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A simple and efficient model for seismic response and low-cycle fatigue assessment of uplifting liquid storage tanks☆

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ABSTRACT

Ground-supported unanchored liquid-storage cylindrical tanks, when subjected to strong seismic loading may exhibit uplifting of their bottom plate, which may have significant effects on their dynamic behavior and structural integrity. In particular, due to uplifting, a substantial amount of plastic deformation develops at the vicinity of the welded connection between the tank shell and the bottom plate that may cause failure of the welded connection due to fracture or fatigue, associated with loss of tank containment. The present study focuses on the base uplifting mechanism and tank performance with respect to the shell/plate welded connection through a numerical simple and efficient methodology that employs primarily a simplified modeling of the tank as a spring-mass system for dynamic analysis, enhanced by a nonlinear spring at its base to account for the effects of uplifting, supported by a detailed finite element model of the tank for incremental static analysis. The latter model is capable of describing with accuracy the state of stress and deformation at different levels of lateral loading, in order to obtain the overturning moment-rocking angle relationship to be used in the simplified model. The methodology is applied in two cylindrical liquid storage tanks of different aspect ratios focusing on local performance of the welded connection, towards assessing the strength of the welded connection. The numerical results provide better understanding of tank uplifting mechanics and strength against failure of the welded connection at the tank bottom. Furthermore, the proposed methodology can be used for efficient assessment of uplifting effects on tank structural safety, towards minimizing seismic risk in industrial facilities.

1. Introduction

Liquid containing tanks made of steel material are used in water storage and distribution systems, as well as in industrial plants for storage and/or process of a variety of liquids and liquid-like materials, including oil, liquefied natural gas, chemical fluids and wastes of various forms. In numerous practical applications, relatively broad aboveground liquid storage tanks are constructed unanchored, in the sense that their bottom plate is in simple contact with the ground, without any anchor bolts. Under strong lateral dynamic loading (e.g. seismic), these tanks may exhibit uplifting of their bottom plate, when the magnitude of the overturning moment exceeds a threshold value. Although uplifting does not necessarily result in tank failure, its consequences may lead to serious damage of any attached piping connections of the uplifted bottom plate, and possible failure of the connection between the tank shell and the bottom plate (Peek, 1988a; Natsiavas and Babcock, 1988). Furthermore, it may result in an increase of the axial stress acting on the tank wall, which may lead to occurrence of “elephant's foot” buckling at lower uplifting sizes (Manos, 1986). This behavior is shown schematically in Fig. 1; for the direction of lateral loading shown in the sketch, Location 1 is the critical location of concern in the present paper, associated with tank uplifting.

The uplifting response of tank base plate is nonlinear due to continuous variation of the base contact area, plastic yielding of the plate material, and the effects of membrane forces associated with large displacements in the plate. A first attempt to understand the uplifting resistance mechanism of a plate has been reported, solving the simple problem of a prismatic beam uplifted at one end (Wozniak and Mitchell, 1978; Leon and Kausel, 1986), ignoring the

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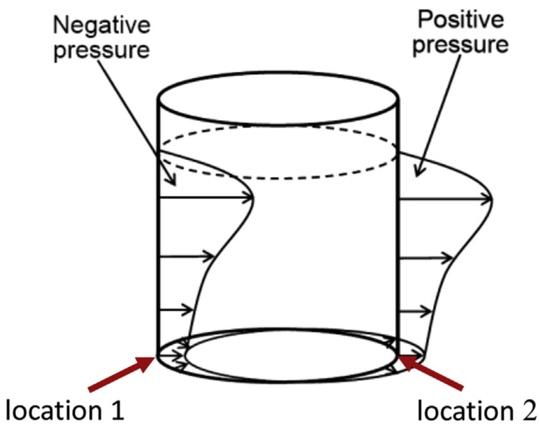

Fig. 1. Locations affected by uplifting during seismic action in an unanchored tank.

effect of membrane forces in the base plate; it was found that the maximum load capacity of the beam is reached at the stage where two plastic hinges develop: one at the uplifted end (i.e. at the shell-plate connection), and the second at the "sagging moment" region of the beam model (Wozniak and Mitchell, 1978; Myers, 1997), shown in Fig. 2. An approximate solution that accounts for the effects of the membrane forces was proposed by Cambra (1982) using simplifying assumptions regarding the magnitude of the axial and shearing forces in the beam based on experimental data from axially symmetric lift, static tilt and dynamic shaking table tests. Auli et al. (1985) employed a second-order beam theory that accounts more accurately for membrane forces, however their methodology did not account for the effects of flexible end conditions of the beam nor for plastic yielding within the beam. Ishida and Kobayashi (1988) used finite element models to solve the uplifting problem as an uplifting beam under rocking conditions. Malhotra and Veletsos (1994a) studied extensively uplifting behavior, idealizing the base plate as a uniformly-loaded semi-infinite prismatic beam on a rigid foundation, considering the effect of elastic end constraints, the influence of the axial force on bending and the effect of plastic yielding in the beam. In a recent publication, Ahari et al. (2009) used a tapered beam model resting on a rigid foundation to simulate base uplift of unanchored tanks and investigated the parameters which are affecting it.

