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Influence of uplift on liquid storage tanks during earthquakes

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Abstract. Previous investigations have demonstrated that strong earthquakes can cause severe damage or collapse to storage tanks. Theoretical studies by other researchers have shown that allowing the tank to uplift generally reduces the base shear and the base moment. This paper provides the necessary experimental confirmation of some of the numerical finding by other researchers. This paper reports on a series of experiments of a model tank containing water using a shake table. A comparison of the seismic behaviour of a fixed base system (tank with anchorage) and a system free to uplift (tank without anchorage) is considered. The six ground motions are scaled to the design spectrum provided by New Zealand Standard 1170.5 (2004) and a range of aspect ratios (height/radius) is considered. Measurements were made of the impulsive acceleration, the horizontal displacement of the top of the tank and uplift of the base plate. A preliminary comparison between the experimental results and the recommendations provided by the liquid storage tank design recommendations of the New Zealand Society for Earthquake Engineering is included. The measurement of anchorage forces required to avoid uplift under varying conditions will be discussed.

Keywords: storage tanks; uplift; fluid-structure interaction; hold-down force; standard

1. Introduction

Liquid storage tanks have enormous significance for communities in earthquake prone regions. These facilities are lifelines for ensuring supplies of essential needs such as potable water, fuel and gas. 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 (Fig. 1) or even collapse in some cases. The damage has two consequences: a) people in regions affected by the earthquake cannot access the life preserving supplies of potable water and other basic but essential needs 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 and Mitchell 1978, Veletsos 1984) largely as a result of the two consequences stated above. A number of codes of practice and design guides have been developed and are discussed and compared in Ormeño *et al.* (2012).

Current standards for seismic designs are based mainly on the spring-mounted masses analogy

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proposed by Housner (1957) (Fig. 2). This analogy indicates that liquid storage tanks behave mainly in two vibration modes (Wozniak and 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 m_0. The portion of the contents which moves independently of the tank shell and develops a sloshing motion is called the convective mass m_1. The predominant mode of vibration of liquid storage tanks during an earthquake is the impulsive mode (Larkin 2008 and Veletsos *et al*. 1992) and its period is very short, generally a few tenths of a second.

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 tank foundation or supporting soil. The early studies of storage tanks assumed the structure to be fixed to the base. However, many storage tanks are not provided with anchorage and thus these structures can uplift.

Despite the beneficial influence of partial uplift on structures being identified and reported several decades ago, e.g., by Housner (1963), Meek (1975), Huckelbridge and Clough (1977), Psycharis (1983), current standards and design recommendations for storage tanks (API 650 2007, NZSEE 2009) give a conservative seismic design for unanchored tanks (Ormeño *et al*. 2012). These documents state that uplift of structures should be avoided, because it has the potential to lead to structural collapse. The belief, due to lack of knowledge, that structural uplift will increase collapse potential, is the real impediment to considering the beneficial effect of uplift in seismic design.

Fig. 1 Foundation sliding (right) and wall damaged due to sloshing motion (left) in Darfield earthquake (2010) (Courtesy of Timbertanks)

