Effect of foundation conditions on the seismically induced stresses of liquid storage tanks

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ABSTRACT: Previous studies have demonstrated that strong earthquakes may cause severe damage to storage tanks. In New Zealand many tanks are built near the coast on soft soils. Because of 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, 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. Studies by other researchers have shown the influence of SFSI on the seismic response of storage tanks in terms of horizontal accelerations and seismic forces. However, there is no experimental investigation about the effect of SFSI on the tank shell stress which is the parameter that controls the design. In this research a physical model is used to evaluate SFSI effects on the tank shell axial compressive stresses. Sand in a laminar box is used to simulate the soil. The experiments were performed using 4 different ground motions and three different tank slenderness ratios (height/radius). The results showed that the axial compressive stresses decreased when the model was placed on a flexible base (sand in a laminar box) in comparison with the rigid base case (model placed directly on the shake table).

1 INTRODUCTION

Storage tanks are very stiff structures with a very short impulsive period (a few tenths of a second) (Larkin 2008). When these structures are placed on soft soils, SFSI will significantly determine the seismic behaviour of storage tanks. Veletsos and Meek (1974) identified two main factors to explain the difference in the seismic behaviour between the same structure placed on firm soil and on soft soil: a) structures on flexible base have more degrees of freedom and, thus, different dynamic characteristics than structures on rigid base and b) a part of the vibrational energy of a structure placed on flexible base will be dissipated by radiation of waves into the supporting medium and by damping in the foundation material.

Veletsos and Tang (1990) also investigated SFSI of storage tanks. They solved the problem in the frequency domain and included the foundation of the tank and also considered impulsive and convective modes of vibration. Their conclusions were: a) a decrease of the natural frequency of the system when SFSI is considered, b) an increase of the damping of the system reducing the peaks in the seismic response, c) the reduction in natural frequency is greater for slender tanks than for broad tanks because the rocking component of the foundation motion is more important for slender tanks, d) the reduction in peak response is more significant for short, broad tanks than for tall, slender tanks because these type of tanks can dissipate more energy by radiation damping and e) the effects of SFSI for convective modes are negligible. The authors also mentioned that SFSI is mainly governed by the relative stiffness of the supporting medium, i.e., by the structure stiffness to soil stiffness ratio. For this reason, when this kind of structure is placed on soft soils, SFSI has an important role in the seismic response of storage tanks.

Larkin (2008) studied the seismic response of storage tanks including SFSI for layered sites. The study confirmed the results given by Veletsos and Tang (1990) regarding the predominant mechanism of dissipating energy as a function of the aspect ratio. Larkin also found that SFSI could increase the seismic response of storage tanks in terms of maximum acceleration, base shear and overturning moment. The seismic response may increase or decrease depending on the characteristics of the tank, the type and depth of soil and frequency content of the earthquake motion.

However, there is no experimental data published about the effect of SFSI on the tank shell stress, which is the principal parameter that controls the design of this type of structure. The objective of this work is to quantify the effect of SFSI on storage tanks in terms of the displacement of the top of the tank and the axial stresses in the tank wall. The study entails the use of an earthquake motion applied to a shake table that supports a soil filled laminar box, to simulate the shear waves travelling through the subsoil, with a PVC model tank on the surface of the soil. The laminar box induces a state of shear in the soil by allowing displacement of the ends of the box.

2 METHODOLOGY

2.1 Tank Model

A PVC tank is used to model a prototype steel tank. Three different aspect ratios (H/R: Liquid level to radius ratio) were studied. The properties of the model and prototype are shown in Table 1. Two different boundary conditions were tested, rigid base (tank placed on the shake table) and flexible base (tank placed on the laminar box). Figure 1 shows both cases. Dynamic properties were computed using NZSEE (2009). The scale factors, based on dynamic similitude, are shown in Table 2.

Figure 1. Rigid base case (left) and Flexible base case using the laminar box (right)

Table 1 Dimensions and properties of tank model and prototype

	Model	**Prototype**
Material	PVC	Steel
Young's modulus (MPa)	$1.6*10^3$	$2.068*10^5$
Diameter (m)	0.50	10.00
Height (m) (#)	0.75	15.00
Wall and base thickness (mm)	4	10
Mass of the contents (kg) (#)	147	1178097

(#) These values correspond to an aspect ratio of 3

Table 2 Scale Factors

Dimension	Scale factor
Length	20
Mass (liquid content only)	8000
Time	4.64
Stiffness	369.5
Acceleration	0.93
Force	7440

2.2 **Experimental arrangement**

Strain gauges were implemented on the tank wall to measure the distribution of axial stresses. A wire transducer was attached to the top of the tank to measure the horizontal displacement of the tank shell. Figure 2 shows the setup used.

