Fragility Assessment of Above Ground Petroleum Storage Tanks under Storm Surge

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ABSTRACT: Catastrophic failure of above ground storage tanks (ASTs) was observed due to storm surge during past hurricanes such as Katrina, Ike and Gustav causing severe environmental and economic impact. This paper evaluates the fragility of ASTs subject to hurricane storm surge to offer a basis for risk assessment of coastal facilities that store hazardous materials such as petroleum. Tank failures related to hurricane wind and earthquakes have been studied in literature; however, the effects of hurricane surge have not been addressed. Therefore, as a first step towards evaluating the fragility of ASTs under storm surge, this study identifies the primary modes of failure caused by storm surge—flotation and buckling. Next, uncertainties associated with each mode of failure are identified and characterized. The prime source of uncertainty considered for non-linear buckling analysis is geometric imperfections on the tank shell. Finally, these uncertainties are included while simulating response of ASTs during surge events. The results of these simulations are used to develop parameterized fragility curves using logistic regression. This methodology is applied to a typical tank from the Houston Ship Channel to assess conditional failure probability under storm surge. Key insights on dominance of the two modes of failure at different surge levels are also obtained. Using these observations, this study suggests structural and non-structural measures to prevent failure of tanks in future hurricane events. In addition, this paper provides a basis for parameterized fragility modeling of ASTs subject to hurricane storm surge that can be further extended to include other threats such as wave impact.

1. INTRODUCTION

Failure of above ground storage tanks during hurricanes Katrina and Rita led to spillage of over 7 million gallons of petroleum products in to the surrounding environment (Godoy 2007). Such spills have adverse long term and short term effects on the surrounding environment and natural habitat (Kingston 2002; Maki 1991). In addition to environmental damage, such oil spills can also have negative effects on mental and physical wellbeing of the surrounding communities (Palinkas et al. 1993) and result in costly cleanup. For example, Murphy oil spill during hurricane Katrina caused by failure of just one large AST led to release of over 1 million gallons of crude oil affecting about 1700 homes. Even though failure of tanks during hurricanes can lead to severe environmental impact, high clean-up costs, law suits and high economic losses, failure of ASTs due to storm surge has received very limited attention in past studies. Existing research on performance of ASTs during hurricanes is primarily focused on buckling of ASTs during hurricane winds (Flores and Godoy 1998; Godoy and Flores 2002; Greiner and Derler 1995). Furthermore, most of the design guidelines such as API 620 (API 2002) and API 650 (API 2013) only provide detailed guidelines to prevent wind buckling of tank shell leaving the implementation of measures to prevent failure due to storm surge and floods on the discretion of the tank owners. Consequently, the vulnerability of tanks to storm surge was exposed again during subsequent hurricane events such as Ike and Gustav (Hyder 2008; Sengul et al. 2012). However, such tank failures could be avoided with knowledge on the behavior of tanks during hurricanes, their failure mechanisms and the uncertainties associated with failure, which is currently lacking in the literature. This study aims to address these gaps by understanding the failure mechanism of ASTs, characterizing the associated uncertainties and developing probabilistic performance for ASTs subjected to storm surge.

Reconnaissance reports on damage to storage tanks during hurricane Katrina and Rita have highlighted two major causes of tanks failure: dislocation of tanks due to flotation, and local and global buckling of tank shell which could be due to wind loads and surge loads for anchored tanks (Godoy 2007). Therefore, the present study will first develop probabilistic models for tank dislocation or uplift. Probabilistic models for buckling of tank shells due to surge loads will also be developed considering the uncertainties in tank shell imperfections, which is not included in wind buckling studies. As the first step to understand the probabilistic behavior of ASTs a typical storage tank must be selected. For this purpose, inventory analysis of ASTs in Houston ship channel was performed and an AST with height 10 m, diameter 15 m is selected. The portfolio analysis, however, did not provide any information on the thickness of the tank shell; therefore, the tank shell is assumed to be 1 cm thick throughout the height of the shell.

