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Damage Models for Storage and Process Equipment Involved in Flooding Events

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The present study focuses on the accidents caused by the impact of floods on storage and process equipment. This type of accident is classified as a NaTech (Natural-Technological) event and resulted in severe consequences in several past accidents. A methodology was developed for the determination of vulnerability models aimed at the estimation of equipment damage probability on the basis of severity or intensity parameters of the flooding. A mechanical model was developed, based on the comparison between the flooding intensity and the resistance of a vessel and/or its support. Simplified vulnerability functions were derived. Finally, a case-study was set up and analysed to show the potentialities of the methodology and the implementation of results in quantitative risk analysis.

1. Introduction

In the framework of chemical and process industry, severe accidents can be triggered by the impact of natural events on process and storage equipment, leading to the loss of containment (LOC) of dangerous substances (Young at al. 2004, Cozzani et al. 2010). This type of accidents, defined as "natural-technological" (NaTech) events, occurred several times in the past, as shown by the analysis of major accident databases (Krausmann et al. 2011a,b) as well as from specific studies (Cruz et al. 2006, Renni et al. 2010, Salzano et al. 2003, Salzano et al. 2009), often leading to catastrophic consequences. The recent catastrophic events occurred in Japan after the Tōhoku earthquake and consequent tsunami (April 2011) evidenced the potential severity of NaTech accidents.

Therefore, the implementation of NaTech scenarios in the framework of Quantitative Risk Assessment (QRA) is a critical task, since a significant risk contribution can be associated to the occurrence of natural events, depending on the plant location (Cruz et al. 2006, Campedel et al. 2008, Antonioni et al. 2009). In order to derive the frequencies of accidental scenarios associated to NaTech events for QRA implementation, a critical issue is the availability of equipment fragility models. These models are aimed at the estimation of equipment damage probability on the basis of the severity of the natural event. Due to the features of a QRA study, that usually requires the assessment of a high number of scenarios, the use of simplified models able to yield a conservative estimation of equipment failure conditions is required to effectively support the assessment of equipment vulnerability (Landucci et al. 2009, Paltrinieri et al. 2009).

The present study was devoted to the vulnerability assessment of process and storage vessels involved in flood events. These equipment items are the more critical units for this type of scenario according to past accidents data analysis (Cozzani et al. 2010). In order to evaluate the resistance of process equipment to flood events, a mechanical model was developed, based on the comparison between the flooding intensity and the resistance of a vessel. The model, validated against the available data obtained from past accident records, was applied in order to derive vulnerability functions for vessels involved in flooding. In order to explore the model features and potentialities, two case-studies were carried out, analysing an actual industrial layout.

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2. Methodology

The approach proposed to assess the vulnerability of equipment items involved in flood events is schematized in Table 1. The key aspect of the methodology and its implementation in Quantitative Risk Analysis (QRA) studies are discussed in the following.

Table 1: Methodology for the assessment of equipment vulnerability

Step	Description
1	Simplified schematization of the reference equipment category
2	Development of a model for mechanical failure under flood loads
3	Model validation (literature data)
4	Derivation of simplified relations for vessel damage probability
5	Estimation of loss of containment event frequencies

2.1 Identification of reference equipment

From the analysis of past accidents triggered by floods (Cozzani et al. 2010), it was evidenced that atmospheric and pressurized storage tanks are the process items that were more frequently damaged in flood events. If equipment geometries are considered, the first vessel type consists in a vertical cylinder with fixed or floating roof operating at atmospheric pressure. If relevant storage capacities are considered (above 10t and/or 10m^3), a flat bottom directly fixed to the ground with a dap joint is usually present. This type of vessel is mainly used for liquid storage (See Figure 1a). The second type of vessel features a cylindrical shape with hemispherical or ellipsoidal bottoms. Usually such vessels are horizontally disposed on saddles or other support types. In the present study, the vessels were considered completely blocked on one edge, while on the other a free slip was present on the vessel axis as schematized in Figure 1b. This solution is often employed in order to avoid stress increase due to thermal dilatation.

Table 2: Reference vessel geometries considered in the present study. See Figure 1 for vessel sketch and parameters identification.

