Study of the seismic response of r/c isolated elevated water tanks

V. I. Fernández-Dávila, F. Gran & P. Baquedano

School of Civil Engineering at Civil Works, Central University,
Santa Isabel, Chile

Abstract

This investigation assesses the seismic response of parametric elastic models of reinforced concrete isolated elevated water tanks. From the study of the physical and geometric variables that characterize elevated water tanks, it was possible to define parametric models with the purpose of obtaining a widely representative family of structures. The parameters were grouped in the following form: a) elevated tank: ratio of heights, ratio of slenderness, ratio of diameters, ratio of diameter to thickness, and ratio of water mass to structure mass, b) isolation system: ratio of slenderness, horizontal and vertical stiffness, c) water: the water-structure interaction effect is modeled using the mechanical analogy proposed by Housner.

This special type of continuous structure, similar to an inverted pendulum, has been discretized according to the lumped mass criterion and the support structure of the tower was partitioned in ten one-dimensional elements. As seismic loads were applied, the design spectrum of accelerations was used as recommended by the Chilean code NCh 2745 Of.2003.

The maximum responses were obtained for the lateral displacements, the shear forces and bending moments. The sensitivity analysis of the structural models of isolated elevated water tanks allowed us to observe that the maximum bending moments and the maximum shear forces are equivalent to one eighth of the maximum responses obtained for a similar fixed-base elevated water tank, and that the relative lateral displacements are lower than 0.2‰, reducing the deformations in the structure significantly.

Keywords: elevated water tanks, dynamic of structures, seismic loads, seismic base isolation, lateral displacements, shear forces, bending moments.
1 Introduction

Chile has suffered devastating seismic effects of great magnitude on many occasions; this resulted in serious consequences such as the loss of human lives and resources. On the basis of past experiences, the repetition of this phenomenon in the future must be thought of as a certain possibility, incurring the same catastrophic effects that have occurred in the past and maybe to a higher degree. Having taken this consideration into account, it is necessary to prepare to face new menaces of this nature, adopting ways to avoid or minimize the effects of earthquakes that could occur in the future [1, 2].

Elevated water tanks are industrial structures built for the purpose of maintaining the water supply. There has been research on this special kind of continuous structure that has its base fixed as well as seismically isolated [3]. The application of seismic isolation systems in other parts of the world has concentrated its research efforts on conventional structures such as buildings; as a consequence, there is need for very attractive research on their application in this special kind of continuous structure generally considered as rigid [2]. Indeed, in recent years, the seismic isolation system has seen an increased application on buildings in countries that have high seismic risks (Japan, United States, Italy, Canada, New Zealand). Its effectiveness was proven during the occurrence of important earthquakes such as Northridge (USA, 1994) and the Kobe (Japan, 1995), due to the fact that these areas included a significant number of structures designed with frictional and elastomeric isolation systems [4].

The objective of this investigation is to study the seismic responses of this special kind of “compound structure” with the purpose of understanding the structural behaviour due to seismic action.

2 Methodology

2.1 Type of structure

A reinforced concrete elevated tank of drinkable water which had a flexible connection between the superstructure and the foundation, designated seismic isolator, was analyzed. These mechanisms (table 1) work in an elastic range and consist basically of a collection of thin rubber plates interspersed with steel plates which are stuck to the rubber with an adhesive gum and then are subjected to a vulcanisation process. A resistant element of low horizontal rigidity and high vertical rigidity was obtained as a result, succeeding to uncouple the structure from the seismic movements of the soil. Twelve isolators that are equidistant to each other and located in the perimeter of support of the structure were used (figs. 1, 2).

The kind of superstructure used is an elevated water tank made of reinforced concrete, which can be considered as a composite structure. This kind of structure comprises a support base or shaft and, in its upper part, a tank or barrel; both elements are of transversal, circular section.
Figure 1: Elevated tank type “composite”, and isolation system: a) transverse section, b) lumped masses model, c) location of isolators in the base, d) projection of isolators in elevation.
This choice was made on the basis of a sensitivity analysis of the tanks of this kind constructed in the central area of Chile and its capacity to support great water masses inside. The kind of isolator considered in the research is the high damping isolator (HDR) [4], due to its high capacity to dissipate the energy coming from the seismic movement of the soil, preventing this energy from being totally absorbed by superstructure.

