Vulnerability and Risk Assessment Analysis of Natech Events Caused by Natural Phenomena

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During the last decades, there has been a growing concern in the chemical and petrochemical industry regarding losses of storage materials caused by natural phenomena. These events have the potential to cause significant damage, especially in areas where large quantities of hazardous substances are stored. The release of these substances may lead to fires, explosions, or the emission of toxic clouds into the atmosphere; and might have a significant impact on the population located in neighbour urban areas and on the environment. When industrial accidents are triggered by natural events such as earthquakes, floods and storms, or any other natural event, these chemical accidents are known as NaTech events (Natural Hazard Triggering Technological Accidents). In this paper, we will focus on the assessment of risk associated to extreme wind events, floods and earthquakes in industrial storage areas. A method for the quantification of risk associated with extreme winds, floods and earthquakes in vertical storage tanks that work in atmospheric conditions is proposed. This method allows to establish possible accidental scenarios, as well as the estimation of different failure or loss probabilities due to shell buckling, roof detachment, tank overturning or sliding, among others. It is a tool that takes the interaction of both the mentioned natural phenomena and the physical and mechanical characteristics of hydrocarbon storage tanks into account. Furthermore, the model makes an evaluation of the different types of losses through fragility curves and normalized Probit curves, which take into account the uncertainty of the involved variables. In addition, the method allows calculating the losses of hazardous material once the storage tank has failed, estimates the consequences of the loss of containment to finally assess the associated risk. This model can be used as a verification and validation tool for existing risk-assessment models of both new and existing tanks; also, it provides insight on the necessary operating conditions and design practices for risk mitigation upon different types of natural phenomena.

Keywords: Wind, flood, earthquakes, vulnerability, storage tanks, risk, hazardous substances, NaTech.

Introduction

Throughout the world there are industries with the capacity to store large quantities of raw materials and products. Some of these materials have the potential to cause serious damage to surroundings when they are released across the atmosphere, causing major accidents. These accidents can occur due to internal factors, such as operational failures; for instance, one of the most serious accidents was the one in Bhopal-India, where there was an unplanned release of Methyl-Isoquanate that spread throughout the city, causing serious health problems and even the death of thousands of people, thus generating large economic losses for both the company and the country (Eckerman, 2017). On the other hand, major industrial accidents can occur due to external factors, such as attacks against industrial infrastructure or natural phenomena. The latter, also referred to as natural hazards, such as floods, earthquakes, hurricanes, among others, have the potential to inflict damage on an industrial facility causing the release of hazardous materials (hazmat). One example is Hurricane Floyd, which affected the oil industry on the east coast of the United States and Canada, leading to the spill of thousands of gallons of crude oil, gasoline and chemicals, causing great environmental damage with incalculable economic losses (Young, Balluz, & Malilay, 2004).

A study conducted in 2004 presented how natural disasters have increased in number in recent decades. This study was conducted on the entire territory of the United States, which yielded the following results: 228 earthquakes, 26 hurricanes, 16 floods, 15 thunderstorms, 13 blizzards and 7 storms (Cruz, Steinberg, Vetere Arellano, Nordvik, & Pisano, 2004). With this evidence, the concern in the chemical and petrochemical industry has increased around the world due to the great potential of natural hazards of causing damage to industrial facilities and hazardous materials storage areas, which may lead to the unplanned release of hazmat in the atmosphere (Cruz & Okada, 2008). These types of events are known as NaTech (Technological Accident Triggered by a Natural Event) (Krausmann, Cruz, & Sanzano, 2016).

Natural hazards have the characteristic of covering very large areas, affecting entire cities in their path, constituted by coastal zones, a great variety of industries and areas of high urban density. All these are factors, together with climatic conditions and subsoil composition, can aggravate or mitigate the consequences of a natural hazard in a certain way. A historical analysis conducted by Campedel showed that the industrial equipments most affected by natural hazards are storage tanks and pipelines. Additionally, the substances involved in most NaTech events are crude oil, diesel and gasoline; substances that, at the time of loss of containment (LOC), have the capacity to cause explosions, fires and toxic dispersions (Campedel, 2008).

Taking into account the great threat presented by natural hazards on industrial facilities, especially in equipment that has the capacity to house large quantities of hazardous material such as storage tanks, it is very important to know how vulnerable these type of equipment is to a natural hazard and what are the risks associated with a NaTech event. Therefore, this paper proposes a methodology to assess the vulnerability and risk of NaTech events in storage tanks due to the impact of earthquakes, floods and wind loads.

Methodology for Vulnerability and Risk Assessment of Storage Tanks Associated with NaTech Events Generated by Different Natural Hazards.

The impact of a natural event can cause serious consequences in the physical integrity of a storage tank. Some of the possible consequences are the buckling of the shell, the sliding and capsizing of the tank, depending on the natural danger. Once one of the previous scenarios has occurred, there may be a loss of containment of the stored material, causing an explosion, fire or toxic dispersion whose final consequences lead to serious damage to the surroundings. To estimate the probability of different types of damage or fragility of storage tanks, several authors propose a set of mathematical relationships, derived from a mechanical models (Table 1).

Table 1. Models for damage estimation.

Author	Natural Event	Description
(Salzano, Iervolino, & Fabbrocino, 2003)	Earthquake	Probit functions are presented to estimate the damage probability of atmospheric tanks due to the impact of an earthquake.
(Landucci, Antonioni, Tugnoli, & Cozzani, 2012)	Flood	Proposed a model to estimate the damage probability, due to the impact of a flood on a vertical storage tank, from empirical correlations.
(Maraveas, Balokas, & Tsavdaridis, 2015)	Wind	Proposed a model to estimate the damage probability, due to the impact of a wind load on a vertical storage tank, from empirical correlations.

Figures 1-4 shows some types of damage that can cause different natural hazards. As the intensity of the event increases, the process equipment is more likely to be damaged (LEF - Learning from Engineering Failures, 2017).

Figure 1. Tank displacement during a flood caused by Hurricane Katrina

Figure 2. Shell Buckling of a tank during a flood caused by Hurricane Katrina.