Vessel type	Vessel class	D (m)	H (m)	t (mm)	Capacity (m^3)	S (m)	P_{cr} (Pa, see Eq.6)
Atmospheric	Small capacity	3-42	3.6–18	5–12.5	< 5000	-	6932–19285
	Medium capacity	21-54	3.6–16.2	12.5	5000 – 10000	-	5180–11171
	Large capacity	48-66	3.6-7.2	12.5-15	>10000	-	4361-12666
Pressurized	Small capacity	1.3-1.6	3.0-3.5	11-14	<10	0.98	-
	Medium capacity	1.6-2.4	4.5-11.1	14-20	10-30	0.98-1.38	-
	Large capacity	2.5-3.8	8.0-24.0	21-32	>30	1.38-1.98	-

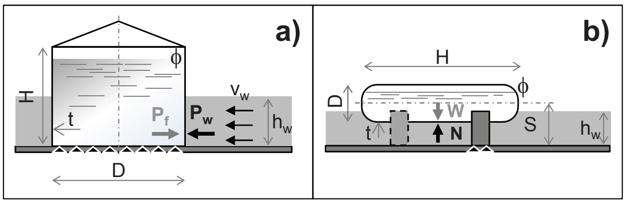


Figure 1: Schematization of a) atmospheric vertical tanks and b) horizontal pressurized tanks.

Table 2 reports the features of the vessels considered in the present study. A specific vessel database was built (Landucci et al. 2012). Vessel geometries were obtained from typical design data used by engineering companies in the chemical and process industry. The design data of the atmospheric tanks were based on API 650 standards, while the volumes and diameters were based on data from several oil refineries. In the case of pressurized vessels, the volumes and diameters were derived from vessels typically used for LPG, vinyl chloride, chlorine and ammonia pressurized storages. Cylindrical vessels with horizontal axis and design pressures between 1.5 and 2.5 MPa were considered. The design data were verified with respect to section VIII of the ASME codes.

2.2 Mechanical model set up

Figure 1a schematizes the forces acting on the atmospheric vessels when impacted by a flood wave. The external load present on the tank shell, namely P_w, is obtained as the sum of a “static” pressure component P_{ws} and of a “dynamic” pressure component P_{wd}:

$$P_w = P_{ws} + P_{wd} = \rho_w \, g \, h_w + \tfrac{1}{2} \, \rho_w \, k_w \, v_w^2 \quad (1)$$

where h_w and v_w are respectively the flooding height and velocity, g is the gravity constant (9.81 m/s^2), ρ_w is the density of the floodwater and k_w is the hydrodynamic coefficient (Gudmestad and Moe 1996). The static pressure component P_{ws} is due to the hydrostatic load of the floodwater, while the dynamic component is due to the drag force associated to the kinetic energy of the wave. For the sake of simplicity, a constant temperature of 293 K and an atmospheric pressure of 1.01 bar were assumed in the present study, thus considering constant the fluid properties in the above relations.

The internal pressure of the tank, P_f, related to the hydrostatic pressure of the internal liquid hold up, has an important role in the evaluation of the resistance of the tank to flood external pressure, as shown in Figure 1. The maximum P_f value, at the bottom of the vessel, may be expressed as follows:

$$P_f = \rho_f \, g \, H \, \phi \quad (2)$$

where ρ_f is the density of the inner fluid, H is the height of the tank and ϕ is the filling level. Therefore, the net pressure P_{net} on the vessel shell may be derived from a simple force balance:

$$P_{net} = P_{ws} + P_{wd} - P_f \quad (3)$$

The external P_{net} acting on the vessel may cause the structural integrity loss by buckling. This phenomenon is described in detail in the literature (Timoshenko and Gere 1961) and typically affects atmospheric vessels. According to Timoshenko and Gere (1961), buckling may occur if the P_{net} reaches a critical value, indicated in the following as P_{cr} (critical pressure). P_{cr} depends only on the vessel geometry and on the construction material, and is independent from the loading conditions. P_{cr} may be calculated by the following expression:

$$P_{cr} = \frac{2\,E\,t}{D}\left\{\frac{1}{\left(\left(n^2-1\right)\left[1+\left(\frac{2nH}{\pi D}\right)^2\right]^2\right)} + \frac{t^2}{3(1-\nu^2)D^2}\left[n^2 - 1 + \frac{2n^2-1-\nu}{\left(\frac{2nH}{\pi D}\right)^2 - 1}\right]\right\}; \quad n \ge \left(\frac{\pi}{2}\right)\left(\frac{D}{H}\right) \quad n \ge 2 \quad (4)$$

