Influence of Uplift and SSI on Liquid Storage Tanks During Earthquakes

M. Ormeño, T. Larkin & N. Chouw
The University of Auckland, New Zealand

SUMMARY:
Previous studies have demonstrated that strong earthquakes can cause severe damage or collapse to storage tanks. In New Zealand many tanks are built near the coast on soft soils. Due to the difference in stiffness between the tank (rigid) and the soil (flexible), soil-foundation-structure interaction (SFSI) has an important effect on the seismic response, often causing an elongation in the period of the impulsive mode. This elongation is likely to produce a significant change in the seismic response of the tank. Another issue not well studied is uplift of the base of the tank. In this research a physical model is used to evaluate SSI and uplift effects. Sand in a soil box is used to simulate the soil. The experiments are performed using a shake table and the focus is on the influence of the impulsive acceleration and uplift.
A preliminary comparison between the experimental results and the recommendations provided by the liquid storage tank design guideline of the New Zealand Society for Earthquake Engineering is included.

Keywords: Storage Tanks, Soil-Structure Interaction, Uplift, physical model

1. INTRODUCTION

Liquid storage tanks have enormous significance for communities in earthquake prone regions. These facilities are the source of supply for several lifelines such as potable water, fuel and are an essential element in sewage disposal. For this reason, it is important that these structures remain operational after an earthquake. However, evidence in the literature (Haroun 1983, Manos and Clough 1985, Cooper 1997) has demonstrated that major earthquakes may cause severe damage to storage tanks or even collapse in some cases (Figure 1). This brings a twofold effect: a) people in regions affected by the earthquake cannot access the basic supplies of potable water and other basic but essential needs after the seismic event and b) economic loss due to tank and pipe damage. Many studies have been carried out to investigate the dynamic behaviour of storage tanks (Housner, 1957, Wozniak & Mitchell, 1978, Veletsos, 1984) largely as a result of item a) above. A number of codes of practice and design guides have been developed and compared (Ormeño et al. 2012).

Current standards for seismic designs are based mainly in the spring-mounted masses analogy proposed by Housner (1957) (Figure 2). This analogy indicates that liquid storage tanks behave mainly in two vibration modes (Wozniak & Mitchell, 1978, Veletsos, 1984). The portion of the liquid contents which moves as if it is fixed to the tank shell is known as the impulsive mass. The portion of the contents which moves independently of the tank shell and develops a sloshing motion is called the convective mass.

The predominant mode of vibration of liquid storage tanks during an earthquake is the impulsive mode (Larkin 2008, Veletsos et al. 1992) and its period is very short, generally a few tenths of a second. In many cases, tanks are built on soft normally consolidated soils (typical in coastal areas), which increases the risk of damage in earthquake prone countries such as New Zealand. Because of these two factors, i.e. a very stiff structure and very flexible foundation soil, the soil-foundation-structure interaction (SFSI) has an important effect on the seismic response and may lengthen the period of the impulsive mode significantly. This elongation is likely to produce a change in the seismic response of the tank from that of a tank sited on an infinitely stiff foundation as some studies have indicated. Current standards deem that SFSI always reduces the base shear and the overturning moment on liquid storage tanks. However Larkin (2008) concludes that this assertion is not always true. A reduction or increase of seismic loading will depend on the specific event and the characteristics of the tank and foundation soil of the local site.

Figure 1. Total collapse of storage tanks in Darfield earthquake (2010) (Courtesy of Timbertanks).

A phenomenon that has not received much attention is uplift of the base of the tank. Uplift is the physical separation of the tank base from the foundation or supporting soil. The seismic response of anchored tanks has been widely investigated, unlike the case of unanchored tanks (Malhotra and Veletsos 1994). The standards yield a conservative design for unanchored tanks because they consider that the uplift of the tank base plate is harmful by producing significant loading on the tank shell. Contrary to the lack of including base plate uplift effects, a theoretical study developed by Malhotra (2000) showed that including uplift could reduce the base shear and the base moment on tanks. In the specific case of an unanchored tank described by Malhotra the overturning moment and base shear was reduced by more than 70% in comparison with these reactions of the equivalent fully anchored tank, i.e. a tank that cannot develop uplift during an earthquake. This reduction is achieved because storage tanks without anchorage may uplift.