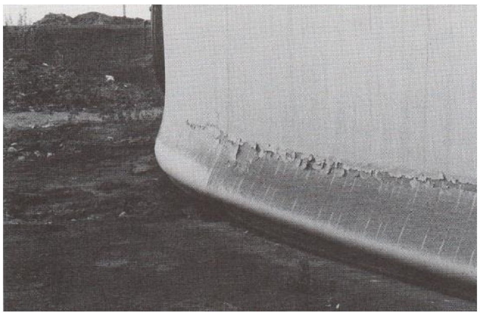

Figure 3. Shell buckling (elephant foot) of a tank during an earthquake.

Figure 4. Shell buckling of a tank during a wind load caused by Hurricane Katrina.

During the development of the correlations used by each of the authors presented in table 1, constant values are assumed for certain input parameters, in spite of their natural variability. The resulting uncertainty associated with these parameters, lead to an unrealistic probability of damage. Additionally, different authors propose methodologies to estimate risk in NaTech events associated with different types of natural hazards (Table 2).

Table 2. Methodologies for risk assessment in NaTech events.

Author	Natural Event	Description
(Antonioni, Spadoni, & Cozzani, 2007)	Earthquake	Methodology to estimate risk associated with NaTech events generated by earthquakes. The equipment of interest in the study are vertical and horizontal storage tanks.
(Cozzani, et al., 2014)	Flood	Methodology is proposed to evaluate risk associated with NaTech events due to the impact of flooding on storage tanks. They evaluate fire and explosion scenarios.
(Necci, Antonioni, Bonvicini, & Cozzani, 2016)	Lightning	Methodology to evaluate risk associated with NaTech events due to the impact of lightning on storage tanks.

Taking into account the information given in Tables 1 and 2, Figure 5 presents the proposed methodology for the assessment of vulnerability and risk in storage tanks associated with technological accidents caused by a natural event, which can be summarized in eight (8) steps, which are:

1) Select the event or natural hazard and asset at risk.
2) Define possible accidental scenarios.
3) Estimate the structural resistance (resistance force and pressure).
4) Estimate the hazard intensity (solicitation).
5) Estimate damage probability.
6) Estimate the losses.
7) Estimate consequences
8) Estimate risk

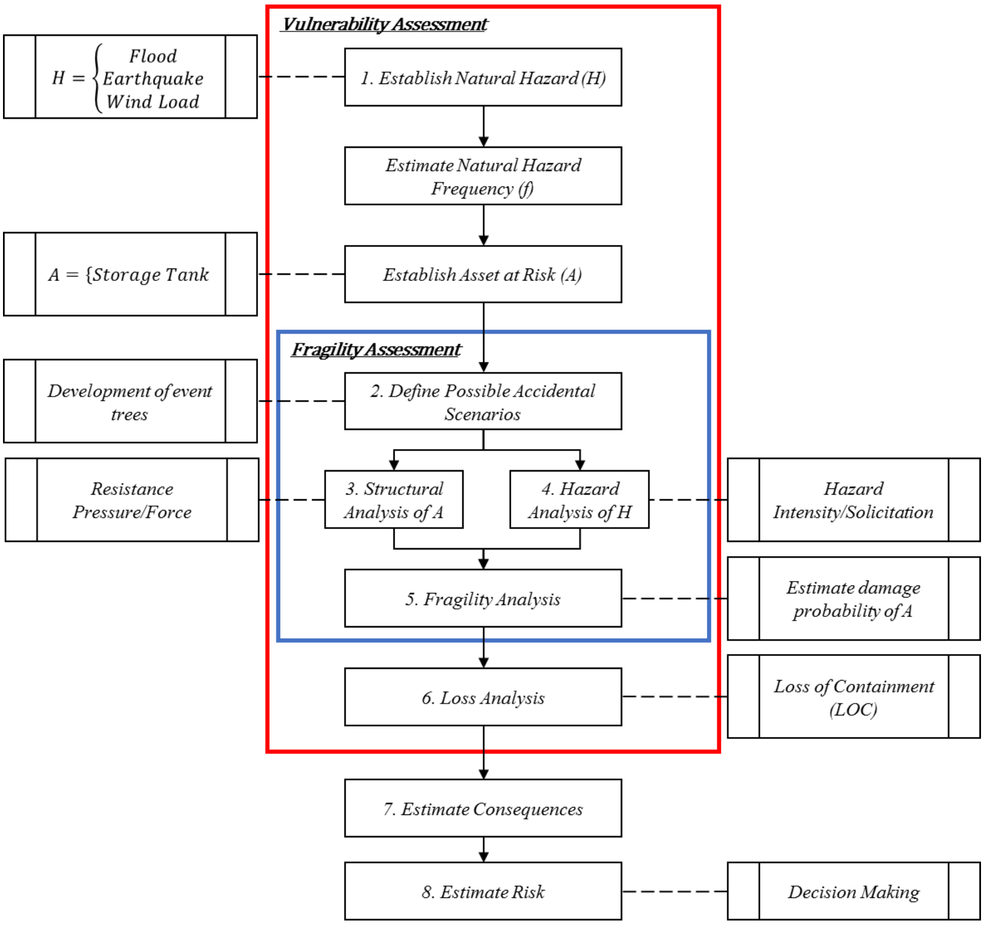

Figure 5. Methodology for vulnerability and risk assessment of storage tanks associated with NaTech events generated by different natural phenomena.

To estimate fragility or damage probability of a storage tank due to the impact of a natural phenomenon, a probabilistic method is proposed, which integrates the random uncertainty associated with the input variables of the used models. For the treatment of uncertainty the Monte Carlo simulation method has been used. Each of the steps presented in Figure 1, are composed of procedures, models and tools, which in conjunction with information that must be fed, allow to perform the vulnerability and risk assessment.

Natural Hazard and Asset at Risk

Natural disasters are those natural phenomena capable of causing a large number of fatalities and damage to property in industrial or highly populated areas, becoming hazardous events. Each of the natural hazards must be characterized by its frequency and intensity. Table 3, present the parameters that characterize the intensity of the different natural hazards that are considered in the present work (step 1, figure 5).

