Effect of base plate uplift on liquid storage tank behaviour in earthquakes

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ABSTRACT

Theoretical studies by other researchers have shown that including uplift could reduce the base shear and the base moment on tanks. However, there is no experimental research that supports that. This paper reports the results obtained from shake table tests of a model tank containing water. The study focuses on a comparison between a fixed base system (tank with anchorage) and a system free to uplift (tank without anchorage). The experiments were performed using stochastically simulated ground motions based on the Japanese design spectrum and two different tank slenderness ratios (height/radius). Measurements were made of the impulsive acceleration at the elevation of the calculated impulsive mass and the horizontal displacement of the top of the tank, and the anchorage forces. The uplift forces are also discussed.

Keywords: Storage tanks, uplift, fluid-structure interaction, earthquake, hold-down force, shake table test

1. INTRODUCTION

After an earthquake event, supplies such as oil, water or food are a priority. Hence, it is essential that liquid storage tanks resist and remain operational after a seismic event. In addition, a possible environmental issue should not be forgotten because storage tanks may contain substances which can pollute the environment. For these reasons, it is very important to design tank and piping systems to prevent leakage during or following an earthquake. Even for less important tanks a subsequent economic and social loss due to damage to the tank can be significant.

Figure 1 shows the usual model for liquid storage tanks given by Housner (1957); it uses a springs-masses equivalent system to take into account the fluid-structure interaction. The mass of the contents is divided into parts which move with different frequencies.

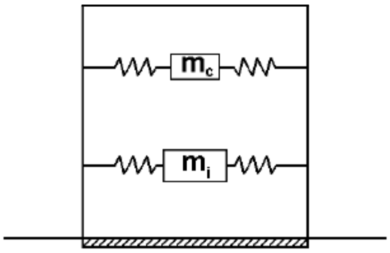

Figure 1. Spring mounted masses after Housner (1957)

Previous studies have shown that two modal masses are sufficient to give good approximations (Housner, 1957); the first mode, where the mass is considered to be fixed to the tank wall, is called the impulsive mode, and the second mode, which involves the upper body of the contents, is known as the convective or sloshing mode.

A lesser known aspect of tank design is the possibility for unanchored tanks to uplift during an earthquake. The current design documents, API Standard 650 (2007) of American Petroleum Institute or "Seismic Design of Storage Tanks" (NZSEE, 2009) of the New Zealand Society for Earthquake Engineering, consider that uplift causes damage to structures. Therefore, they recommend using anchors in order to avoid any uplift. Ormeño et al. (2012) discussed and compared a number of codes of practice and design specifications.

Recently, the works of Malhotra (2000) and Malhotra and Veletsos (1994 a, b, c) show that uplift can reduce base shear and overturning moment, therefore, there is an important contrast between numerical work performed by Malhotra (2000) and the recommendations of design documents. This situation has prompted this experimental investigation to determine the influence of uplift on liquid storage tank.

The experiments were performed with a scaled model liquid storage tank on a shake table. The experiments focused on the comparison between fixed base (with anchorages) and free base (unanchored), for two slenderness aspect ratios (height of fluid upon radius). The shake table excitations were numerically simulated ground motions (Chouw and Hao, 2005).

2. METHODOLOGY

The experiments were designed to excite the tanks with two aspect ratios, using two different earthquakes time histories. Two situations were considered: a) the tank bolted (anchored) to the shake table and b) the tank free to uplift (without any anchorage system). In both situations the horizontal top displacement of the tank, and the impulsive acceleration were recorded at the height of the computed impulsive mass. In the fixed base case the hold-down forces in the bolts were also recorded and in the free base case the uplift of the bottom plate was measured.

The use of a scale model to represent a prototype structure requires that similitude conditions be met as far as possible. The Buckingham π theorem (Buckingham, 1914) was utilised for this purpose. The following table shows all the scale factors used.

Table 1: Scale factors

Dimension	Scale factor
Length (m)	10
Time (s)	9.090
Mass (kg)	1000
Acceleration (m/s²)	0.121
Force (N)	121.1
Stress (Pa)	1.211

All the experiments were performed with a cylindrical aluminium (AL) tank, and 4 AL angles were welded to the tank base for fixing the tank to the shake table (see Figures 2 and 3). The angles were stiff relative to the rigidity of the wall during the excitation. Table 2 lists the tank characteristics.