The objective of this work is to quantify the simultaneous effect of SFSI and uplift on storage tanks.

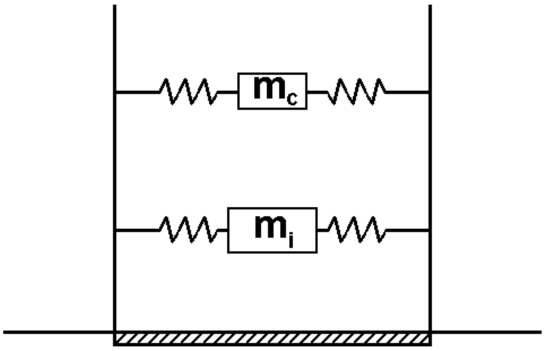

Figure 2. Spring-mounted masses analogy for storage tanks

2. METHODOLODY

2.1 Tank Model

A cylindrical tank model made of aluminium (Figure 3) was used to represent a cylindrical steel tank. The dimensions and properties of the model and prototype are shown in Table 1.

Table 1. Dimensions and properties of tank model and prototype

	Model	**Prototype**
Material	Aluminium	Steel
Young's modulus (MPa)	$6.895*10^4$	$2.068*10^5$
Diameter (m)	0.60	6.00
Height (m)	1.00	10.00
Thickness (mm)	3	12

The content considered for both tanks, model and prototype, was water.

Figure 3. Experiment model made of aluminium on the shale table

The equations to compute the dynamics characteristics of model and prototype are obtained from "Seismic Design of Storage Tanks" of the New Zealand Society for Earthquake Engineering (NZSEE Design Guide 2009). In this way, according to the standard procedure, the period of vibration of the first impulsive (tank + liquid) horizontal mode, T_f , with no incorporation of SFSI, is:

$$T_f = \frac{5.61 \cdot \pi \cdot H}{k_h} \cdot \sqrt{\frac{\gamma_l}{E \cdot g}} \tag{1}$$

where H = liquid height;

k_h = period coefficient which depends on the ratio of the liquid height to tank radius;

γ_l = unit weight of the liquid;

E = Young's modulus for tank material; and

g = gravitational acceleration.

To compute the impulsive and convective masses and their eccentricities above the base, the charts given by the Design Guide were used. Masses and their heights depend exclusively on the height to radius ratio k_h.

Scale factors for the experiment are shown in Table 2.

Table 2. Scale factors

Dimension	**Scale factor**
Length	10
Mass (content)	1000
Time	5.77
Stiffness	30.25
Acceleration	0.3
Force	300

2.2 Model of soil

To model the subsoil, a sand box was used (Figure 4). The internal dimensions of the sand box are 1100x800x500. All the lengths are in mm. The box was filled up to 400mm in height.

To include the effect of SFSI, the standard provides an expression (Equation 2 below) for the period of vibration, $\overset{\vee}{T}_f$, to modify the fixed-base period (Equation 1) to account for the foundation flexibility:

$$\overset{\vee}{T}_f = T_f \cdot \sqrt{1 + \frac{K_f}{K_x} \cdot \left[1 + \frac{K_x \cdot h_f^2}{K_\theta} \right]} \tag{2}$$

The standard procedure considers two impulsive modes. The second impulsive mode of the tank-foundation system is given by the following equation:

$$\overset{\vee}{T}_0 = 2\pi \cdot \sqrt{\frac{m_r + m_b}{K_x} + \frac{m_r \cdot h_r^2}{K_\theta}} \tag{3}$$

where m_r = rigid impulsive mass;
m_b = mass of the base;
h_f = height of the flexible impulsive mass;
h_r = height of the rigid impulsive mass;
K_f = effective stiffness of the tank-liquid system;
K_x = the horizontal translational stiffness; and
K_θ = rocking stiffness of the foundation.

