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Capacity of liquid-filled steel conical tanks under vertical excitation

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ABSTRACT

Liquid tanks in the form of truncated cones are commonly used for liquid storage in North America and in other locations. This paper is a part of an extensive research program aimed to develop a comprehensive design procedure for liquid-filled steel conical tanks under seismic loading. Because of the inclination of the walls of conical tanks, the vertical component of the ground motion excitation has a significant effect on conical tanks compared to the case of cylindrical tanks. To the best of the authors' knowledge, the current study is the first to focus on the assessment of the capacity of steel conical tanks under the vertical component of a seismic excitation. The study is carried out numerically using an in-house finite element model by conducting nonlinear static pushover analysis under a load distribution simulating hydrodynamic pressure associated with vertical ground excitations. The numerical model accounts for the effects of geometric and material nonlinearities as well as initial geometric imperfections. Charts are developed to estimate the capacity of steel conical tanks to resist vertical ground excitations based on yielding and buckling criteria for different imperfection levels. The developed charts are used to estimate the capacities of a number of steel conical tanks which are then compared to the hydrodynamic loading associated with various seismic zones.

1. Introduction

Steel conical tanks are commonly used as liquid-containments. They consist of vessels made up of welded steel panels having pure truncated conical shapes or combined conical-cylindrical shapes as shown in Fig. 1. To the best of the authors' knowledge, no design specifications for water structures worldwide provides a clear and rational procedure for the seismic design of such structures. A number of design guidelines [1–3] recommend converting conical tanks into equivalent cylinders with equivalent height, radius, and thickness. This equivalent cylinder approach can be questionable under horizontal ground motion, but it is definitely far from reality under vertical ground motion as will be discussed later in this section.

Researchers realized the importance of studying the effect of ground motions on the behavior of liquid tanks long time ago specially after the Alaska earthquake 1964 where considerable damage occurred to a large number of liquid storage tanks. Earlier studies were based on assuming the tank walls to be rigid when evaluating the hydrodynamic pressure resulting from ground motions [4–6]. It was then realized that the flexibility of the tank walls and the interaction that happens between the vibration of the walls and the contained fluid affect significantly the hydrodynamic pressure and consequently the structural response [7–9].

In order to reduce the computation time for analyzing liquid-tank systems, a practical alternative is to model the contained liquid as lumped masses attached to the tank wall rigidly or through linear springs instead of modeling the contained fluid as a continuum. The masses-springs system is called equivalent mechanical model whose main objective is to match the resulting forces and moments obtained using dynamic analysis for the continuum liquid-tank system subjected to the same horizontal ground excitation. Haroun and Housner [9] introduced a three masses mechanical model for cylindrical steel tanks subjected to horizontal excitations. The three masses are the impulsive fluid mass, the convective fluid mass, and the mass reflecting the effect of the flexibility of the tank walls. The impulsive mass represents the mass of the fluid vibrating in synchronism with the ground and rigidly connected to the tank walls, while the convective one represents the mass of the fluid undergoing sloshing motion at the free surface.

On the resistance side, a number of studies related to the buckling capacity of cylindrical liquid tanks under horizontal ground excitations are found in the literature. Virella et al. [10] investigated the dynamic buckling of anchored cylindrical steel tanks with different slenderness ratio subjected to real earthquake records numerically using the finite element method in order to estimate the critical horizontal peak ground acceleration (PGA) at which elastic or plastic buckling for the cylindrical shell will take

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Fig. 1. Combined steel conical tank.

place.

Virella et al. [11] proposed a nonlinear static procedure based on the capacity spectrum method found in ATC-40 in order to assess the elastic buckling of above-ground anchored steel tanks due to horizontal seismic excitations. The objective was to obtain the minimum peak ground acceleration (PGA) value that produces buckling in the tank shell. The obtained critical PGA estimates were then compared with those calculated using the dynamic buckling analyses performed in the latter study.

Djermane et al. [12] attempted to evaluate the current design guidelines related to dynamic instability provided by AWWA-D100 and EC8 provisions for cylindrical steel tanks using a numerical shell finite element model. The idea was to evaluate the critical PGA values that cause the tank instability and then compare with their counterparts obtained by the codes' provisions.

