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Capacity of liquid steel conical tanks under hydrodynamic pressure due to horizontal ground excitations

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ABSTRACT

Steel conical tanks are widely used for liquid storage around the world and especially in North America. A number of those tanks collapsed in the last decades at different places as a result of instability of the steel shells. Despite being widely used, no specific design procedure is available for conical tanks under dynamic conditions. Most of the previous studies related to steel conical tanks focused on calculating the acting forces due to a seismic event. This study however, focuses on evaluating the capacity of conical tanks under hydrodynamic pressure resulting from horizontal ground excitation using non-linear static pushover analysis. The capacity is then compared to the seismic demand obtained using a previously developed mechanical model found in the literature for different seismic zones. This paper is a part of a larger study aiming to provide a simplified design procedure for steel conical tanks when subjected to earthquakes. The study is conducted numerically using a non-linear finite element model that accounts for the effects of large deformations and geometric imperfections on the stability of steel conical tanks.

1. Introduction

Steel conical-shaped liquid storage tanks are commonly used for the purpose of storing different kinds of liquids. The contained liquid can either be water used for both drinking as well as fire protection or a chemical used in a specific industry. Steel vessels are advantageous in comparison to their concrete counterparts as they are composed of prefabricated steel panels, which simplify the erection procedure and reduce construction costs. A conical tank consists solely of a pure truncated cone, as shown in Fig. 1 (a) or might be capped with a cylindrical part and is referred to as combined conical tank as shown in Fig. 1(b). Although such tanks whether pure or combined are commonly constructed, no specific design procedure is found for conical tanks in most liquid-tanks specifications. The only guidelines, found in some design provisions [1–4] are based on treating a conical-shaped tank as a cylindrical tank with equivalent height, radius, and thickness.

The main difference between conical and cylindrical tanks in the structural behavior is due to the inclination of the conical tank wall. For the case of hydrostatic pressure, the volume of the contained liquid can be divided into two portions: vol. 1 and vol. 2 as shown in Fig. 2. The latter volume increases as the base of the tank is approached and is associated with a decrease in the vessel radius. This leads to the development of high compressive meridional stresses σ_m in this region. Tensile hoop stresses σ_h are also induced circumferentially through the tank shells. The hydrodynamic pressure due to horizontal seismic excitation will amplify both σ_m and σ_h at one side of the tank and reduces them at the other side based on the direction of the ground acceleration.

The equivalent cylinder proposed by AWWA [2] and API [1] is based on the average conical tank radius and a total height equals to the inclined wetted surface height of the conical tank. On the other side ECS [3] and ACI [4] recommend using an equivalent cylindrical tank that has the same free surface diameter as the conical tank and a depth that results in the same volume as the conical tank. Jolie et al. [21] assessed the equivalent cylinder concept proposed by different specifications in terms of the resulting base shear and overturning moments. The study showed that while the base shear is overly-estimated by the AWWA and API, it remains well-predicted by the Eurocode. All the design codes are found to under estimate the overturning moment, which was related to not including the effect of the vertical hydrodynamic pressure component when assuming the tank walls to be vertical not inclined.

A conical tank in static conditions has to support its own weight in addition to the applied hydrostatic pressure acting on the tank walls and base. For steel conical tanks, the hydrostatic pressure will be more critical than the weight of the tank due to the relatively light weight of steel structures. For the case of liquid-storage conical tanks under dynamic loads, the behavior is more complicated than other ordinary structures. This is due to the presence of the contained liquid, which vibrates with different dynamic (vibration) characteristics than those of the tank walls.

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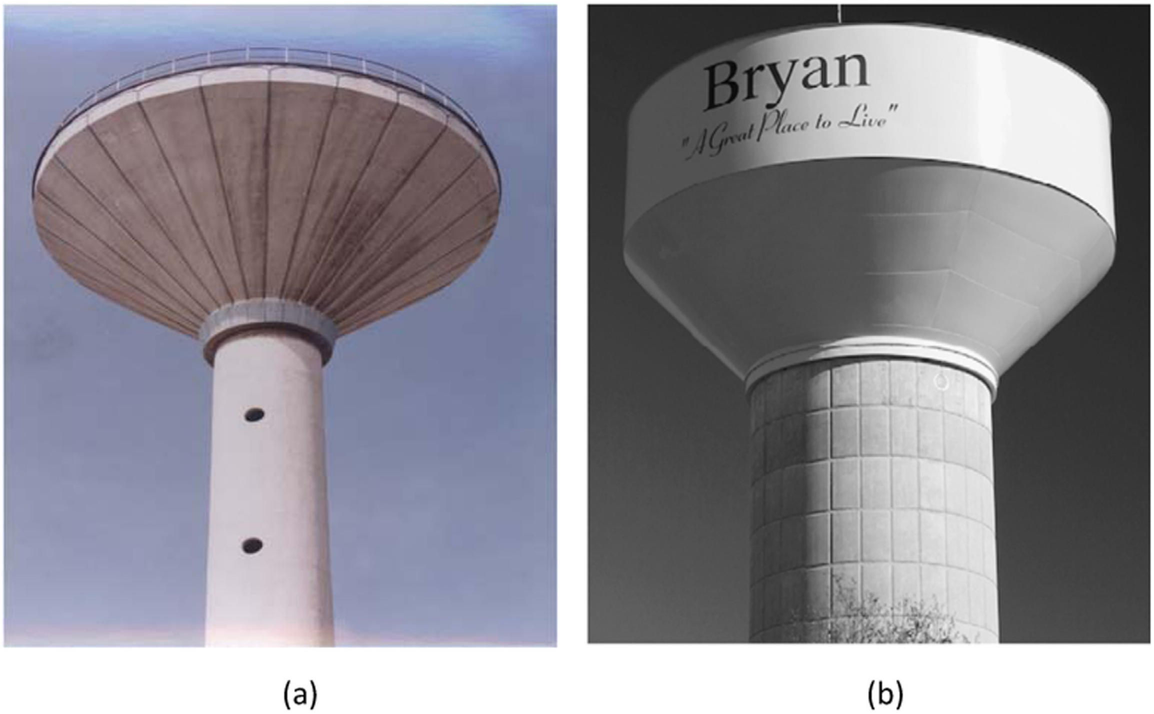

