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Equivalent mechanical model for seismic forces in combined tanks subjected to vertical earthquake excitation

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ABSTRACT

Liquid-storage tanks with circular cross sections are commonly built with a combined vessel consisting of a truncated cone and a superimposed top cylindrical cap. Unlike cylindrical tanks, combined tanks are characterized by the inclination of the walls of the conical segment. As a result, compressive meridional stresses are induced in the shell by the hydrostatic pressure of the contained fluid and the hydrodynamic pressure associated with vertical ground excitation. The current paper aims at identifying the dynamic characteristics of liquid-filled combined tanks subjected to vertical ground excitation. Numerical analysis is conducted based on a coupled finite-boundary element formulation that accounts for the associated fluid–structure interaction. An equivalent model is developed to duplicate forces induced in liquid-filled combined vessels subjected to vertical base excitation. The proposed model accounts for the flexibility of the vessel walls. Meanwhile, the contained fluid is idealized as rigid and flexible components. The proposed equivalent model provides a simplified tool to predict seismically-induced forces in liquid-filled vessels subjected to vertical earthquake excitation.

1. Introduction

Storage tanks exist in large numbers in various places around the globe. A common use of such non-building structures is for storage of water, oil and chemicals. The geometry of containment vessels with circular cross sections may be classified as:

(1) Vessels consisting of pure cylindrical shells which are referred as “cylindrical tanks”.
(2) Vessels constructed from tapered cones which are denoted as “conical tanks”.
(3) Vessels consisting of truncated cones with superimposed top cylindrical caps as shown in Fig. 1. Due to the combined conical–cylindrical geometry of this configuration, it is always referred to as “combined tanks”.

During an earthquake event, the loss of function of critical infrastructure systems, such as tanks that contain water and hazardous chemicals represents significant risk to life and increases the scale of economic loss. Safety of water tanks during earthquakes is crucial for extinguishing fires that usually occur during such events. Besides, severe environmental impairment and pollution can result from damaged petroleum and chemical-storage tanks. Studies of pre-recorded seismic data indicate that the amplitude of the vertical component of ground excitation might surpass the maximum amplitude of the horizontal component particularly near the epicenter of the earthquake [1]. Besides, the impact of the vertical earthquake component on the response of special structures with relatively low vertical stiffness, such as liquid-storage tanks and suspension bridges, can be significant.

A limited number of studies are available in the literature for the seismic behavior of combined tanks. Such studies focused on the antisymmetric response of combined tanks due to lateral base excitation. The first investigation related to the dynamic behavior of combined tanks was conducted by Sweedan and El Damatty [2] to identify the dynamic response of empty and liquid-filled combined shells under lateral base excitation using shake table testing of scaled tank models. The experimental findings validated the assumption of de-coupling between the long-period fundamental sloshing oscillation and the structural response of the shell. The characteristics of the antisymmetric lateral modes of empty and liquid-filled combined vessels were identified experimentally and numerically in later studies by El Damatty et al. [3,4]. Information regarding the response of combined tanks to vertical excitation is not yet available.

On the other hand, research studies related to seismic behavior of cylindrical vessels are quite intensive. An extensive literature survey summarizing these studies is reported by Cho et al. [5]. Vertical acceleration acting on a cylindrical liquid-filled tank results in an axisymmetric distribution of hydrodynamic pressure

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Fig. 1. A photo of an elevated liquid-storage combined tank.

that leads to the development of hoop stresses. As a result of the vertical alignment of cylindrical vessels, no axial stresses are developed in the walls when subjected to vertical excitation. The impact of the flexibility of the walls of cylindrical tanks on magnifying the hydrodynamic pressure induced by vertical excitation was first reported by Veletsos and Yang [6]. In 1984, Veletsos and Kumar [7] developed a simplified procedure to evaluate the effect of vertical shaking on liquid-storage cylindrical tanks. Haroun and Tayel [8,9] investigated the impact of the vertical component of a ground excitation on the response of cylindrical tanks. A design procedure for evaluating the response of fixed and partly fixed cylindrical tanks to vertical excitation was proposed by Veletsos and Tang [10]. In case of conical and combined tanks, the inclination of the walls complicates the state of stresses developed in the vessel. The axisymmetric hydrostatic pressure results in both tensile hoop stresses and compressive meridional stresses acting on the inclined walls of the containment vessel [11]. Vertical ground acceleration acting on a conical or combined liquid-filled tank results in an axisymmetric distribution of hydrodynamic pressure. A critical state of stresses is reached when the dynamically induced stresses magnify those stresses resulting from the hydrostatic pressure. Sweedan [12] and Sweedan and El Damatty [13] studied the dynamic behavior of pure conical vessels subjected to vertical excitation. The investigation revealed that inclusion of the response to vertical excitation results in substantial increase in the compressive meridional stresses developed in the vessel walls.

The design specifications provided by the American Water Works Association (AWWA D100) [14] adopt a detailed design procedure for cylindrical tanks subjected to vertical ground excitation. However, no direct guidelines are provided for seismic design of combined tanks where the specifications suggest approximating the combined vessel geometry with a simple cylinder with an equivalent volume. The major drawback of this approximation is being unable to predict the meridional compressive stresses resulting from the effect of the hydrodynamic pressure on the inclined walls of vertically-excited combined tanks.

The current paper is motivated by the lack of information regarding the seismic design and behavior of combined tanks. To the best of the author's knowledge, this study represents the first investigation on the response of combined tanks to vertical ground excitation. The study aims at developing a simplified mechanical model that duplicates the seismic forces associated with the hydrodynamic pressure developing inside combined vessels when subjected to vertical earthquake excitation. In the proposed mechanical model, the contained fluid is simulated using two mass components: a rigid mass oscillating in synchronism with the tank's base vibration and a flexible mass associated with the vibration of the tank's walls. The flexibility of the walls of the vessel is modeled as a linear spring connecting the flexible mass component to the rigid base. A coupled finite-boundary element model is employed to simulate the liquid-shell continuum and the associated fluid–structure interaction phenomenon. Parametric analyses are conducted to assess the natural frequency of the axisymmetric mode of vibration of liquid-filled combined vessels. Modal analysis is also performed to identify the contribution of the contained fluid mass to the impulsive responsive. Charts are developed for the variation of the equivalent fluid masses with wide spectrum of geometric parameters of combined vessels.

2. Fluid–structure interaction and governing equations

The vertical component of earthquake excitation affects a liquid-filled combined tank in the form of vertical base acceleration, $\ddot{G}_V(t)$ along the Z-axis as depicted by Fig. 2a. Research studies related to circular tanks with cylindrical or conical geometry have shown that natural vibrations along the vertical axis of the tank are associated with the development of axisymmetric hydrodynamic pressure inside the vessel. This pressure can be decomposed into two main components; namely the impulsive component and the sloshing component. The impulsive component varies in synchronism with the vibration of the walls of the containment vessel and is significantly influenced by the flexibility of the walls of the vessel [6]. On the other hand, the low-frequency sloshing component results from the oscillation of the free surface of the contained liquid. This results in free surface waves with a period of oscillation that is much longer than the fundamental period of the liquid-filled structure. As such, decoupling between the tank's vibration and the liquid sloshing motion is a common assumption to simplify the analysis of such structures. In the current study, the contained liquid is assumed to be incompressible, inviscid and irrotational. Thus, the impulsive hydrodynamic pressure, p_d, developing inside the vessel is governed by Laplace's differential equation

$$\nabla^2 p_d(r,z,t) = 0 \qquad (1)$$

As a result of the flexibility of the vessel walls, the hydrodynamic pressure resulting from the vibration of the fluid