SEISMIC WALL STRESSES OF LIQUID STORAGE TANKS
CONSIDERING SOIL-STRUCTURE INTERACTION

Diego HERNANDEZ-HERNANDEZ¹, Tam LARKIN², Nawawi CHOUW³

ABSTRACT

Seismic design of storage tanks has been less developed in past decades in comparison to building or bridge design. The main reason is the complexity due to a number of significant factors involved in the seismic behaviour of the soil-footing-tank-liquid systems. Among these factors, the complex influence of the supporting soil, the use of an earthquake design process developed for common structures, i.e. without fluid-structure-soil interaction, and the interaction between the liquid and the tank wall. This research focuses on the temporal and spatial development of axial and hoop stress that occur in the tank wall while responding to earthquake loading considering the complete fluid-structure-soil system. To reveal the influence of the flexibility of the supporting soil, shake table experiments were performed. The ground motion considered was stochastically simulated based on the New Zealand design standard for soft soil. The results show that the flexibility of the supporting soil affects significantly the development of stresses in the tank wall. The wall stresses of the tank when on a flexible foundation increased more than fivefold in comparison to the stresses obtained from the tank when on a rigid foundation.

Keywords: Storage tanks; Shake table experiments; Wall stresses; Soil-Structure Interaction; Laminar box

1. INTRODUCTION

Liquid storage tanks are structures commonly built in urban and industrial areas. They are used to store different types of liquids, i.e. water, petrol or other chemicals. The integrity of these tanks following strong ground motion is a key factor in the rate of recovery of the affected communities. The tanks often supply water for human consumption or as a source of water for firefighting. In the case of fuel or other chemical liquids, tank failure may cause explosions, and in the worst scenario, may be a threat to human life.

Common seismic damage to tank walls takes the form of diamond buckling or elephant’s foot. Diamond buckling takes place around the shell at a distance above the base of the tank or at the junction of the shell and the base plate. This type of buckling usually appears in thin shells, e.g. stainless wine tanks (Moore & Wong, 1984) and in tanks with high aspect ratio (i.e. ratio of the tank radius to the liquid height). In contrast, elephant’s foot appears in the lower course of the shell of broad tanks, i.e. tanks with an aspect ratio lower than one (Niwa & Clough, 1982). One of the probable cause of this type of damage is the strong vertical acceleration occurring in earthquakes (NZSEE, 2009). The cause of the forms of damage has a common source, i.e. a concentration of high axial and hoop stresses due to hydrodynamic forces. The magnitude and distribution of these stresses vary according to several factors. Those include the geometry of the tank, the material properties, the aspect ratio and uplift. Uplift is defined as the transient separation of part of the base from the supporting ground.

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Another factor that influences the response of storage tanks is soil-structure interaction (SSI). Numerical studies have been carried out to gain an understanding of SSI, but opinions disagree on some of the key features of SSI. Some studies have shown that a flexible soil site reduces the tank response (Cho, et al., 2004; Haroun & Abou-izzeddine, 1992; Veletsos & Tang, 1990). Larkin (2008) ascertained that force reduction depends on soil and tank properties, mainly due to changes in the natural frequency of vibration of the tank. When the natural frequency of the tank is close to the natural frequency of the site, an amplification in response may be observed (Daysal & Nash, 1984; Durmus & Livaoglu, 2015; Livaoglu, 2008; Ma & Chang, 1993; Veletsos, 1991). Haroun & Abou-Izzeddine (1992) and Kim et al. (2002) showed that magnification in the response is closely related to the shear wave velocity and thickness of the soil at the site. Hence, in the process of design assuming a rigid base does not always guarantees conservative results (Seeber, et al. 1990).

Despite the large number of numerical studies available in current literature, only a few experimentally based research studies have been performed, especially considering SSI (Hori, 1987; Ormeño, et al., 2012, 2013a, 2013b). Ormeño et al. (2013b) tested a PVC cylindrical tank on a shake table, focusing on the development of axial and hoop stresses. To simulate a flexible base support, a rigid box with sand was utilised. Overall, it was concluded that SSI leads to a significant reduction in axial and hoop stresses, but that the reduction is very sensitive to the aspect ratio of the tank.

