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Nonlinear numerical evaluation of large open-top aboveground steel welded liquid storage tanks excited by seismic loads

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A R T I C L E I N F O

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A B S T R A C T

A numerical study is conducted using finite element models of large, circular, cylindrical, aboveground, steel, open-top, liquid storage tanks subjected to horizontal seismic forces. Nonlinearities of both material properties and geometry deformations are included. Soil-structure interactions are implemented into the finite element models by using a series of elastic springs representing a stiff soil foundation. Hydrodynamic hoop stresses, elephant's foot buckling, and uplift are measured for tanks with height to radius ratios, or aspect ratios, between 0.4 and 2.0. The finite element models are compared to the provisions of API 650 Annex E, with special attention to the anchorage ratio, J. The results show that, while the finite element models are much more complex than the theoretical and empirical equations provided in API 650, the total hoop and axial compressive stresses are comparable. Furthermore, the anchorage ratio limits set by API 650 seem to be in good agreement with the finite element models in terms of uplifting behavior.

1. Introduction

Behavior of large, aboveground, steel, welded, liquid storage tanks under the presence of seismic loads introduce several critical failure criteria to the structure not exhibited during normal operating levels. Such risks could include elephant's foot buckling or diamond shape buckling, hydrodynamic hoop stresses, sloshing forces, or uplift. In the United States, these failure criteria are often accounted for by using the design standard developed by the American Petroleum Institute, API 650 [1].

API 650 is based primarily on the works of Housner [2,3]. Housner developed a useful tool, referred as the "spring-mass analogy" to analyze aboveground storage tanks experiencing seismic forces by breaking the system into two main components (Fig. 1). These components include the impulsive mode and the convective mode. The impulsive mode consists a portion of the contained liquid that moves coincidentally with the structure. Impulsive forces are assumed as a rigid mass connected to the tank at a particular height. The convective mode, on the other hand, is a portion of the contained liquid that is free to move both horizontally with the tank as well as vertically along the tank wall. The convective mode is often referred to as the "sloshing" mode due to the liquid waves created during seismic events. The model developed by Housner, however, is based on the works of Jacobsen who developed expressions for impulsive liquid pressures exerted on cylindrical tanks, which assumes a rigid base connection and undeformable walls [4]. In reality, for unanchored tanks, the tank base is free to move vertically and horizontally with respect to the foundation. Moreover, due to fact that aboveground storage tanks have thin shells, and thus exhibit thin-shell behavior, all tanks deform to a certain degree under seismic loads.

Many researchers investigated the effects of tank flexibility in order to understand the true behavior of tanks subjected to horizontal ground accelerations and to develop models to ensure a safe design of the structure [5–19]. Veletsos showed that the response of rigid tanks attain a maximum response acceleration that is approximately equal to the maximum ground acceleration caused by the seismic event, while flexible tanks can respond to seismic events with response acceleration higher than the ground acceleration [8–10]. Veletsos also showed that wall flexibility is observed to only influence the response of impulsive mode by increasing the period of motion [9,10]. Housner and Haroun investigated similar effects of tank flexibility and compared their results to full-scale shake table tests. They used their findings to develop a procedure for modeling deformable tanks subjected to seismic forces [5,6]. Their model modified the spring-mass analogy of Housner by including a single degree of freedom for the relative wall deformation with respect to the ground (Fig. 2). Malhotra later developed a method similar to that of Veletsos and Housner and Haroun which includes the effects of impulsive and convective forces beyond the first mode of vibration [16–18]. The works of Malhotra for flexible tanks have been adopted by Eurocode 8 for the seismic design of aboveground storage

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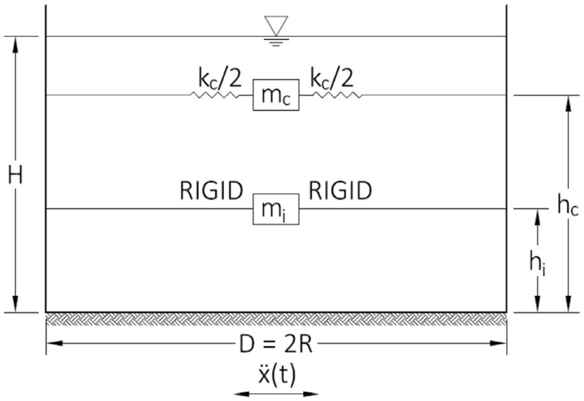

Fig. 1. Spring-Mass Analogy developed by Houser [2,3].

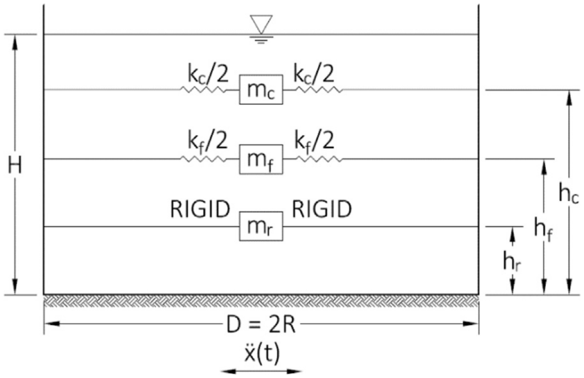

Fig. 2. Modified Spring-Mass Analogy accounting for tank flexibility developed by Housner and Haroun [6,7].

tanks [20]. However, these methods have not gained much attraction within the United States and have not been implemented into API 650, which still assumes a rigid base and wall.