Table 2: Characteristics of the tank

	Symbol	Units	Prototype	Experimental model
Tank Proprieties				
Radius	R	m	3	0.3
Height		m	10	1
Thickness of the wall	h_s	mm	30	3
Thickness of the angles		mm	40	4
Thickness of the base plate	h_b	mm	30	3
Mass	M	kg	17558	17,6
Young Modulus	E	MPa	210 000	173 554
Poisson ratio	ν	-	0.33	0.33
Yield stress of the material	σ_y	MPa	250	206.612

Figure 2. LVDT and SG

To measure the top displacement of the tank a wire transducer (Siko) was used, for the acceleration piezo-electric accelerometers of 2 g were applied. For the uplift an LVDT was used to measure the vertical displacement of the angles and the hold-down forces were measured with strain gauges (SG) glued on a flattened surface of the bolts.

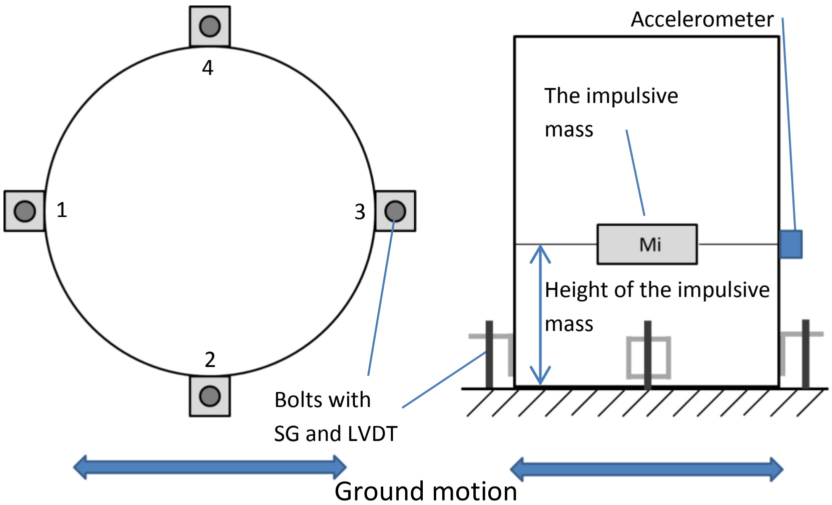

Figure 3. Sketch of the tank with the sensor location

The forcing function was provided by 2 stochastically generated ground motions based on the Japanese design spectrum for hard soil.

3. RESULTS AND DISCUSSION

The two following plots show the impulsive accelerations of the tank with H/R values of 1 and 3 for the simulated ground motion 1 (SGM1). In both considered SGM1 and SGM2 cases, similar acceleration response amplitude can be observed.