This paper elucidates, through an experimental study using a laminar box, the influence of a soil site (flexible support) on the temporal and spatial development of axial and hoop stresses in a tank wall from the seismic action.

2. EXPERIMENTAL METHODOLOGY

2.1 Tank model

A low-density polyethene (LDPE) tank, of 450 mm diameter and 750 mm in height is used to model a prototype steel tank. The similitude conditions may be defined using the Buckingham π theorem, along with the Cauchy number for a Single-Degree-of-Freedom (SDOF) system. Neglecting the influence of oscillations at the fluid free surface in the tank, i.e. the convective mode of response, the model can be analysed as a SDOF system based on the impulsive mode. Consequently, only the impulsive inertia forces on the tank wall are considered (Veletsos & Tang, 1990). The model and prototype properties are shown in Table 1 and the scale factors are shown in Table 2. The fundamental periods were estimated according to the NZSEE (2009). The following equations were used to derive the scale factors after fixing the scale for length (20) and mass (8000):

\[
SF_{\text{Length}} = \frac{r_{\text{pro}}}{r_{\text{mod}}} = \frac{4.500}{0.225} = 20
\]

\[
SF_{\text{Mass}} = \frac{M_{\text{pro}}}{M_{\text{mod}}} = \frac{858.833}{107} \approx 8000
\]

\[
SF_{\text{Time}} = \frac{T_{\text{pro}}}{T_{\text{mod}}} = \frac{0.143}{0.066} = 2.17
\]

\[
SF_{\text{Accel}} = SF_{\text{Length}} \times SF_{\text{Time}}^2 = \frac{20}{2.17^2} = 4.25
\]

\[
SF_{\text{Stress}} = \frac{SF_{\text{Mass}}}{SF_{\text{Time}}^2 \times SF_{\text{Length}}} = \frac{8000}{2.17^2 \times 20} \approx 85
\]
Table 1. Properties of the model and prototype

<table>
<thead>
<tr>
<th>Material</th>
<th>Model LDPE</th>
<th>Prototype Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (Pa)</td>
<td>$0.3 \times 10^9$</td>
<td>$2.1 \times 10^{11}$</td>
</tr>
<tr>
<td>Radius (m)</td>
<td>0.225</td>
<td>4.500</td>
</tr>
<tr>
<td>Height (m)</td>
<td>0.675</td>
<td>13.500</td>
</tr>
<tr>
<td>Wall thickness (m)</td>
<td>0.004</td>
<td>0.010</td>
</tr>
<tr>
<td>Liquid Mass (kg)</td>
<td>107</td>
<td>858833</td>
</tr>
<tr>
<td>Impulsive period T (s)</td>
<td>0.066</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Table 2. Scale factors

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>20</td>
</tr>
<tr>
<td>Mass</td>
<td>8000</td>
</tr>
<tr>
<td>Time</td>
<td>2.17</td>
</tr>
<tr>
<td>Acceleration</td>
<td>4.25</td>
</tr>
<tr>
<td>Stress</td>
<td>85</td>
</tr>
</tbody>
</table>

Two support conditions for the tank were utilised: 1) the tank sitting directly on the shake table to represent a rigid support condition, representing a tank supported on rock, Figure 1(a) and 2) the tank supported on sand contained in a laminar box (described in Section 2.3) i.e. a flexible support condition representing a soil site, Figure 1(b). All tests were performed with water at a height yielding an aspect ratio of three (liquid height of 675 mm). The tank is unanchored, hence uplift could occur.

Figure 1. LDPE tank (a) rigid base (b) flexible base (c) measurement locations

### 2.2 Setup

Three columns of strain gauges were attached to the external face of the LDPE container. Each column is identified by the angle $\phi$ that is formed between the radius vector and the direction of movement of the shake table, Figure 1(c). At each height, two strain gauges are employed, one in the circumferential direction (to evaluate hoop stress) and one in the $x$-direction (to evaluate the axial stress). In both
foundation support cases (rigid and flexible) an accelerometer was attached to the shake table. In the case of flexible foundation, an additional accelerometer was placed on the sand surface. In order to obtain the axial $\sigma_x$ and hoop $\sigma_\phi$ stress on the surface of the shell of the tank, it is necessary to combine the data from two strain gauges at each height, according to Equations (1) and (2) (Flügge, 1973; Ugural, 2009).