Fig. 1. (a) Pure conical tank, (b) combined conical tank.

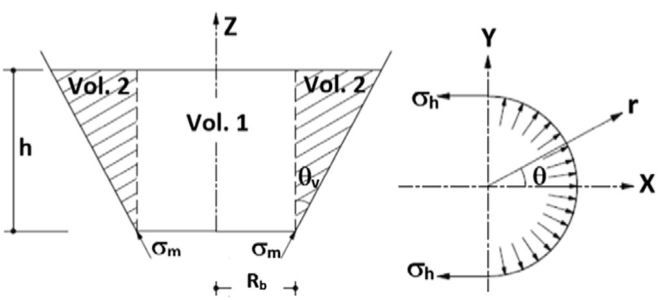

Fig. 2. Stresses induced due to inclination of the wall.

For a liquid-filled conical tank subjected to an earthquake excitation, the walls, the floor, and the contained liquid are subjected to acceleration. As a result, the walls are affected by the inertial forces of the wall in addition to the hydrodynamic pressure of the contained liquid. The contained liquid can be divided into two parts: the first part is mainly the lower amount of liquid, which moves with the walls of the tank and is called the impulsive liquid mass. The second part is mainly the upper amount of liquid and is called the convective liquid mass, which undergoes sloshing due to vibration. The ratio of the convective mass to the impulsive one increases as the tank becomes shallower. Also, the frequency of the impulsive vibration modes is much higher than those of the convective vibration mode.

The first study related to steel conical tanks was conducted by Vandepitte et al. [27] after the collapse of a conical steel water tower in Belgium. In this study, a large number of small-scale conical tank models were tested experimentally under hydrostatic pressure. The models were gradually filled with water till buckling occurred. The test results were used to develop a set of design curves for different base restraining conditions. The effect of geometric imperfections on the safety factor of the conical tanks was also studied. In 1990, a steel conical water tower collapsed in Fredericton, Canada when it was filled with water for the first time. Vandepitte [26] concluded that the main cause of failure was related to the inadequate thickness of the tank walls at the base. This was due to the designer's underestimation of the amplitude of the geometric imperfections as their design was based on results obtained from the field of aerospace where a superior quality control takes place.

Several attempts have been made to provide a simplified design procedure for steel conical tanks under hydrostatic pressure suitable for everyday use by practicing engineers. El Damatty et al. [9] developed a simple design approach for steel conical tanks with a load factor value of 1.4 taking into account geometric imperfections, snow and roof weights, and the existence of an upper cylindrical cap. The idea was to avoid the yielding state of tanks, which was shown to always precedes buckling for the tank at any point. An economic design approach was also proposed by reducing the tank wall thickness as height increases. This study was limited to conical tanks with vertical inclination angle of 45°. Sweedan and El Damatty [25] extended the latter study of combined conical tanks under hydrostatic loading using regression analysis based on the results of large number of analyzed tanks. This large database included a variation of tank dimensions, angle of inclination of the wall, cylindrical cap ratio, yield strength values, and geometric imperfection level.

The first studies regarding seismic behavior of cylindrical liquid tanks were based on the assumption that the tank walls are rigid, i.e., the flexibility of the tank walls has no effect on the contained fluid vibrations [18–20]. This notion was considered valid until the earthquake in Alaska in the year 1964 where considerable damage occurred to a large number of cylindrical liquid storage tanks in the form of roof damage, wall buckling, and total collapse [14].

More studies were carried out after earthquake in Alaska in an attempt to accurately interpret the vibration characteristics, taking into consideration the effect of the wall flexibility where the tank deformations affect the hydrodynamic pressure, i.e., fluid–structure interaction takes place. It was concluded that the flexibility of cylindrical tank walls amplifies the tank's response. Therefore, it has to be accounted for [16,17,28].