In which E and ν are respectively the elastic modulus and Poisson's ratio of the construction material, t and D the vessel thickness and diameter and n is an integer number which minimizes P_{cr}. Therefore, given a set of vessels of interest, the P_{cr} is evaluated and compared with the P_{net}, which results from different flooding and storage/processing conditions. If P_{net} is higher than P_{cr} the failure for instability of atmospheric vessels is hence predicted by the model.

The same type of approach was extended in order to set up the mechanical model for horizontal cylindrical vessels, which schematization is reported in Figure 1b. 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 (e.g., saddle or other support structures) and the ground. As reported in the results of past accident data analysis (Cozzani et al. 2010), the rupture of the framework may cause the displacement of the vessel, with the consequent rupture of the vessel connections and potential impact with adjacent units or structures. Hence, the possibility of having a LOC following a flood impact is directly related to the integrity of the framework connection to the ground. The connection is subjected to the lift force due to floating action of the floodwater and, on the same time, by the shear action due to the flood wave drag force. For preliminary evaluations, only the flood lift force was considered in the present study (marked with N in Figure 1b). Hence, if this force is higher than the whole structure weight (marked with W in Figure 1b), thus including both steelwork and inner fluid weight, the failure occurs. This evaluation is on the safe side and may be expressed as follows:

$$N > W \Rightarrow \omega(h_w, D, H, S)\, g \rho_w V_{ext} > \rho_s g\left(V_{ext} - V_{int}\right) + \phi \rho_f g V_{int} \quad (5)$$

where V_{int} and V_{ext} are respectively the inner and outer volume of the vessel, ρ_s the density of the construction material, and ω is the fraction of the total volume submerged by the flooding. This latter parameter depends on the flood height (h_w), but also on the vessel geometry (diameter D and length H) and framework height (S) as expressed by the geometrical relationships summarized in Table 3. Finally, Table 4 summarizes the parameters selected for the present study. The critical pressure of the atmospheric vessels (P_{cr}) is reported in Table 2 for the database vessels. More details on the mechanical model set-up are reported elsewhere (Landucci et al. 2012).

Table 3: Definition of the submerged fraction of a horizontal cylindrical vessel.

ID	Equation	Parameters definition
(a)	$h = min[(h_w-(S-R));D]$	h = Geometrical parameter; R = D/2
(b)	$V_{sub} = min[H(0.5\pi R^2+R^2 arcsin((h-R)/R)+(h-R)(2hR-h^2)^{0.5});V_{ext}]$	V_{sub} =Submerged vessel volume
(c)	$\omega = V_{sub} / V_{ext}$	Submerged vessel fraction

Table4: Values of parameters assumed as constant in the present study.

Parameter	Value	Units	Source
E	2.1×10^{11}	Pa	American Society of Mechanical Engineering codes
k_w	1.8	-	Gudmestad and Moe 1996
ν	0.3	-	American Society of Mechanical Engineering codes
ρ_f	1000*	kg/m^3	American Petroleum Institute (API) Standard 650
ρ_s	7800	kg/m^3	American Society of Mechanical Engineering codes
ρ_w	1100	kg/m^3	Gudmestad and Moe 1996

* Assumed for model validation

2.3 Model validation

Data on flood damage to equipment items are scarce and not detailed, often providing only qualitative information (Young et al. 2004,Cozzani et al. 2010, Krausmann et al. 2011a,b). Hence, in order to validate the model, a damage threshold was derived from a previous study based on an extended past accident analysis (Rijkswaterstaat 2005, Landucci et al. 2012). The damage threshold was estimated as the value of external pressure P_w below which vessel damage and/or loss of containment was never reported in past accidents. This resulted equal to 9.4 kPa, associated to a flood wave with a velocity of 2 m/s and a maximum height of 0.5 m. Failure model predictions may be validated comparing the resistance of the vessels considered in the database (see Table 2) with respect to the damage threshold considered.