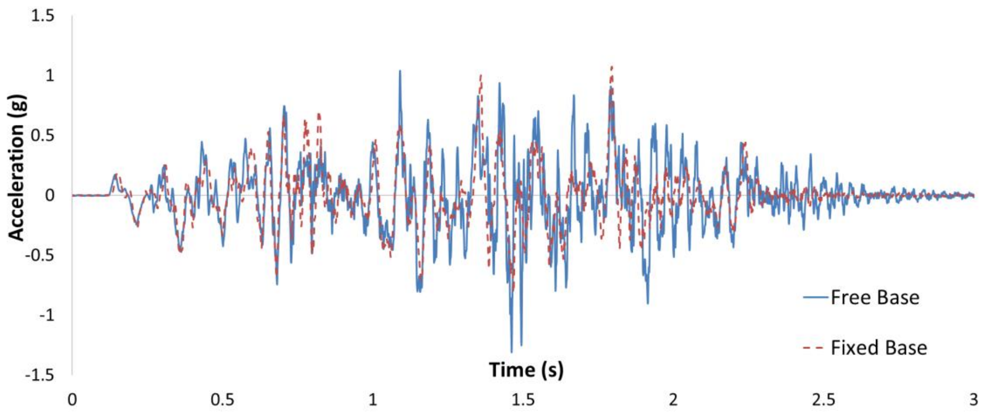

Figure 4. Tank wall acceleration for H/R = 1due to the ground excitation SGM1

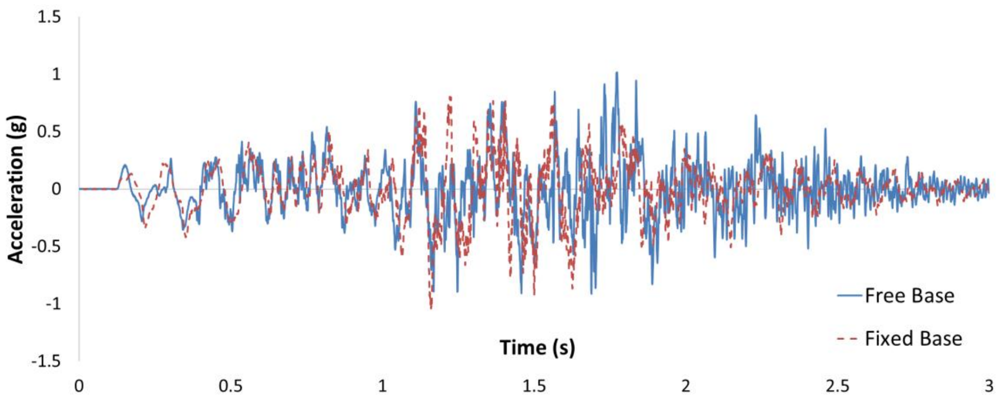

Figure 5. Tank wall acceleration for H/R = 3 due to the ground excitation SGM1

It can also be seen that the peaks are mainly lower in the fixed base case, which support the specification given in the design documents (NZSEE, 2009, API 650, 2007). Figure 6 gives a sketch of the tank with uplift, and Equation 1 gives the expression for the total acceleration. Care needs to be taken in interpreting these results because the systems are different and respond in a different manner. The tank on free base is subjected to rotation acceleration.

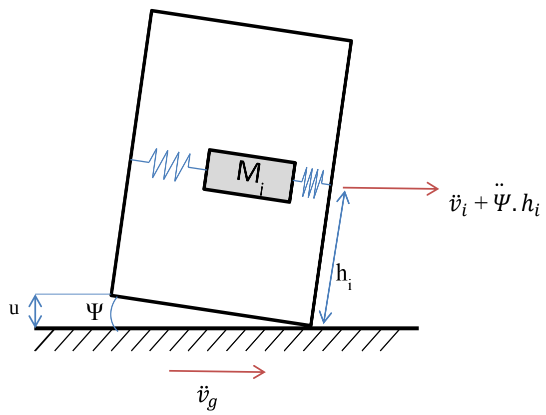

Figure 6. Sketch of the rocking tank

The total acceleration as measured by the sensor is:

$$\ddot{v}_t = \ddot{v}_g + \ddot{v}_i + \ddot{\Psi}.h_i \quad (1)$$

where:

$\ddot{v}_t$ = the total acceleration
$\ddot{v}_g$ = the acceleration of the shake table
$\ddot{v}_i$ = impulsive translational acceleration of the fluid
Ψ = the rotation caused by uplift
h_i = height of the impulsive mass (592 mm)
u = uplift
M_i = impulsive mass

The importance of the rotation acceleration is not yet known, and it is not easy to separate it from the total acceleration. In Equation 1 the last term ($\ddot{\Psi}.h_i$) has no impact on the stresses in the wall of the tank. Another variable that can explain these results is the stiffness of the base plate of the model. Because of the thickness of the base plate and shell, the model developed a rigid body rocking motion during the tests. In most of practical cases, the base plate of storage tanks can deform during a ground motion which is equivalent to have a spring in the base (Figure 7) as was shown by Malhotra (2000). This effect can also reduce the tank wall acceleration and the impact force generated by rocking response and lead to a probability of buckling with resulting elephant foot.