The approach for probabilistic performance assessment for the selected tank is presented in the following sections. Section 2 describes the procedure adopted to study the floatation and buckling behavior of ASTs under storm surge. The uncertainties associated with the resistance of tanks against floatation and the stochastic imperfections that affect the buckling behavior of ASTs are also characterized. Section 3 discusses results of the probabilistic analysis; wherein, the probability of failure is determined for different modes of failure. Based on dominance of different modes at different surge heights, suggestions to prevent failure of tanks are also discussed. The last section concludes the paper.

2. FRAGILITY ANALYSIS

ASTs have very thin shells compared to the dimensions of the tank and are designed to withstand large internal pressure due to stored liquid. However, external pressures make them vulnerable to buckling or crushing. In case of surge, water surrounding the tanks may exert enormous pressure on the shell and may cause it to buckle. So, tanks with flotation prevention mechanisms may still get damaged by storm surge. Therefore, in addition to floatation failure, buckling of tanks due to external surge pressure is also addressed for anchored tanks in order to assess overall surge performance. The following sub-sections describe the procedure for probabilistic performance assessment of ASTs under storm surge.

2.1. Floatation analysis

Flotation analysis is carried out for the AST selected in the previous section using the Archimedes principle. Difference between self-weight and the buoyancy forces leads to the following limit state equation

$$\underbrace{\left(\pi DH + \frac{2\pi D^2}{4}\right)tg\rho_s}_{W_t} + \underbrace{\pi\frac{D^2}{4}Lg\rho_l}_{W_l} - \underbrace{\pi\frac{D^2}{4}Sg\rho_w}_{F_b} > 0; S < H \qquad (1)$$

In the above equation, D, H and t are tank diameter, height and shell thickness respectively; S and L are surge height and height of liquid inside the tank; ρ_l, ρ_s and ρ_w are densities of liquid stored inside the tank, steel and sea water; and g is acceleration due to gravity (9.81 m/s^2). The terms W_t, W_l and F_b represent the weight of tank shell, weight of internal liquid and the buoyant force respectively. Eq. (1) is valid for un-anchored tanks, i.e. free to float, where surge height is less than tank height. Since surge greater than 10 m (AST's height) is highly improbable Eq. (1) is used throughout this study.

Tanks installed with flotation prevention mechanisms such as anchors may also be vulnerable to dislocation. Similar to un-anchored tanks, the limit state equation can be written using the Archimedes principle as

$$W_t + W_l + R_a - F_b > 0; S < H \qquad (2)$$

where, W_t, W_l and F_b are same as in Eq. (1). R_a is the resistance offered by anchors against uplift. Strength of cast in place anchor bolts is obtained as the minimum of steel strength (R_s), concrete cone failure strength (R_{cc1}) for sufficient edge distance or R_{cc2} for insufficient edge distance and side face blowout strength (R_{cb}) (Eligehausen et al. 2006). The total resistance offered by anchors (R_a) is calculated by multiplying the resistance from an individual anchor with the number of anchors, n_a. The expressions for R_a ,R_s, R_{cc1}, R_{cc2} and R_{cb} are given below

$$R_a = n_a \times \min\{R_s, R_{cc1}, R_{cc2}, R_{cb}\} \tag{3a}$$

$$R_S = A_S f_{ut} \tag{3b}$$

$$R_{cc1} = \varepsilon_1 k h_{ef}^{1.5} f_c^{0.5} \tag{3c}$$

$$R_{cc2} = \varepsilon_2 \frac{A_{C,N}}{A_{C,N}^0} \Psi_{S,N} R_{cc1} \tag{3d}$$

$$R_{cb} = \varepsilon_3 20.9 c_1^{0.75} A_h^{0.5} f_c^{0.75} \tag{3e}$$

In the above equations, A_s is the area of the anchor bolt; f_{ut} is the ultimate strength of steel; f_c is concrete strength, k is a constant equal to 16.8, h_{ef} (in mm) is the embedment depth of the anchor; $A^0_{C,N}$ and A_{CN} are projected areas of the concrete cone for anchors with large edge distance and limited edge distance respectively (in mm^2); $\psi_{S,N}$ is a modification factor which is less than or equal to one; c_1 is the edge distance (in mm); A_h is bearing area of head (in mm^2); ε_1, ε_2 and ε_3 are normally distributed bias removal terms. For further details Eligehausen et al. (2006) may be referred.