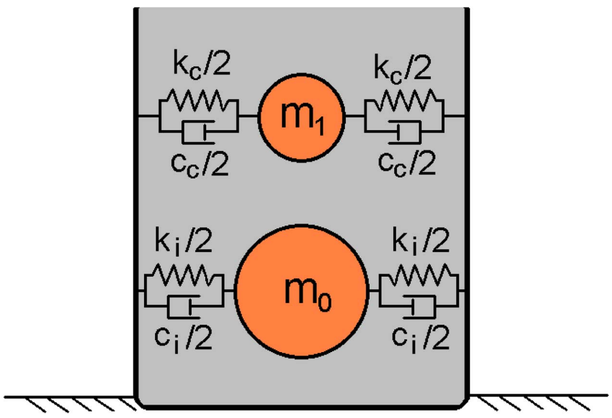

Fig. 2 Spring-mounted masses analogy for storage tanks

Indeed, studies of structural uplift in earthquakes have been considered by a number of researchers. In some of these studies the structures were assumed to be rigid (e.g., Apostolou *et al.* 2007, Taniguchi 2002). Consequently, only the rocking performance of the rigid body was considered in these investigations while the natural modes of the structures were ignored. Kodama and Chouw (2002) have demonstrated the significance of structural flexibility, since uplift behaviour of flexible structures is not the same as that of rigid structures. Qin *et al.* (2012) showed that uplift can reduce plastic hinge development of the structure. Loo *et al.* (2012) investigated the effectiveness of slip-friction connectors as a hold-down mechanism to control the structural uplift behaviour.

In the specific case of storage tanks, Wozniak and Mitchell (1978) included in their work a solution for unanchored tanks allowing uplift. Ishida and Kobayashi (1988) and Malhotra and Veletsos (1994a) investigated the behaviour of unanchored tanks by using small deflection beam theory to model the bottom plate of the tanks. Both works reported the relationship between bending moment of the beam and uplift (vertical displacement) of the extreme fibre of the base (Fig. 3). In their subsequent works, Malhotra and Veletsos (1994b,c) provide the relationship between base rotation and base moment and the seismic response of storage tanks for a given ground motion including uplift.

The constraints shown in Fig. 3 in the extreme of the beam correspond to the motion restriction imposed by the tank wall to the bottom plate.

Malhotra (2000) used the moment-rotation relationship given by Malhotra and Veletsos (1994b) (Fig. 4) to carry out a simplified nonlinear analysis for performance-based seismic design of tanks. In the example given by Malhotra (2000), the overturning moment and base shear were reduced by more than 70% from that of the equivalent fully anchored tank. This reduction is due to the fact that in storage tanks without anchorage uplift is possible, and in this way, the bottom plate can deform plastically.

From Fig. 4 Malhotra (2000) found the force-displacement relationship of the impulsive mass m_0 and the equivalent viscous damping of the tank with uplift. In this way, he computed the decrease in the seismic forces mentioned above by using a simplified nonlinear analysis for the performance based seismic design of tanks, which included the determination of the acceleration-deformation spectrum (demand curve).

The objective of the work reported here is to quantify the effect of uplift on storage tanks in terms of the impulsive acceleration and the displacement of the top of the tank. The study entails the use of an aluminium model tank that is subjected to earthquake motion on a shake table.

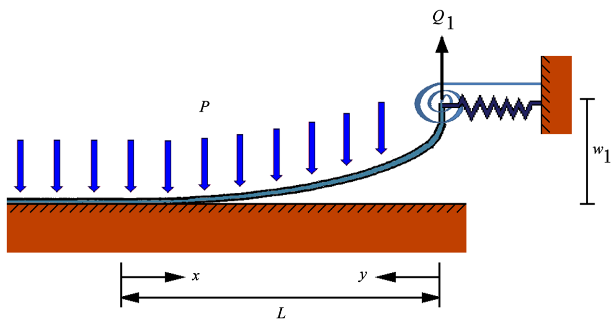

Fig. 3 Beam model used by Malhotra and Veletsos (1994a) to represent the bottom plate

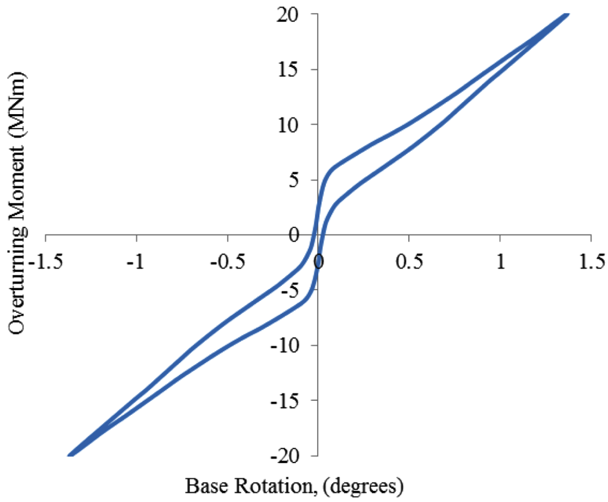

Fig. 4 Uplift resistance of the base plate from Malhotra (2000)

where P = uniform pressure on the bottom plate;
Q_1 = upward force on the bottom plate due to the overturning moment;
w_1 = uplift due to the upward force; and
L = uplifted length of the beam in the model