With the advancement in computing technology, there has been an increasing trend toward finite element modeling (FEM) of aboveground storage tanks subjected to seismic forces [13–40]. Several researchers have developed simple FEM methods for the analysis of tanks [21–28,39,40]. One such method commonly discussed is the lumped mass method in which the impulsive and convective forces obtained using Housner's spring-mass analogy are applied to the storage tank at their corresponding height. This method was shown to produce results in terms of shell stresses similar to that of Housner's theory for rigid tanks [24]. A slightly modified version of the lumped mass method is the added mass approach in which the impulsive and convective force distributions are converted in equivalent masses along the height of the shell. Livoaglu and Dogangun showed that the results between the lumped mass and added mass approaches for rigid tanks produce nearly identical results in terms of period of vibration, base shear force, and overturning moment [24]. Several researchers have conducted studies where the liquid is modeled as discrete fluid elements [30,33,39,40]. Sobhan and co-workers used static pushover tests for steel anchored tanks with nonlinear materials and geometry effects with fluid elements in order to evaluate the critical buckling load of the tank shell [40]. However, using fluid elements increases the complexity of the finite element model significantly which in turn increases the computing time to solve the analysis. Virella and co-workers developed a method to analyze tanks subjected to horizontal seismic forces. Their method is similar to the Capacity Spectrum Method (CSM) used for buildings in which the level of seismicity to cause buckling of the shell can be determined [25].

The lumped-mass model, added mass approach and fluid element method have all been used to confirm the theoretical impulsive and convective period of vibrations developed by Housner [21–24,39]. Furthermore, many studies have also been completed to determine the effects of wall flexibility, base flexibility, and the presence of a roof on the impulsive and convective periods [15,23–25,29–33,39]. Natsiavas and Babcock used experimental and analytical tests to show that the behavior of uplifting, flexible tanks is not the same as rigid tanks and that the natural period of the flexible tanks increases considerably compared to rigid tanks [15]. Moreover, FEMs have been used to confirm that the impulsive period of vibration significantly increases due to the flexibility in the walls and base, while the convective period was rather uninfluenced [5–10,15]. Many researchers have also studied the effect of the roof on the impulsive and convective periods [29–31]. Amiri and Sabbagh-Yazdi showed that the natural period of the tank were observed to decrease with the addition of a roof compared to identical tanks with open tops [30]. The mode shapes for open-top tanks produced greater displacements compared to that of tanks with roofs. Amiri and Sabbagh-Yazdi developed a simple parameter based on their findings that can be used to determine if the roof should be included in finite element models depending on the tank's liquid height and tank radius [30]. Virella and co-workers determined natural period of the tank is dependent on the type of roof provided for tanks of identical size [31].

The findings of increased impulsive periods for flexible tanks has often been used to explain an increase in the maximum shell compression stresses for flexible tanks when compared to rigid tanks – the change in the tank period is accompanied by a change in the tank stresses [5–10,15–18]. Natsiavas and Babcock showed that the stresses in the tank shell increased when the tank was allowed to uplift from the foundation using experimental and analytical tests [15]. Malhotra showed that the overturning moment in the shell near the base for tanks on flexible foundations decreases compared to tanks on rigid foundations [16–18]. However, more plastic cycles are likely to occur as a result of a flexible foundation. Malhotra also observed that increasing the base plate thickness reduced the base uplift, but at the expense of increasing the overturning moment stresses in the shell [16–18].

Many researchers have furthered the discussion of the vulnerability of unanchored tanks under seismic loads by implementing nonlinear materials and nonlinear geometry deformations using FEM [22–39]. El-Zeiny created fluid-structure interaction FEMs using dynamic analysis for an unanchored tank under large seismic loads [22]. Virella and co-workers used a nonlinear static procedure (NLSP) to determine the critical peak ground acceleration (PGA) to cause diamond-shaped buckling near the top of the tank for tanks of varying aspect ratios with roofs and pinned bases [25]. A separate study by Virella and co-workers showed that the critical PGA of broad tanks to cause diamond-shaped buckling can be pin-pointed between values of 0.25 g and 0.35 g [32]. Berahman and Behnamfar used a statistical approach to develop seismic fragility curves for several unanchored storages. These curves provide the probability of failure of a tank at a given level of seismicity and were based on data bases containing historical performance of tanks under horizontal seismic loads [35].

While many researchers have studied the effects of nonlinear, flexible, aboveground storage tanks under horizontal seismic loads, few have compared the results of their tests with the current design practices used worldwide [36,41–44]. Spritzer and Guzey compared the design philosophies of API 650 Annex E, the Japanese design recommendations, and the New Zealand Society of Earthquake Engineering (NZSEE) for unanchored tanks in high seismic regions [1,41,45,46]. Their study showed that while each document prescribes similar provisions for buckling, hydrodynamic hoop stresses, uplift, and sloshing, the estimated failure of the tank in each document varied. Hamdan compared the limit states for several tank geometries under seismic loads using the design provisions of API 650, ASCE, Eurocode 8, NZSEE and the Japanese recommendations [1,20,42,45–47]. Their study had similar conclusions of variability in each design code. Moreover, Hamdan observed the design guides do not provide