Seismic fragility curves for the shell-base connection of unanchored steel liquid storage tanks with energy dissipation devices

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SEISMIC FRAGILITY CURVES FOR THE SHELL–BASE CONNECTION OF UNANCHORED STEEL LIQUID STORAGE TANKS WITH ENERGY DISSIPATION DEVICES

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ABSTRACT

Since the prosperous wine industry in some seismic countries such as the US, Italy, New Zeeland, Chile and Argentina, among others, the seismic protection of wine storage tanks is of practical importance. Unanchored steel wine storage tanks may lift off their base due to the overturning moment caused by the hydrodynamic wall pressures generated during earthquakes. The partial uplift of the base can generate large inelastic rotation demands and possible failure at the shell-base connection. In this article, the seismic fragility of the shell-base connection of an unanchored steel wine storage tank is characterized. Moreover, an evaluation of external energy dissipation devices for an improvement in the seismic performance is presented. Fragility curves are calculated to evaluate the seismic performance. The fragility curves are developed by the results obtained from a mathematical model to perform the nonlinear time history analysis of a typical unanchored wine storage tank, with and without the external energy dissipation system, subjected to several artificial ground motions. The artificial ground motions are based on ground motion prediction from earthquakes recorded in Chile. Finally, the seismic fragility for the shell-base connection of unanchored steel wine storage tank located in Chile is presented. Furthermore, the seismic fragility of a same damage state for a typical unanchored steel wine storage tank with and without energy dissipation devices are compared. The limit state probability reduction is of 106%.

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ABSTRACT

Since the prosperous wine industry in some seismic countries such as the US, Italy, New Zeeland, Chile and Argentina, among others, the seismic protection of wine storage tanks is of practical importance. Unanchored steel wine storage tanks may lift off their base due to the overturning moment caused by the hydrodynamic wall pressures generated during earthquakes. The partial uplift of the base can generate large inelastic rotation demands and possible failure at the shell-base connection. In this article, the seismic fragility of the shell-base connection of an unanchored steel wine storage tank is characterized. Moreover, an evaluation of external energy dissipation devices for an improvement in the seismic performance is presented. Fragility curves are calculated to evaluate the seismic performance. The fragility curves are developed by the results obtained from a mathematical model to perform the nonlinear time history analysis of a typical unanchored wine storage tank, with and without the external energy dissipation system, subjected to several artificial ground motions. The artificial ground motions are based on ground motion prediction from earthquakes recorded in Chile. Finally, the seismic fragility for the shell-base connection of unanchored steel wine storage tank located in Chile is presented. Furthermore, the seismic fragility of a same damage state for a typical unanchored steel wine storage tank with and without energy dissipation devices are compared. The limit state probability reduction is of 106%.

Introduction

Liquid-storage tanks are used in many different civil engineering applications and industrial facilities. Some of these applications are the storage of liquids such as water, wine, oil, nitrogen, high-pressure gas, petroleum, etc. There are several configurations of liquid storage tanks. However, the most common type of liquid storage tank is the ground-supported cylindrical tank without any anchorage, because they are easy to design, efficient to resist primary hydrostatic pressure, and can be easily constructed. Nevertheless, these tanks have shown poor seismic performance under several strong earthquake ground motions [1 - 9].

Despite the several types of damage observed in the liquid storage tanks, the most

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common types of damage are: damage of the piping connections, damage of the roof caused by sloshing, buckling in the walls caused by the high compressive stress, and damage of the shell-base connection caused by the plastic rotation of the base plate. However, the failure that controls the seismic behavior of the storage tanks is the plastic rotation [10].

Under strong ground motion the unanchored steel liquid storage tanks may lift off their base due to the overturning moment caused by the hydrodynamic wall pressures. The partial uplift of the base can generate large inelastic rotation demands and possible damage at the shell-base connection by a low-cycle failure (see Fig. 1) [11,12]. The failure of this connection could result in the total loss of the liquid contained. In order to avoid this issue, codes of standard practice such as the Eurocode and New Zealand's Recommendations limit the value of the plastic rotation at the connection to 0.2 radians [13, 14]. However, recent studies suggest that 0.2 radians is excessively conservative and that a limit of 0.4 radians is better justified [15,16].

Because of the booming wine industry in some seismic countries such as the US, Italy, New Zeeland, Chile and Argentina, among others, the seismic protection of the shell-base connection of unanchored steel wine storage tanks under earthquake hazard is of paramount economical importance. However, as stainless steel wine tanks were not in service when the 1985 Chilean earthquake happened [17], the poor local evidence of the seismic behavior of this kind of structures is reduced to the recent earthquake in central Chile (2010). Therefore, the available information of seismic hazard in metallic wine storage tanks is scarce. It is important to note that at the present the steel tanks represent the 80% of the country's wine storage capacity [18].

