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# Fragility Curves of Storage Tanks Impacted by Strong Winds

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Industrial infrastructures may be subjected to severe damage by strong winds, storms, tornadoes, and hurricanes. For instance, the two hurricanes Katrina and Rita in 2005, in the Gulf of Mexico (United States) resulted in multiple damages to approximately 611 industrial equipment such as offshore platforms, oil pipelines, and storage tanks. This type of events is defined as NaTech (Natural accidents triggered by Natural Events). Due to their structural characteristics, atmospheric storage tanks are particularly vulnerable to NaTech. Indeed, the interaction of strong winds may result in a structural damage and the following release of hazardous substances in the environment. In this work, a computational tool was developed in order to obtain fragility curves for storage tank, designed on the basis of API-650, and subjected to strong winds. This tool includes the reduction of uncertainty by Monte Carlo simulations, and it analyzes individual tanks and the entire tanks area. The model includes different damage modes such as the buckling of the wall due to external pressure and the damage to the tank shell due to the impact of the projectiles transported by the wind, in addition to the loss of containment calculation once the equipment has failed. Finally, the tool takes into account the mechanical characteristics of the tank together with its operating conditions for the fragility analysis, the results of which will be the input information to include events of natural origin within the classical risk analysis.

## 1. Introduction

Recently, around the world it has been seen as different extreme natural phenomena such as earthquakes, hurricanes, floods, and so on, which have caused serious consequences in populations and environment, obtaining huge economic losses and enormous damage to infrastructure, including industrial facilities. Given that different hazardous materials or hazmats (flammable, explosive, and toxic substances) are handled in the industry, the unwanted and uncontrollable release of hazardous material presents a great risk not only to human, but also to the environment and assets (Young et al., 2004). In addition, several studies have been conducted which the increase in the frequency and severity of occurrence of this type of natural events is evident (Cruz et al., 2004); for instance, only in the United States in the decade of the 90s occurred 228 earthquakes, 26 hurricanes, 16 floods , 15 storms, 13 blizzards, and 7 storms (Cred, 2004). Moreover, only in floods, 1022 occurred worldwide in the same decade, resulting in an increase of 74% compared to previous decades (Cred, 2004). It is important to note that commonly industrial accidents caused by natural events tend to have more serious consequences than those suffered by a mechanical or human error (Cozzani et al., 2014), due to the area affected by the event and the domino effect once the natural hazard has damaged an industrial facility (Yang et al., 2018). These type of accidents are known as NaTech events (Natural Hazard Triggering Technological Accidents) (Salzano et al., 2013). In fact, according to a study carried out by (Campedel, 2008), the process equipment that is commonly affected by natural events are the storage tanks. Normally the consequences produced by a NaTech event in this type of equipment is quite significant due to the capacity to store large quantities of hazmats.

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The center for chemical process safety (CCPS) defines the risk for industrial accidents as the measure of economic loss, personal injury or damage to the environment, in terms of the probability of occurrence or frequency of the incident and the magnitude of the losses or injuries (Center for Chemical Process Safety, 2009). From this definition, several authors have proposed different models and methodologies to estimate the damage from different types of industrial equipment impacted by a natural hazard. For instance, (Salzano et al., 2003) presented a probit model to estimate the probability of damage of an atmospheric storage tank due to the impact of an earthquake, (Landucci et al., 2012) and (Landucci et al., 2014) proposed a model for the calculation of damage probability of vertical and horizontal storage tanks by the impact of a flood, and (El Hajj et al., 2015) performed an analysis from fault trees and generic events to identify the accidental scenarios involved in a flood. These models allow evaluating the resistance of a storage tank impacted by a natural hazard, taking into account the mechanical characteristics of the equipment and the characteristics in magnitude of each of the natural hazards, such as the speed and height of flood or the peak ground acceleration in the event of an earthquake.

## 2. NaTech Tank Analyzer

To estimate the probability of damage of a storage tank by the impact of a wind load or impact by a projectile dragged by the wind, a computational tool was designed using the mathematical software MATLAB R2016a. The tool was named Natech Tank Analyzer (NaTanks) for the assessment of fragility for storage tanks in NaTech events. NaTanks is based on a methodology in which a characterization of the storage tank, the natural hazard (extreme wind), and a probabilistic approach to obtain the fragility curve of the equipment associated with the NaTech event should be carried out. Below are the steps to obtain the fragility curves using the NaTanks tool.

