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The effects of long-term corrosion on the dynamic characteristics of ground based cylindrical liquid storage tanks

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ABSTRACT

Results of numerical investigations on the effects of material degradation due to corrosion on the dynamic characteristics of ground-based, anchored, steel liquid storage tanks are presented. Internal corrosion is considered as a time-dependent constant thinning of the wall, at locations in contact with residual water, water condensate, atmospheric oxygen and acid gases. Dynamic analyses are performed on numerical tank-liquid models, having different aspect ratios and wall thicknesses at different stages of wall thinning at the specified locations. The aim of the analyses is to determine the corrosion effects on the natural periods and mode shapes of vibration. Steady-state, harmonic base excitation analyses are also carried out to determine the corrosion effects on the hydrodynamic pressures produced in the liquid. It is found that progressive corrosion has significant effects on the tank fundamental period and its associated mode shape of vibration as well as the magnitude and location of the maximum hydrodynamic pressure and that as design provisions should cover the service life of the tank, the errors associated with the current code provisions for design of such tanks cannot be ignored.

1. Introduction

Liquid storage tanks are important lifeline structures. As a result, their safety during earthquakes is of prime concern and has been the subject of numerous investigations. The subject of liquid–shell dynamic interaction under ground shaking is of particular interest in seismic design of liquid storage tanks. Earlier works by Housner, Veletsos, Haroun and others on this subject [1–4] contributed to the design codes for steel tanks such as AWWA-D100 [5] and API 650 [6]. In recent years, other factors affecting the seismic response of ground-based storage tanks such as partial filling of liquid, base anchorage, roof effects, vertical and rocking motions, etc. have also been investigated [7–12]. In all these studies a perfect shell with constant thickness was considered.

1.1. The effects of shell imperfections on the dynamic response

The dynamic properties of thin-walled cylindrical shell structures are highly dependent on the nature and magnitude of imperfections in the geometry of these structures. Most importantly, circumferential imperfections have been reported to have an especially detrimental effect. Earlier investigations on the effects of imperfections in cylindrical shells showed that large local buckling can occur at the locations of the imperfections [13,14]. Similar findings were reported for relatively thick cylindrical shells by Singer [15] based on the results of an experimental study and by Mandara and Mazzolani [16] based on numerical investigations. Seung-Eock and Chang-Sung [17] also studied the effects of initial imperfections on the buckling strength of cylindrical tanks under axially compressive loads. In their numerical work they found that the buckling strength of the tank is noticeably reduced as a result of initial imperfections. On the effects of out-of roundness and initial shell imperfections on the dynamic characteristics of liquid-filled cylindrical tanks, Watawala and Nash [18] and Zui and Shinke [19] reported that these imperfections result in prominence of the higher order circumferential modes in dynamic response and the resultant hydrodynamic pressures. In an experimental investigation, Maheri and Severn [20,21] also showed that due to the initial imperfections in the shell of liquid-filled, open-top, cylindrical tanks, lower order circumferential wave forms are not excited and that the fundamental mode of shell–liquid system is associated with higher order circumferential modes. They also found that the higher the shell diameter to thickness ratio, the higher the order of the first excitable circumferential wave form will be. Menos [22] also investigated the effects of non-uniformity of the shell thickness on the fundamental period of vibration of anchored storage tanks.

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1.2. Corrosion in liquid storage tanks

In recent years, a significant increase in demand is met concerning the safe operation period of oil storage tanks. The planned service life of storage tanks is 20–40 years. However, in a number of cases, corrosion-induced failures of storage tanks are already detected after 1.5–2.5 years in service [23]. According to the American Petroleum Institute, approximately 20% of hydrocarbon products lost as leakage are caused by corrosion damage in storage tanks [6]. Corrosion in storage tanks occurs mainly due to the presence of well water, water condensate, atmospheric oxygen and acid gases inside the tank. The atmospheric corrosion of the tank from outside is less significant [24]. Moreover, for the long period of operation, oil-derivative sediments containing, among others, hydrogen sulfide appear. It adds to the local acidification of the environment. Due to the causes mentioned above, the sections of the shell most susceptible to corrosion are the lower and upper sections of the tank wall. The effect of interior environment on material degradation due to corrosion may be idealized by three distinct zones: zone (I) corresponds to the upper part of the wall, which, considering the change in liquid level, may not be in permanent contact with oil and is likely to corrode due to water condensate, atmospheric oxygen and acid gases; zone (II) corresponds to the middle part of the wall characterized by being in permanent contact with oil and therefore not susceptible to corrosion and zone (III) represents the lower part of the wall in contact with residual water and likely to suffer the most from corrosion. The rate of corrosion in zone (I) is generally less than that of zone (III), being around 0.4 mm/yr as opposed to 0.4–0.6 mm/yr in zone (III) [23].