$$\sigma_x = \frac{E}{1-\nu^2} \left( \epsilon_x + \nu \epsilon_\phi \right)$$ (1)

$$\sigma_\phi = \frac{E}{1-\nu^2} \left( \epsilon_\phi + \nu \epsilon_x \right)$$ (2)

where $E$ is the modulus of elasticity; Poisson’s ratio, for LDPE $\nu = 0.34$ (Nitta & Yamana, 2012); $\epsilon_x$ axial strain; $\epsilon_\phi$ hoop strain.

### 2.3 Laminar box

A 2 m cubic laminar box is used to simulate the earthquake-induced shear deformation of the sand that results from the simulated seismic motion (Figure 2). Each layer of the laminar box can move up to 175 mm in the horizontal direction. More information regarding the characteristics of the box can be found in (Qin and Chouw, 2017). The box is filled to a height of 1.43 m with sand with an average density of 1.58 t/m$^3$.

![Figure 2. Cubic laminar box filled with sand](image)

To ascertain the shear stiffness of the sand the shear wave velocity was measured at the beginning of the experiment, by performing an impulse test. The setup and the recorded accelerations are shown in Figure 3. A circular steel plate was placed on the sand surface and hit by a hammer. The impact produces a downward travelling shear wave that was recorded by two accelerometers with a distance 700 mm apart. The average shear wave velocity $v_{s_m}$ may be estimated by dividing the travel distance $\Delta L$ by the travel time $\Delta t$. The wave velocity changes with depth since the effective mean stress is a function of depth. From Figure 3, the travel time is $\Delta t = 1.1554 - 1.1514 = 0.004$ s. The estimated mean velocity $v_{s_m} = \frac{0.70}{0.004} = 175 \frac{m}{s}$.

An empirical method to estimate the shear wave velocity is by Equation (3) (Larkin, 1978):
\[ v_s = \sqrt{\frac{D_r + 25}{100} \sqrt{\frac{0.422 \times 10^6 (\sigma'_m)^2}{\rho}}} \]  

where \( D_r \) is the sand relative density, experimentally obtained as \( D_r = 56\% \); \( \rho \) is the sand mass density, for this case it is 1580 kg/m\(^3\); \( \sigma'_m \) is the mean stress at the respective depth, estimated as \( \sigma'_m = (\sigma'_v + 2\sigma'_h)/3 \); \( \sigma'_v \) is the effective vertical stress and \( \sigma'_h \) is the horizontal effective stress.

The stresses may be estimated by elastic solutions for a uniform surface circular stress, in this case 675 kPa. This gives estimates of the mean stress as:

\[ \sigma'_{m100} = 405 \, Pa \]
\[ \sigma'_{m800} = 135 \, Pa \]

Thus, the shear wave velocity is:

\[ v_{s100} = \sqrt{\frac{0.564 \times 1580 + 25}{100} \sqrt{\frac{0.422 \times 10^6 (405)^2}{1580}}} = 222 \, \text{m/s} \]
\[ v_{s800} = \sqrt{\frac{0.564 \times 1580 + 25}{100} \sqrt{\frac{0.422 \times 10^6 (135)^2}{1580}}} = 169 \, \text{m/s} \]

\[ v_{s_{100}} = \frac{222 + 169}{2} = 196 \, \text{m/s} \]
The estimated mean shear wave velocity is similar to the result obtained experimentally.

2.4 Excitation applied

The shake table excitation was simulated based on the target spectrum for a soft soil condition, i.e. classification D of the NZS 1170.5, Figure 4(a). The target spectrum was calculated utilizing the NZSEE recommendations for time domain analysis of liquid storage tanks (NZS 1170.5, 2004; NZSEE, 2009). However, the NZ 1170.5 code specifies the lower limit of the frequency range of interest ($T_{\text{min}} > 0.4$ s), and Ormeño, et al. (2015) found this process could omit the contribution of the natural frequency of liquid storage tanks. The 0.4 s limit was established because lower periods are difficult to determine, especially when structures present complex geometries and diverse materials. For tanks, that normally have regular geometry and are made of one material, this restriction may lead to an underestimation of the response. For that reason, the lower limit of frequency given by NZS 1170.5 was not applied in this work. Hence, the lower limit applied is $0.4T_{\text{pro}} = 0.057$ s and the upper limit is $1.3T_{\text{pro}} = 0.186$ s. The response spectrum of the simulated excitation and the target spectrum are shown in Figure 4(b). The range of frequencies of interest for matching the response and the natural period of vibration of the tank with an assumed fixed base are shown.

