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Quantitative Risk Assessment of Cascading Events Triggered by Floods

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NaTech (natural-technological) events caused by the impact of floods on industrial facilities may lead to major accidents following damages to structures and equipment. In this study, we explored the quantitative assessment of NaTech accidents triggered by floods. A specific methodology was developed, adopting equipment vulnerability models aimed at determining the failure frequency of equipment affected by flooding. A reference case study was analysed, taking into account a flood scenario impacting on an industrial facility. Risk results with and without flood-triggered NaTech scenarios were compared, determining the influence of NaTech scenarios on the overall risk profile.

1. Introduction

An increasing concern is present worldwide for the impact of cascading effects triggered by natural events (Youg et al. 2004). Severe scenarios may be expected if the impact of floods on process plants where relevant quantities of hazardous substances are stored or processed (Cozzani et al. 2010). Loss of containment (LOC) of hazardous materials may be expected, leading to direct impact on the population and to possible mid- and long term effects on the environment due to the release of chemicals in flood water. These events are usually defined as “natural-technological” (NaTech) accidents (Youg et al. 2004). Specific studies (Salzano et al., 2009) demonstrated that NaTech events often occurred in the past, affecting industrial facilities (Renni et al., 2010) and treatment plants (Panico et al., 2013).

Therefore, considering NaTech scenarios in the framework of safety reports and of Quantitative Risk Assessment (QRA) of industrial facilities, where relevant quantities of hazardous substances are stored or processed, is of utmost importance (Cruz et al., 2006). This may allow for the correct assessment of the risk associated to site operation and for the robust and effective emergency planning in residential areas near to these industrial sites and in perspective may become a requirement for the safe operation of such sites.

The present study is aimed at exploring the quantitative assessment of risk caused by floods impacting on industrial facilities where relevant quantities of hazardous substances are present. Specific equipment vulnerability models were implemented in a QRA methodology, allowing a detailed calculation of risk profiles due to NaTech events triggered by floods. A reference case study was defined and analyzed comparing results with and without flood-triggered NaTech scenarios.

2. Methodology

The methodology for the introduction of NaTech scenarios in Quantitative Risk Assessment was developed in a previous study (Antonioni et al. 2009) and is summarized in Figure 1. The recent updates to the methodology are briefly discussed in the following.

The starting point of the methodology is the identification of reference flood conditions, thus determining the reference scenarios to be considered in the QRA. Each flood event needs to be characterized in terms of frequency and of severity by a sufficiently simple approach, suitable for the use in a risk assessment framework (step 3). The standard parameter for flood frequency evaluation is the return period (τ), that is given by hydrological studies and is usually available from local competent authorities. The flooding frequency (f) can thus be estimated as follows:

$$f = 1/\tau \tag{1}$$

Next, an impact vector, whose elements represent the severity of the flood scenario, needs to be defined for each of the reference scenarios selected. Flood severity can be quantified by two parameters (Cruz et al., 2006): water effective depth (h_w) and water speed (v_w). The effective depth should take into account the possible effect of protection measures, such as concrete supports higher than the ground level to which the vessel saddles are fixed. Simplified hazard ranking criteria based on inventory and physical state of hazardous substances may be used to identify critical equipment items that should be included in the analysis (step 4) (Antonioni et al. 2009). The application of equipment vulnerability models is then needed to assess the equipment damage probability (step 5). These models are discussed in the Section 2.1. Consequence assessment of the single scenarios triggered by the natural event (step 6) may be carried out by using conventional models (Van DenBosh & Weterings 2005).

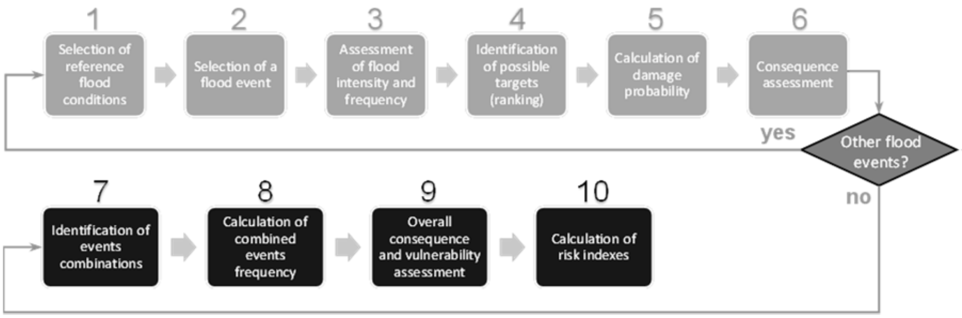

Figure 1: Overview of the methodology adopted for the QRA of NaTech scenarios caused by flood.