2. Methodology

2.1 Tank Model

A model comprising of a cylindrical aluminium tank (Fig. 5) was used to represent a prototype steel tank. The Buckingham π theorem (1914) was utilised to meet the similitude conditions between the scale model and the prototype. In most of the practical cases of seismic design storage tanks can be modelled as a single degree of freedom (SDOF) system only considering the impulsive mode of vibration (Larkin 2008). In this way the Cauchy number, as defined by Qin *et al.* (2012), is considered to meet the requirements of similitude. This relation is shown in Eq. (1).

$$\frac{F_i}{F_e} = \frac{m \cdot a}{k \cdot u} \tag{1}$$

where F_i = inertial force;
F_e = elastic restoring force;
m = impulsive mass of the system m_0 (see Fig. 2);
a = impulsive horizontal acceleration (It is measured by an accelerometer located at the height of the impulsive mass of the content);
k = impulsive translational stiffness of the impulsive spring k_i (see Fig. 2); and
u = horizontal deflection

A good approximation for computing the impulsive mass of the system is to consider only the impulsive mass of the liquid, i.e., the mass of the tank wall will not be included in the calculation of the impulsive mass. In this way, since the model and the prototype store the same liquid (water), the length scale factor determines the mass scale factor. The stiffness (k) is determined by the geometry and the mechanical properties of the tank and liquid. Once these properties are set in the model and prototype, the only variable that can be adjusted to meet the relationship shown in Eq. (1) is the acceleration (a). Eq. (2) shows the dimension of acceleration

$$[a] = [l]\cdot[t]^{-2} \tag{2}$$

where l = length; and
t = time

However, length (l) is already set, therefore, the time scale factor must be adjusted to meet the requirement of Eq. (1).

The dimensions and properties of the model and prototype are shown in Table 1. Scale factors for the experiment are shown in Table 2. The tank wall was made of only one sheet of aluminium with one vertical welded seam. The bottom plate of the model is also made of one sheet of aluminium.

The model was not provided with a roof to enable comparison with the theoretical equations given by the current standards and design recommendations for computing the properties and seismic response of storage tanks. These documents assume that the top of the tank wall is not stiffened by ring girders or a roof structure. This approximation satisfies most of the practical cases where the tank is provided with a roof (NZSEE 2009).

Three different liquid levels were used in order to investigate the sensitivity of the response to different liquid height to radius ratios (aspect ratio). The liquid levels considered were 300 mm,

Table 1 Dimensions and properties of tank model and prototype

	Model	Prototype
Material	Aluminium	Steel
Young's modulus (MPa)	$6.895*10^4$	$2.068*10^5$
Density of the tank material (kg/m^3)	2700	7850
Diameter (m)	0.60	6.00
Height (m)	1.00	10.00
Wall and base thickness (mm)	3	12
Mass of the contents (kg) (#)	254.5	254469

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

Table 2 Scale factors

Dimension	Scale factor
Length	10
Mass (liquid content only)	1000
Time	9.12
Stiffness	12.13
Acceleration	0.12
Force	120

Fig. 5 Experimental aluminium model on the shake table

600 mm and 900 mm to give aspect ratios of 1, 2 and 3.

Two different boundary conditions were utilised: fixed to the shake table and free to uplift. Four bolts were used to anchor the tank to the shake table (Fig. 6). Strain gauges were attached to a flattened surface of the shank of the bolts to measure the hold down force (compression or tension) during the table motion. Angles of aluminium welded to the tank shell were used as anchor bolt brackets. The thickness and size of the angle were selected to ensure that it was stiff enough to avoid the bending.

