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Toward an inventory and vulnerability of aboveground storage tanks in Puerto Rico

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Abstract

Research on the buckling behavior of thin walled metal tanks used in the oil industry has been performed at the Civil Infrastructure Research Center of the University of Puerto Rico for almost 10 years. However, the mechanics of behavior is only part of the complete picture and to address the impact of hurricanes or earthquakes on the oil industry it is necessary to have an inventory of tanks in Puerto Rico, which is the subject of this paper. This research has been done using data from aerial photographs supplemented by site visits. The information obtained are the diameter, height and the type of roof. This limited data is very useful because the design of tanks is regulated by American Petroleum Institute codes and follows rather standard geometric patterns. A vulnerability assessment of a typical existing tank is presented. It was found that this tank would not be able to sustain the current seismic and hurricane wind demand from actual codes. It is suggested that the information obtained from this study can be used to construct fragility curves for tanks.

Keywords

Tanks, Vulnerability curves, Seismic buckling, Hurricane wind.

1 Introduction

Most oil storage tanks in Puerto Rico were constructed at the refineries in the 1960s and 1970s. Neither the level of seismic risk nor the wind design standards were as rigorous at that time, as they are today. This creates the problem that the seismic and wind responses of these structures, for the level of natural hazards expected in Puerto Rico are unknown. For that reason, the expected damage that could occur in aboveground storage tanks in Puerto Rico is uncertain. To fill this gap the authors performed a survey to identify the typical geometries of tanks in Puerto Rico, which could be used in an evaluation of their vulnerability to seismic and wind. This is the first step toward developing fragility curves for tanks with typical geometries observed in Puerto Rico.

2 Methodology

The inventory of tanks considered in this survey was based in the geometries of aboveground storage tanks observed in site visits to tank farms in Puerto Rico. There are three regions in Puerto Rico where most of the oil tank farms are located: (a) Northern region: most of the tanks are located the municipalities of Cataño and Bayamón; (b) Southern region: the vast majority of the tanks are located in oil facilities in Peñuelas; (c) South eastern region: tanks are located in oil facilities in Yabucoa. The tanks located in the northern and southern region of the island were included in the survey (with the south eastern region still to be included) and attention is only directed to aboveground cylindrical tanks because most of the steel tanks used to storage water or oil are constructed in this way.

The important features of the tanks, such as roof systems (either floating roof or fixed roof), diameter length, aspect ratios (cylinder height/diameter ratio) were considered in the survey. The survey was conducted using aerial photographs, from which only two geometric parameters could be identified: the type of roof (classified as fixed roof or floating roof); and the diameter of the tank. Notice that the roof type (e.g. cone, flat or dome roof) is not included in the survey, since they can not be distinguished from just aerial photographs. Typical tanks with cone and floating roofs are illustrated in Figure 1. Notice that the height of the cylinder can not be identify from the aerial photographs; however, a triangulation was made with lateral photographs (such as those in Figure 1) which were obtained during the site visits (Virella 2004).

(a)

(b)

Figure 1 - Typical tank geometries in Puerto Rico; (a) Tank with cone roof, (b) Tank with floating roof

3 Survey of tanks

Table 1 presents the number of tanks included in this survey, their location and the type of roof. This table shows that 307 tanks were included in the survey, most of the tanks (68%) are located in the southern region (Peñuelas), and about 73 % of all the tanks have fixed roofs while 27% have floating roof.

The tanks were classified in eight different groups depending on their diameters (D), as shown in Table 2.

Location	Tanks with fixed roof	Tanks with floating roof	No. of tanks
Northern region	76	22	98
Southern region	149	60	209
Total	225	82	307

Table 1 Tanks included in the survey

The numbers of tanks within each group are illustrated in Figures 2 and 3 for tanks with fixed and floating roofs. For the tanks with fixed roofs most of the tanks fall within groups II (43.6%) and III (24.4%), so that most tanks with fixed roofs have diameters in the range of 10m and 30m. For the tanks with floating roofs shown in Figure 3, the largest number of tanks fall within group II (32.9%), followed by groups III and V with 15.9 % of the total. The dominant single diameters for the tanks with floating roofs are the same obtained for the tank with fixed roofs (10m $\leq$ D $\leq$ 50 m). For the combine fixed and floating roof tanks (Figure 4), the dominant diameter falls within group II; i.e. about 41% of the tanks have diameters in the range of 10m and 20m.