2.1 Equipment vulnerability models

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. have developed a simplified approach to evaluate the failure probability of vertical atmospheric tanks for liquid storage (Landucci et al. 2012) and of horizontal atmospheric or pressurized vessels (Landucci et al. 2014). The approach is based on the evaluation of vessel mechanical integrity under the action of the flood, which results in both a “static” external pressure component, due to the depth of the flooding (h_w), and in a “dynamic” external pressure component, due to the flood water velocity (v_w) and to the associated drag force. It is worth mentioning that the failure following the mechanical impact by objects transported in the water is not accounted in the model.

In the case of atmospheric vertical vessels, it was evidenced that the vessel filling level is the more relevant parameter for the evaluation of the equipment integrity and of the failure probability. Thus, a critical filling level (CFL) was defined for each equipment item involved in a specified flooding event of given intensity (e.g., having assigned h_w and v_w), as the liquid level below which the failure for instability is possible. The CFL for atmospheric vertical vessel is evaluated as follows:

$$CFL = \left(\frac{\rho_w k_w}{2} v_w^2 + \rho_w g h_w - P_{cr} \right) \Big/ \rho_f g H \tag{2}$$

where ρ_w = flood water density (1100 kg/m^3); k_w = hydrodynamic coefficient (1.8); g = gravity acceleration (9.81 m/s^2); ρ_f = stored liquid density (kg/m^3); and H = vessel height (m). P_{cr} is the instability critical pressure of the vessel and may be derived applying the following simplified correlation (Landucci et al. 2012):

$$P_{cr} = J_1 C + J_2 \tag{3}$$

where C = vessel capacity (m^3); J_1 = -0.199 Pa/m^3; and J_2 = 6950 Pa.

On the basis of the CFL, the vessels damage probability (Ψ) is derived by the ratio between the “unsafe” operative conditions with respect to all the possible operative conditions, represented by the filling level ϕ:

$$\Psi = \left(CFL - \phi_{\min} \right) / \left(\phi_{\max} - \phi_{\min} \right) \tag{4}$$

In the present approach, for the sake of simplicity, a linear distribution of possible operative filling levels between ϕ_{min} (=1%) and ϕ_{max} (=75%) is assumed in the definition of Ψ for vertical vessels. Nevertheless, more specific data, when available, may be introduced in Eq. (4) to obtain an equipment-specific vulnerability model. The approach was extended by Landucci et al. (2014) in order to obtain the fragility model for horizontal cylindrical vessels, both atmospheric and pressurized. In this case, the possibility of having a rupture following the flood event is related to the resistance of the connection between the vessel framework and the ground. In order to estimate the failure probability of a horizontal vessel due to flood impact, two threshold parameters were used as a reference: the critical water velocity, $v_{w,c}$ and the CFL for horizontal vessels. CFL is evaluated in this case with the simplified correlations reported below, adopting ϕ_{min} (=1%) and ϕ_{max} (=90%):

$$CFL = (\rho_{ref} \cdot A)/(\rho_l - \rho_v) \cdot (h_w - h_c) + (\rho_{ref} \cdot B - \rho_v)/(\rho_l - \rho_v) \tag{5}$$

where ρ_{ref} = 1000 kg/m^3, ρ_l and ρ_v are respectively the stored liquid and vapour densities, h_c is the height of concrete basement (= 0.25 m in the present study), A and B are coefficients summarized in Table 1. The parameter $v_{w,c}$ represents a threshold condition for velocity over which the drag force generated by flood water is sufficient to cause the failure of the bolt connection for a given floodwater height. The simplified correlations for the estimation of $v_{w,c}$ is reported below, with coefficients defined in Table 1.

$$v_{w,c} = E \cdot (h_w - h_c - h_{\min})^F \tag{6}$$

If flood water speed is higher than $v_{w,c}$, the failure probability is unitary (Ψ = 100%) without adopting the criterion based on the CFL (e.g. by applying Eq. (4).

