Structural Safety 70 (2018) 48–58

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Storm surge fragility assessment of above ground storage tanks

Sabarethinam Kameshwar *, Jamie E. Padgett

Department of Civil and Environmental Engineering, Rice University, 6100 Main St. MS-318, Houston, TX 77005, United States

ARTICLE INFO

Article history:
Received 5 July 2016
Received in revised form 24 April 2017
Accepted 7 October 2017

Keywords:
Above ground storage tanks
Surge
Buckling
Flotation
Fragility
Metamodel

ABSTRACT

This study proposes a dual layer metamodel based approach to develop parameterized fragility functions for above ground storage tanks (ASTs) subjected to hurricane induced storm surge. ASTs are extensively used in petrochemical facilities for storing large volumes of hazardous substances. Failure of ASTs due to storm surge may lead to spills that can cause severe environmental damage and considerable economic loss. A significant number of ASTs are located in coastal areas which are susceptible to hurricanes, such as in the Houston Ship Channel, Texas. However, tank design guidelines are deficient in addressing prevention of surge related failures. Although their vulnerability has been exposed during past hurricanes, the literature lacks studies on performance analysis of ASTs during storm surge events. In this light, a method is presented to derive fragility functions for the most important failure modes of ASTs – flotation and buckling – in addition to the system fragility, considered as series system of failure modes. For this purpose, a novel dual layer metamodel based approach is proposed where a limited number of simulations are used to train the first binary classifier, which predicts failure of tanks, upon which the second metamodel is trained; the final metamodel is used to derive parameterized fragility functions. This approach significantly reduces the number of limit state evaluations, which may require costly finite element simulations, and enables accurate fragility assessment to capture the nonlinear behavior of tanks under surge loading, while also considering the correlation between failure modes during system fragility modeling. Results indicated that the fragility estimates of a typical tank obtained with the dual layer metamodel compare well with those derived by high fidelity methods such as Monte Carlo Simulations. In order to demonstrate the application of the parameterized fragility functions to study the effect of variation in design and construction parameters, fragilities of four case study tanks are evaluated. The results highlight the effect of parameter variation on the fragilities and offer insights into the influence of alternative design impacts on tank vulnerability. For example, anchoring tanks significantly reduces the probability of flotation; however, anchoring leads to buckling dominated failures.

1. Introduction

Aboveground storage tanks (ASTs) are often used for bulk storage of hazardous materials, including a variety of fuels and chemicals at industrial sites such as petrochemical and oil & gas facilities. ASTs are typically thin walled steel shells constructed as vertical cylindrical structures. This shape allows ASTs to sustain large internal liquid pressure using a relatively thin shell. Consequently, ASTs are very light in weight and susceptible to flotation during storm surge induced by hurricane events. Furthermore, the thin walls make ASTs susceptible to buckling failures due to external forces such as wind and storm surge. The vulnerability of ASTs has been observed during past hurricanes such as Katrina and Rita where several tanks failed due to hurricane wind and surge, spilling over 26500 m^3 of petroleum products into the environment [1]. In one of the cases, flotation failure of just one tank lead to a 4000 m^3 spill leaving over 1700 homes un-inhabitable at a cost over $330 million in clean up and litigation [2]. The vulnerability of tanks to storm surge was exposed again during subsequent hurricane events such as Ike and Gustav [3,4]. Tank failures can lead to catastrophic oil spills which not only adversely affect the surrounding environment [5,6] but also impact the physical and mental wellbeing of surrounding communities [7].

In order to prevent tank failures during extreme hazards, such as earthquakes, design codes like API 620 [8] and API 650 [9] provide standards for designing ASTs. API 650 provides extensive guidelines to prevent failures due to earthquakes and hurricane winds. For example, anchorage is prescribed to prevent uplift during earthquakes and the use of stiffening rings and thicker walls are recommended to prevent shell buckling due to strong winds. However, API 650 and other similar design codes provide no

* Corresponding author.
E-mail address: sabarethinam.kameshwar@gmail.com (S. Kameshwar).

https://doi.org/10.1016/j.strusafe.2017.10.002
0167-4730/

mandatory guidelines to prevent failures due to storm surge and floods. Any measures to prevent surge and flood related failures are left at the discretion of the purchaser. Furthermore, most state regulations fail to impose any additional requirements for such prevention, with few exceptions such as the state of Colorado [10] which requires a method to be declared for flotation prevention during flood conditions in order to obtain a permit.

Literature also has largely focused on seismic performance assessment of ATSs with limited investigation of ASTs' performance during hurricane winds and tsunamis. A large number of experimental and analytical studies have been conducted to understand the seismic performance of ASTs [11–14]. Furthermore, studies have used data on past performance of AST under earthquakes to derive empirical fragility curves using probit analysis and convolved the fragilities with seismic hazard curves to estimate risk [15,16]. For hurricanes, studies have primarily focused on deterministic wind buckling capacity estimation of ASTs [17–20], while some studies propose new designs for AST components such wind girders [21]. Similarly, few deterministic studies exist on behavior of ASTs during tsunamis where forces acting on ASTs are evaluated and deterministic performance analyses are conducted [22,23].