For the sensitivity analysis, eight real tanks that fulfill the required geometry have been adopted. These tanks constitute the pattern database, having identified the more relevant geometric and physical features (tables 2, 3) from the study of each one of them. Geometric properties considered were (fig. 1): $H_t$, $H_c$, $H_f$, representing the total height and the heights of the tank and the support structure, respectively; in addition, $e_f$, $e_c$, representing the thicknesses of the support structure and the tank, respectively; $\phi_f$, $\phi_c$, representing the diameters of the support structure and the tank, respectively; and $H_{c1}$ and $H_{c2}$, representing the fixed and variable height of the tank, respectively. The modeling of the tanks, as structures of the reversed pendulum kind, is justified by the data of table 3, which verify that more than 50% of their total weight is found in the upper level [5].

Table 1: Characteristics of the isolators.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Reinforced rubber</th>
<th>No reinforced rubber</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRHD$^1$</td>
<td></td>
<td>45</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>$\sigma_t$</td>
<td>MN/m$^2$</td>
<td>28</td>
<td>21</td>
<td>420</td>
</tr>
<tr>
<td>$\sigma_u$</td>
<td>%</td>
<td>680</td>
<td>420</td>
<td>40</td>
</tr>
<tr>
<td>E</td>
<td>MN/m$^2$</td>
<td>1,9</td>
<td>5,9</td>
<td>210.000</td>
</tr>
<tr>
<td>G</td>
<td>MN/m$^2$</td>
<td>0,54</td>
<td>1,37</td>
<td>81.000</td>
</tr>
<tr>
<td>k</td>
<td>MN/m$^2$</td>
<td>1.000</td>
<td>1.200</td>
<td>176.000</td>
</tr>
<tr>
<td>$\nu$</td>
<td></td>
<td>0,4997</td>
<td>0,4997</td>
<td>0,29</td>
</tr>
<tr>
<td>Resilience</td>
<td>%</td>
<td>80</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>$V_s$</td>
<td>m/s</td>
<td>37</td>
<td>37</td>
<td>5.000</td>
</tr>
</tbody>
</table>

$^1$International Rubber Hardness.

Figure 2: Elastomeric seismic isolator.
Table 2: Characteristics of the real tanks and seismic data.

<table>
<thead>
<tr>
<th>No</th>
<th>Tank</th>
<th>Capacity (m³)</th>
<th>H₀ (m)</th>
<th>Hc (m)</th>
<th>Hf (m)</th>
<th>φ₀ (m)</th>
<th>φc (m)</th>
<th>φf (m)</th>
<th>e₀ (m)</th>
<th>e_c (m)</th>
<th>e_f (m)</th>
<th>H₁₁ (m)</th>
<th>H₁₂ (m)</th>
<th>Seismic data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pontigo-Buin</td>
<td>2.000</td>
<td>31,3</td>
<td>10,1</td>
<td>21,2</td>
<td>23,8</td>
<td>12</td>
<td>0,2</td>
<td>0,25</td>
<td>2,1</td>
<td>8,0</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Linderos</td>
<td>2.000</td>
<td>38,3</td>
<td>10,1</td>
<td>28,2</td>
<td>23,8</td>
<td>12</td>
<td>0,2</td>
<td>0,25</td>
<td>2,1</td>
<td>8,0</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Paine</td>
<td>1.000</td>
<td>35,8</td>
<td>6,8</td>
<td>29,0</td>
<td>19,0</td>
<td>12</td>
<td>0,2</td>
<td>0,20</td>
<td>1,7</td>
<td>5,2</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Los Tilos</td>
<td>1.500</td>
<td>29,8</td>
<td>8,8</td>
<td>21,0</td>
<td>19,0</td>
<td>12</td>
<td>0,2</td>
<td>0,20</td>
<td>3,6</td>
<td>5,2</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Estadio-Estación Buin</td>
<td>1.500</td>
<td>32,8</td>
<td>8,8</td>
<td>24,0</td>
<td>19,0</td>
<td>12</td>
<td>0,2</td>
<td>0,20</td>
<td>3,6</td>
<td>5,2</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Melipilla</td>
<td>500</td>
<td>30,3</td>
<td>5,3</td>
<td>25,0</td>
<td>12,9</td>
<td>9</td>
<td>0,2</td>
<td>0,20</td>
<td>1,6</td>
<td>3,7</td>
<td>3</td>
<td>III</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>El Monte</td>
<td>500</td>
<td>25,3</td>
<td>5,3</td>
<td>20,0</td>
<td>12,9</td>
<td>9</td>
<td>0,2</td>
<td>0,20</td>
<td>1,6</td>
<td>3,7</td>
<td>3</td>
<td>III</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>El Trébol</td>
<td>2000</td>
<td>38,3</td>
<td>10,1</td>
<td>28,2</td>
<td>24,2</td>
<td>12</td>
<td>0,2</td>
<td>0,25</td>
<td>2,3</td>
<td>7,8</td>
<td>2</td>
<td>II</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3: Weights of the elevated water tanks (kN).