As was previously discussed, the survey of the tanks discussed in this study was carried out using aerial photographs, so that the height of the tanks could not be measured. In a study by Virella (2004), a sample of 28 typical tank geometries of oil storage tanks in Puerto Rico was considered, and measurements of the cylinder height and diameter were performed from photographs. The tanks were classified in four different groups, depending on the aspect ratio (H/D) as presented in Table 3.

Group	Diameter
I	$D < 10$ m
II	$10 \leq D \leq 20$m
III	$20 < D \leq 30$m
IV	$30 < D \leq 40$m
V	$40 < D \leq 50$m
VI	$50 < D \leq 60$m
VII	$60 < D \leq 70$m
VIII	$70 < D \leq 80$m

Table 2 - Groups in which tanks are classified based on their diameters.

Figure 5 illustrates that most of the tanks fall within groups II (50%) and III (32.1%) accounting in combination for a total of 82.1% of the total tanks in the sample. Thus, it may be concluded that the majority of the tanks have aspect ratios in the range of 0.40 and 0.60 (Group II).

Group	H/D
I	$0.24 \le H/D < 0.40$
II	$0.40 \le H/D \le 0.60$
III	$0.60 < H/D \le 1.0$
IV	$H/D > 1.0$

Table 3 - Groups in which tanks are classified based on their aspect ratios

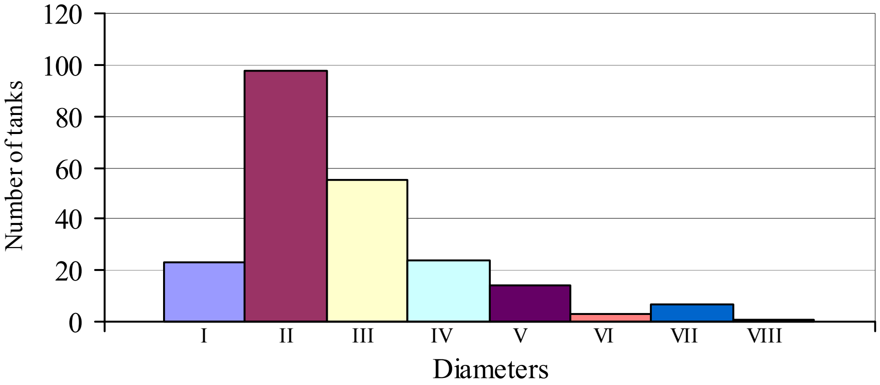

Figure 2 - Total number of tanks with fixed roofs within each diameter group

For the purpose of assessing the vulnerability to earthquake and hurricane wind of typical tanks in Puerto Rico, the following geometries were selected from the results of the survey discussed before for typical tanks with fixed or floating roof:

- Diameter: $10\text{m} \le D \le 20$ m
- Aspect ratio: $0.40 \le H/D \le 0.60$
- Selected geometry: D = 15 m, H/D = 0.50.

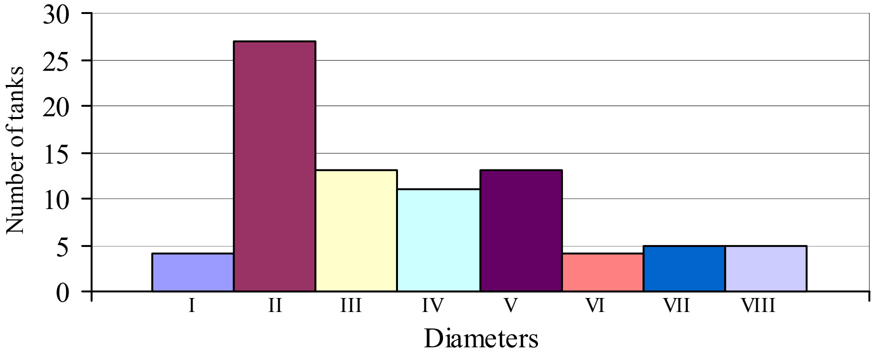

Figure 3 -Total number of tanks with floating roofs within each diameter group

Although the thicknesses of the shell of the tanks could not be obtained in the survey, this parameter can easily be designed with the API 650 code for any geometrical pattern of the tank. As the authors are mostly interested in vulnerability studies for existing tanks (which were designed in the 1960's and 1970's), these shell thicknesses can be accurately estimated with the serviceability design presented in the API 650 (1988) code. This design is shown in Figure 6 for the typical tank geometry selected. Notice from the figure that a cone roof is used for the fixed roof tank model, whereas for the floating roof this cone roof is not present. Also the rise and the thickness of the roof were not taken into account in the vulnerability curves presented in the following sections, which assume that the damage occurs at the cylindrical shell.

