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Seismic analysis of liquid storage composite conical tanks

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ABSTRACT

Composite tanks with truncated cone vessels, consisting of an outer thin steel shell and an inner concrete wall, are becoming common. Such composite conical tanks benefit from the high buckling resistance to compressive meridional forces of the concrete walls and the efficiency of the steel shells in resisting tensile hoop stresses. Motivated by the lack of information in the literature and the codes of practice about the seismic behaviour and design of such structures, this paper represents the first comprehensive study focusing on the seismic analysis of composite conical tanks. The study is conducted numerically using an in-house developed model that accounts for the hydrodynamic pressure resulting from the vibration of the contained fluid. The model also accounts for the interaction between the fluid and the structure vibrations. In this model, both the steel and concrete walls are modelled separately using shell elements and a special interface element is included to account for the connecting shear studs. The model is capable of conducting both free vibration and seismic analyses for the composite tank-liquid system taking into account the sloshing effect. The model is used to assess the adequacy of using a simplified technique in the seismic analysis and design of such structures. In order to examine the seismic behaviour of those structures, a real composite conical tank is considered as a case study. Time histories and maximum values for stresses at the concrete and steel walls, forces at the base, and forces in the studs under different earthquake excitations are reported. Those values are compared to their counterparts resulting from the hydrostatic pressure to assess the importance of including the seismic loads in the analysis of such structures.

1. Introduction

Earthquakes are often followed by fire events that might cause devastating property damage and human losses. These fires are usually initiated from the rapture of gas lines and power lines, as reported by Scawthorn et al. [1]. As such, the availability of a large water supply after earthquakes is crucial to extinguish fires. Therefore, large capacity water reservoirs must be safe and need to remain functional after earthquakes. Among various tank types, conical tanks are quite common in many locations around the globe. These tanks consist of vessels that have truncated conical shapes. Traditionally, the vessels were made of either steel or reinforced concrete. From stress analysis point of view, each material has its own advantages and disadvantages. Under hydrostatic loading, conical vessels are subjected to meridional compressive stresses and tensile hoop stresses. Concrete tanks have good resistance to the meridional compressive stresses, while their resistance to the tensile hoop stresses is weak. On the other hand, steel conical tanks, as thin shell structures, are controlled by their buckling capacity in resisting the meridional compressive stresses, while they are strong in resisting the tensile hoop stresses. Recently, attempts have been made to construct composite conical tanks that benefit from the advantages of both materials. Fig. 1 shows a composite conical tank that has been recently constructed in a low seismic region. The vessel consists of an inner reinforced concrete wall and an outer steel shell connected through shear studs. This type of composite construction represents an efficient system to provide large water storage capacity with reasonable thicknesses for the concrete wall and steel shell. To the best of the author's knowledge, the seismic behaviour of composite conical tanks was not studied previously in the literature.

Madhuri and Madhukar [2] conducted a review on the seismic analysis of elevated water tanks. They stated that generally three cases should be considered while analyzing elevated water tanks: empty, partially filled, and fully filled conditions. When they are subjected to earthquakes, partially filled tanks suffer less than half of the force to which the fully filled tanks experience. Early work on the analysis of cylindrical tanks under seismic horizontal excitations was conducted analytically by Haroun and Housner [3]. They divided the seismic forces resulting from hydrodynamic pressure acting on a tank into three components; the first component is associated with the rigid motion of the tank, the second component is due to the flexibility of the tank's

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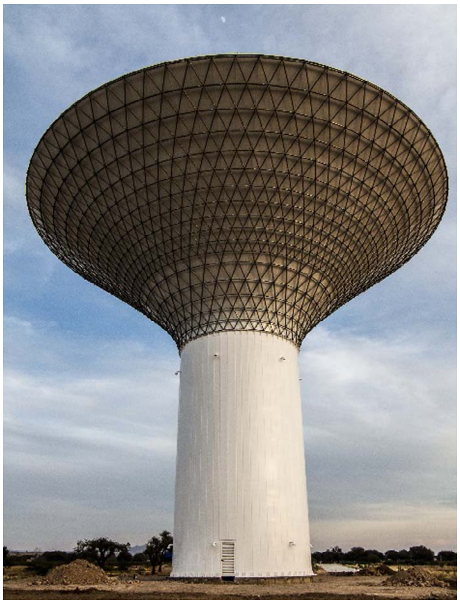

Fig. 1. Photograph of a composite conical tank.

walls, and the third component is associated with the top surface liquid sloshing. Shortly afterwards, Haroun and Housner [4] extended their study by developing a finite element model where the tank's wall was modelled using ring elements, while the liquid was modelled using the boundary element theory. They developed a mechanical model to simulate the hydrodynamic pressure developed inside flexible tanks without considering the rocking at the base. Haroun and Ellaithy [5] extended this mechanical model to account for the rocking. The extended model was used by Haroun and Ellaithy [6] to study the response of cylindrical tanks under horizontal excitations.