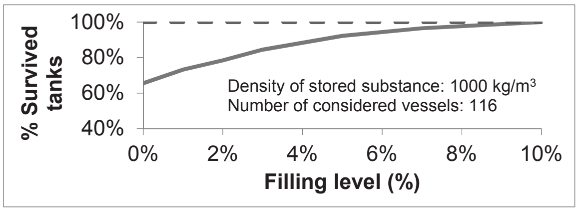


Figure 2: Results of the validation for atmospheric vessels: fraction of the tanks able to withstand the reference flood impact as a function of the filling level.

Figure 2 shows the fraction (%) of atmospheric vessels able to withstand the reference flooding conditions. Most of the vessels (more than 65%) do not fail even when empty. When different liquid levels are considered, the results evidence that all the vessels are able to withstand the reference flooding conditions when filling level is higher than 10%. In the case of pressurized vessels, the reference flooding condition leads to negligible damages to the framework, thus no damage is predicted by the model even in the case of empty tanks. Therefore, the validation evidenced that failure conditions predicted by the model are in sufficient agreement with the available literature data.

2.4 Evaluation of vessels vulnerability and damage frequency

In Section 2.3 it was evidenced that the filling level is the key operating parameter for the definition of the tank resistance to a given flood scenario. Hence, in order to estimate the probability of possible vessel damage, i.e., the vessel vulnerability to a flood, the introduction of a “critical filling level” (CFL) may be used as a reference. The CFL may be defined as the minimum residual filling level able to increase the inner vessel pressure or weight in order to withstand the flood. As suggested by Landucci et al. (2012), in the case of atmospheric vessels the CFL may be expressed modifying eq.(3) and the terms defined in Eqs. (1) and (2) obtaining the following expression:

$$CFL_{atm} = \frac{\frac{\rho_w k_w}{2} v_w^2 + \rho_w g h_w - P_{cr}}{\rho_f g H} = \frac{P_{ws} + P_{wd} - P_{cr}}{\rho_f g H} \qquad (6)$$

Similar considerations can be introduced for pressurized vessels, recombining eq.(5) as follows:

$$CFL_{press} = \frac{\rho_s}{\rho_f} + \frac{\omega\rho_w - \rho_s}{\rho_f}\frac{V_{ext}}{V_{int}} \tag{7}$$

According to its definition, the CFL delimits the "safe" operating conditions for a selected vessel (either atmospheric or pressurized) given the flood parameters, v_w and h_w. If the filling level is lower than the CFL, the tank is in the "unsafe" zone since the vessel is not able to resist to the external pressure. On the basis of these considerations, the vessels damage probability Ψ is derived by the ratio between the "unsafe" operative conditions with respect to all the possible operative conditions:

$$\Psi = \frac{CFL - \phi_{min}}{\phi_{max} - \phi_{min}} \tag{8}$$

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. Nevertheless, more specific data, when available, may be introduced in eq. (8) to obtain an equipment-specific vulnerability model.
Once evaluated the damage probability Ψ associated to the flood event with fixed intensity (v_w;h_w) for each vessel, frequency f_{LOC} (1/y) associated to the damage induced by flooding may be calculated multiplying the damage probability, Ψ, by the frequency, of the occurrence of the considered flood event, f (1/y).

3. Results and discussion

3.1 Definition of the case studies

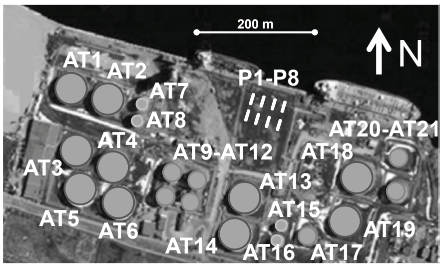
In order to test the potential of the methodology in a typical QRA framework, a vulnerability analysis of a tank farm (Figure 3) was carried out to assess the expected damage probability and the associated hazardous materials release frequencies (f_{LOC}) caused by severe flood conditions. Figure 3 summarizes the features of the vessels analysed and reports the densities of the stored substances. Two reference flooding scenarios were considered:

- Case study A: flood velocity $v_{w,A}$= 2 m/s and height $h_{w,A}$ = 0.5 m with expected frequency of $4x10^{-3}$ 1/y.
- Case study B: flood velocity $v_{w,B}$= 0.5 m/s and height $h_{w,B}$ = 2 m with expected frequency of $2x10^{-3}$ 1/y.