The aforementioned beam models did not take into account the two-dimensional nature of the problem under consideration, neglecting the effect of hoop stresses, which develop in the base plate close to the junction of the bottom plate with the tank wall. A fundamental step towards understanding uplifting in liquid storage tanks has been the consideration of a partially-uplifted base plate model. Such studies have been reported in Peek and Jennings (1988), Peek (1988b) using a combination of the finite-difference solution method and energy method, whereas the Ritz energy method has been employed in Haroun et al. (1987), Haroun and Badawi (1988). Malhotra and Veletsos (1994b) have improved the "plate model" approach computing the vertical uplift and rocking resistances of a circular plate to uniformly uplifting forces distributed along its boundary, presenting solutions methodologies for axisymmetric vertical uplifting, as well as for asymmetric rocking uplifting, using a series of semi-infinite prismatic beams.

Apart from the above analytical models, notable experimental works for the behavior of unanchored fluid-filled tanks have been performed in the 80's at UC Berkeley (Clough, 1977; Niwa, 1978; Clough and Niwa, 1979; Lau and Clough, 1989); they refer to shaking table and static tilt tests. Furthermore, Shih (1981) reported scale model tests in an effort to obtain a better understanding of the response and the failure mechanism of the tanks. In subsequent publications, Natsiavas (1988, 1990) and Natsiavas and Babcock (1987) presented analytical models for determining the dynamic response and the hydrodynamic loads developed on unanchored liquid-filled tanks under horizontal base excitation. More recently, Malhotra and Veletsos (1994c), based on their previous works (Malhotra and Veletsos, 1994a, 1994b), investigated the effects of uplifting of the bottom plate of the tank on the entire tank-liquid system, for a rigid foundation using a simplified model.

The present study examines the uplifting mechanism of tank bottom subjected to seismic loading and its effects on tank structural integrity, using numerical simulation tools. Two typical liquid storage tanks are modeled using finite elements, both anchored and unanchored, and their behavior is discussed considering also the relevant seismic provisions in EN 1998-4 (European Committee for Standardization, 2006). The main purpose of the present study is the proposal of a simple and efficient methodology for the analysis and design of the shell-bottom plate connection, where

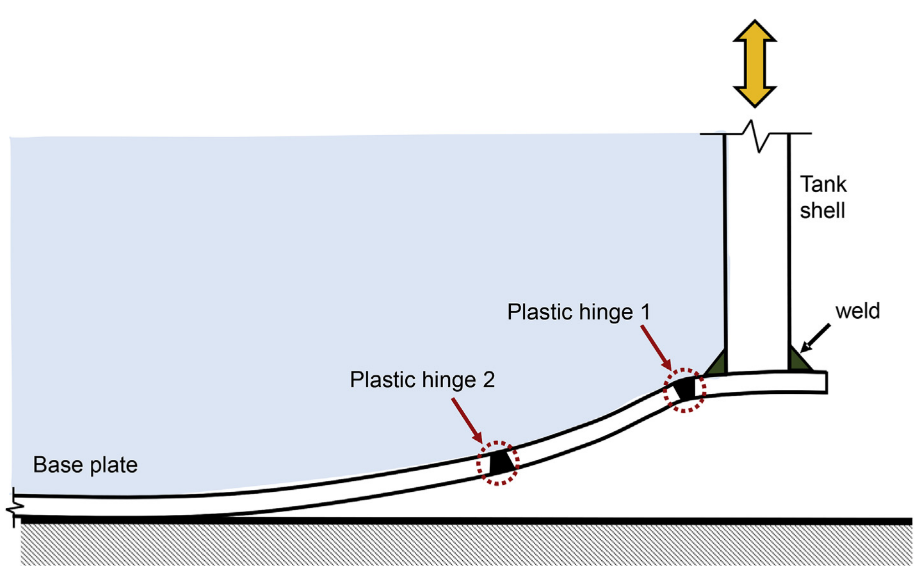

Fig. 2. Locations where plastic hinges develop on the base plate; (1) at the shell-plate connection; (2) at the "sagging moment" region.