For the unanchored tank tests, four LVDTs were used to measure the uplift of the tank model. Uplift was measured at the same position as the aluminium angles (Fig. 7).

A wire transducer was used to measure the top horizontal displacement of the tank while an accelerometer was fixed to the tank wall at the calculated height of the impulsive mass to obtain the record of the tank wall acceleration, see Fig. 7. As was mentioned above, the predominant mode in

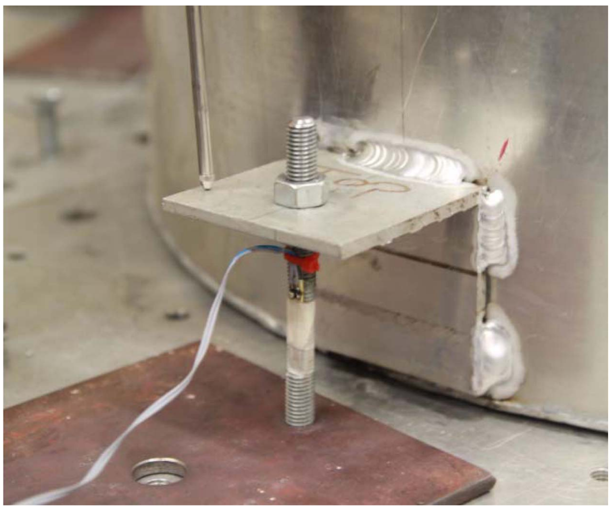

Fig. 6 Anchor bolt used to fix the tank to the shake table

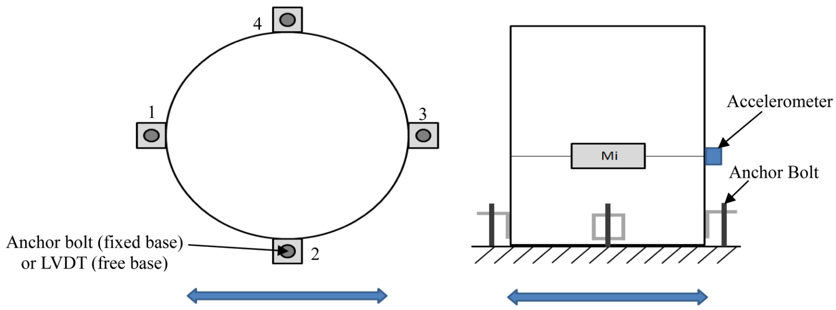

Fig. 7 Plan view and elevation of the tank model

the seismic behaviour of storage tanks is the impulsive mode of vibration and, for this reason the accelerometer was placed at this elevation.

The equations to compute the dynamic characteristics of the model and prototype were obtained from the NZSEE recommendations 2009. The period of vibration of the first impulsive (tank + liquid) horizontal mode, T_f in second, is

$$T_f = \frac{5.61 \cdot \pi \cdot H}{k_h} \cdot \sqrt{\frac{\gamma_l}{E \cdot g}} \tag{3}$$

where H = liquid height;
k_h = period coefficient which depends on the ratio of the liquid height to tank radius (Fig. 8);
γ_l = unit weight of the liquid;
E = Young's modulus of the tank material; and
g = gravitational acceleration

In this way, the impulsive period of the model and prototype vibration for an aspect ratio of 3 is 0.008 s and 0.073 s, respectively.

where t = tank wall thickness; and
R = mean radius of the tank

NZSEE recommendations (2009) give the relationships shown in Fig. 9 to determine the modal