### 2.1 Step 1: tank characterization

Figure 1 shows the interface of the NaTanks tool, which is basically composed of three tabs. In the first tab, there is the input information required to characterize the storage tank, which is designed according with the API-650 standard (American Petroleum Institute, 2007), from this standard, the sizing of a tank will be based on the three main components, the shell, the roof and its base. In the NaTanks tool, it is necessary to input all the characteristics of the shell of the tank, because they are necessary to specify the geometric dimensions of the tank. In the case of the base and roof, the parameters are optional, due to these characteristics can be or not in a storage tank. Below is the information required for each of the components of the tank:
Base (optional): bottom plate thickness, anchor to the ground, concrete ring, number of anchor bolts, and diameter of anchor bolts.
Roof (optional): thickness, kind of roof, support (only for fixed roof), and type of seal (only for floating roof).
Shell (mandatory): thickness per ring, material, diameter, and height.

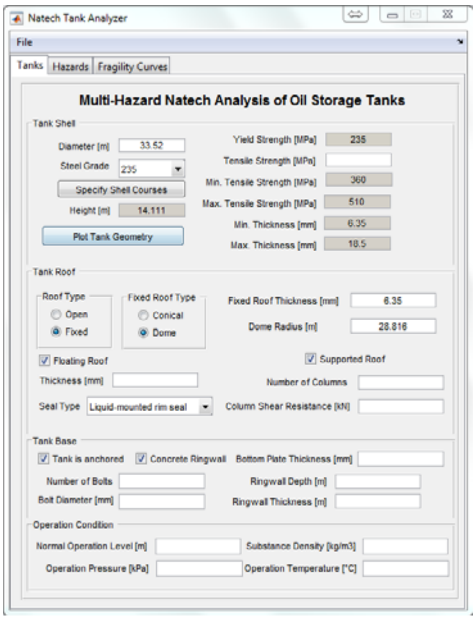


*Figure 1. NaTanks first tab: Sizing of a storage tank based on API-650*

The proposed methodology for fragility assessment was applied to a vertical storage tank, which works at atmospheric conditions. Table 1 shows the characteristics of tank TK-201. Additionally, in Figure 1 the parameters are present within the NaTanks tool.

*Table 1. Characterization of a storage tank (TK-201) according to API-650*

| Parameter | Unit | Value |
|---|---|---|
| Steel Grade | - | 235 |
| Thickness | mm | 6.35 – 18.5 |
| Stored fluid | - | Diesel |
| Filling degree | % | 3, 5, 8, 10 |
| Typo of Roof | - | Dome |
| Roof Thickness | mm | 6.35 |
| Dome Radius | m | 28.816 |

### 2.2 Step 2: natural hazard characterization

In Table 2, the characterization of the natural hazard is made, and in this case is strong wind. As shown in Figure 2, the wind load will be characterized based on the wind speed, which allows establishing the type of hurricane to which the storage tank is exposed, taking as reference the Saffir/Simpson scale. This tab allows calculating the load generated by a defined wind speed. It presents the distribution of the pressure, the Non-Uniform wind pressure $p$, and the equivalent uniform pressure $q_{eq}$.

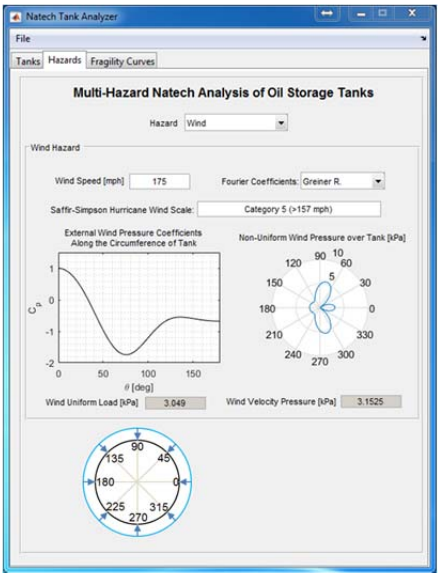


*Figure 2. NaTanks second tab: win load characterization base on the wind speed*

### 2.3 Step 3: fragility curves generation

To derive the fragility curves of a storage tank impacted by a wind load, the tool performs Monte Carlo simulations to the uncertainty associated with the parameters of the models that exhibit a natural random behavior. The fragility curves are a function of the damage probability. Figure 3 presents a diagram that summarizes the general methodology for estimating the probability of damage, which is an iterative process, which seeks to treat the uncertainty of the parameters considered.