While risk assessment methods exist for ASTs subjected to earthquakes and several deterministic performance assessment studies are present for ASTs under hurricane wind and tsunamis, there is a large gap in the literature in understanding and modeling the performance of ASTs subjected to hurricane induced storm surge. The literature lacks studies that adequately address the safety of ASTs subjected to storm surge. Godoy [1] reports the performance of ASTs during hurricanes Katrina and Rita and attributes tank failure to flotation and buckling. A recent study by Kameshwar and Padgett [24] performed fragility assessment of a case study tank under storm surge considering flotation and buckling failure. However, the methodology used by Kameshwar and Padgett [24] was not tailored to support fragility assessment of a regional portfolio of tanks or to study effect of variation in design parameters on fragility; furthermore, a system fragility formulation considering multiple failure modes is also lacking. In view of the compelling evidence of AST vulnerability to storm surge, consequences of tank failure, and lack of research on storm surge performance assessment of ASTs, this study develops a method to derive fragility functions for ASTs subjected to storm surge. Herein, fragility functions are developed for flotation, buckling, and system failure of ASTs. The fragility functions express the probability of failure given the geometry and design parameters of ASTs, in addition to storm surge inundation. These parameterized fragility functions will be helpful in understanding the failure mechanisms as the geometry and the tanks' features are varied. Additionally, the resulting probabilistic models for AST performance can be used in the future to assess the benefits of large-scale regional coastal protection systems.

The next sections of the paper present the steps involved in developing the parameterized fragility functions. Using reconnaissance reports, section two identifies the potential failure modes of ASTs under storm surge to be studied. In section three, the resistance and demands for flotation failure, and demands for buckling failure are evaluated using closed form equations while finite element simulations are used to determine buckling resistance. Using the capacities and demands, classifiers are trained to identify tank failures, which are used further to derive the fragility functions described in sections four and five. In order to demonstrate the application of the fragility functions, the performance of four case study tanks is evaluated and the insights obtained from the results are discussed in section six. Finally, section seven summarizes the conclusions and the main contributions.

2. Failure modes

A reconnaissance report on performance of ASTs in the states of Texas and Louisiana, USA, during hurricanes Katrina and Rita by Godoy [1] attributes tank failures to tank dislocation due to flotation, global shell buckling caused by strong winds, and debris impact. Cozzani et al. [25] have analyzed over 272 flood related accidents in industries and identified ASTs as one of the most vulnerable components. They identify floatation, debris impact, collapse of tank due to water pressure, i.e. buckling, and collapse of floating roof as possible causes of tank failure. Based on the performance of ASTs during Katrina, Rita, and the 2012 floods in Colorado the Regional Response Team 6 fact sheet #103 [26] (Recommended Best Practices for Flood Preparedness) also identifies flotation, buckling due to floods and storm surge, and debris impact as potential failure modes. Furthermore, analysis of a case study tank subjected to storm surge by Kameshwar and Padgett [24] also found flotation and surge buckling to be important failure modes. In addition to flotation, sliding and wave impact may also damage tanks during a hurricane. However, as a first step towards understanding the storm surge performance of ASTs, this study will primarily focus on fragility assessment for the two most important failure modes (based on prevalence from past reconnaissance): flotation and storm surge buckling.

Flotation failures are caused when the uplift created by the surge, due to buoyancy forces, is greater than the self-weight of the tank. Some tanks may be fitted with anchors to prevent flotation; however, such tanks may also float if the uplift forces overcome the combined resistance due to the anchors and the tank's self-weight. A buoyant tank may float away from its position and spill its contents as it settles at a different place or hits other tanks nearby. Additionally, spills may be caused by ruptured pipelines, a direct consequence of AST flotation. Spills, due to flotation failure of tanks, may adversely affect the environment and accrue costs due to clean up and litigation. Considering the consequences of a spill, initiation of flotation is considered a failure in this study, even though not every buoyant AST may result in a spill. Shell buckling of tanks, in extreme cases, may also lead to rupture of the tank shell resulting in a spill. Therefore, initiation of buckling is also considered as a failure. Shell buckling due to storm surge occurs when the hydrostatic water pressure exceeds the load resisting capacity of the tank. Usually, ASTs are primarily designed to withstand large internal pressures and external wind pressure; however, they have limited capacity against storm surge. Overall, failure of ASTs due to either of the failure modes will affect the post-hurricane functionality of tanks leading to economic loss caused by delay in restarting operations, and in severe cases both failure modes can lead to spills. Therefore, the system failure of ASTs is modeled with a series system assumption; i.e. ASTs are assumed to fail if they float and/or buckle.

3. Load and resistance models

3.1. Flotation failure

The buoyancy forces exerted on a tank due to storm surge are evaluated using the Archimedes principle; i.e., the buoyancy force equals the weight of the water displaced. Therefore, the buoyancy force on a tank prior to flotation is evaluated as:

$$F_f = \frac{1000\rho_w g\pi D^2 S}{4}; \quad S < H \tag{1a}$$

$$F_f = \frac{1000\rho_w g\pi D^2 H}{4}; \quad S > H \tag{1b}$$