<table>
<thead>
<tr>
<th>Tank</th>
<th>W_fuste</th>
<th>W_cuba</th>
<th>W₁</th>
<th>W₁</th>
<th>W_total</th>
<th>W_sup = W_cuba + W_H₂O</th>
<th>W_sup/W_total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pontigo-Buin</td>
<td>5.000</td>
<td>5.390</td>
<td>10.390</td>
<td>20.000</td>
<td>30.390</td>
<td>25.390</td>
<td>83,6</td>
</tr>
<tr>
<td>Linderos</td>
<td>6.650</td>
<td>5.390</td>
<td>12.040</td>
<td>20.000</td>
<td>32.040</td>
<td>25.390</td>
<td>79,3</td>
</tr>
<tr>
<td>Paine</td>
<td>5.470</td>
<td>3.410</td>
<td>8.880</td>
<td>10.000</td>
<td>18.880</td>
<td>13.410</td>
<td>71,0</td>
</tr>
<tr>
<td>Buin</td>
<td>3.960</td>
<td>3.980</td>
<td>7.940</td>
<td>15.000</td>
<td>22.940</td>
<td>18.980</td>
<td>83,6</td>
</tr>
<tr>
<td>Estadio Buin</td>
<td>4.520</td>
<td>3.980</td>
<td>8.500</td>
<td>15.000</td>
<td>23.500</td>
<td>18.980</td>
<td>80,8</td>
</tr>
<tr>
<td>Melipilla</td>
<td>3.530</td>
<td>1.750</td>
<td>5.280</td>
<td>5.000</td>
<td>10.280</td>
<td>6.750</td>
<td>65,6</td>
</tr>
<tr>
<td>El Monte</td>
<td>2.830</td>
<td>1.750</td>
<td>4.580</td>
<td>5.000</td>
<td>9.580</td>
<td>6.750</td>
<td>70,5</td>
</tr>
<tr>
<td>El Trébol</td>
<td>6.650</td>
<td>5.520</td>
<td>12.170</td>
<td>20.000</td>
<td>32.170</td>
<td>25.520</td>
<td>79,3</td>
</tr>
</tbody>
</table>

2.2 Fluid-structure interaction

The fluid-structure interaction was determined using the equivalent mechanical model proposed by Housner [6]. Effectively, according to this model, the motion of the total mass of water can be represented in the following way: a) a solitary mass of the tank, called fixed or impulsive mass (M₀); and b) a mass that represents the phenomenon of surge of water, named movable or convective mass (M₁) and connected to the walls of the tank through a spring of total stiffness K [6]. Eqns. (1) to (6) allow us to evaluate the impulsive and convective masses, the stiffness of the spring, the water vibration period, and the location of these masses measured from the base of the tank.