Several parameters in limit state equation of un-anchored and anchored tanks, i.e. in Eq. (1) and Eq. (2), are considered as random variables. Densities of steel and sea water are considered to be uniformly distributed; liquid height inside the tank is also considered to be uniformly distributed. These parameters are assigned uniform distribution due to lack of information and the unbiasedness of the uniform distribution. Parameters directly or indirectly used in Eq. (4) such as strength of steel (f_s), concrete (f_c) and the error terms are also treated as random variables. The distributions of the random variables along with their parameters are shown in the Table 1.

Table 1: Parameters for random variables.

Parameter	Distribution	Mean	C.O.V.*
ρ_w (kg/m3)	Uniform	1024.5	0.0025
ρ_s (kg/m3)	Uniform	7900	0.011
ρ_l (kg/m3)	Uniform	500	0.192
L (m)	Uniform	4.5	0.58
f_s (MPa)	Lognormal	415	0.08
f_c (MPa)	Normal	20	0.15
ε_1	Normal	0.99	0.18
ε_2	Normal	1.04	0.26
ε_3	Normal	0.96	0.18

*C.O.V. refers to coefficient of variation

2.2. Buckling analysis

For the purpose of buckling fragility analysis, the tank is modeled in LS-DYNA (Hallquist 2012) using shell elements. The tank is subjected to internal liquid pressure and external hydrostatic pressure due to surge. Global geometric imperfections in the shell are modeled following Kameshwar and Padgett (in review) which are based on observations on imperfections measured on tanks and silos (Hornung and Saal 2002; Teng et al. 2005). As per Kameshwar and Padgett, the imperfections are modeled using a double Fourier series. For the selected tank, imperfections are given by

$$F(\theta, Z) = \sum_{m=0}^{M}\sum_{n=0}^{N} C_{mn} \cos(m\theta + \varphi)\cos\left(\frac{n\pi Z}{10}\right)$$
$$C_{mn} = |N(0,1)| e^{-m/5 - n/4}\left(1 + \left|\cos\left(\frac{m\pi}{5}\right)\right|\right)\left(1 + \left|\cos\left(\frac{n\pi}{4}\right)\right|\right) \tag{4}$$
$$I(\theta, Z) = R_{sign} U(0.01, 0.065) F(\theta, Z) \big/ \max|F(\theta, Z)|$$

In the above equation, θ is the angle in radians; Z is the height along the axis of the tank; $N(0,1)$ refers to a standard normal variable; R_{sign} is a random variable which takes values 1 or -1, with equal probability; and $U(0.01,0.065)$ is a uniformly distributed random variable with lower bound 0.01 and upper bound 0.065. These imperfections are used in non-linear finite element analysis to identify the surge height causing initiation of buckling for various internal liquid levels and internal liquid densities. Since post buckling behavior of ASTs is not studied in this paper, a load control scheme is utilized where each load step corresponds to increase in external surge height. The surge height at which the load control scheme is unable to converge due to loss of equilibrium is considered as the critical surge height causing buckling. The proposed scheme for evaluating the critical surge height was compared to an Arc-length solution scheme for the empty tank for the critical surge height; the two methods provide similar results.

A set of internal liquid height and liquid density values is created using Latin Hypercube Sampling (LHS) (McKay et al. 1979) to evaluate the critical surge height for different values of liquid height and density. The values of internal liquid height and density range from 0-9 m and 500-1000 kg/m^3 respectively. For each point in the set, a new stochastic imperfection is simulated and the critical surge height is evaluated, which is used with an Adaptive Basis Function Construction scheme (Jekabsons 2010) to obtain the following relation between liquid height and density and critical surge height (S_{cr}):

$$\begin{aligned} S_{cr} &= 4.92 + 6.84L + 6.0e-3L^3 - 0.04L\rho_l - \\ &2.61e-6L^4\rho_l + 2.05e-5L^3\rho_l 8.33e-5L\rho_l^2 - \\ &7.61e-8L\rho_l^3 + 2e-11L\rho_l^4 \end{aligned} \quad (5)$$

The R^2 value for the fit in Eq. 5 is 0.99 and the root mean squared error (RMSE) is 0.13. Thus, the limit state equation can be written as

$$S_{cr} + \varepsilon_4 - S > 0 \quad (6)$$

In the above equation, ε_4 accounts for error due to the polynomial fit which is modeled as a normal variable with zero mean and standard deviation equal to the RMSE of the fit.