Recently, the effects of corrosion on the uplift capacity of bottom annular plate of storage tanks subjected to seismic loading [25] and the stability loss due to corrosion of thin-shell cylindrical tanks [26,27] have been reported. Also, in a recent study, Virella et al. [28] investigated the effects of varying (tapered) shell thickness on the dynamic properties of anchored liquid storage tanks. To the knowledge of the authors, however, the time-dependent effects of the general corrosion processes on dynamic characteristics of cylindrical tanks and the resultant magnitude and distribution pattern of hydrodynamic pressures have not been investigated. In this paper, these effects are studied by performing corresponding analyses on thin-walled cylindrical tanks subjected to general corrosion.

2. Numerical models

2.1. Shell–liquid models

The tanks considered in this paper are clamped at base and have cone roofs supported by a number of radial beams and columns. Since only anchored tanks are considered, the bottom of the tank is not included in the model. The tank geometries chosen are similar to those considered by Virella et al. [28]. The geometries used in this work have height to diameter ratios: $H/D=0.40$ (Models 1–4), $H/D=0.63$ (Models 5–10) and $H/D=0.95$ (Models 11–16), where H and D are shown in Fig. 1. In all the models, the tank was assumed to contain liquid to a level of 90% of the height of the tank wall.

ANSYS computer program was selected to carry out the numerical analyses. In the FE models, the tank roof system is represented by shell and beam elements. The tank wall is also modeled by shell elements (SHELL63). Shell63 has bending and membrane capabilities. Both in-plane and normal loads are permitted [29]. Triangular shell elements are used in the roof and quadrilateral elements are used for the wall. The finite element mesh for the wall and the roof of Model 5 ($H/D=0.63$) is shown in Fig. 2.

The hydrodynamic pressure exerted on the shell of a vibrating tank may be of three forms: (i) convective pressure due to the sloshing of the liquid inside the tank, (ii) impulsive pressure due to the rigid body motion of the tank and (iii) a series of impulsive pressures due to the coupled shell–liquid flexible responses [21]. For convenience, in the eigen-solution, only those modes corresponding to the impulsive modes, in which there is a coupling action between the shell and liquid, are considered in this paper. The more significant convective (sloshing) modes are known to be of much higher periods to interact with the impulsive modes. The eight node solid fluid element (FLUID80), with three DOFs per node, has been chosen to model the incompressible fluid content. The fluid element is particularly well suited for liquid–solid interaction problems. The formulation of the fluid elements is described in Ref. [29]. The liquid mesh has 48,600 elements for Models 1–4 and 72,900 elements for Models 5–16. Crude oil is used in the computations with a density $\rho=860$ kg/m^3 and a bulk modulus $K=1.65$ GPa. In order to satisfy the continuity conditions between the liquid and shell media at the wall boundary, the coincident nodes of the liquid and shell

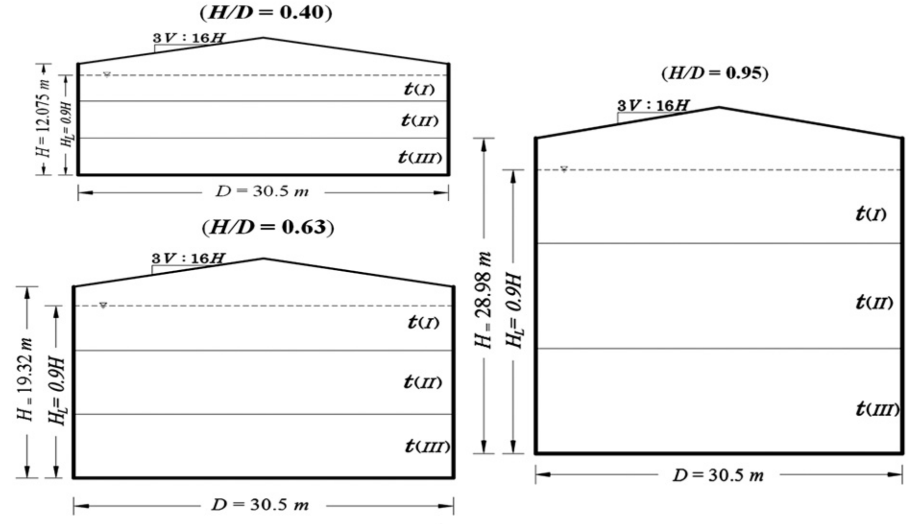

Fig. 1. Geometries of the selected tanks.