Table 1: Coefficients of the simplified correlation for the estimation of horizontal vessels critical filling level and water critical velocity (Landucci et al. 2014)

Correlation coefficient	Equation	Definition
A	5	A = 1.339×D$^{-0.989}$, D = tank diameter (m)
B	5	B = -1.2 (W$_t$-374.4)$^{-0.107}$, W$_t$ = vessel tare weight (ton)
E	6	E = 5.497×L$^{-0.692}$, L = vessel length (m)
F	6	F = -0.06 ln(L/D)-0.375

2.2 Consequence assessment and risk recomposition

The main assumptions introduced for the consequence assessment of NaTech scenarios triggered by floods are summarized in the following.

For horizontal vessel, flooding may cause vessel displacement, with following rupture of pipe connections and nozzle flanges. Thus, the release event was selected as the more severe between: (1) the release of the entire content of the vessel considering a full bore rupture of pipe connections (release type R1); and (2) the release in 10 min of the entire inventory (release type R2). Moreover when a dispersion model is applied for the calculation of toxic effects or of flash-fire thresholds, values in the range of 0.1 to 1mm (e.g., typical of water surfaces) should be selected for the roughness length (Van DenBosh & Weterings 2005).

For atmospheric vertical tanks, a flood can affect the integrity of the tank shell due to its limited thickness. Hence, a catastrophic release can be assumed and the resulting liquid pool can be considered unconfined (release type R3). In fact, flood water level must be higher than a possible catch basin wall in order to affect the tank. Other possible interactions among the released chemicals and the water are not accounted for the sake of simplificy.

On the basis of the above defined release scenarios and source terms, Event Tree Analysis (ETA) was applied to determine the possible final outcomes according to conventional procedures as those of the “Purple Book” (Uijt de Haag and Ale, 1999). Physical effects associated to the final outcomes of the release scenarios were calculated by literature models (Van DenBosh & Weterings 2005).

Steps 7-10 were carried out following the NaTech risk assessment framework introduced for domino effect risk assessment (Cozzani et al. 2014). A single accidental scenario induced by flooding may thus be defined as an event involving the contemporary damage of k of n units resulting in k final outcomes, with k comprised between 1 and n. The total number of different overall scenarios that may be generated by a single flooding condition, N_f, may be calculated as follows:

$$N_f = \sum_{k=1}^{n} \binom{n}{k} = 2^n - 1 \tag{7}$$

The probability of a single overall NaTech scenario involving the contemporary damage of k units resulting in k events due to flooding, identified by the vector $\mathbf{J}^k_m$, may be calculated as follows:

$$P_f^{(k,m)} = \prod_{i=1}^{n} \left[1 - \psi + \delta\left(i, \mathbf{J}_m^k\right)\left(2\psi - 1\right)\right] \tag{8}$$

where the function $\delta(i,\mathbf{J}^k_m)$ equals 1 if the i-th event triggered by flooding belongs to the vector $\mathbf{J}^k_m$, 0 if not. The expected frequency of the m-th overall flooding scenario involving k simultaneous equipment damages, $f_f^{(k,m)}$, may be calculated as:

$$f_f^{(k,m)} = f \cdot P_f^{(k,m)} \tag{9}$$

where *f* is evaluated according to Eq. 1. In order to limit the number of combinations considered for the risk assessment, a frequency cut-off value was assumed, excluding combinations of events having frequency lower than 10^{-10} 1/y. More details on the determination of scenario combinations are provided by Antonioni et al. 2009.

3. Application to a case study

In order to demonstrate the application of the methodology and to understand the importance of considering flood-induced NaTech scenarios, a QRA of a case-study was carried out. The layout of the industrial facility selected for the study is shown in Figure 2.

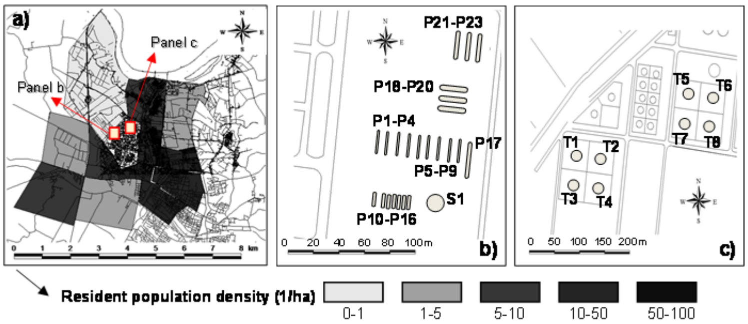

Figure 2: Layout for the case study: overview and population density (a); equipment positioning (b and c)

Table 2: Main features of the vessels selected for the case study. LG = liquefied gas, L = liquid.