2.3. Fragility analysis

First order reliability methods can be used to evaluate the fragility for each of the failure modes as closed form equations for the limit state are available. However, first order reliability methods do not provide a closed form fragility function which may be used to assess the impact of variation in parameters on fragility. Therefore, in order to obtain closed form expressions for fragilities, logistic regression (Hosmer and Lemeshow 1989) is used which describes the probability of the occurrence of a binary event such as failure or survival of the tank. The probability of tank failure conditioned on a given set of parameters is estimated by logistic regression as

$$P(event|X) = \frac{e^{g(X)}}{1+e^{g(X)}} \quad (6)$$

where, X is a vector of parameters (L, S, and ρ_l) and the function $g(.)$ is the logit function, a polynomial in X, which predicts the logarithm of odds in favor of tank failure. Thus, if the logit function, $g(X)$, is greater than zero the probability of failure will be over 0.50. The coefficients of the polynomial terms and the intercept in the logit function may be determined by using the maximum likelihood principle. In this study, all the terms in the polynomial are not included; only the most influential terms are added to the logit function via step-wise regression. Furthermore, logistic regression makes no assumptions on the distribution of the input variables in X. To obtain fragility functions, a set of 10,000 parameters values is generated using LHS for each failure mode to span the entire range of applicable parameters described in Table 1. The limit state function is evaluated at all of the points and step-wise logistic regression is performed to obtain fragility functions, described in the next section.

3. RESULTS AND DISCUSSION

3.1. Logit functions

While performing logistic regression for flotation of anchored and un-anchored tanks, density of steel and sea water were excluded from the logit function. However, the uncertainty due to these variables was propagated in the analysis considering their effect as aleatoric uncertainty. The logit function for flotation of an un-anchored tank is obtained as

$$\begin{aligned} g(\rho_l, S, L) &= -48.40 + 0.0019\rho_l + 130.11S - \\ &0.055L - 0.127L\rho_l \end{aligned} \quad (7)$$

Similarly, the logit function for anchored tanks (with 30, 25.4 mm diameter, steel anchors with strength f_s embedded in concrete with strength f_c

(see Table 1 for details) around the circumference) is

$$g(\rho_l, S, L) = -7.79 + 9.68E - 4\rho_l + 2.032S - 0.188L - 0.0018L\rho_l \quad (8)$$

The logit function for the buckling of the AST is:

$$g(S, L, \rho_l) = -55.80 + 16.69S - 2.32L + 6.87\rho_l + 0.58SL - 0.0019L\rho_l - 1.06S^2 - 0.31L^2 \quad (9)$$

Using the logit functions shown above, the conditional probabilities of failure are obtained which are convolved further with the probability distributions of the parameters to derive failure probabilities conditioned on select parameters, such as surge height and internal liquid level.

3.2. Fragilities of individual failure modes

The method described above is also used to obtain fragilities conditioned solely on surge height. For un-anchored tanks with gasoline (liquid 1), the fragility surface is shown in Figure 1. The density of gasoline is considered as a uniformly distributed random variable with a mean density of 740 kg/m^3 and a C.O.V. of 2.3%. As the surge height increases, liquid level higher than the external surge is required to prevent failure because the internal liquid has lower density than sea water. As can be seen from the figure, the transition from survival to failure is very sharp which indicates that uncertainties in parameters such as: densities of steel, sea water and liquid 1 do not have significant impact on the probability of tank uplift. The effect of density of steel is negligible because self-weight of the tank is relatively low compared to weight of internal liquid and buoyant forces. While the effect of sea water density and density of liquid 1 is insignificant due to the low coefficient of variation. Considering the internal liquid level to be uniformly distributed the probability of failure for liquids with different densities and different surge level is shown in Figure 2 where liquid 2 corresponds to crude oil with uniformly distributed density with a mean density of 850 kg/m^{3}and 2.0% C.O.V. For very low surge heights, about 0.4 m, the probability of failure is very low. This is due to the self-weight of the empty tank which is sufficient to resist the buoyancy force due to very low surge. However, as the surge height increases, the probability of failure increases. At surge heights over and above 7 m, the tank with liquid 1 is almost certain to become buoyant. This is due to the relative difference in the densities of the internal liquids and sea water. Liquid 2 has higher density, compared to liquid 1, and consequently it has lower probability of failure.