Table 3. Characterization of natural hazards.

Natural Hazard	Characterization Parameters	Author
Flood	Water depth and water velocity	(Krausmann, Cruz, & Sanzano, 2016)
Earthquakes	Ground acceleration	(Krausmann, Cruz, & Sanzano, 2016)
Wind Load	Wind speed.	(Maraveas, Balokas, & Tsavdaridis, 2015)

Antonioni et al. 2015, presents an expression to calculate the frequency of occurrence of a natural event in terms of the return period ($\boldsymbol{t_r}$), which is measured in years and given by studies carried out for each phenomenon (Anees, et al., 2016), (Portués-Mollá et al., 2016). These values are normally reported by local authorities or databases for specific regions (Castaño-Uribe, Carrillo, & Salazar, 2002), (Campos G., et al., 2012). The frequency of a natural event can be estimated as follows:

$$f = \frac{1}{t_r} \quad (1)$$

As Campedel mentioned in his paper "Analysis of Major Industrial Accidents Triggered by Natural Events Reported in the Main Available Chemical Accident Databases", storage tanks are one of the most affected equipment due to the impact of a natural phenomenon. This work will assess the vulnerability and risk associated with NaTech events in vertical storage tanks that work at atmospheric conditions.

Definition of Possible Accidental Scenarios

To define the possible final accidental scenarios (step 2, Figure 5), which can be triggered by floods, earthquakes or extreme winds on a vertical storage tank, the event tree method is used (Delvosalle, 2004). Some authors through databases have made different types of historical data analysis, presenting as a result the different types of structural damage that can cause the impact of a natural hazard on a storage tank. From these analyses the event tree can be constructed for a NaTech event (Figure 6), where the initiating event will be the intensity or solicitation of the natural event, additionally, 3 types of secondary critical events were identified: damage modes, failure modes due to damage and release modes due to failure (LOC).

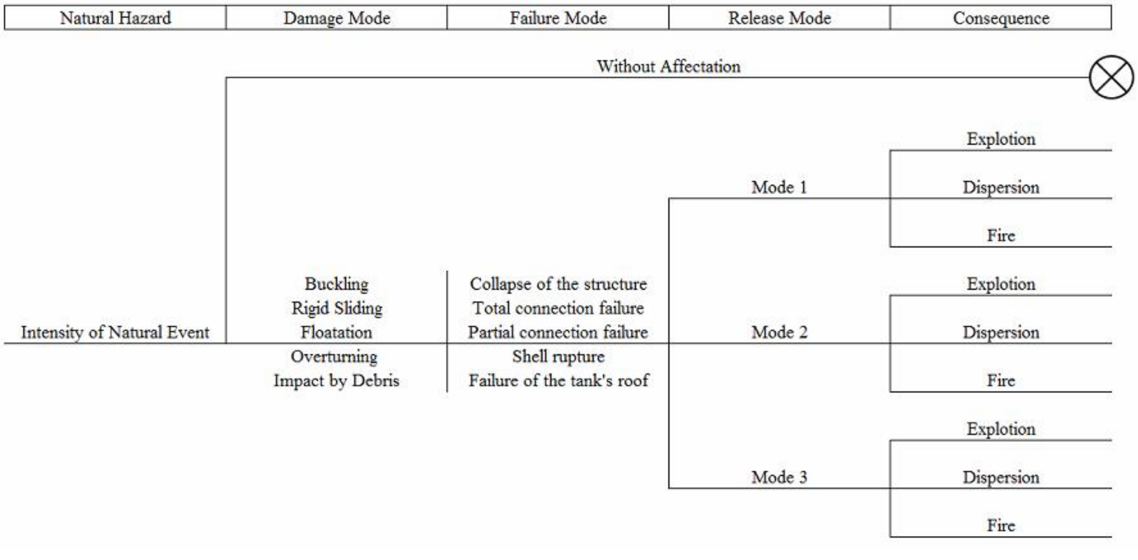

Figure 6. General event tree for NaTech events caused by different natural hazards.

At the end of the event tree are the consequences of a loss of containment, which is the main factor to a final damage over the surroundings, that is, people, infrastructure and environment. It should be noted that not all types of damage apply to all natural hazards.

Structural Resistance

As mentioned above, the process equipment of the present study will be the vertical cylindrical vessels for liquid storage, the operating conditions of the equipment are close to atmospheric (step 3, Figure 5). To characterize and parameterize this type of equipment, the standard API-650 and API-620 were taken as reference, standards used worldwide to design storage tanks in the oil and gas industry. In Figure 7, the main components of a vertical storage tank are presented. From the physical characteristics of the tank and its elements, it is possible to estimate the resistance of the equipment when hit by a disturbance or external load.

There is no clear way to classify storage tanks based upon a single criterion. In order to perform a complete sizing of the tank, the equipment will be classified according to 3 main components: the tank shell, the roof type and the base type.

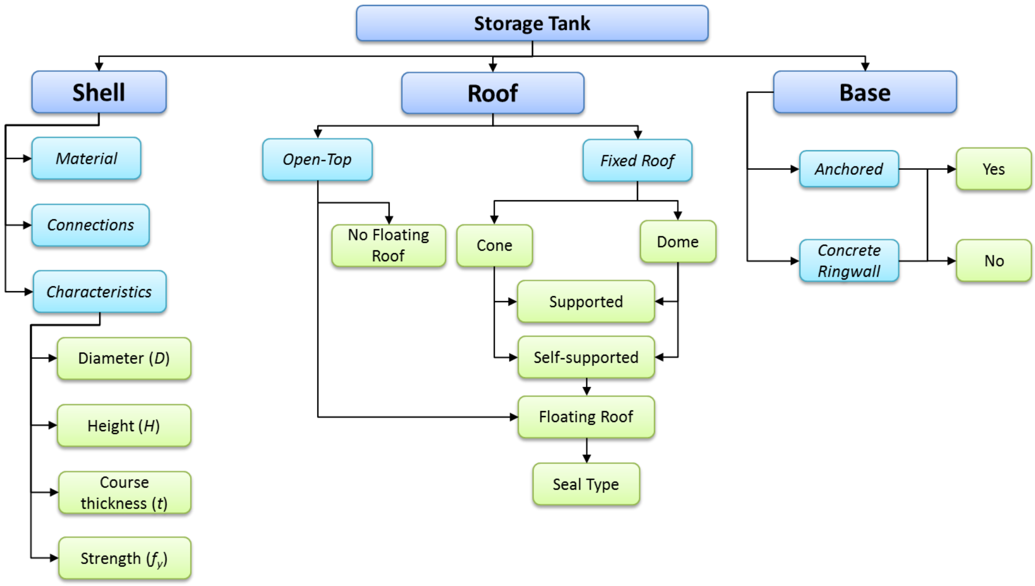

Figure 7. Characterization of a storage tank based on API-620/650 standards.