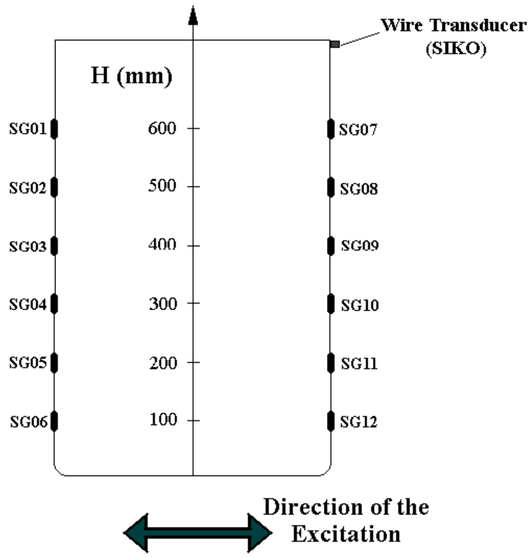

Figure 2. Experimental Setup. Strain Gauge distribution and wire transducer (Siko) at the top

2.3 **Ground Motions**

A set of four different earthquake records were used in testing the model tank. The earthquakes selected are shown in Table 3. The earthquakes were scaled using the procedure given in NZS1170.5 (2004). The target spectra used is given by NZSEE recommendations (2009), this originates from a modification of the spectrum given by NZS 1170.5 (2004) for the specific case of liquid storage tanks. The parameters necessary to compute the spectrum given by NZSEE recommendations (2009) were selected for Rotorua and a site classification of C. The ground motions were selected according to the recommendations given by Oyarzo-Vera *et al.* (2012) and used to perform a time-history analysis for a Rotorua site. The response spectra of the earthquakes, scaled to meet the target design spectrum, and the target spectrum are shown in Figure 3. The shake table was used to reproduce the ground motions. The similitude requirements were met by applying the time and acceleration scale factors shown in Table 2.

Table 3 Earthquake records selected

Record Name	El Centro, USA (*)	Delta, USA (*)
Date	19 May 40	15 Oct 79
Magnitude (Mw)	7	6.5
Distance (km)	6	22
Depth (km)	10	10
Fault Mechanism	Strike-Slip	Strike-Slip

(*) Both horizontal components of these earthquakes were selected to create the family of ground motions

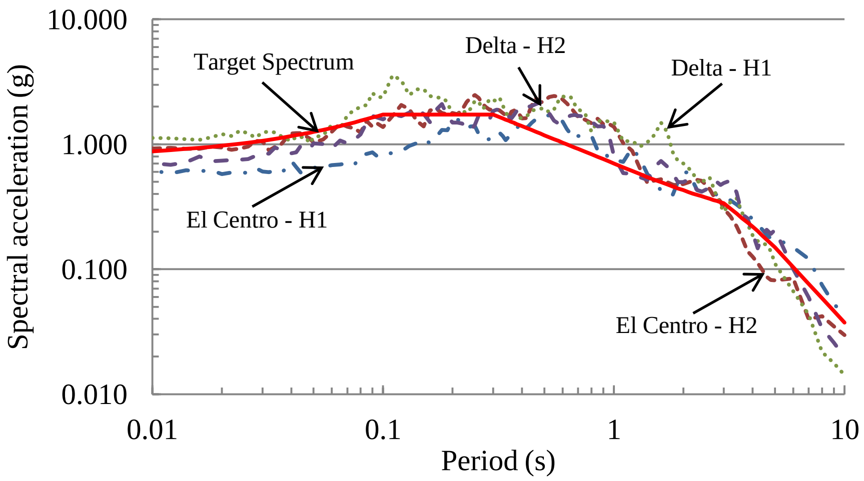

Figure 3. Scaled earthquake spectra and target NZ design spectrum for soil type C

2.4 **Subsoil**

The foundation soil was simulated using sand in a laminar box able to reproduce the shear deformation of the soil under a horizontal excitation (Figure 4). Horizontal aluminium frames are implemented to make possible the shear deformation of the soil in the direction of the excitation. The sand utilised to fill the box has a relative density of 88%. The box was filled up to a height of 600 mm.