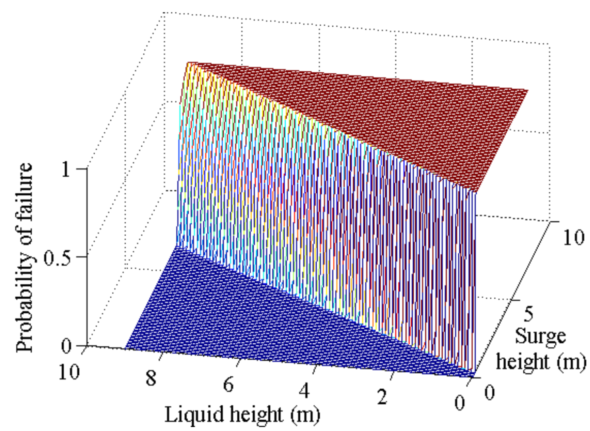

Figure 1: Unanchored AST flotation fragility surface

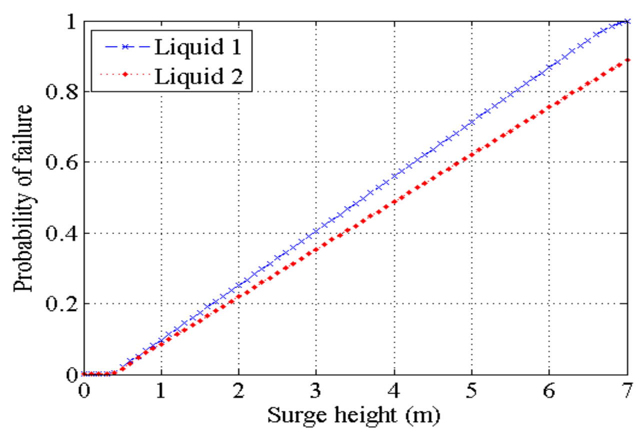

Figure 2: Un-anchored tank flotation fragility curve

Figure 3 shows the uplift fragility surface for the anchored tank, filled with liquid 1. The qualitative trend in this figure is similar to the trend observed in Figure 1. However, uncertainty in the strength of concrete and steel has pronounced effect, observed from the smoothness of the fragility surface. In this case also, to decrease failure probability, higher liquid heights are required for higher surge heights. Comparing Figure 1 and Figure 3, it can be observed that the anchoring system significantly decreases the failure probability. The un-anchored tanks would certainly float at a surge height of 7.0 m; however, the anchored tank has lower probabilities of failure even at this surge height. At lower surge levels, the probability of failure is very low as the self-weight and the anchor resistance is sufficient to resist uplift. Figure 4, shows the fragility of the tank for the two liquids conditioned only on the surge height. This figure also clearly highlights the effectiveness of anchors in decreasing the failure probability at all surge levels.

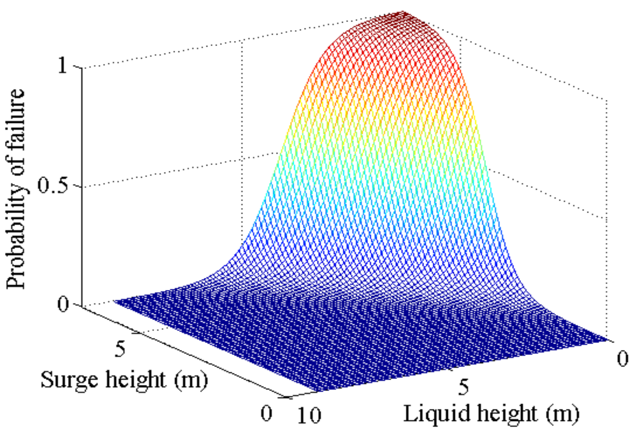

Figure 3: Anchored AST flotation fragility surface.