$\overset{\vee}{T}_f$ and $\overset{\vee}{T}_0$ are the periods of vibration including SFSI for the first two impulsive modes of flexible tanks.

Figure 4. Sand Box

2.3 Earthquake

A simulated earthquake based on the Japanese Spectrum of Design was used to test the tank model and the soil-tank model system. The earthquake used in the tests is shown in Figure 5.

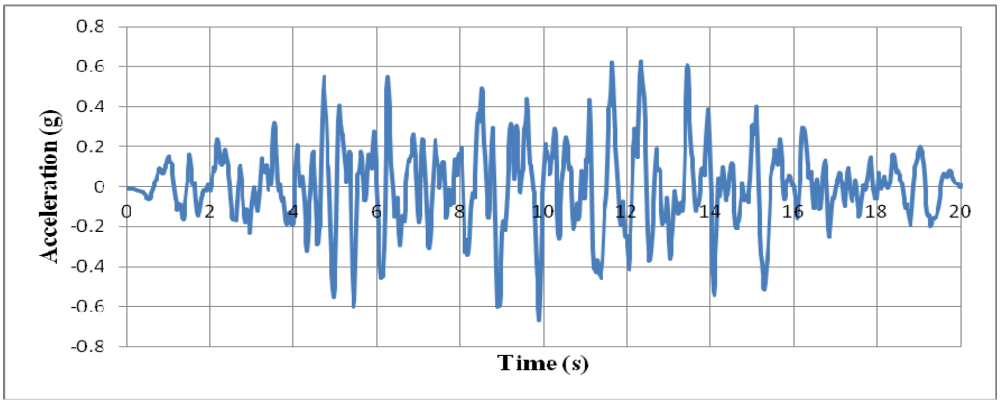

Figure 5. Earthquake

2.4 Measurements

To measure the vertical displacements (uplift), LVDT were implemented in the extremes of the tank in the same direction of the excitation (Figure 7). Other two were located in the extremes of the other horizontal orthogonal axe of the tank. Angles made of aluminium reinforced with a piece of timber (to make them stiffer) were located in these points (Figure 6). Horizontal displacements were measured by a SIKO Line Actuator. This device located in the top of the tank is able to measure displacements by an elastic cable. An accelerometer was located in the tank wall at the same height of the impulsive mass of the content. As was mentioned above, the predominant mode in the seismic behaviour of storage tanks is the impulsive mode of vibration and, for this reason the accelerometer was put in this location.