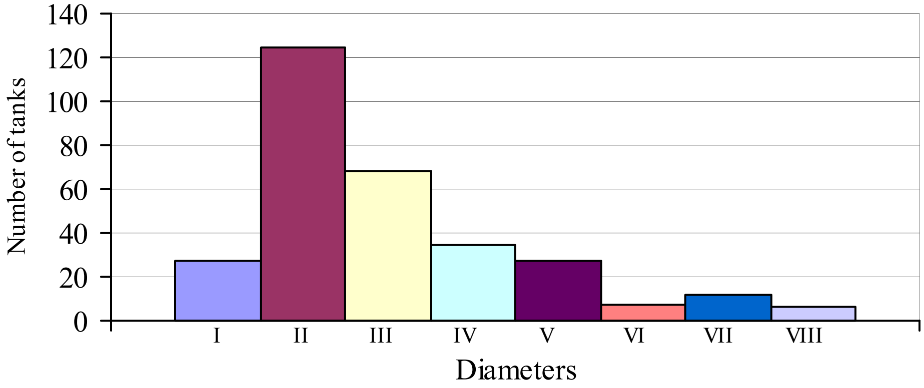

Figure 4 -Total number of tanks within each diameter group

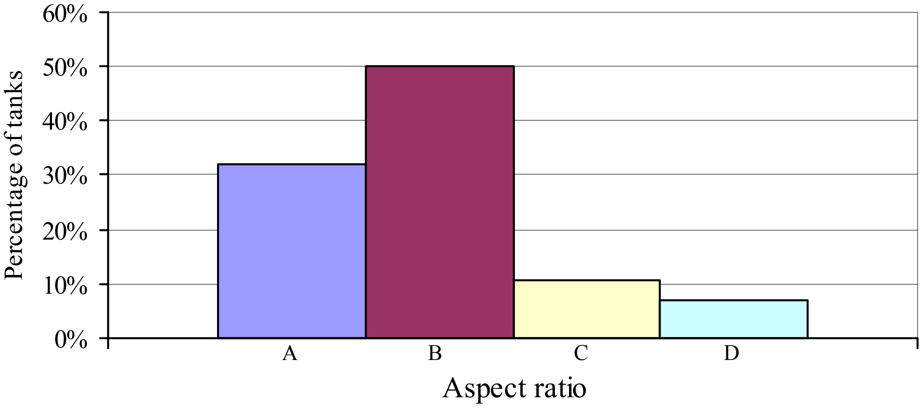

Figure 5 -Total number of tanks within each aspect ratio group.

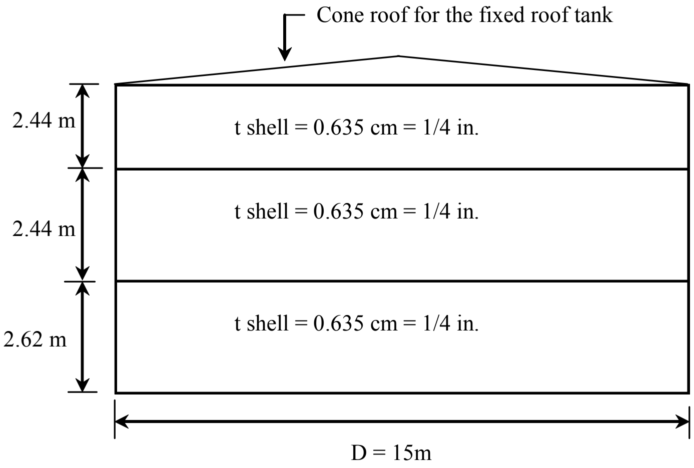

Figure 6 -Typical tank for vulnerability analyses.