Buckling fragility of the tank for liquid 1 with different liquid levels and surge heights is shown in Figure 5. It can be observed that the fragility varies non-linearly with surge height and liquid height. For large surge heights, higher liquid level is required. However, this trend is not observed for lower surge heights where surge heights up to 4.0 m do not induce buckling, due to the inherent strength of the tank. For the two liquids, Figure 6 shows the buckling fragility of the tank conditioned on surge height. In Figure 6, it can be observed that at 4.5 m surge the probability of failure is very low but it increases sharply as the surge height increases. Increase in liquid density decreases the failure probability, but not as significantly as observed for uplift fragility. This observation is in part due to the small increase density relative to the density of the sea water surrounding the tank. The trends in buckling fragility of the tank lead to interesting system fragility observation, discussed next.

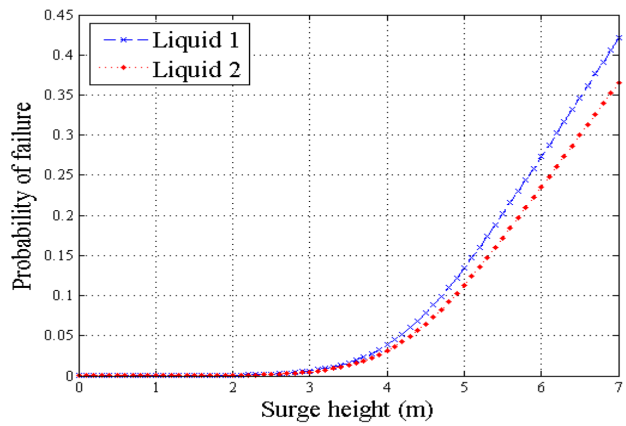

Figure 4: Anchored tank flotation fragility curve.

3.3. System fragility and mitigation strategies

System fragilities for the un-anchored tanks will be the same as shown in Figure 2 since floatation is the only mode of failure. However, for the anchored tank two failure modes are possible, i.e. buckling and uplift. If the tank uplifts, buckling of the tank shell is avoided; and if the tank does not uplift buckling may occur. So, the two modes of failure can be considered to be in series with each other. Furthermore, in this study the two modes are also assumed to be mutually exclusive and collectively exhaustive. It is acknowledged that other failure modes, such as surge induced debris impact, are possible but are beyond the scope of this study. Therefore, the system fragility of anchored tanks can be obtained as the maximum of the two failure probabilities. Figure 7 shows the system fragility for the anchored tank with liquid 1. In this figure, P_f – Float refers to the probability of failure due to floatation, Pf – Buckling refers to buckling fragility and P_f – System, shown by solid red line, is the system fragility. It can be seen from the figure that for surge up to 4.9 m the system has low probability of failure, dominated by floatation failure. As the surge height increases further, failure probability increases sharply because buckling starts controlling the system fragility.

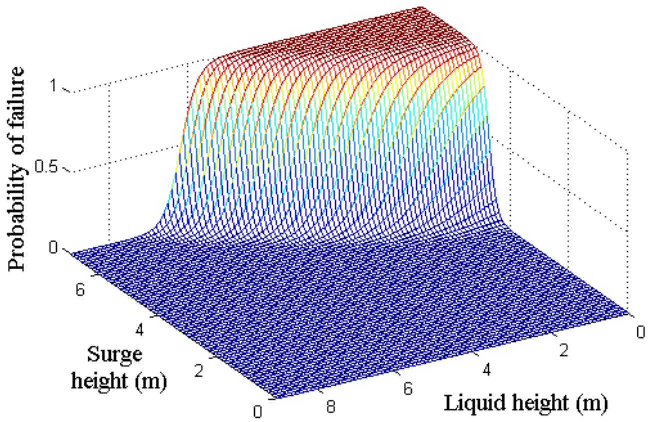

Figure 5: Anchored AST buckling fragility surface.