Hazard Intensity

Using the mechanical models presented in Table 1 and international standards, a comparison is made between the intensity of the phenomenon and the resistance of the storage tank (taking into account each of the elements that make up the equipment). Based on this, it is possible to estimate the probability of different types of damage (step 4, Figure 5). The intensity or solicitation exerted by each natural hazard can be calculated from its characteristic parameters. Table 4 presents the different types of damage associated with each natural hazard and its respective load over the tank.

Table 4. Types of damage caused by different natural hazards.

Natural Event	Type of Damage	Solicitation	Characterization Parameters	Parameters with uncertainty
Flood	Buckling	Water Pressure	Water depth and water velocity	Water density, hydrodynamic coefficient
	Rigid Sliding	Sliding Force		
	Floatation	Floatation Force		
	Impact by Debris	Impact Force		
Earthquakes	Buckling	Acting Compression Stress	Ground acceleration	Fluid density, yield stress
	Overturning	Overturning Moment		
Wind	Buckling	Wind Pressure	Wind speed.	Exposure, ground and wind coefficients
	Impact by Debris	Impact Force		

As mentioned above, models that represent the loads exerted by natural hazards present uncertainty in some of their parameters. As an example, the parameters that show variability in a flood are the density of the water and the hydrodynamic coefficient, these can vary depending on the terrain and the atmospheric conditions of the area.

Damage Probability

A basic reliability problem is proposed, where a solicitation S acts on a system with a resistance R (step 5, Figure 5). Taking into account the random nature of the variables, the probability of damage $\boldsymbol{p_d}$ can be defined through the equation 1 and 2 (Sanchez Silva, 2010):

$$p_d = p(R - S < 0) \tag{2}$$

$$p_d = p(g(R,S) < 0) \tag{3}$$

Where $g(R,S)$ is the system limit state equation (LSE). Therefore, each damage mode has an LSE. Following the definition of the LSE, equation 3 and 4 forms the basis for the Monte Carlo simulations:

$$p_d = \sum_{i=1}^{N_{sim}} \frac{g(i)}{N_{sim}} \tag{4}$$

$$g(i) = \begin{cases} 1 \; if \; R - S \leq 0 \\ 0 \; otherwise \end{cases} \tag{5}$$

Table 5 presents the different types of damage analyzed for each of the natural hazards; additionally, the proposed expressions for calculating the probability of damage for each type of damage are presented.

Table 5. Limit state equation for different types of damage.

Natural Event	**Type of Damage**	**Tanks Resistance (R)**	**Solicitation (S)**	**LSE**	**Damage Probability**
Earthquake	Buckling	σ_r	σ_θ	$g(\sigma_r, \sigma_\theta) = \sigma_r - \sigma_\theta$	$p_d = p(\sigma_r - \sigma_\theta \leq 0)$
	Overturning	-	J	$g(J) = 1.54 - J$	$p_d = p(1.54 - J \leq 0)$
Flood	Buckling	P_r	P_w	$g(P_r, P_w) = P_r - P_w$	$p_d = p(P_r - P_w \leq 0)$
	Floatation	F_{fcr}	F_f	$g(F_{fcr}, F_f) = F_{fcr} - F_f$	$p_d = p(F_{fcr} - F_f \leq 0)$
	Rigid Sliding	F_{scr}	F_{sld}	$g(F_{scr}, F_{sld}) = F_{scr} - F_{sld}$	$p_d = p(F_{scr} - F_{sld} \leq 0)$
	Debris Impact	F_r	F_i	$g(F_r, F_i) = F_r - F_i$	$p_d = p(F_r - F_i \leq 0)$
Wind	Buckling	P_r	q_{eq}	$g(P_r, q_{eq}) = P_r - q_{eq}$	$p_d = p(P_r - q_{eq} \leq 0)$
	Debris Impact	t F_r	h_p F_i	$g(t, h_p) = t - h_p$ $g(F_r, F_i) = F_r - F_i$	$p_d = p(t - h_p \leq 0)$ $p_d = p(F_r - F_i \leq 0)$

The algorithm for calculation the probability of damage was developed using the Matlab® coding environment with 5000 iterations within the Monte Carlo simulation, with an average run time of 30 seconds using an Intel® Core™ i5 computer of 2.70GHz.

The dose response curves are functions that seek to estimate the probability of affectation of a structure that has been exposed to a dose. The Probit method is a good approximation for this type of curves (Crowl & Louvar, 2011). This method consists in using the relationship between the probabilities of affectation ($\hat{p}$) and the Probit points (Equation 5), to establish a linear function that allows the estimation of the Probit points as a function of the dose.

$$\hat{p} = 0.5\left(1 + \frac{Y - 5}{|Y - 5|}\right) \mathrm{erf}\left(\frac{|Y - 5|}{\sqrt{2}}\right) \tag{6}$$

For the Probit method application, a logarithmic function is proposed which relates the Probit points (Y) with the impact vector or dose (V) of the natural event (Table 2), which is presented below:

$$Y = k_1 + k_2 ln(V) \tag{7}$$

Loss of Containment

After the damage and failure of the process equipment, the loss of containment occurs (step 6, Figure 5). From a loss of containment of hazardous substances, different scenarios can be generated such as fires, explosions or toxic dispersion. A source model estimates the flow of material spilled as a result of tank failure. The rupture of the shell of the tank or its connections can be modeled as a flow of hazardous material Q_m through an orifice, equation 8:

$$Q_m = \rho C_o A \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^0\right)} - \frac{\rho g C_o^2 A^2}{A_t} t \tag{8}$$

$$V_L = \int_0^{t_f} Q_m dt \tag{9}$$

Where ρ is the density of the stored fluid, $\boldsymbol{C_o}$ is the discharge coefficient, $\boldsymbol{A_t}$ is the transverse area of the tank, $\boldsymbol{g}$ is the acceleration due to gravity, $\boldsymbol{h_L^0}$ is the initial level of the fluid over the hole of the leak, $\boldsymbol{P_g}$ is the gauge pressure, $\boldsymbol{t}$ is the discharge time, $\boldsymbol{A}$ is the orifice area and $\boldsymbol{V_L}$ is the total spilled volume. Having a failure probability and an estimated loss in case of failure, one can compute the expected losses for the considered hazards.