On the other hand, due to the existence of uncertainties related to the structural performance and predominantly with the excitation, probabilistic seismic risk analysis is one of the best tools for measuring the seismic performance of one structural system [19-25]. Nevertheless, despite this probabilistic seismic risk analysis has received increasing attention in the last two decades; previous works of probabilistic seismic risk analysis for liquid storage tanks are scarce. Only some recently investigations have presented a probabilistic seismic risk analysis for a few kinds of storage tanks, for example a probabilistic seismic risk analysis was published by Curadelli in order to assess the effectiveness of certain retrofit on spherical storage tanks [19].

Consequently, in order to characterize the seismic reliability of the shell-base connection of an unanchored steel wine storage tank with and without energy dissipation devices, the objective of the study reported herein is to develop fragility relations for the shell-base connection of a typical unanchored steel wine storage tank prior to and after the installation of the energy dissipation devices subject to seismic shaking hazard. Moreover, with the purpose of evaluating the effectiveness using energy dissipation devices in this structure, the seismic fragility of a same damage state for a typical unanchored steel wine storage tank with and without energy dissipation devices are compared. The fragility curves are developed with the results obtained from a mathematical model capable to perform the highly nonlinear time history analysis of a typical unanchored steel wine storage tank subjected to a strong ground motion [26-28]. This mathematical model considers the material and geometrical nonlinearities, the fluid-structure and soil-structure interaction. Several artificial ground motions are considered in order to obtain robust results. The artificial ground motions are based on ground motion prediction from earthquakes recorded in Chile. The structure with energy dissipation devices presented a significant increase in structural reliability, measured by means of the reduction of the limit state probability.

Wine-Tank Considered

The most important failure on the continuously supported tanks, in order to avoid the loss of the liquid contained, is the low-cycle failure at shell-base connection [11-16]. Therefore, this investigation is focused in the use of energy dissipation anchors to avoid such failure mode.

The system considered is a typical cylindrical stainless steel tank with a capacity of 30.000 l. The radius of the tank is R = 1.46 m, and the height of the liquid contained is H = 4.5 m. The thickness of the wall and base plate are 2 mm. The Young´s modulus of elasticity and the yielding stress of the tank material are 200 GPa and 248 MPa, respectively. The Poisson´s modulus is 0.3. The liquid contained is wine whose density is 1000 kg/m3. The base of the tank is resting on a rigid surface. The wall tank is anchored to a surrounding ring foundation by a series of U-shaped strip dampers (Fig. 2). The foundation where the tank rests is excited by a unidirectional horizontal ground motion $\ddot{x}_g(t)$. When the tank is subjected to strong shaking, the flexible base plate presents a partial uplifting, and that induces rocking of its wall. The U-shaped steel dampers dissipate energy when a parallel relative movement between the adjacent surfaces occurs (Fig. 3), in this case the vertical movement of the tank wall. The plastic deformation happens when the straight part of the strip changes to curved and the curved part of the strip changes to straight [29].

Wine-Tank Model

In order to obtain the principal dynamic behavior of the wine-tank considered, a simplified mathematical model is used [26-28]. The model is shown in Fig. 4. The hydrodynamic pressures and forces in the tank can be expressed as the sum of two components. The first consists of an impulsive component, which represents the effect of the part of the liquid that is considered to move in synchronism with the tank wall as a rigid mass. The second consist of a convective component, which represents the effect of the part of the liquid that presents a sloshing motion. However, as the wine storage tank is filled to a height, sloshing is not possible. Therefore, in this model is only considered the impulsive component. The values of the impulsive mode for the tank that was considered in this analysis are: m_i = 18.6 tons; h_i = 2.04 m; $f_i = \omega_i / 2\pi$ = 11.26 Hz; ζ_I = 2%. Where the impulsive mass is m_i; the natural frequency of fixed-based impulsive component is denoted by ω_i, and its damping ratio is denoted by ζ_i ; and h_i is the height of the resultant of the hydrodynamic wall pressures due to the impulsive component.

The rocking resistance of the base plate is represented by the rotational base spring. The relationship between the base moment M_T and the spring rotation ψ is obtained by the method of analysis of the partially uplifted base plate. In this method are considered the nonlinearities due to (1) the membrane action, (2) the plastic yielding, (3) the varying contact with the foundation, and (4) the varying hydrodynamic base pressures [26-28]. U-shaped strips dampers present a nonlinear force-displacement relationship.