\[
\frac{M_0}{M_F} = \frac{\tanh \left( \frac{\sqrt{3} D}{2 H} \right)}{\frac{\sqrt{3} D}{2 H}}, \quad \frac{M_1}{M_F} = \frac{363}{512} \frac{\tanh \left( \frac{\sqrt{13.5} H}{D} \right)}{\frac{\sqrt{13.5} H}{D}}
\]
\[
\frac{H \cdot K}{W_F} = \frac{45}{2} \left( \frac{M_F}{M} \right)^2 \left( \frac{H}{D} \right)^2, \quad T_a = 2\pi \sqrt{\frac{M}{K}}
\]

\[
h_0 = \frac{3}{8} H \left[ 1 + \alpha \left( \frac{M_F}{M_0} - 1 \right) \right], \quad h_1 = H \left[ 1 - \frac{\cosh \left( \sqrt{13.5} \frac{H}{D} \right) - \beta}{\sqrt{13.5} \frac{H}{D}} \right]
\]

where \(M_F\) and \(W_F\) are the total mass and weight of the water, respectively; \(\alpha\) and \(\beta\) are variables depending on the pressures of the walls; \(h_0\) and \(h_1\), are the heights of the impulsive and convective masses, respectively, both measured with respect to the bottom of the tank; \(T_a\), fundamental period of vibration of the convective mass; \(H\) and \(D\), are the height and diameter of the tank, respectively. The values considered for this study were \(\alpha = 0\), and \(\beta = 1\) [6], because the pressures of the water stored on the walls of the container are considered. In the present study the height \(H\) is equal to the height \(H_c\), and the diameter \(D\) is equal to \(\phi_c\) of the analyzed model (fig. 1a). In addition, \(W_f\) is equal to \(W_{H2O}\).

2.3 Parametric analysis of the structure

From the study of the most relevant elastic characteristics that determine the behavior of the eight elevated water tanks defined in the database, it was possible to select ten parameters of interest that, if combined suitably, allow the representation of an ample family of this type of structure [1, 2, 7, 8]. The parameters are as follows:

- (RH) Height ratio (tank – structure of support) \(= \frac{H_c}{H_f}\)
- (RD) Diameter ratio (tank – structure of support) \(= \frac{\phi_c}{\phi_f}\)
- (RR) Height – Diameter ratio \(= \frac{H}{D}\)
- (HD) Slenderness ratio \(= \frac{H}{\phi}\)
- (DEc) Ratio of diameter to thickness in the tank \(= \frac{\phi_c}{e_c}\)
- (DEf) Ratio of diameter to thickness in the support structure \(= \frac{\phi_f}{e_f}\)
- (RDc) Ratio of diameter to thickness ratios \(= \frac{DE_c}{DE_f}\)
- Mass ratio \(= \frac{M_{H2O}}{M_t}\)
- (RHc) Height ratio in the cube \(= \frac{H_c}{H}\)
- (RHa) Slenderness ratio of isolator \(= \frac{H_a}{\phi}\)

Table 4: Values adopted for the parameters and number of studied cases.

<table>
<thead>
<tr>
<th>Id</th>
<th>Tank</th>
<th>Isolator</th>
<th>Seismic</th>
<th>N° of total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RR</td>
<td>HD</td>
<td>RDc</td>
<td>RHc</td>
</tr>
<tr>
<td>1</td>
<td>0,10</td>
<td>2,4</td>
<td>1,0</td>
<td>0,2</td>
</tr>
<tr>
<td>2</td>
<td>0,21</td>
<td>2,9</td>
<td>2,0</td>
<td>0,4</td>
</tr>
<tr>
<td>3</td>
<td>0,36</td>
<td>3,2</td>
<td>—</td>
<td>2,7</td>
</tr>
</tbody>
</table>

—Value does not exist.
Table 4 shows the geometric and seismic parameters considered in this study, as well as the values assigned to each one of them. These values were obtained from the analysis of sensitivity of results to the values adopted for each parameter of the eight structures of the database pattern. From this new database, a family of 972 elevated water tank structures could be generated.

2.4 Sensitive analysis

A sensitivity analysis was performed in which the responses of a tank modeled by finite elements (MEF) and another one modeled by the criterion of lumped masses were compared (MC); in the latter model, the support structure was discretized into 10 elements and the tank into five elements, both being of frame type [2]. The responses that were compared were the periods of vibration, the lateral displacements, the shear forces, and bending moments. The tank modeled by finite elements was meshed with elements of type shells [9] of size 1×1 m².