4 Vulnerability of tanks under earthquake loading

In this section the seismic vulnerability of tanks with the typical geometries obtained from the survey is evaluated. Typical vulnerability curves for different failure modes of the tank subjected to earthquakes are used for the evaluation. These curves were obtained from Rammersorfer et al. (1990), based on results of Fischer et al. (1990), in which static analyses of anchored and unanchored tanks were performed and the critical horizontal acceleration that induces different modes of tank wall instability was found. These curves are presented in the form of critical horizontal acceleration (a_h^{crit}) versus cylinder height to radius ratio of the tank (α = H/R).

The vast majority of the tanks in Puerto Rico have been designed as unanchored shells, i.e. the bottom is allowed to uplift in case that the overturning induced by the earthquake loads surpass the total weight of the tank and foundation system. In some cases, the tank is directly placed over the soil and other times it is founded over a concrete ring which is not attached to the cylindrical wall, so the tank has the capability to uplift under seismic loading. For that reason, the vulnerability of the tank is assessed for the typical geometry selected in the previous section by considering unanchored tank conditions. Notice also that the unanchored tank assumption is more conservative than an anchored condition, since a much smaller a_h^{crit} is obtained.

For the seismic vulnerability evaluation, the tank with cone roof of Figure 6 is selected, which has H/D = 0.50, or α = 1.0. The following values of a_h^{crit} are obtained from Figure 7 for this geometry:

- Failure mode: Elastic buckling, a_h^{crit} = 0.12g.
- Failure mode: Membrane yielding, a_h^{crit} = 0.14g.

These results mean that a typical tank would initially fail by elastic buckling and would probably have membrane yielding as a post-buckling effect. Notice that the a_h^{crit} of 0.12g, which induces buckling in the tank shell, is a lower horizontal acceleration than most actual design codes specified for Puerto Rico. For example, in the case of rock conditions at the base, a PGA of 0.30g is specified in the UBC (1997) code for Puerto Rico. In that case for the design earthquake considered in the actual design codes (i.e. with a recurrence interval of 475 years), the typical tank is expected to fail and will probably have serious damage.

5 Vulnerability of tanks under wind loading

Major hurricanes, including Hugo (1989), Marilyn (1995), and Georges (1998), affected the Caribbean islands in the last twenty years, causing damage to the structural integrity of steel storage tanks. In the particular case of Puerto Rico, after hurricane Georges, buckled tanks were observed and there is evidence that this buckling occurred due to the high wind velocities recorded (120 mph sustained, and wind gusts up to 150 mph). Previous works have been focused in obtaining the wind pressure distributions and the critical buckling load of tanks under such loadings (Flores & Godoy 1998, Portela & Godoy 2005).

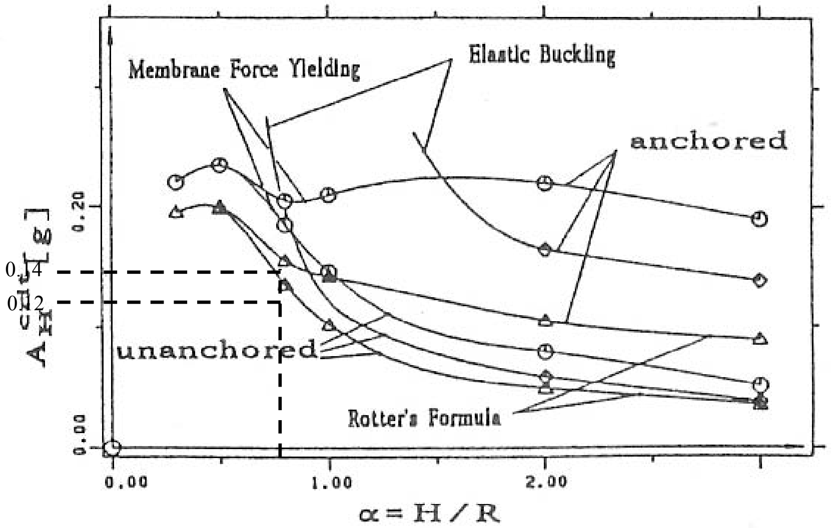

Figure 7 - Vulnerability curves of steel cylindrical tanks subjected to earthquakes (Reproduced from Rammerstorfer et al. 1990).