Energy Dissipation System

The external energy dissipation system consists of 10 metallic dampers arranged in a circular form at the base. The dimensions of the U-shaped strip dampers are b = 10 cm, l = 20 cm, r = 3 cm, and t = 1 cm. These dampers are used to anchor the tank wall to the foundation. Each damper has the bilinear approximation for the force-displacement relationship shown in Fig. 5 [29]. The first proposals of using dampers of this type to improve the seismic behavior in structures are attribute to Kelly et al [30] and Skinner et al [29].

Fragility Curves

With the purpose of assessing the effectiveness of the energy dissipation system, it was developed and compared the probability of achieving or exceeding a limit state of damage in the shell-base connection of the tank, with and without the external energy dissipation system, for a particular value of the ground motion intensity. The relationship between the probability of that a certain damage state will be reached or exceeded and the ground motion intensity is usually known as the fragility curve. In order to obtain the fragility curves, it is necessary: (1) a group of ground motion normalized by the peak ground acceleration (PGA); (2) a failure criterion; and (3) the fragility model.

Seismic Ground Excitation

A fundamental aspect to develop the fragility curves is that an ensemble of ground motions is required. Artificial acceleration time histories or actual earthquake records may be used [19]. In the present investigation a set of forty-two artificial seismic ground motions in accordance with the Chilean code spectrum were assumed [31]. Each record was normalized to fifteen specified levels of peak ground accelerations. The total set of forty-two artificial records scaled to the fifteen levels of PGA are the seismic ground excitation ensemble considered for the probabilistic analysis.

Failure Criterion

Despite numerous failure criterions have been proposed in the technical literature [32-37], for the investigation developed herein it was just considered a clear limit state of damage in the shell-base connection based on previous works for storage liquid tanks [15,16]. Therefore, the limit state or failure is reached when the plastic rotation at the connection becomes equal or more than 0.4 radians. It is considered just one damage state (failure or no failure) because the purpose of the present work is to compare the performances prior to and after the structural retrofit.

Consequently, it is possible to define a failure random variable C, as

$$C\begin{cases} =1 & \text{if } \theta/\theta_{\text{lim}} \geq 1 \quad (\text{failure}) \\ =0 & \text{otherwise} \quad (\text{no failure}) \end{cases} \tag{1}$$

where θ is the maximum value of the plastic rotation during a seismic event and θ_{lim} is the value of the plastic rotation that provokes the failure at the connection, $\theta_{\lim} = 0.4$ rad.

The Fragility Model

The conditional failure probability distribution is calculated, counting the relative numbers of times that the response reaches the limit value for the plastic rotation, and it can be expressed as

$$P_C = P\left[C = 1 \mid x\right] = P\left[\theta / \theta_{\lim} \geq 1 \mid x\right] \tag{2}$$

where C is the random variable that represents the limit state of the structure and x is related with the ground motion intensity level, it is expressed in terms of the peak ground acceleration. Therefore, P_C is the probability of event $\theta / \theta_{\lim} \geq 1$ given a peak ground acceleration of x.

The fragility curves related to seismic analysis, and as function of the peak ground acceleration, have a log-normal functional form given by (see e.g. [37-39])

$$P_C\left[\theta / \theta_{\lim} \geq 1 \mid x\right] = \phi\left[\frac{1}{\beta}\ln\left(\frac{x}{\mu}\right)\right] \tag{3}$$

where $\phi[]$ is the standard normal cumulative distribution function, μ is the median value of peak ground acceleration for which the connection reaches the 50th percentile of fragility, and β is the logarithmic standard deviation of PGA for the limit state $\theta / \theta_{\lim} \geq 1$. These parameters are determined by fitting a log-normal function to the conditional failure probability distribution obtained from Eq. 2.

Discussion of the Results

The seismic fragilities relations for the storage tank in the original and the updated state were estimated by the procedure described in the previous section. The fragility points obtained from the simulation (Eq. 2) were fitted by a log-normal function with 95% of confidence for each state, with and without the energy dissipation devices (Fig. 6).

It is observed a considerable rise in the capacity against failure of the structure with the external energy dissipation system (Fig. 6). For example, in order to reach the fifty percent of probability of failure of the original structure, the median fragility, it is necessary a peak ground acceleration of 2.48 m / s^2. On the other hand, the median fragility of the structure with the energy dissipation devices it is necessary a peak ground acceleration of 5.12 m / s^2. This modification in the value of the median fragility represents an increase of 106%.