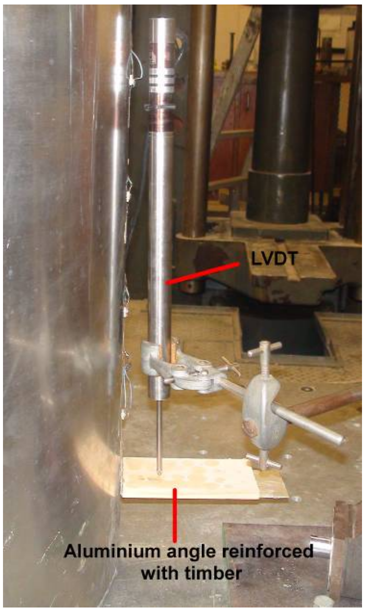

Figure 6. Aluminium angle reinforced with timber

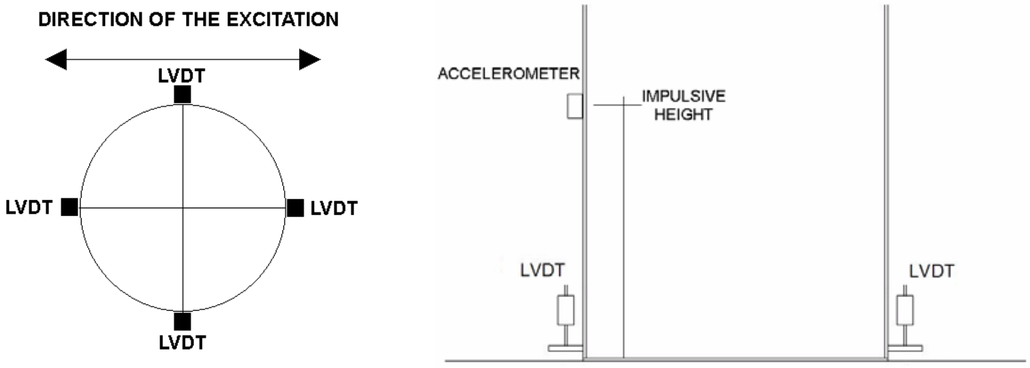

Figure 7. Plan view and elevation of the tank model

3. RESULTS

The tank was filled to two different heights to take into account two different aspect ratios. The selected heights were 300mm and 750mm. In this way, the ratios of the liquid height to tank radius (aspect ratio) were 1.0 and 2.5.

Table 3 shows the maximum acceleration of the system measured at the height of the mass corresponding to the impulsive mode of vibration, uplift and settlement (for flexible base) for the two aspect ratios considered. Results for rigid and flexible base are included. All these results are scaled to the prototype.

Table 3. Results

	Rigid Base		**Flexible Base**	
H/R	1.0	2.5	1.0	2.5
Amax (g)	0.30	0.60	0.20	0.18
Uplift (mm)	17	74	13	67
Settlement (mm)	-	-	85	140

Figure 8 shows the uplift behaviour of the circumference of the tank for a flexible base. The case shown is for the aspect ratio of 2.5.

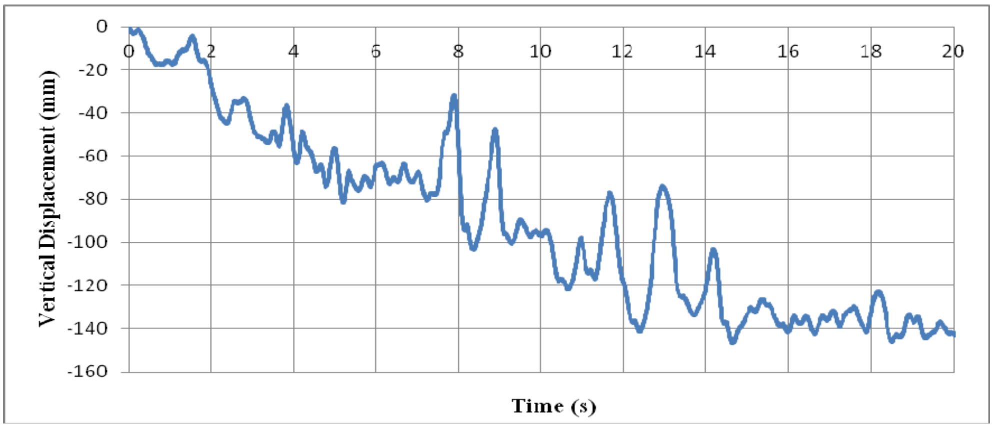

Figure 8. Time history of the vertical displacement for the aspect ratio of 2.5

For the prototype considered, the New Zealand Standard (NZSEE Design Guide 2009) gives the following values of uplift in the case of rigid base:

Table 4. Uplift according to the NZSEE Standard (2009)

H/R	Uplift(mm)
1.0	0
2.5	265

4. CONCLUSIONS

A scaled model of a storage tank without anchorage has been tested on a shake table, using an earthquake record, to measure maximum accelerations and vertical displacement. The experiments included a rigid base case and a flexible base (sand) case.

Results showed that for the case of a rigid base, the acceleration of the impulsive mass increased with the aspect ratio of the tank-liquid system. However, for the case of the flexible base, the impulsive acceleration was almost independent of aspect ratio. For both aspect ratios considered, the impulsive accelerations decreased when SSI was considered.

Uplift displacement is very sensitive to the aspect ratio. For a 2.5 times increase in aspect ratio the uplift increased by 500 %. However, uplift did not change significantly between the rigid or flexible base case.

Finally, uplift results obtained from the experiment were significantly less than the uplifts given by the current New Zealand design guide.

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