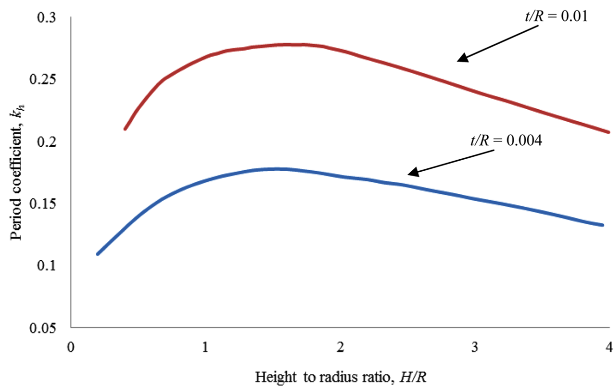

Fig. 8 Period Coefficient k_h for First Horizontal Tank - Liquid Mode, from NZSEE recommendations (2009)

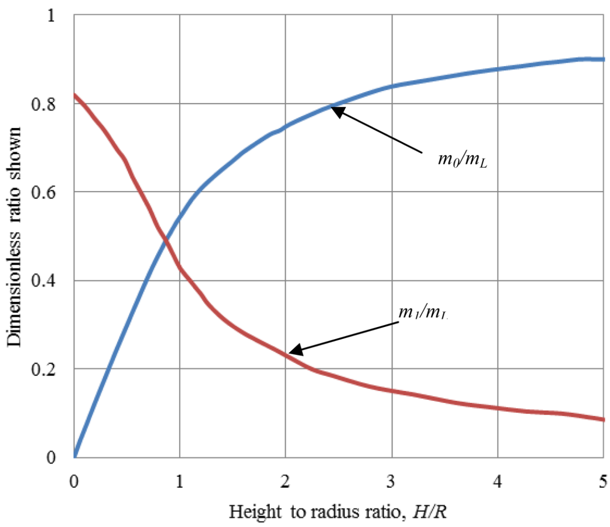

Fig. 9 Impulsive and convective mass components, from NZSEE recommendations (2009)

masses of the tank-fluid system.

where m_0 = impulsive mass;
m_1 = mass of the first convective mode of vibration;
m_L = mass of the fluid

Once impulsive mass and impulsive period are determined, the impulsive stiffness (k_i) is computed using Eq. (4).

$$k_i = \frac{4 \cdot \pi^2 \cdot m_0}{T_f^2} \tag{4}$$

2.2 Ground motions

A set of six different earthquake records were used in testing the tank model. The earthquakes selected are shown in Table 3. The earthquakes were scaled using the procedure given by NZS 1170.5 (2004). This procedure establishes that at least three records must be used and scaled by two factors: the record scale factor (k_1) and the family scale factor (k_2). The aim of the process is to minimise the difference between the response spectra of the chosen records and the target spectrum in the range of periods between 0.4 T_1 and 1.3 T_1 where T_1 is the largest translational period in the direction being considered. 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 study utilises six earthquake records in an effort to have an improved statistical basis compared to that required by NZS 1170.5 (2004). The parameters necessary to compute the spectrum given by NZSEE recommendations (2009) were selected for Auckland and a site classification of C. The ground motions were selected according to the recommendations given by Oyarzo-Vera *et al.* (2012) to perform a time-history analysis for an Auckland site. The scaled response spectra of the earthquakes and the target spectrum are shown in Fig. 10. A shake table was used to

Table 3 Earthquake records selected

Record name	El Centro, USA	Delta, USA	Kalamata, Greece	Convict Creek, USA (*)	Matahina Dam D, NZ
Date	19 May 40	15 Oct 79	13 Sep 86	25 May 80	02 Mar 87
Magnitude (Mw)	7	6.5	6.2	5.9	6.6
Distance (km)	6	22	10	6	16
Depth (km)	10	10	8	16	10
Fault Mechanism	Strike-Slip	Strike-Slip	Normal	Strike-Slip	Normal

(*) Both horizontal components of this earthquake were selected to create the family of ground motions