The maximum errors found were: 2.3% in the periods of vibration, 8.8% in the lateral displacements, 6.6% in the base shear forces, and 4.3% in the bending moments.

It was observed that the responses determined with criterion MC are greater than the responses obtained by MEF. This comparison was made on an empty and a full water elevated tank, considering, in addition, situations of isolated base and fixed [1, 7].

2.5 Design spectrum

The seismic load that was used corresponded to the design spectrum of the NCh 2745 Of. 2003 code [10]. In this norm, there is the type of elastic spectrum, which must be reduced by the factor of reduction $R$ that is indicated in the code of industrial structures NCh 2369 Of. 2002 [5]. This design spectrum (fig. 3) depends on as much the seismic zone as the type of ground on which the structure is founded.

![Design spectrum utilized.](image-url)
3 Analysis of the results

The analysis of the 972 parametric models of the elevated water tanks was carried out using a computational tool called SAP2000 [9]. In order to obtain the maximum responses, the complete quadratic combination rule (CQC) was used [5]. On the basis of this method, the total displacements were obtained, as well as the shear forces and bending moments.

It was decided in the study that half of the models be founded on soil type II and the rest on soil type III (Fig. 3) [5], with the purpose of comparing the seismic responses of interest. The validity of this study is limited to the adopted parameters being in the following ranges: RR ∈ [0.10;0.36]; HD ∈ [2.4;3.2]; RDE [1.0;2.7]; RHc ∈ [0.2;0.4]; RM ∈ [0.9;2.0]; RHs ∈ [0.35;1.00]; Soil type [2;3].

Figure 4: Seismic responses of the Pointigo-Buin tank: (a) shear forces, (b) bending moments and (c) lateral displacements.

The analysis of results shows the following:

- When comparing the tanks on fixed base with those on isolated base it was verified that, with the incorporation of the isolation device, the shear
forces (Fig. 4(a)), and the bending moments are reduced by 50% (Fig. 4(b)).

- In the cases of fixed and isolated bases, it is demonstrated that the main cause for the abrupt increment of the magnitudes of the shear force is water movement due to seismic excitation.
- The lateral displacement experiences a strong increment of its magnitude in the zone of the isolator that borders 1000%, since the lateral stiffness of the latter is considerably smaller than it is for the support structure (Fig. 4(c)).
- For the totality of the parametric models, it was verified that the safety factors against buckling and rollover of the isolators were satisfactory.

4 Conclusions

a) When comparing elevated r/c tanks of fixed base with the corresponding ones of isolated base, it was verified that the incorporation of the isolation device reduces the shear force and the bending moments by 50%, and although the water remains as the main influence on the fundamental period of vibration, the isolation system takes the second modal shape of vibration, which, in the case of fixed tanks, is associated with the structure (figs. 5, 6).

b) The Chilean code [11] indicates that the relative displacement at all levels of the structure must be smaller than 2‰. From the analysis of the database, it is seen that the tanks fulfil this requirement since the maximum relative displacement was of 1.2‰. This means that the tank moves laterally almost as a rigid body.

c) The incorporation of an isolation system in the high tanks has the consequence of the support structure being subjected to compressive stress; this is different from the tank, which does not have this flexible fusion that generates additional tensile strain.

Figure 5: First three modal shapes of the tank No 1 with fixed base and water full: (a) first mode, (b) second mode, (c) third mode.
Figure 6: First three modal shapes of the tank Nº 1 with isolated base and water full: a) first mode, (b) second mode; (c) third mode.

d) The differences between the maximum responses found by the finite element analysis and the analysis with lumped masses using expressions for the fluid-structure interaction [6] were of 2.3% for the periods of vibration, of 8.8% for the lateral displacements, 6.6% for the base shear force and of 4.3% for the bending moments [1, 7].

e) The geometric form that is acquired by the representative outline of the maximum responses of the elevated tanks with isolation is similar to that of the same structure without isolation. Therefore the seismic behavior of a structure fixed and isolated is similar, varying only in the maximum values.

f) From this one study it is possible to obtain simplified expressions for the analysis of elevated water tanks with seismic isolation at its base [8].

Acknowledgement

The authors wish to thank the School of Civil Engineering at Civil Works of the Central University, for their support for this investigation.

References