Consequences assessment due to the impact of a natural hazard

In a NaTech event different types of consequences can occur, these are usually related to injuries or fatalities of people around the area of the accident, on the other hand, it is very common damage to property and surroundings, meaning large monetary losses and damages to the environment (step 7, figure 5). For example, a LOC of fuel on an earthquake can generate a pool of flammable liquid, causing a fire with the potential to cause fatalities and great economic losses. On the other hand, a LOC in a flood could generate a toxic dispersion in liquid phase that will spread throughout the flood area, causing serious damage to public and private property, as well as to the flora and fauna in the surroundings.

Table 2 presents methodologies for calculating risk, where the authors propose different models to estimate the consequences of NaTech events for different natural hazards. These commonly take into account the type of substance stored in the equipment, characteristics of the surroundings (terrain, population density) and the type of incident (fire, explosion or toxic dispersion).

Risk Calculation for a NaTech Event

The Center for Chemical Process Safety (CCPS) defines risk as a measure of human injury, environmental damage or economic loss in terms of the incident probability and the magnitude of the consequence or injury (step 8, figure 5). From this definition, the risk calculation for a NaTech event can be expressed as the probability or frequency of an accidental scenario by its consequence, as shown by Equation 10 (Center For Chemical Process Safety - CCPS, 2000):

$$R = F(scenario, frequency, consequence) \tag{10}$$

$$R = f_s * C \tag{11}$$

Where $\boldsymbol{C}$ is the consequence, and $\boldsymbol{f_s}$ is the frequency of the accidental scenario, which is calculated from the natural hazard frequency and the damage and failure probability of the equipment:

$$f_s = f * p_d * p_f \tag{12}$$

It is important to highlight that risk should not only be seen as a measure, since it allows to evaluate the occurrence of an unwanted event in order to support the decision making to reduce the frequency of occurrence or the consequence of the event.

Case-Studies: Damage Probability Due to Buckling of a Storage Tank Impacted by Different Natural Hazards.

Step 1

The proposed methodology was applied to a vertical storage tank of a Colombian petrochemical company (TK-623), the tank operates at atmospheric conditions and has a dome roof. The natural hazards analyzed were those presented in Table 1. Table 6 and 7 show the characteristics of both the process equipment and the natural hazards.

Table 6. Properties and characteristics of TK-623.

Parameter	Unit	Value
Diameter	(m)	33.5
Height	(m)	12.2
Material	(-)	SS-316
Thickness	(m)	0.0165
Stored fluid	(-)	Diesel
Filling degree	(%)	0; 10; 25 (Wind and Flood) 60; 80; 100 (Earthquakes)

Natural Hazard	Parameter	Unit	Value
Wind	Wind speed	km/h	50-360
Flood	Wave speed	m/s	2.0
	Wave height	m	0.5-2.5
Earthquakes	Peak ground acceleration	%g	0-1

Table 7. Characterization of natural hazards.

Because the area where the TK-653 is located is more prone to flooding, wind loads and earthquakes will not be taken into account for vulnerability assessment, however, the fragility assessment of the equipment facing different natural hazards will be presented. For a flood with wave speed of 2 m/s and wave height of 1.3 m, the return period is 500 years, that is, a frequency of $2*10^{-3}$ (1/year).

Steps 2 through 5

According to Figure 6, the type of damage that will be analysed is the shell buckling of the TK-653 by the impact of three different natural hazards. Each event was characterized based on the parameters mentioned in Table 4.

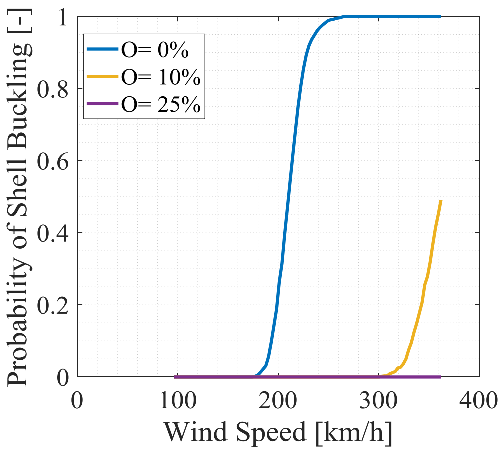

Figure 8. Probability of damage due to buckling of the TK-653 impacted by a wind load and three different filling levels.

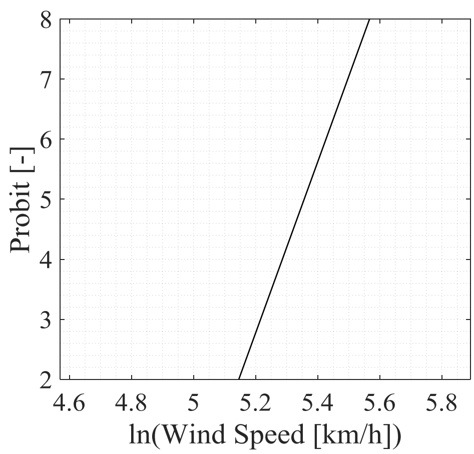

Figure 9. Probability of damage due to buckling of the TK-653 (O=0%) impacted by a wind load represented by a Probit function.