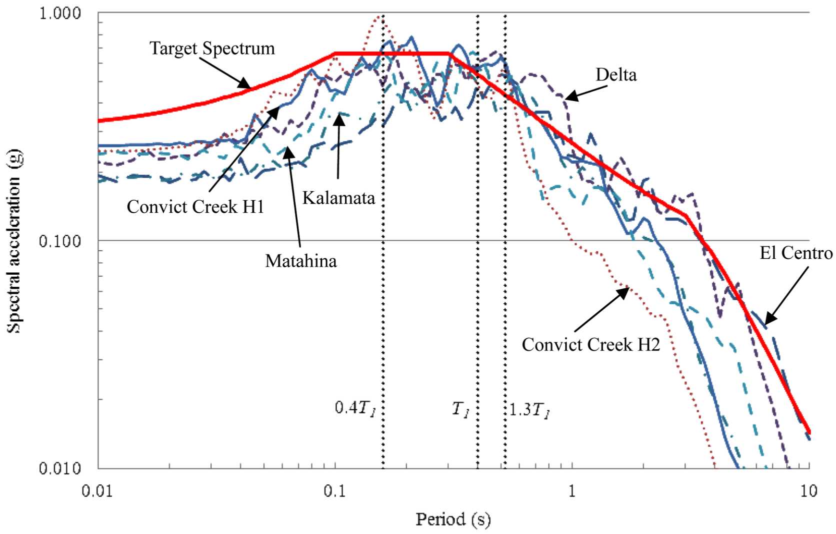

Fig. 10 Scaled earthquake spectra and target NZ design spectrum

reproduce the ground motions. The similitude requirement was met by applying the time scale factor shown in Table 2.

3. Results

It is useful to compare the values of the experimental maximum acceleration with the seismic coefficient given by NZSEE (2009) for the impulsive mode. The seismic coefficient is the value defined by NZSEE (2009). It is the ratio of the horizontal load due to the impulsive mode of vibration to the weight of the tank. The aspect ratio is one of the most influential parameters that affects the seismic response of liquid storage tanks. It is expected that a variation in this parameter will be reflected in the tank acceleration. These values are shown in Table 4 for the three aspect ratios analysed and both boundaries conditions. All experimental results are scaled to the prototype size and are given in terms of the gravitational acceleration.

Whereas NZSEE (2009) shows an increase in the seismic coefficient when the aspect ratio increases, the results of measurement of the tank wall acceleration do not show any increasing trend with increasing period ratio. This can be explained by analysing the impulsive period of the system. In

Table 4 Maximum accelerations and seismic coefficient given by NZSEE (2009)

Aspect ratio	$H/R = 1$		$H/R = 2$		$H/R = 3$	
Ground motion	Anchored	Unanchored	Anchored	Unanchored	Anchored	Unanchored
El Centro	0.267	0.400	0.365	0.353	0.283	0.340
Delta	0.228	0.269	0.250	0.374	0.451	0.343
Kalamata	0.332	0.525	0.545	0.473	0.320	0.396
Convict Creek H1	0.270	0.365	0.299	0.363	0.336	0.310
Convict Creek H2	0.164	0.173	0.237	0.155	0.124	0.220
Matahina	0.360	0.566	0.424	0.390	0.241	0.333
NZSEE (2009)	0.355	0.355	0.483	0.483	0.605	0.605

Table 5 Impulsive period T_f

H/R	T_f(s)
1	0.022
2	0.043
3	0.073

Table 5 the impulsive period of vibration, T_f, for the aspect ratios analysed is given for the prototype.

It is noticeable from Table 5 that all cases analysed represent very stiff structures. The tank example used herein is not exceptional, generally tanks are very stiff (Larkin 2008). In this specific case, the range of periods shown in Table 5 is in the very low period zone before the plateau of the spectrum of design given by NZSEE (2009) as can be seen in Fig. 10. This explains the increase in the seismic coefficient with aspect ratio in NZSEE (2009) since the period increases with aspect ratio. However, NZS 1170.5 establishes as minimum value for T_1 of 0.4 seconds, i.e., the range of the spectrum that coincides with the values of the impulsive period is out of the scaled range. This can explain why there is no coincidence between the trend noticed in the coefficient given by NZSEE (2009) and the values obtained from the experiments. As was mentioned above, the impulsive period of storage tanks is shorter than 0.4 sec for most of the practical cases, therefore, this procedure generally does not scale the ground motions in the range of the impulsive period.