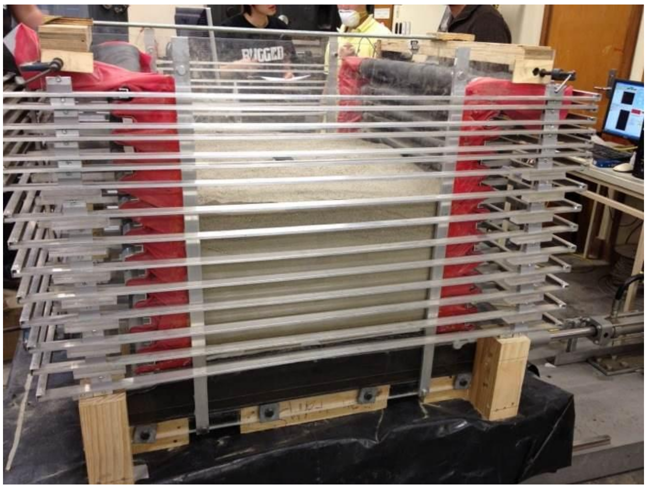

Figure 4. Laminar Box utilised to model the subsoil (Cheung et al. 2013)

3 RESULTS

Table 4 shows the ratio between the maximum displacement of the top of the tank shell for the flexible base condition and that measured for the rigid base condition.

Table 4 Maximum top displacement ratio

Ground Motion	H/R=1	H/R=2	H/R=3
El Centro H1	0.977	0.972	1.004
El Centro H2	0.923	0.681	0.904
Delta H1	1.348	0.976	1.289
Delta H2	1.028	0.997	1.059

In 5 of the 12 ratios shown in Table 4, higher values of displacement were obtained for the flexible base case than the rigid base case, i.e., in 7 of the 12 cases analysed, maximum values of top displacement are higher when the tank was placed on a rigid base. There is no a clear trend evident in Table 4.

However, the parameter that largely controls the design of liquid storage tanks is the stress in the tank shell. Figures 5 and 6 show the maximum outer axial compressive stress obtained for both horizontal components of the El Centro motion for the three aspect ratios considered.

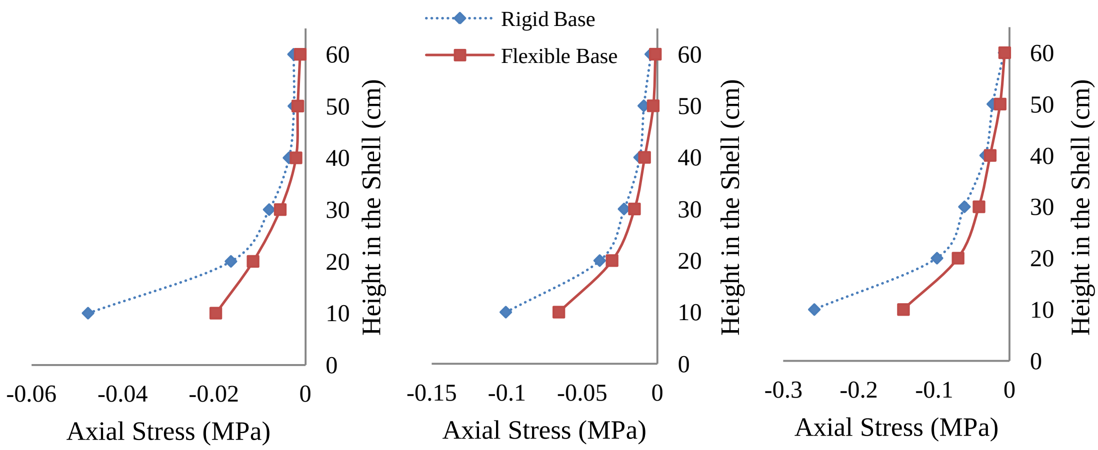

Figure 5. Maximum axial compressive stress for El Centro H1. H/R = 1 (left), H/R = 2 (centre) and H/R = 3 (right).