Another effect little studied is the effect of uplift on the sloshing response. For tall slender tanks the sloshing mode plays a very minor role in the tank loading. Hence while uplift may induce an increase in sloshing motion, it is likely that this will be of minor importance.

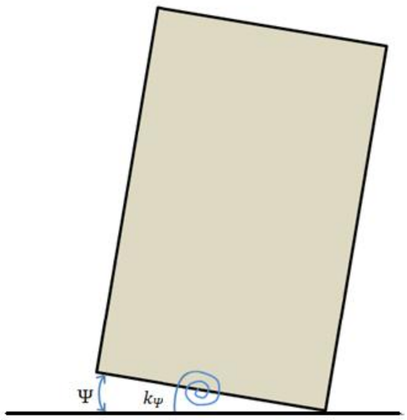

Figure 7. Spring at the base representing the stiffness of the bottom plate

A display of the hold-down forces and uplift in Figure 8 shows that for the unanchored base when the tension in the bolts starts to develop, uplift begins. Correspondingly, a compression occurs in the bolts when uplift starts on the other side of the tank. An examination of the acceleration time history in Figures 4 and 5 shows that both systems respond similarly without a significant influence of both boundary conditions considered in spite of the loss of rigidity when there are no hold-down bolts.

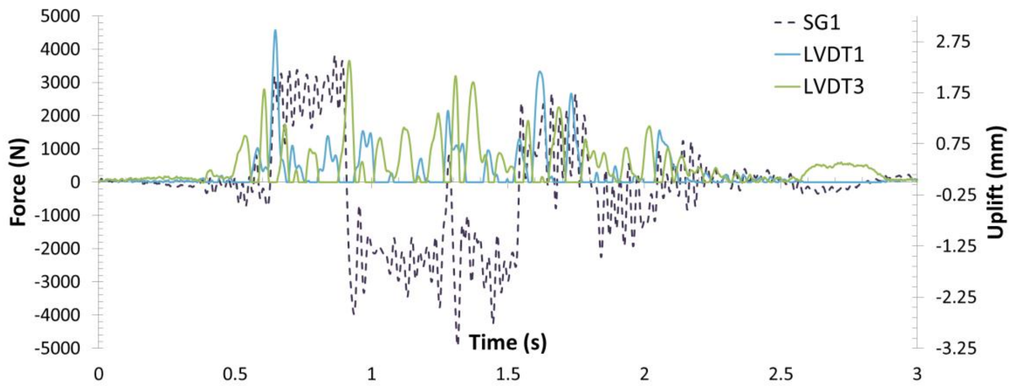

Figure 8. Time history of the hold-down force and the uplift (H/R = 1)

Table 3 shows the response of the prototype tank for both aspect ratios. It is calculated by applying the scale factors in Table 1 to the measured values of the scaled model. A comparison of acceleration of the tank walls shows that the free base gives higher accelerations for an aspect ratio of 1 while for an aspect ratio of 3 the fixed base case yields higher tank wall accelerations.

Table 3. Results due to SGM2

Earthquake:	SGM2			
Max acceleration (g)	0.777	Max displacement (m)	0.320	
Min acceleration (g)	-0.634	Min displacement (m)	-0.379	
	H/R = 1		H/R = 3	
	Fixed base	Free base	Fixed base	Free base
Max Acceleration (g)	0.674	0.832	0.774	0.755
Min Acceleration (g)	-0.563	-0.661	-0.839	-0.569
Max H. Displacement (m)	0.222	0.239	0.251	0.226
Min H. displacement (m)	-0.269	-0.257	-0.287	-0.368
Max Uplift (mm)	-	18.990	-	57.169
Max Hold-down Tension (kN)	462.79	-	1724.19	-

4. CONCLUSIONS

An experimental investigation of the uplift effect on the seismic response of a storage tank was carried out. Two different ground motions and two different aspect ratios were considered. For both excitations the impulsive acceleration is higher in the free base case. However, because the rotational accelerations were not measured the result of the experiments cannot be used to confirm or deny the numerical results obtained by Malhotra (2000).

Further experiments including measurement of rotational acceleration are needed to validate, in terms of excitations and aspect ratio, whether free base can be beneficial to the structure.

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