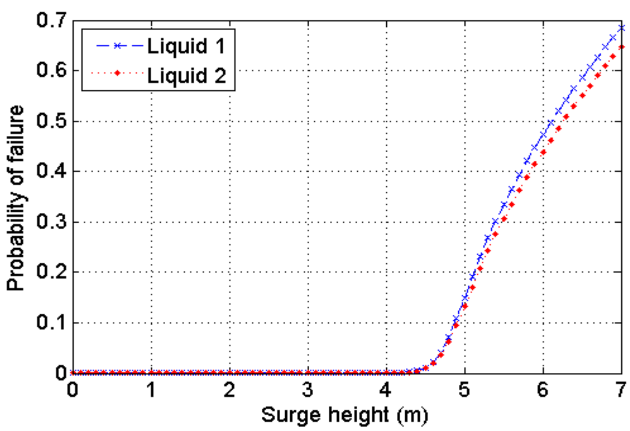

Figure 6: Anchored tank buckling fragility curve.

As seen from Figure 7, sufficient anchoring may prevent the uplift of the tank but doing so will make the tank vulnerable to buckling. Even if the anchoring systems are optimized to minimize the probability of floatation, the fragility will be dominated by buckling. In this case, structural measures such as use of stiffening rings or increasing the thickness of the shell may be adopted. Non-structural measures may also be used to prevent failure of tanks based on the fragilities shown in this section. Consistently, for all the cases it can be seen that higher liquid levels inside the tank lead to lower probabilities of failure and higher surge levels lead to higher failure probability. So the first non-structural measure may be maintaining higher internal liquid levels during storm events.

Alternatively, tanks may be prevented from exposure to surge by constructing the facilities away from the coast; though this may be considered for new facilities only. For existing tanks, protective structures such as dikes or levees around facilities housing ASTs may be considered. However, these solutions may always not be practical; therefore, a combination of operational strategies and structural measures may be used to prevent the tank failures.

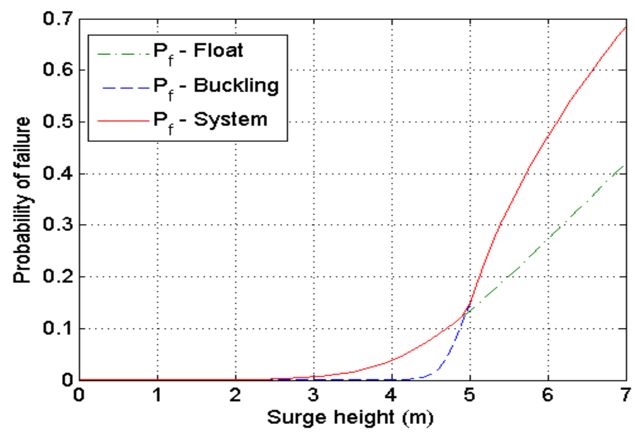

Figure 7: Anchored tank system fragility

4. CONCLUSIONS

This study has focused on the fragility assessment of a selected above ground petroleum storage tank subjected to hurricane surge loads. Two primary modes of failure ajamre identified and analyzed, namely: floatation and buckling of the tank shell. For each mode of failure random variables are identified and failure probabilities are evaluated. Stochastic imperfections are generated to model geometric imperfections for buckling fragility evaluation. Response of the AST is simulated under storm surge which is used for logistic regression to evaluate fragility functions. Furthermore, closed form fragility expressions obtained from logistic regression are convolved with probability distributions of variables and finally fragilities conditioned on surge height alone are obtained. Fragility associated with individual mode of failure provides insight on the likelihood of the failure mode and the system fragility shows interesting trends on dominance of uplift for low surge heights and buckling failure for higher surge heights. Based on system fragility observations this study suggests mitigation measures using structural retrofits; operational measures and their combination. This study has taken the first steps towards evaluating storm surge fragility for ASTs; future work will focus on extending the procedure to a portfolio of tanks and assess the effect of mitigation measures such as increasing shell thickness and providing stiffener rings.

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