As can be seen, from figure 8 and 9, as the wind speed increases the probability of damage by shell buckling increases as well, this is because when the wind speed increases, the pressure or load on the storage tank also increases. Additionally, it can be observed how the filling level (*O*) of the tank significantly influences in the probability of damage. When the tank is completely empty, less wind speed will be needed to produce the damage. By filling the tank at a level of 10%, this level of filling gives the tank additional resistance thanks to the weight of the stored fluid, causing the need of greater wind speeds to produce buckling of the tank's shell.

Some authors agree that for a wind load, such as those caused by hurricanes or tornadoes, to affect or damage a storage tank, the equipment must be empty or partially full (0% to 10% fill level); additionally, they establish that the damage will be more possible to occur in the upper part of the tank. (Uematsu, Koo, & Yasunaga, 2014), (Zhao & Lin, 2014). The same results were obtained in the present work. From these results, the most relevant final consequence of the NaTech event will be the damage or loss of the process equipment and not the loss of containment of hazardous material itself (Maraveas, Balokas, & Tsavdaridis, 2015). These results are consistent with the system since it is expected that as the impact of the wind load increases, the tank is more likely to be damaged. The same behaviour can be evidenced in the curves of the Probit model.

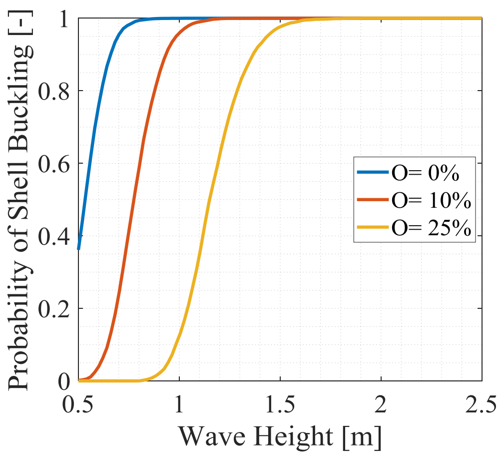

Figure 10. Probability of damage due to buckling of the TK-653 impacted by a flood and three different filling levels.

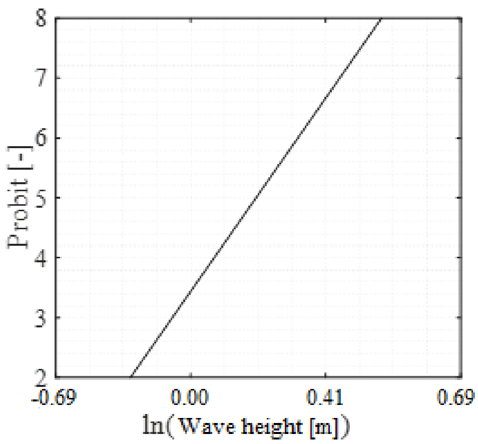

Figure 11. Probability of damage due to buckling of the TK-653 (O=25%) impacted by a flood represented by a Probit function.

Figures 10 present the fragility curve for TK-653 impacted by a flood. On the other hand, Figure 11 presents the probability of damage as a Probit curve, which is a transformation of the previous figure. As the flood becomes deeper, the probability for the tank to suffer buckling damage increases. It is expected that if the speed of the flood decreases, the probability profile moves to higher heights and therefore the probability of damage decreases, because the pressure exerted by the flood will be proportional to the speed of the flood. When the speed decreases, the depth of the flood must increase to replace the gradient of pressure that the speed delivers. The same behaviour can be evidenced in the curves of the Probit model. Unlike a wind load, shell buckling by flood is more likely to occur in the lower part of the tank, since this part is the one in contact with the floodwater. Possibly causing the rupture of the shell or the pipes connections and therefore the loss of containment. These results are consistent with the system since it is expected that as the impact of the flood increases, the tank is more likely to be damaged.

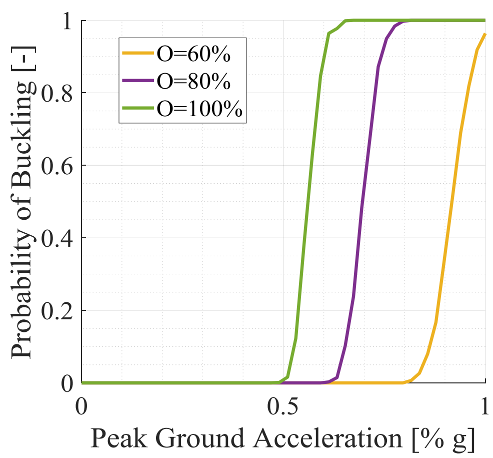

Figure 12. Probability of damage due to buckling of the TK-653 impacted by an earthquake and three different filling levels.

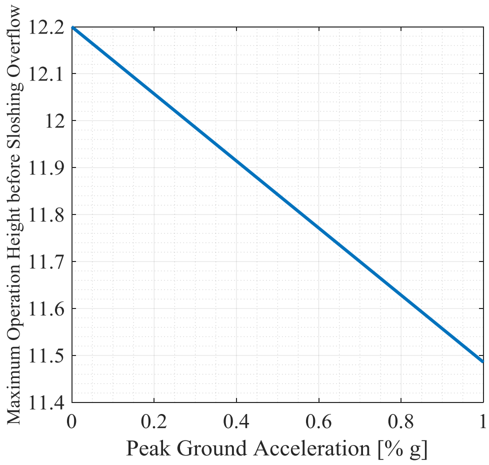

Figure 13. Maximum Recommended Operation Height for TK-653 impacted by an earthquake.

Figures 12 present the fragility curve for TK-653 impacted by an earthquake. On the other hand, Figure 13 presents the maximum recommended operation height, which takes into account mode 1 and mode 2 sloshing of the tank's stored liquid in order to calculate the expected sloshing height. As the peak ground acceleration increases, the probability for the tank to suffer shell buckling (elephant foot) damage increases. As can be seen in Figure 12, the filling level has a direct impact on the probability of damage, as the tank is more full, the pressure exerted by the fluid on the shell will increase and the excited mass increases significantly, causing greater shear forces and overturning moments to be exerted on the tank's structure. That said, it is more likely that the shell buckling damage occurs in the lower part of the tank, forming the elephant foot, due to the exerted compression stress accumulating near the tank's support structure.