The results shown in the Fig. 6 would be interpreted also as a significant reduction of the probability of failure, 106% for the median fragility value, when the structure is equipped with the energy dissipation system. This reduction is a directly consequent of the increase in the quantity of the dissipated energy and the strengthening of the uplifting base behavior.

It is important to remark that the measuring of the effectiveness of the dissipation devices in this investigation is different to the deterministic approaches shown in previous works. The results presented herein are obtained with a probabilistic method that offers a better measure of the seismic performance because it considers the uncertainties related with the excitation.

Conclusions

The effectiveness of a particular energy dissipation system in a typical wine storage tank is assessed by means of the fragility curves concept. The fragility relationship of the storage tank with and without the energy dissipation system is developed by simulation. This fragility analysis shows that the energy dissipation devices are very effective and the reduction of the limit state probability for the median fragility is 106%.

Using external energy dissipation systems may represent a significant improvement in the seismic reliability of ground-supported cylindrical wine storage tanks.

Figures

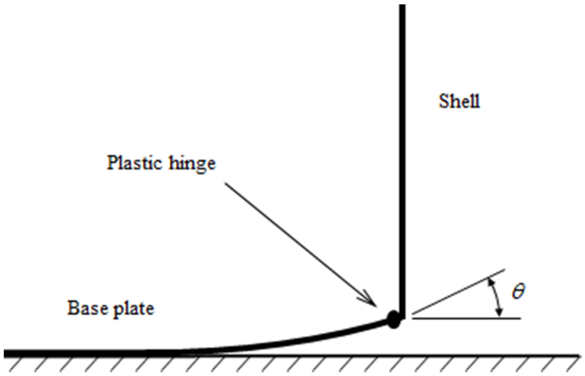

Figure 1. Uplifting tank base and the plastic hinge in shell-base connection.

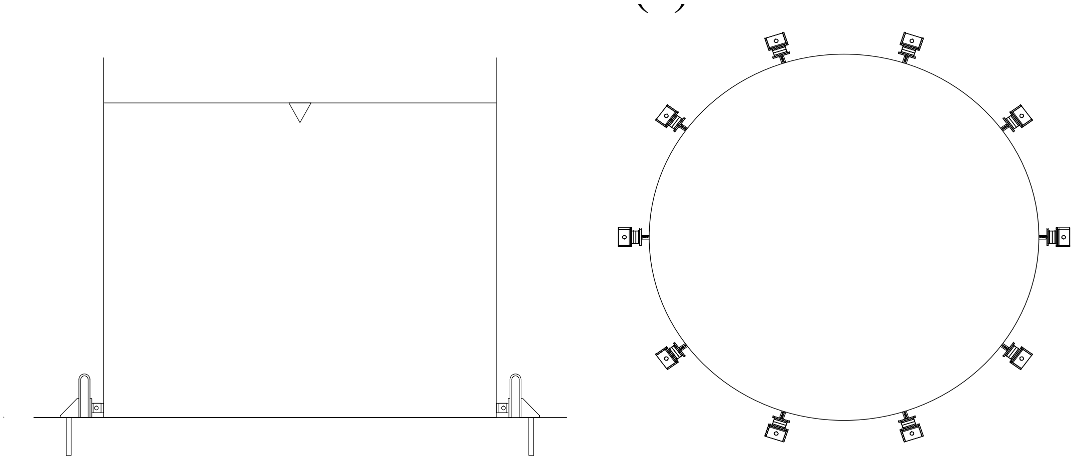

Figure 2. Continuously supported storage tank anchored with U-shaped strip dampers. (a) elevation simplified view; and (b) plan simplified view.

