	System potentially unavailable	4	2	8
Signal processing	Power outage	System not working	System unavailable	4	3	12

Considering the table obtained, it is clear that the main vulnerability of firefighting water network in case of flood is the dependence of pumps and control systems on power connection, which is usually not available in case of flood (Karagiannis et al., 2017). Thus, safety barriers connected to firefighting water network (such as WDS, sprinklers and foam-water based systems) should be considered unavailable during flooding scenarios: e.g., according to Cozzani et al. (2010), pieces of equipment mostly involved in flood-related failure are atmospheric tanks, while flammable hydrocarbons are the most frequently released substances. Thus, considering a LOC of flammable liquid, pool formation and pool fire over floodwater are possible scenarios (Cozzani et al., 2010). Fire has the potential to trigger domino effect, thus nearby LPG vessels are critical assets and are usually protected with WDS. As previously said, WDS should be considered unavailable, thus escalation of Natech accident is more likely with respect to the case of accident from conventional failure. This can be represented through the Event Tree (ET) reported in Figure 4. Conventional WDS Probability of Failure on Demand (PFD) and effectiveness (η) are PFD = 4.33e-2 and η=1, respectively (Landucci et al., 2016). Gate symbolism is the same as in (Landucci et al., 2016).

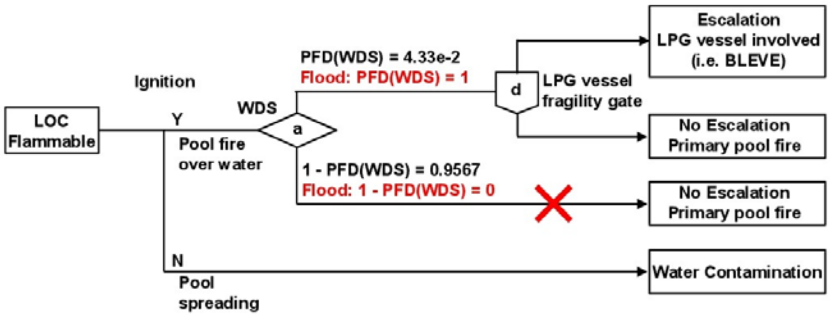


Figure 4: Event Tree for Natech-domino accident triggered by flood. PFD for LPG protection WDS is reported in black (Landucci et al., 2016), while tailored PFD for WDS in case of flood is in red. BLEVE: boiling liquid expanding vapour explosion. See (Landucci et al., 2016) for gates definition.

During flood-triggered scenarios, PFD should be considered unitary since the barrier relies on water supply from firefighting water network, which is not available because power outage is extremely likely. It is clear from the ET that the worst scenario (catastrophic failure of LPG vessel, with consequent BLEVE and fireball) results to be more probable, and that if WDS was evaluated unaffected by flood, the calculation would have led to underestimate worst scenario likelihood.

6. Conclusions

In the present study, the issue of taking into account safety barriers in Natech risk assessment is introduced with specific focus on floods. A short selection of case histories is presented, highlighting that safety barriers can be unavailable in case of natural hazards. Some failure patterns have been identified, and FMECA is presented for the safety barrier assessment, since they should not be taken for granted in case of complex scenarios, such as Natech accidents. In particular, natural hazards are likely to affect lifelines and power grid connection, impeding the activation of protection systems. The methodology is applied to the firefighting water network, showing its vulnerability to floods. It is demonstrated that considering WDS unaffected by flood would lead to underestimation of high consequence scenarios (i.e., domino scenario following Natech accident).

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