Features	P1-P9	P10-P16	P17	P18-P20	P21-P23	S1	T1-T4	T5-T8
Capacity (m^3)	50	30	115	150	100	3179	6511	6511
Diameter (m)	2.7	2.4	2.75	3.2	2.8	15	24	24
Length or Height (m)	10	6.5	20.1	19.4	18	18	14.4	14.4
Shell thickness (mm)	23	21	24	27	24	12.5	12.5	12.5
Tare weight (ton)	12.3	5.9	29.2	36.1	26.2	110	165	165
Filling level	90%	90%	90%	90%	90%	75%	75%	75%
Substance	Propylene	Propane	LPG[a]	Ammonia	Chlorine	Solvent[c]	Gasoline	Benzene
Physical state	LG	LG	LG	LG	LG	L	L	L
Pressure (bar)	8	8.5	2	8.5	6.7	1.05	1.05	1.05
Liquid density (kg/m^3)	615	450	550	600	1400	650	750	877
Vapor density (kg/m^3)	13.8	15.4	4.8	4.9	19.3	0.97[b]	0.97[b]	0.97[b]
Inventory (ton)	32	12	59	84	140	1550	3656	4275
Release type[d]	R2	R2	R2	R2	R2	R3	R3	R3
Final outcome	Flash fire	Flash fire	Flash fire	Tox. disp.	Tox. disp.	Pool fire	Pool fire	Pool fire
Frequency (1/y)	4.5×10^{-7}	4.5×10^{-7}	4.5×10^{-7}	5.0×10^{-7}	5.0×10^{-7}	4.5×10^{-6}	4.5×10^{-6}	4.5×10^{-6}

a: assumed as pure butane; b: average density of the purge gas (e.g., nitrogen blanketing); c: flammable liquid; see definition in Section 2.2

Table 2 reports the features of the vessels considered and the inventories of hazardous substances. Both horizontal and vertical tanks were considered, as shown in Figure 2b and 2c. All the horizontal vessels were assumed to be supported on a concrete base (0.25m higher respect to ground level).

Figure 2a shows the population density adopted for the calculation of societal risk. A single flood scenario was considered in the QRA study, with a return time of 500 y, water depth h_w = 2 m and water velocity v_w = 0.5 m/s. The flooding frequency was derived applying Eq. (1), obtaining f = 2×10^{-3} 1/y.
In order to understand the importance of NaTech scenarios triggered by floods, a QRA of the "conventional" scenarios due to internal failures was first performed, to obtain reference values for individual and societal risk. The expected frequency of top events were defined according to (Uijt de Haag and Ale 1999) and are summarized in Table 2. The physical effects calculated by literature models (Van DenBosh & Weterings 2005) were then implemented in the Aripar-GIS software (Cozzani et al. 2014).

4. Results and discussion

Table 3 shows the release frequencies obtained from the equipment vulnerability models considering the reference flood scenarios and the equipment geometrical data. The failure probabilities calculated were lower than 20% for atmospheric tanks. In the case of pressurized horizontal vessels, higher vulnerability values (up to 100% failure probability) were obtained. As shown in Table 3, the critical velocity $v_{w,c}$ for all the pressurized tanks is higher than the value of v_w assumed for the case study. Hence, tank failure probability was evaluated only according to the estimated CFL, thus due to the high depth of the considered flooding.

Table 3: Vessel failure probability and frequency of loss of containment calculated for the case study.