Regarding the analysis of conical tanks, El Damatty et al. [7] developed a numerical model to study the stability of steel conical tanks under seismic loading. They evaluated the horizontal and vertical forces resulting from the hydrodynamic pressure using the boundary element theory. These forces were considered by incorporating a fluid-added mass matrix in the nonlinear dynamic analysis. The developed numerical model was used by El Damatty et al. [8] to study the behaviour of steel conical tanks under seismic loading. Free vibration and nonlinear time history analyses were carried out on a set of tall and broad tanks where the material and geometric nonlinearities were considered. In their investigation, they found that steel conical tanks, which are designed under hydrostatic loading, are sensitive to seismic loading and they have high tendency to develop localized buckling. Musa and El Damatty [9] utilized the numerical model by El Damatty et al. [7] to evaluate the capacity of steel conical tanks under horizontal ground excitations. They presented the base shear capacities for different tank dimensions in the form of charts. These capacities were then compared to the seismic demand obtained from a mechanical model that was previously developed by El Damatty and Sweedan [10]. The mechanical model was used for both steel and concrete pure conical tanks subjected to horizontal excitations. The parameters of the mechanical model were provided in the form of charts in terms of the tanks' geometric layout dimensions. The mechanical model parameters were validated by extrapolating the curves to an inclination angle of 0° and comparing them with those of cylindrical tanks, which were reported by Haroun and Housner [3]. A recent study was conducted by Jolie et al. [11], where they assessed the design procedure of conical tanks under horizontal excitations in the current codes. This procedure was based on replacing the conical tank with an equivalent cylindrical tank. They implemented this procedure to determine the response of a number of steel conical tanks under horizontal excitations. The results were compared with those predicted by the equivalent mechanical model that was previously developed by El Damatty and Sweedan [10]. Jolie et al. [11] found that the procedure in the current codes is not adequate for designing of conical tanks under horizontal ground motions.

Regarding the effect of vertical excitations, Haroun and Tayel [12] developed a theoretical model to evaluate the vertical natural frequencies and mode shapes of cylindrical tanks. About the same time, Haroun and Tayel [13] suggested an analysis method to predict the response of cylindrical tanks under vertical excitations. They concluded that the vertical component of earthquake excitations develops axial stresses much smaller than those resulting from the horizontal component of earthquake excitations. The sloshing component due to the vertical excitation has been experimentally observed to have a negligible value when it was compared with the impulsive component. They also found that the response due to the higher vibration modes was minimal when it was compared with the response of the fundamental mode. Veletsos and Tang [14] suggested a simple practical procedure for evaluating the response of cylindrical tanks under the vertical component of ground excitations. In their procedure, not only they accounted for the interaction between the tank's wall and contained liquid but also they considered the interaction between the supporting system and the soil medium. A good agreement was observed between the results obtained from the suggested procedure and their counterparts resulting from exact analytical solutions.

Sweedan and El Damatty [15] proposed an equivalent model for conical tanks under vertical ground excitations. In their study, they developed a simple procedure for estimating the fundamental natural frequency and the seismic forces on conical tanks subjected to vertical seismic excitations. They presented the mechanical model parameters in the form of charts that depend on the vessel's dimensions. The mechanical model parameters were validated by extrapolating the curves to an inclination angle of 0° and comparing the results with those corresponding to the cylindrical tanks reported by Veletsos and Tang [14]. They showed that including the shell mass in the model has an insignificant effect on the axisymmetric fundamental frequency. Recently, Jolie et al. [16] assessed the importance of considering the vertical component of the ground acceleration when analyzing steel conical tanks. In their study, the normal forces due to the vertical seismic excitations were evaluated using the mechanical analogue that was previously developed by Sweedan and El Damatty [15]. They found that the vertical ground accelerations have a significant effect on the meridional stresses compared with those resulting from hydrostatic pressure.

The first objective of the current study is to develop a Finite Element Model for Composite tanks (CFEM) to perform free vibration and time history analyses. Both the hydrostatic and hydrodynamic loads are included in the model taking into account the fluid structure interaction. The second objective of the current paper is to propose a simplified approach for the seismic analysis of such tanks. This approach, denoted as Equivalent Section Method (ESM), involves transforming the composite section to a single material section having an equivalent wall thickness. This equivalent section is used along with a mechanical analogue developed in the literature to analyze composite tanks under seismic excitations. The validity of this approach is assessed by comparing the results obtained from the sophisticated CFEM with those resulting obtained from the simplified ESM. The third objective of the current investigation is to assess, through a case study, the significance of including the seismic loads in the analysis of composite tanks.

The paper starts by presenting the details of the CFEM and ESM that are used to perform the seismic analysis of composite conical tanks. The description and material properties of a set of four composite conical tanks with different dimensions are then reported. Afterwards, a comparison between the fundamental frequencies obtained from the CFEM and ESM for the four tanks is carried out. A time history analysis is performed to the four tanks using the CFEM. The forces at the tanks' bases are then evaluated and compared with those obtained from the