Unlike wind loading and flooding, the probability of tank damage will increase to high fill levels, while for wind and flood, the damage is more likely to low fill levels. Figure 13 shows the fill level values at which the overflow can occur due to sloshing effects as the intensity of the natural hazard increases.

The calculation of damage probabilities takes into account the uncertainty associated with the input parameters to the models, so that it integrates the natural behavior of these parameters. This will improve the results of the risk analysis associated with NaTech events caused by different natural phenomena, because the calculated values are input information for the quantitative risk calculation.

Step 6 through 8

As mentioned above, the type of damage to the case study is the shell buckling of the tank. Some studies presents the probabilities of failure for each one of the types of failure that can be generated by the shell buckling of a tank (Villalba Hernandez, 2016). The present analysis will take into account the failure due to the total failure of the connection, with a probability of failure value of 0.4. The connection to the tank is located 1 m above the base of the tank.

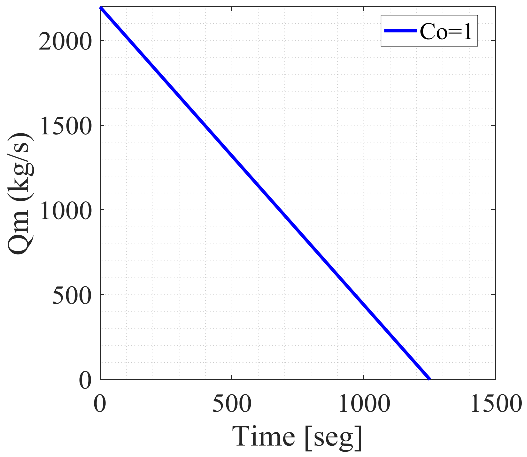

Figure 14. Flow of spilled diesel due to tank damage.

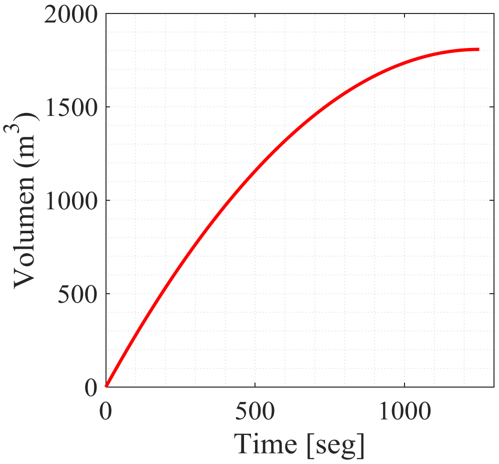

Figure 15. Volume of spilled material vs. release time.

Figures 14 through 16 show the amount of hazardous material spilled over time for a tank that is filled up to 25%. The time it takes to empty the tank to the level of the orifice is approximately 1251 s (21 min).

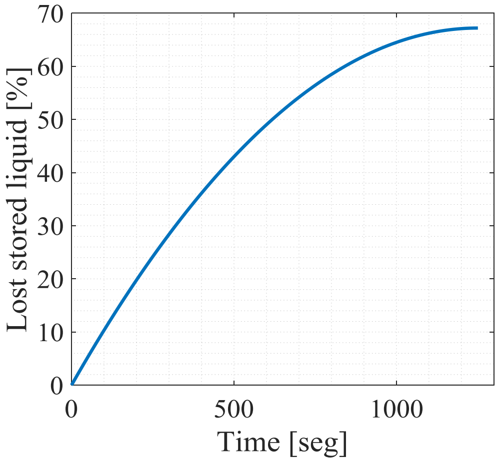

Figure 16. Percentage of stored liquid lost from the time of release due to TK-653 damage.

Taking into account that the evaluated scenario was flooding, the most likely final scenario is a liquid toxic dispersion, and due to the drag capacity of the flood movement, the water will mix with the diesel spilled and will be spread throughout the space where the flood is present, affecting the environment, water sources, among others.

Table 8. Values obtained for a NaTech event generated by flooding in a storage tank filled with Diesel up to 25% level.

Information for Risk Estimation	Unit	Value
Damage Mode	[-]	Buckling
Damage Probability	[%]	82.3
Failure Mode	[-]	Total Connection Failure
Failure Probability	[%]	0.4
Frequency of the Accidental Scenario	[1/year]	$6{,}56{*}10^{-4}$
Spilled Volume	[m^3]	1807.15
Consequence	[-]	Toxic dispersion in liquid phase

The proposed methodology (Figure 5) for the vulnerability and risk assessment in NaTech events was applied to a flood scenario, additionally an analysis of the equipment's fragility was presented against the three natural hazards of interest. The results of the case study (flood) are presented in Table 8. As mentioned in the previous steps, it is assumed that the volume of spilled material is the amount of inventory that the tank stores until the leak source during its operation. With the results obtained and the consequence model proposed by Villalba N. and Cozzani et al., It is possible to determine the risk for a NaTech event caused by a flood in a storage tank.

Conclusions

The focus of this work is to analyze the undesired events that can occur if a vertical storage tank were to fail during a flood, earthquake and a storm surge that leads to strong wind loads. The proposed methodology is a simple, systematic and repeatable tool that integrates both qualitative and quantitative information of causes and consequences of industrial accidents. It allows a researcher to perform a risk assessment associated with NaTech events caused by different natural events considering the variability or uncertainty of parameters associated with the natural phenomenon.

In the case study, which aims to represent the conditions of real infrastructure in Colombia, results coming from each of the studied hazards (wind loads, hydraulic loads, and seismic forces) were computed and analyzed. In general, the results concurred with existing literature in terms of the effect of input parameters, such as the fill level of the storage tank, on the damage probabilities and the behavior of fragility curves. Furthermore, the proposed loss methodology was used to estimate the expected losses due to the applicable damages in the tank's structure. Finally, this lead to the computation of risks and expected consequences for the input hazards, which is of great value in order to feed risk mitigation frameworks present elsewhere.