From the methodology presented in Figure 3, the values of the parameters that present uncertainty in each of the models are generated. Some authors propose different variabilities for parameters that have randomness due to their natural behavior, for this type of behavior the tool allows selecting which values of the models will have uncertainty and assign the type of probability distribution for each parameter. The types of distribution that were included in the tool are Normal, Uniform, Lognormal, Exponential, Weibull, and Gamma. Table 2 presents the parameters with uncertainty for Monte Carlo simulations; its variability was established taking into account a historical data analysis from different databases and suggestions by different authors.

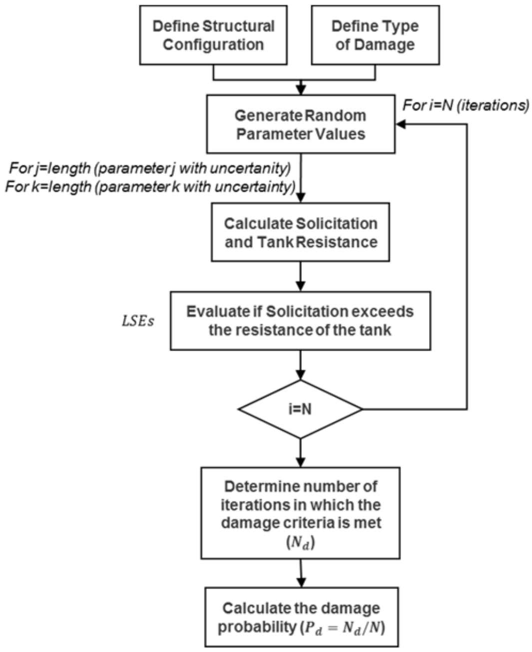


*Figure 3. Methodology to estimate damage probability of a storage tank integrating the uncertainty within a purely probabilistic framework*

*Table 2. Parameters with random behaviour*

| Parameter | Unit | Distribution | Mean ($\mu$) | Coefficient of variation |
|---|---|---|---|---|
| Air density | $Kg/m^3$ | Normal | Air density of the affected area | 9.6 % |
| Debris density | $Kg/m^3$ | Uniform | Debris density | 10.2 % |
| Product density | $Kg/m^3$ | Lognormal | Density of the stored* | 9.1 % |
| Velocity pressure exposure coefficient | - | Exponential | 1.26 | 11.9 % |
| Topographic factor | - | Weibull | 1.0 | 5 % |
| Wind directional factor | - | Gamma | 0.95 | 8.2 % |

* At 1atm and 25 $^{o}$C

To determine the probability of failure of a component of the storage tank after the tank has suffered a damage, a historical data analysis was made from several databases that collect information related to industrial accidents caused by different natural events. Since a significantly high wind load or wind speed is needed to damage a tank, the probabilities of failure were determined for high and very high loads. Table 3 summarizes the values obtained for each of the types of failure associated with a high wind load.

*Table 3. Failure probabilities for different types of failure on storage tanks (Ramirez, 2018)*

| Failure Mode | High Wind Load | Very High Wind Load |
|---|---|---|
| Collapse of the structure | 0.08 | 0.10 |
| Total connection failure | 0.11 | 0.13 |
| Partial connections failure | 0.23 | 0.17 |
| Shell rupture | 0.32 | 0.40 |
| Failure of the tanks roof | 0.26 | 0.20 |

The frequency of the final accidental scenario $f_e$, that is the NaTech event, is determined by combining the frequency of the natural hazard, the probability of damage, and the probability of failure, as it is presented below:

$$f_e = f \cdot p_d \cdot p_f \tag{1}$$

Natural hazards are not only characterized according to their intensity, but also to their frequency of occurrence. (Antonioni et al., 2015) presented an expression to calculate the frequency of a natural hazard in terms of the return period ($t_r$), which is measured in years and is estimated data for different types of natural