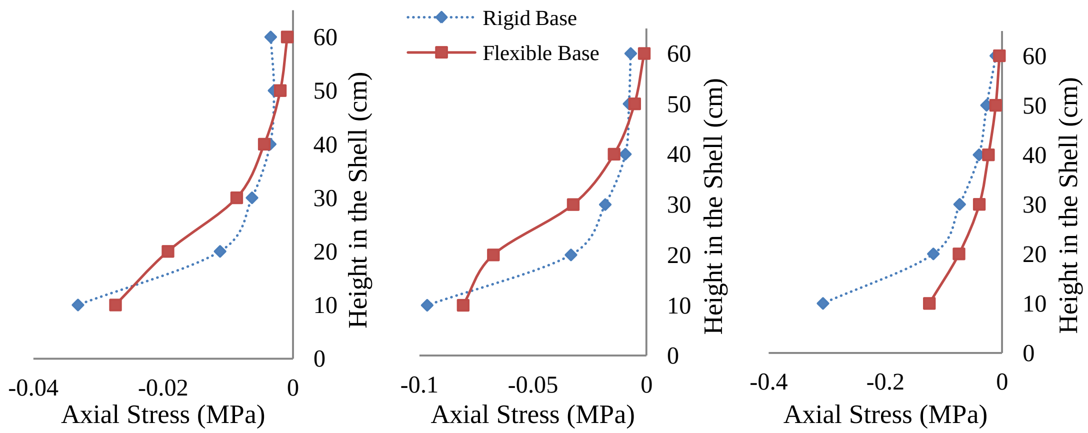

Figure 6. Maximum axial compressive stress for El Centro H2. H/R = 1 (left), H/R = 2 (centre) and H/R = 3 (right).

From Figures 5 and 6 it is noticeable that the axial compressive stress decreased when the tank was placed on the laminar box. To provide an overview of the effect of SFSI on the axial compressive stresses, the bottom value (which is the maximum) is shown in Table 5. This table shows the reduction in the maximum axial stress at the bottom of the tank wall for the 4 ground motions considered.

Table 5 Decrease of the maximum axial compressive stress due to SFSI

Ground Motion	H/R=1	H/R = 2	H/R=3
El Centro H1	59 %	35 %	46 %
El Centro H2	17 %	16 %	59 %
Delta H1	35 %	37 %	54 %
Delta H2	30 %	46 %	63 %

Table 5 shows that for all the cases analysed (4 ground motions and 3 aspect ratios) the maximum value of axial compressive stress of the tank shell decreased when the tank was placed on a flexible base. Even though the model can reach higher horizontal displacements in some cases, as seen in Table 4, SFSI always had a beneficial effect in terms of the axial compressive stresses. This fact can be explained by the rotation of the tank base supported by the subsoil. This rotation may cause higher horizontal displacements of the tank compared to the displacements of the tank placed on a rigid base. However, only the lateral displacement due to the tank shell deformation is instrumental in producing wall stress through structural distortion. For this reason, it is possible in the flexible base case to obtain higher displacements and lower axial stresses in some cases.

4 CONCLUSIONS

The main aim of this work is to provide shake table experimental results of SFSI in storage tanks under seismic loading, specifically focussing on tank shell axial stresses. A series of experiments on a model PVC liquid storage tank, with 3 aspect ratios, have been described. These experiments were carried out to determine the effect of SFSI on the outer shell stress of liquid storage tanks using 4 scaled recorded earthquake motions. Previous theoretical studies carried out by other researchers have reported the effect of SFSI on the seismic forces acting on storage tanks. The authors could find no publications reporting experimental studies that investigated directly the effect of SFSI on tank shell stresses. The shell axial stresses are the critical design parameters for liquid storage tanks, particularly under seismic loading.

The experimental results showed that SFSI lowers the maximum axial compressive stresses of the tank shell. For the 4 ground motions and 3 aspect ratios utilised, i.e. 12 cases, the maximum recorded average maximum compressive stress decreased by between 16% and 63% when SFSI took place.

In 42% of the experiments the maximum top displacement was higher when the tank was placed on the laminar box. These results do not contradict the results obtained for the axial stresses. It is possible to get higher lateral displacements of the tank wall and lower wall axial stress since the sole factor governing tank shell axial stress is the distortion of the wall itself. The horizontal displacement due to rotation of the subsoil has no impact on the tank shell axial stress.

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