A tool was developed to calculate the probability of different types of storage tank damage. This tool includes fragility and Probit functions, which are based on analytical models obtained from the treatment of the uncertainty present in the input parameters to the models, also allows to perform a simple vulnerability evaluation of a tank measured in the percentage of lost material once it has suffered the damage due to the impact of a natural hazard. This methodology can validate existing risk-assessment models of both new and existing storage tanks, and provides insight on the necessary operating conditions and design practices for risk mitigation upon different types of natural phenomena.

References

American Petroleum Institute. (2002). *API-620: Design and Construction of Large, Welded, Low-Pressure Storage Tanks.* Washington, D. C.

American Petroleum Institute. (2012). *API-650: Welded Tanks for Oil Storage.* Washington D.C.

Anees, M. T., Abdullah, K., Nawawi, M., Nik Ab Rahman, N. N., Mt. Piah, A. R., Zakaria, N. A., . . . Mohd. Omar, A. (2016). Numerical modeling techniques for flood analysis. *Journal of African Earth Sciences*, 478-486.

Antonioni, G., Landucci, G., Necci, A., Gheorghiu, D., & Cozzani, V. (2015). Quantitative assessment of risk due to NaTech scenarios caused by floods. *Reliability Engineering and System Safety*, 334-345.

Antonioni, G., Spadoni, G., & Cozzani, V. (2007). A methodology for the quantitative risk assessment of major accidents triggered by seismic events. *Journal of Hazardous Materials*, 48-59.

Campedel, M. (2008). Analysis of Major Industrial Accidents Triggered by Natural Events Reported In the Principal Available Chemical Accident Databases. *JRC Scientific and Technical Reports*.

Campos G., A., Holm-Nielsen, N., Díaz G., C., Rubiano V., D. M., Costa P., C. R., Ramírez C., F., & Dickson, E. (2012). Análisis de la gestión del riesgo de desastres en Colombia: un aporte para la construcción de políticas públicas. *Banco Mundial Colombia*.

Castaño-Uribe, C., Carrillo, R., & Salazar, F. (2002). Sistema de Información Ambiental de Colombia Tomo III. Perfil del estado de los recursos naturales y del medio ambiente en Colombia 2001. *IDEAM. Min. Medio Ambiente. Bogotá*.

Center For Chemical Process Safety - CCPS. (2000). *Guidelones for Chemical Process Quiantitative Risk Analysis.* New York: Wiley-Interscience.

Cozzani, V., Antonioni, G., Landucci, G., Tugnoli, A., Bonvicini, S., & Spadoni, G. (2014). Quantitative assessment of domino and NaTech scenarios in complex industrial areas. *Journal of Loss Prevention in the Process Industries*, 10-22.

Crowl, D. A., & Louvar, J. F. (2011). *Chemical Process Safety: Fundamentals with applications.* Boston: Prentice Hall.

Cruz, A., & Okada, N. (2008). Methodology for preliminary assessment of Natech risk in urban areas. *Natural Hazards, 46*(2), 199-200.

Cruz, A., Steinberg, L., Vetere Arellano, A. L., Nordvik, J.-P., & Pisano, F. (2004). *State of the Art in Natech Risk Management.* Italia.

Delvosalle, C. (2004). *ARAMIS: ACCIDENTAL RISK ASSESSMENT METHODOLOGY FOR INDUSTRIES IN THE CONTEXT OF THE SEVESO II DIRECTIVE.* Mons: Major Risk Research Centre.

Eckerman, I. (2017). The Bhopal Saga: Causes and Consequences of the World’s Largest Industrial Disaster. *14th World Congress on Disaster and Emergency Medicine, 20*.

Krausmann, E., Cruz, A., & Sanzano, E. (2016). *Natech risk assessment and management : reducing the risk of natural-hazard impact on hazardous installations.* Boston: MA: Elsevier.

Landucci, G., Antonioni, G., Tugnoli, A., & Cozzani, V. (2012). Release of hazardous substances in flood events: Damage model for atmospheric storage tanks. *Reliability Engineering and System Safety, 106*, 200-216.

LEF - Learning from Engineering Failures. (2017). *TANKS THAT FAILED DUE TO WIND.* (LEF) Retrieved 11 2017, 22, from http://lef.uprm.edu/Failure%20of%20two%20Tanks/Examples%20Wind.html

Maraveas, C., Balokas, G. A., & Tsavdaridis, K. D. (2015). Numerical Evaluation on Shell Buckling of Empty Thin-Walled Steel Tanks Unider Wind Load According to Current American and European Design Codes. *Thin-Walled Structures, 95*, 152-160.

Necci, A., Antonioni, G., Bonvicini, S., & Cozzani, V. (2016). Quantitative assessment of risk due to major accidents triggered by lightning. *Reliability Engineering and System Safety*, 60-72.

Portugués-Mollá, I., Bonache-Felici, X., Mateu-Bellés, J., & Marco-Segura, J. (2016). A GIS-Based Model for the analysis of an urban flash flood and its hydro-geomorphic response. The Valencia event of 1957. *Journal of Hydrology*, 582-596.

Salzano, E., Iervolino, I., & Fabbrocino, G. (2003). Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis. *Journal of Loss Prevention in the Process Industries, 16*, 403-409.

Sanchez Silva, M. (2010). *Introducción a la Confiabilidad y Cvaluación de Riesgos: Teoría y aplicaciones en ingeniería.* Bogota D.C.: Universidad de los Andes.

Uematsu, Y., Koo, C., & Yasunaga, J. (2014). Design wind force coefficients for open-topped oil storage tanks focusing on the wind-induced buckling. *Journal of Wind Engineering and Industrial Aerodynamics*, 16-29.

Villalba Hernandez, N. (2016). *Marco de referencia para el análisis del riesgo asociado a eventos Natech provocados por inundaciones.* Bogota: Universidad de los Andes.

Young, S., Balluz, L., & Malilay, J. (2004). Natural and technologic hazardous material releases during and after natural disasters: a review. *Science of The Total Environment, 322*(1-3), 3-20.

Zhao, Y., & Lin, Y. (2014). Buckling of cylindrical open-topped steel tanks under wind load. *Thin-Walled Structures*, 83-94.