(Anees et al., 2016). These values are commonly reported by local authorities and databases for specific regions or areas in the world. The frequency of occurrence of a natural hazard is defined as follows:

$$f = \frac{1}{t_r} \tag{2}$$

Once Monte Carlo simulations finished, the damage probabilities for a given structural configuration of a tank and different wind intensities are obtained. With these results, it is possible to obtain the fragility curve whose behavior can be observed in Figure 4. Figure 4 shows the tab of the NaTanks tool where the fragility curves are obtained for a certain type of damage associated with a storage tank impacted by a wind load. As it can be seen, the tool allows defining the type of damage to evaluate the wind intensity and the number of iterations for the Monte Carlo simulation. The curves correspond to tank TK-201, defined in Table 1.

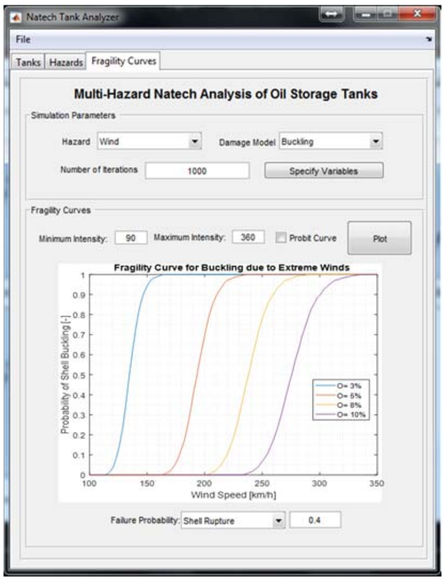


*Figure 4. NaTank third tab: fragility curves for NaTech Events*

## 3. Analysis of results

From the fragility curves, for a vertical storage tank with a dome roof, it is evident that as the wind speed increases the probability of buckling damage also increases. Since the pressure or wind load is directly proportional to the wind speed, the tank will be subject to a greater threat as the natural hazard intensifies. Additionally, 4 curves are presented which correspond to different filling levels ($O$). It is observed as the tank is getting more and more full, the curve moves to the right, which indicates that the tank will have a factor of additional resistance by the stored fluid and more wind will be required to damage the tank. Simply fill the tank to a level of 10 % to prevent a very high wind load from damaging my system. Table 4 shows the results of the TK-201 impacted by a wind load with a speed of 250 Km/h (hurricane category 5), which has a return period of 150 years.

*Table 4. Accidental scenario*

| Information for Risk Assessment | Unit | Value |
|---|---|---|
| Hurricane category 5 | Km/h | 250 |
| Asset at risk | - | Storage Tank TK-201 ($O = 8\,\%$) |
| Damage mode | - | Shell Buckling |
| Damage probability | % | 75.1 |
| Failure mode | - | Shell Rupture |
| Failure Probability | % | 40 |
| Frequency of final accidental scenario | 1/year | 0.002 |

(Zhao & Lin, 2014) concluded that for natural hazards with strong winds it is unlikely that a storage tank will be affected, unless its filling level is below 15 %. On the other hand, other authors affirm that the damage may occur in the upper part of the structure (Uematsu et al., 2014). In the present work, it was possible to verify the afore-mentioned. From the results, the possible final consequence will be the damage and loss of the equipment, not the loss of containment of hazmat. The calculation of the final accidental scenario takes into account the uncertainty associated with the input parameters of the natural hazard models for the calculation of the damage probability, so that the natural behavior of these parameters is taken into account. These results will improve the risk analysis associated with NaTech events caused by wind-related hazards, given that the values found are input to quantitative risk methods.

## 4. Conclusions

In the present work, an available computational tool to perform fragility analysis for vertical storage tanks subject to a natural hazard was made. This tool takes into account the natural behavior of parameters included in the models that characterize the hazard. The methodology used by the tool is simple, systematic, and repeatable, which integrates both qualitative and quantitative information to evaluate the accidental scenario. Thus, the results obtained of the tool will be able improve the risk analysis associated with NaTech events caused by wind-related hazards, given that the out values could be input to quantitative risk methods.

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