In both case studies, the values of flood frequency were derived from site specific data obtained by local authorities. Specific models are available in the literature for these parameters (Rijkswaterstaat 2005).

3.2 Vessels vulnerability and failure frequencies

Table 5 reports the vulnerability values obtained for the tanks applying the CFL approach. In the case of high velocity flooding with limited water height (e.g., case study A) lower values of ψ are obtained, while in the case of more severe flooding with high water depth (e.g., case study B), all the tank farm is subjected to severe damages. The atmospheric tanks with higher capacity are less resistant with respect to the smaller ones, due to the lower values of critical pressure (P_{cr}, see Eq.4 and Table 2). It is worth to remark that these less resistant vessels are also featured by higher inventories of hazardous materials, thus damage is likely to result in more severe accident scenarios. The pressurized vessels are not affected by limited depth waves since they are usually supported at a higher height with respect to the ground (see Figure 1). Nevertheless a high vulnerability is expected in case of high depth flooding. Table 5 shows also the evaluated LOC frequencies calculated for each tank on the basis of vulnerability assessment for the two case studies ($f_{LOC,A}$ and $f_{LOC,B}$). As shown in Table 5, LOC frequency values range between 4×10^{-6} and 2×10^{-3} 1/y. It should be remarked that LOC events due to internal failure causes usually have comparable or even lower frequencies (Uijt de Haag and Ale 1999), confirming that in flood-prone zones, NaTech scenarios triggered by floods may have potentially a significant impact on the risk profile of an installation.



Atmospheric tanks	C (m^3)	D (m)	H (m)	t (mm)	P_{cr} (Pa)	ρ_f (kg/m^3)
AT1,AT2	12361	54	5.4	12.5	5221.3	950
AT3-AT6	8241	54	3.6	12.5	11171	750
AT7,AT8	4120	18	16.2	12.5	7815.3	900
AT9-AT12	7630	30	10.8	12.5	5563.7	650
AT13,AT14	12361	54	5.4	12.5	5221.3	750
AT15,AT16	4120	18	16.2	12.5	7815.3	1100
AT18,AT19	12361	54	5.4	12.5	5221.3	850
AT17,AT20,AT21	5087	30	7.2	12.5	8603.3	750

Pressurized tanks	C (m^3)	D (m)	H (m)	t (mm)	V (m)	ρ_f (kg/m^3)
P1-P8	100	2.8	18	24	1.58	500

Figure 3: Layout of the case study considered. The panel shows the characteristics of the vessels considered and stored fluid density. P_{cr} is evaluated by Eq.4. See Figure 1 for parameter definition.

Table 5: Results of the case study: vessels vulnerability (ψ, %) and expected failure frequency (f_{LOC}, 1/y) as a function of the critical filling level (CFL in %).

Vessel ID	Case study A			Case study B		
	CFL (%)	ψ (%)	f_{LOC} (1/y)	CFL (%)	ψ (%)	f_{LOC} (1/y)
AT1,AT2	8.2	9.8	$3.9x10^{-4}$	33	43	$8.7x10^{-4}$
AT3-AT6	1.0	0	-	40	53	$1.1x10^{-3}$
AT7,AT8	1.1	0.1	$4.2x10^{-6}$	10	12	$2.4x10^{-4}$
AT9-AT12	5.5	6.1	$2.4x10^{-4}$	24	31	$6.1x10^{-4}$
AT13,AT14	10.4	13	$5.1x10^{-4}$	42	55	$1.1x10^{-3}$
AT15,AT16	1.0	0	-	8	9	$1.9x10^{-4}$
AT18,AT19	9.2	11	$4.4x10^{-4}$	37	48	$9.7x10^{-4}$
AT17,AT20,AT21	1.4	1	$2.3x10^{-5}$	25	32	$6.5x10^{-4}$
P1-P8	0.0	0	-	51	61	$1.4x10^{-3}$

4. Conclusions

A model was developed to calculate the damage probability of atmospheric and pressurized vessels in flood events. The modelling approach was validated against available literature data and allowed the identification of the more critical parameters affecting vessel resistance to floods. Model application to case-studies confirmed that NaTech scenarios caused by floods may significantly affect the risk profile of industrial facilities.

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