![Ground excitation](image)

Figure 4. Ground excitation. (a) Simulated ground motions for a soft soil condition defined by NZS 1170.5 code and (b) response spectrum of the simulated ground motion and target spectrum of the NZS 1170.5

3. RESULTS

Figure 5 shows the time-history of axial and hoop stresses calculated at 20 mm and 75 mm for both cases of support, for the $0^\circ$ column, i.e. co-linear with the applied excitation. Considering Figure 5(a), the maximum hoop stress for a rigid base is 140 kPa. Considering a flexible support, at the same height, the maximum stress is 730 kPa. Hence, the presence of the soil resulted in a 520 % larger hoop stress.
A similar increase is found in the axial stress, Figure 5(d).

Figure 5. Time-history stresses for 0° column, (a) hoop stress at 20 mm (b) hoop stress at 75 mm (c) axial stress at 20 mm and (d) axial stress at 75 mm

Extracting the maximum tensile (positive) and compressive (negative) stress, the spatial distributions of maximum axial and hoop stresses are plotted in Figure 6. The hoop and axial stresses are plotted against the normalised height x/H, where x is the distance from the tank base and H is the height of the tank. Figure 6(a) and 6(b) show that the difference in magnitude of the hoop stress is significant, especially near the tank base. At approximately one-third of the tank height, the tensile hoop stress of the tank with a flexible support has a lower magnitude than that when a rigid base is present. On the other hand, axial stress is overall lower in magnitude considering a flexible base, except at 20 mm above the base.

The large differences between hoop and axial stresses are due to the variation in magnitude of the acceleration of the shake table and the sand free surface, see Figure 7. The maximum acceleration at the sand surface is 55% larger than that in the shake table. This difference suggests a nonlinear response of the sand in the laminar box, which produces a considerable change in the applied frequencies.
Figure 6. Maximum axial and hoop stresses distribution for 0° column, (a) tensile hoop stress (b) compressive hoop stress (c) tensile axial stress and (d) compressive axial stress

Figure 7. Acceleration records of the shake table and at the sand surface

To establish that the table acceleration is similar with and without the laminar box, both table accelerations are shown in Figure 8. The acceleration record of the shake table from both base cases present similar frequencies and differ little in magnitude. It shows that the mass of the laminar box with
sand, ≈ 10 t, does not substantially interfere with the input acceleration of the shake table. The major differences are at the beginning and at the end of the records. Those discrepancies are because the shake table is programmed to start and end smoothly due to safety reasons when a large weight is in place.

Figure 8. Acceleration records of the shake table with and without the laminar box

4. CONCLUSIONS

A LDPE tank was used as a model for a steel prototype tank and tested on a shake table considering two support conditions: 1) rigid foundation medium (the shake table); 2) flexible foundation medium (sand). The depth of water in the tank was such that an aspect ratio of three prevailed. The main aim was to investigate the effect of a flexible foundation on the temporal and spatial development of axial and hoop stresses. The results of the experiments reveal:

The maximum hoop stresses were more than five times larger for the flexible foundation than that of the rigid foundation. The amplification is because the soil produces a change in the frequency alignment between the applied ground motion and the natural frequency of the tank. As it was shown in Figure 7, the acceleration in the sand surface was larger than that in the shake table. Along the tank wall, the axial stresses are smaller when the tank is placed on a flexible foundation in comparison with those when the tank is on a rigid foundation. This corroborates previous experimental studies considering SSI. However, at 20 mm from the tank base, the axial stresses are more than twice in the case of the flexible foundation compared to the rigid case.

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7. REFERENCES