The dimensions of the tanks found in Puerto Rico vary in diameter, height, shell thickness, and in their top boundary condition. Two types of top configurations were selected based in the most common roof geometries found: tanks with open top and with cone roof. In the analysis, the wind pressure distributions acting in the shell were assumed constant in height and variable around the circumference according to Rish (1967), and in the roof were used distributions from Macdonald et al. 1988. Figure 8 presents critical wind velocities for circular steel tanks with different H/D ratios according to Sosa (2005). The critical velocity is the one producing the first critical buckling load in the tank, considering geometrical nonlinearity. Comparisons between the open-top and the tanks with roof show that for H/D ratios > 0.4, the critical wind velocity for tanks with roof is 20 to 30% higher than for open-top tanks. For smaller aspect ratios the difference between both top configurations is in the order of 35%, as is the case of H/D = 0.25. In such cases, the buckling mode is localized at the top windward region of the shell, as observed in field inspections of buckled tanks after Georges in 1998. This region has the lowest shell thickness, and is where the highest wind positive pressures develop in the tank.

The most representative dimensions of the tanks in Puerto Rico corresponds to a diameter of 15m and a ratio H/D = 0.5. From Figure 8, this geometric configuration buckles at a critical wind speed of 148mph for the tank with cone roof and 121mph for the open-top tank. The tank with cone roof has a critical velocity which is close to the design wind speed for Puerto Rico (145mph at 10m height from ground), as established by ASCE 7 (2005). The case of the open-top tank is even more critical because the velocity is very close to the sustained winds during hurricane Georges (120mph). These values do not account for other effects that reduce the critical wind velocity of the tanks, such as imperfections in the shell.

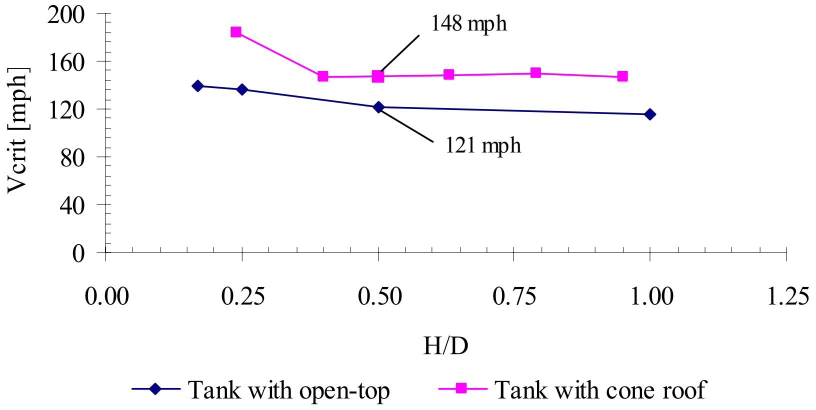

Figure 8 - Critical wind speed for tanks with different H/D ratios.

6 Conclusions

A survey was performed to establish the typical tank geometries of storage tanks in Puerto Rico, including tanks with fixed and floating roofs. For both types of tanks the dominant geometry was characterized with diameters (D) in the range of 10m to 20m and aspect ratios (H/D) from 0.40 to 0.60.

A vulnerability assessment was performed for a typical tank geometry with diameter of 15m, aspect ratio H/D = 0.50 and unanchored base condition, for earthquake and hurricane wind loadings. The earthquake vulnerability assessment pointed to a failure mode by elastic buckling for an a_h^{crit} = 0.12g which is much smaller than the design peak ground acceleration specified in modern design codes for Puerto Rico. It is then concluded that existing tanks in Puerto Rico are vulnerable to have serious damage if they are subjected to the design earthquake prescribed in modern seismic codes. The existing tanks in Puerto Rico are also found to be vulnerable to damage under the wind loadings expected. As shown in the results, the tanks with cone roof have critical velocities in the order of the 3-seconds gust defined by local wind specifications. Even worse is the scenario presented by open-top tanks, with critical wind velocities in the order of sustained winds measured in the Island during previous hurricane events.

This study is a first step toward the development of fragility curves of tanks for earthquakes and hurricane winds. Fragility curves can be developed from computational analysis of the tanks using the typical geometries found in Puerto Rico. The results from the vulnerability analysis provide the justification for a future study in which the extension of the expected damage along with their probabilities of occurrence should be established by means of fragility curves.

Acknowledgement

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