Considering the acceleration of the tank wall at the height of the impulsive mass for the two boundary conditions (fixed and free); it is useful to employ the ratio of the maximum tank wall acceleration without anchorage to the one with anchorage, *MAR*, defined in Eq. (5). Fig. 11 shows the MAR for the six different ground motions and for the three different aspect ratios used.

$$MAR = \frac{Maximum\ Acceleration\ of\ the\ Tank\ Wall\ measured\ for\ the\ unanchored\ tank}{Maximum\ Acceleration\ of\ the\ Tank\ Wall\ measured\ for\ the\ anchored\ tank} \quad (5)$$

It is seen that for most of cases analysed MAR is higher than 1, i.e., for 6 of 18 cases the maximum acceleration decreased when anchorage was not present. This result shows that for a third of the total cases a tank free to uplift reduces the seismic forces compared to an equivalent fixed tank for the type of fluid-structure interacting system employed in these experiments. This suggests that the effect of allowing uplift on the seismic response depends on the characteristics of the tank and the ground motions considered.

An important parameter in the case of a fixed base is the force in the hold down bolts. Fig. 12 shows the time-history of the hold-down force for the values of aspect ratio of 1 and 3. The record

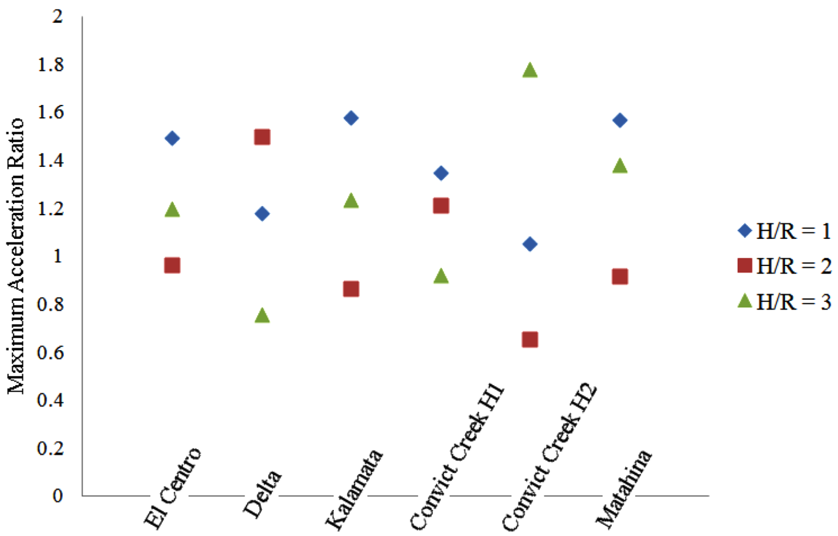

Fig. 11 Influence of ground motions on the maximum tank wall acceleration

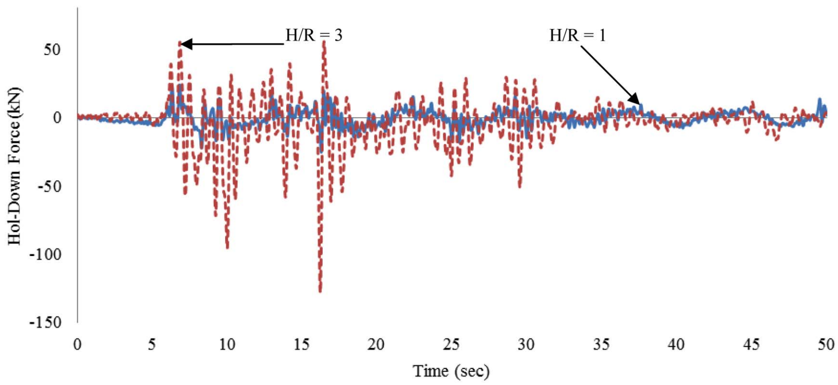

Fig. 12 Hold-down force due to the El Centro earthquake

was obtained from the bolt located in point 1 shown in Figure 7. The time-history used is that from the El Centro ground motion. It should be realised that the measured hold down force is the summation of the force originating from the impulsive and convective actions. In the experimental data the force cannot be partitioned into the two types of tank response, i.e. convective and impulsive.