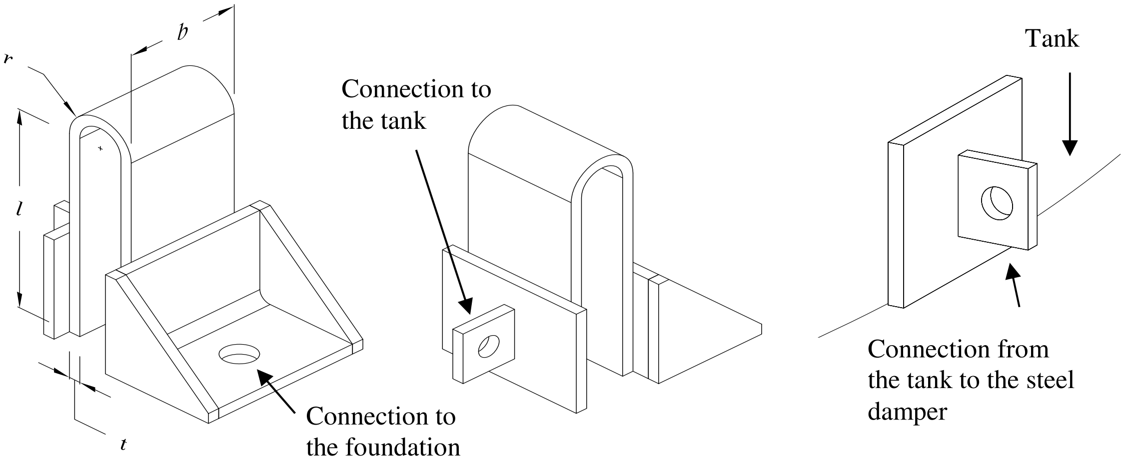

Figure 3. U-Shaped strips steel damper.

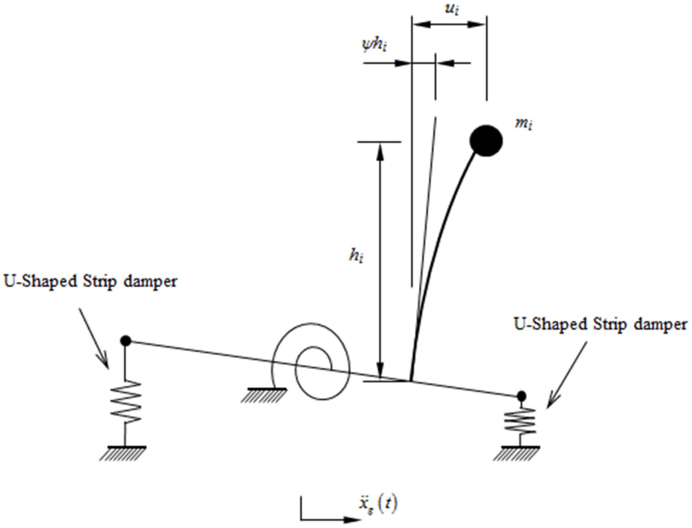

Figure 4. Model of wine-tank-dampers system shown in Fig 2.

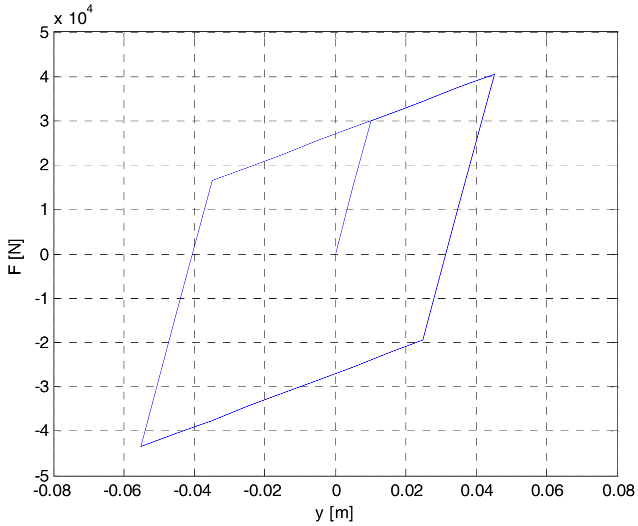

Figure 5. Bilinear force-displacement relationship for steel damper.

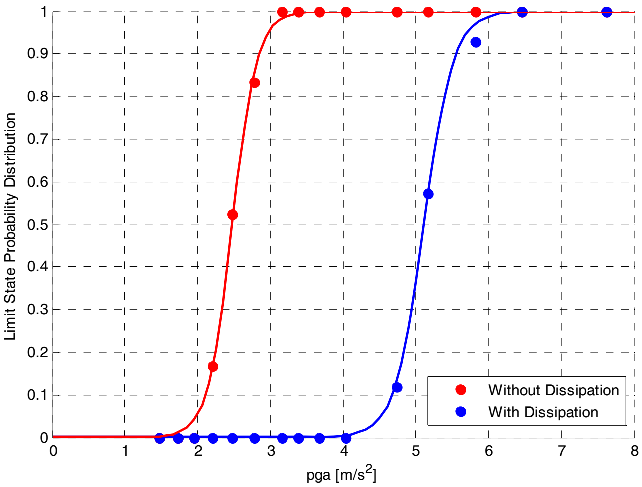

Figure 6. Seismic fragility relations for the structure with and without external dissipation devices.

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