Vessel	$v_{w,c}$ (m/s)	CFL	Vulnerability (%)	Frequency (1/y)
P1-P9	0.9	0.699	77.40%	1.55×10^{-3}
P10-P16	1.24	1	100.00%	2.00×10^{-3}
P17	0.56	0.832	92.30%	1.85×10^{-3}
P18-P20	0.57	0.576	63.60%	1.27×10^{-3}
P21-P23	0.6	0.304	33.00%	6.60×10^{-4}
S1	-	0.135	16.90%	3.38×10^{-4}
T1-T4	-	0.153	19.30%	3.86×10^{-4}
T5-T8	-	0.131	16.30%	3.26×10^{-4}

Table 4: Cumulated frequencies of flood-triggered scenarios, considering the possible failure combinations. FF = Flash fire; TOX = toxic dispersion of ammonia or chlorine; PF = pool fire

P1-P9	P10-P16	P17	P18-P20	P21-P23	S1, T1-T4, T5-T8	Simultaneous final outcomes	Cumulated frequency (1/y)
D	AD	AD	D	ND	ND	TOX & FF	3.42×10^{-4}
D	AD	AD	D	ND	D	TOX & FF & PF	2.18×10^{-4}
D	AD	AD	ND	ND	ND	FF	1.96×10^{-4}
D	AD	AD	D	D	ND	TOX & FF	1.68×10^{-4}
ND	AD	AD	D	ND	ND	TOX & FF	9.98×10^{-5}
D	AD	AD	ND	D	ND	TOX & FF	9.63×10^{-5}

On the basis of the failure frequencies estimated from the equipment vulnerability models, about 30000 scenarios (over a total number of 2^{32}–1 possible combinations) resulted in a frequency value above the cut-off value of 10^{-10} 1/y, but only 11000 of them contribute significantly to the overall risk. For the sake of simplicity, a summary of the scenarios triggered by the reference flood event are reported in Table 4, where also their description and expected simultaneous final outcomes are described.
Figure 3a reports the individual risk calculated for the conventional scenarios considered for the case-study. The risk contour at the threshold value of 10^{-6} 1/y is within the industrial area, while only lower individual risk levels are present in the residential areas. Societal risk is expressed in terms of Potential Life Loss (PLL), 7.5 fatalities per thousand year are expected. When flood-triggered NaTech scenarios are considered, individual risk values increase up to three order of magnitude with respect to those obtained considering only conventional scenarios (see Figure 3b). This is mainly due to the fact that typical flood frequencies calculated on the basis of the expected return times are higher than the typical baseline frequencies for technological accidents. Moreover, multiple scenarios increase the severity of the consequences due to the simulations failure of equipment. This is confirmed by the values calculated for PLL, that increased to 4 fatalities/y when including NaTech events. The analysis of the case studies demonstrated that a high impact on the risk profile of industrial facilities storing and processing hazardous materials is associated to NaTech scenarios caused by flood events. This is due to the fact that, in flood-prone zones, flooding frequencies may reach values that

are orders of magnitude higher with respect to those related to component failures due to internal causes (e.g., mechanical failure, corrosion, erosion, rupture induced by vibrations, etc.). Therefore, a risk-based approach might be suggested for the design of supports and anchorage of safety-critical units, as those storing or processing flammable or toxic liquefied gases under pressure. The protection design should take into account both parameters related to the credible flooding scenarios and the resistance of the vessel.

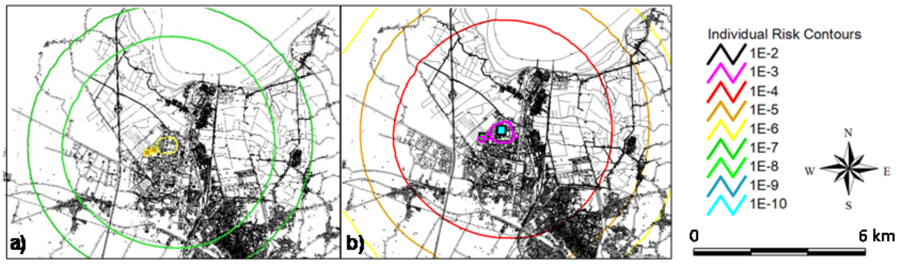

Figure 3: Individual risk contours (1/y) calculated for a) accident scenarios deriving from conventional release events due to internal failures; b) introducing NaTech triggered by flooding.

5. Conclusions

A methodology for the assessment of risk contribution associated to NaTech scenarios triggered by floods was presented. The methodology was based on the implementation of equipment vulnerability models to calculate the failure probability of tanks as a function of flood severity. The application to a case-study confirmed that NaTech scenarios caused by floods may have an important influence on industrial risk. The methodology application also highlighted the importance of an appropriate design of the vessel supports and basements to limit the potential impact of floods on process and storage equipment.

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