Numerous studies, e.g. Malhotra and Veletsos (1994a,b,c) and Malhotra (2000), have shown the convective mode has a very minor influence in the case of tall slender tanks ($H/R = 3$) while conversely the impulsive mode has a minor influence in the case of squat tanks ($H/R = 1$). In the case of this experimental work the excitation of the shake table was terminated at 32 seconds. It can be seen for the case of aspect ratio 1 (squat tank) the hold down forces are similar to the values found in the loading period, while in the case of the aspect ratio 3 (slender tanks) the hold down forces are very small in comparison with those in the excitation period. Finally, the maximum uplift for each case and the value given using NZSEE (2009) are given in Table 6. These values are contrasted with the values given by NZSEE (2009). The values are shown for the prototype.

It is clear that the values given by NZSEE (2009) are much higher that the values obtained from

Table 6 Prototype uplift (experimental values scaled)

	Uplift (mm)		
Ground motion	H/R = 1	H/R = 2	H/R = 3
El Centro	3.08	3.46	5.66
Delta	2.16	3.11	9.68
Kalamata	5.51	3.77	9.03
Convict Creek H1	2.58	2.98	5.20
Convict Creek H2	1.67	1.73	2.48
Matahina	2.54	6.10	6.71
NZSEE (2009)	183	278	455

the experiment. This mismatch is not very surprising. As was noted by Ormeño *et al.* (2012), even the values of uplift given by the API Standard 650 and NZSEE (2009) are not similar when the same tank is analysed. In the specific case of NZSEE (2009), this document provides an equation that is based on a quasi-static equilibrium of forces and moments acting on the tank. It does not take into account how an uplift of the base plate affects the impulsive mode. Furthermore, the stiffness of the bottom plate, a parameter that was demonstrated by Malhotra and Veletsos (1994a,b,c) and Malhotra (2000) as one of the most influential in the computation of uplift, appears just implicitly in the equation given by NZSEE (2009). In the specific case analysed herein, the bottom plate has a thickness of 12 mm (prototype), which is a very stiff bottom plate compared with most practical cases.

4. Conclusions

A series of experiments have been described that were carried out to determine the role of base plate uplift in the seismic forces acting on liquid storage tanks. The experimental results showed that in 66% of the cases the tank wall acceleration increased when the tank was not provided with anchorage. On the other hand, for an aspect ratio of 2 this percentage is the opposite, i.e., in 66% of the cases the tank wall acceleration increased when the tank was provided with anchorage. This suggests that including anchorage in storage tanks does not always decrease the seismic forces acting on the structures as some design documents affirm. The results of this experimental study show that the response of the tank may either increase or decrease. The factors determining the outcome are the dynamic properties of the tank and the characteristics of the ground excitation.

Using seismic records scaled to the design spectrum given by NZSEE (2009) does not guaranteed that the values of the maximum acceleration will be similar to the values given by the spectrum of design. This is because liquid storage tanks are very stiff structures and their impulsive period is outside the period range subjected to the scaling process specified by NZS 1170.5 (2004). Therefore, the NZS 1170.5 (2004) procedure is not appropriate and another alternative should be sought to perform time-history analysis of liquid storage tanks.

As was expected for fixed tanks, the influence of the convective mode on the value of the hold-down forces decreases with the aspect ratio. However, the contribution of the sloshing mode to the hold down forces does not change dramatically with variation of the aspect ratio.

The results achieved here imply that NZSEE (2009) overestimates the maximum uplift. A procedure that considers the effect of uplift in the seismic response, and incorporates explicitly the stiffness of the bottom plate of the tank, needs to be developed to give more realistic values to practising engineers.

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