Buratti and Tavano [13] discussed different buckling modes for liquid-containing circular cylindrical steel tanks that are fully anchored at the base with a special focus on the secondary buckling occurring in the top part of the tank. A case study for a broad cylindrical tank was used in order to investigate various aspects of dynamic buckling using a finite element model where the fluid was modeled in the form of lumped added masses.

The previous studies focused on the horizontal component of the ground excitation. Regarding the vertical component, vertical accelerations are transmitted to a horizontal hydrodynamic loading acting on the tank walls amplifying the hydrostatic induced pressures that might lead to inelastic buckling of the steel shell. As a result, it is important to include the effect of vertical ground excitations when it comes to analyzing liquid storage tanks. Marchaj [14] attributed the failure of metallic tanks during past earthquakes to the lack of consideration of vertical acceleration in their design. Veletsos and Kumar [15] studied the effect of wall flexibility on the response of cylindrical tanks when subjected to vertical component of ground shaking. It was concluded that the hydrodynamic effects for a flexible tank might be substantially larger than those induced in a rigid tank of the same dimensions, and for an intense excitation, they might be of the same order of magnitude as the hydrostatic effects.

The latter study considered only the radial motion of the tank walls and neglected the effect of axial deformations. This assumption was validated by Haroun and Tayel [16] who provided an analytical method for the computation of the dynamic characteristics in terms of natural frequencies, corresponding mode shapes and stress distributions for partly filled cylindrical tanks subjected to vertical excitations. Results were compared to numerical solution where the liquid region was treated analytically and the elastic shell was modeled by finite elements [17] and both methods showed excellent agreement.

Veletsos and Tang [18] provided a practical procedure to evaluate the dynamic response of rigid and flexible steel and concrete cylindrical tanks with different base conditions when subjected to vertical excitations including soil-structure interaction. The main conclusion was that soil-structure interaction reduces the maximum hydrodynamic effects and might be approximated by a change in the fundamental natural frequency of the tank-liquid system or an increase in damping

Haroun and Tayel [19] analyzed some cylindrical liquid storage tanks under simultaneous horizontal and vertical excitations numerically using finite element method. The goal of the study was to assess the relative importance of inclusion of the vertical component of the earthquake in the behavior of the cylindrical tanks. The axial stresses resulting from the vertical component was found to be much lower compared to those induced due to the horizontal component of the earthquake due to overturning moment. However, the hoop stresses due to vertical component was higher than those due to horizontal component which might lead to the yielding of the steel shell increasing the probability of buckling of the tank walls near the base of the tank.

Haroun and Abou-Izzeddine [20] performed a parametric study in order to evaluate the effects of different factors that influence the seismic response of an elastic cylindrical tank supported on a rigid base when subjected to a vertical excitation by considering shell–liquid–soil interaction. It was concluded that foundation-soil–tank interaction reduces the tank response in general, and this reduction is a function of the soil shear-wave velocity as well as tank geometric properties.

A number of studies have been done related to conical tanks under hydrostatic pressure. Motivated with the collapse of a conical steel water tower in Belgium, Vandepitte et al. [21] tested a large number of small-scale conical tank models experimentally under hydrostatic pressure by gradually filling the model till buckling occur. Design charts for different base restraining conditions were developed based on this experimental program. In 1990, a steel conical water tower collapsed in Fredericton, Canada due to underestimation of the effect of geometric imperfections [22] in addition to analyzing the conical tank as a pressurized vessel which is not always a conservative assumption. A number of studies assessed the inelastic stability of pure and combined liquid-filled steel conical tanks including the effect of geometric imperfections and residual stresses due to welding of the steel panels forming the conical shell studies [23–25].

El Damatty et al. [26] and Sweedan and El Damatty [27] provided a simplified design procedure for steel conical tanks under hydrostatic pressure for steel conical tanks taking into account geometric imperfections. The idea was to avoid the yielding state of tanks which was shown to always precedes buckling for the case of hydrostatic pressure.

El Damatty et al. [28,29] derived a fluid-added mass matrix for both horizontal and vertical ground motions to be incorporated in time history analysis using coupled shell element-boundary