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Influence of base plate bending stiffness on the seismic performance of liquid storage tanks

Diego Hernandez-Hernandez*, Tam Larkin and Nawawi Chouw

Department of Civil and Environmental Engineering, The University of Auckland, Auckland Mail Centre, Private Bag, 92019, Auckland 1142, New Zealand

Abstract

In the past, a number of investigations have been performed on the seismic behaviour of storage tanks. At the University of Auckland, a number of shake table experiments on tanks with different aspect ratios have been recently performed. The earthquake ground excitation was simulated based on a design spectrum from the New Zealand code NZS 1170.5, classification D for soft soils. The results show that the base plate stiffness of storage tanks may play a significant role in the magnitude of hoop stresses caused by the passage of the earthquake. To incorporate a low-damage seismic design philosophy, the tank is allowed to separate partially at the base. This temporary separation initiates rigid body like motion of the tank and thus reduce the wall local deformations. Consequently, the stress development along the wall can be reduced from that occurring with full base plate contact. This research focuses on the effect of the base plate thickness on the hoop stress development along the height of the tank wall for five radial directions.

Keywords: Storage tanks; base plate stiffness; seismic analysis; hoop stress.

1. Introduction

Liquid storage tanks are lifeline structures used in industrial and urban areas. Past experiences of seismically induced damage of storage tanks have demonstrated their susceptibility to earthquakes. The damage can manifest as “elephant footing”, rupturing of pipeline connections, overturning of the tank or simple collapse. In the case of failure during a strong earthquake, they may produce environmental damage, explosions and, in an extreme case, they could pose a

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* Corresponding author. Tel.:+64 027-394-6841;
E-mail address: dher840@aucklanduni.ac.nz

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threat to human life. Post-earthquake recovery necessitates a reliable water supply for fire-fighting and drinking water. For all these reasons tanks are a critical lifeline facility for communities recovering from the effects of strong ground motion.

One of the principal causes of failures of storage tanks is the high stresses developed in the tank wall. The partial separation of the base from the foundation, known as uplift, significantly affects the magnitude and distribution of those stresses and, for unanchored tanks, uplift is the phenomenon that governs seismic design [1]. Theoretical and experimental investigations have been made to predict and improve the seismic performance of liquid storage tanks. Haroun and Badawi [2] and Haroun and Al-Zeiny [3] reported that uplifting involves inherent nonlinearities due to the plastic hinges developed in the base plate. Due to the complexity and time demands for developing a meaningful solution [4-5], Ishida and Kobayashi [6] and Malhotra and Veletsos [7] developed simplified methods of analysis considering the behaviour of the base plate as a beam. More recently, Kobayashi et al. [8] presented a computational model based on the finite element method that considers uplift and cross-sectional deformations of the tank wall.

Experimental research on seismic uplift has been carried out by Clough [9] and Niwa [10], who reported on experimental studies for broad and tall storage tanks respectively. They presented the static and dynamic axial and hoop stress distribution and the cross-sectional deformation at mid-height, as a function of time. Both studies considered constant the base plate thickness. Recently, Taniguchi [11] performed experimental tests and evaluated the influence of the mass of liquid that contributes to uplift but the contribution of both the tank wall and base plate thickness were ignored. Ormeño et al. [12] experimentally assessed the effect of uplift on the tank wall stresses. Even though most codes and guidelines state that uplift should be avoided, in that study, it was demonstrated that, for certain aspects ratios (ratio of the tank radius to liquid height: H/R), uplift may reduce both axial and hoop stresses, even though higher displacements and accelerations occur. The favourable effect of uplift has also been reported in the seismic behaviour of other structures [13-16].

The base plate stiffness directly affects the uplift resistance, which is evident in the results of some of the studies above [3,5,7]. However, more work is required to clarify the influence of the base plate stiffness on the hoop stress development along the tank height. To the authors' knowledge, experimental tests varying the base plate stiffness have not been reported. Hence, the objective of this work is to experimentally evaluate the influence the base plate stiffness has on the distribution of hoop stresses circumferentially and along the height of the tank wall.

2. Experimental methodology

2.1. Tank model

A low-density polyethylene (LDPE) container (750mm height, 450mm diameter) is used to simulate a prototype steel tank. Three aspect ratios (1, 2 and 3) were considered. The tank is unanchored hence uplift can occur. The properties of the prototype and model are described in Table 1. The fundamental period of the prototype was estimated according to the New Zealand Society for Earthquake Engineering (NZSEE): Recommendations for the design of liquid storage tanks [17].

Veletsos and Tang [18] demonstrated that convective effects (oscillations at the fluid free surface) can be evaluated independently of the impulsive effects (inertia forces on the tank wall). For this reason, and for practical purposes, storage tanks are usually analysed as a single degree of freedom (SDOF) system considering only the impulsive effects. Hence, the similitude conditions between the prototype and the model were defined using the Buckingham π theorem [19] and applying the Cauchy number, defined in [20], for SDOF systems. The similitude conditions are shown in Table 1 whereas the scale factors are shown in Table 2.

2.2. Setup

Five vertical columns of strain gauges were attached to the external face of the container to measure hoop stresses, as shown in Fig. 1. The columns are referred to by the azimuth with respect to the line of motion of the shake table. In