SHAKING TABLE TESTS ON AN ISOLATED LEGGED WINE STORAGE TANK: A NOVEL DEVICE FOR SEISMIC ISOLATION

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ABSTRACT

Seismic protection of wine storage tanks has become a very important issue due to the boom of the winery industry in some seismic countries such as the U.S, Italy, New Zealand, Chile and Argentina. Therefore, in this paper, the effectiveness of a novel seismic isolation system has been investigated by shaking table tests on a full-scale legged wine storage tank. A comparison of the seismic behavior of fixed base and isolated base configurations is presented. The isolation system consisted on flat sliding bearings and a central leg acting as restoring element. The restoring force of the central leg was performed by means of five compression springs. The experiments were carried out using 3 natural and 3 artificial records. Measurements were made of the shear and axial forces in one leg of the tank, and the horizontal displacement of the tank. The experiments showed the beneficial effects of using the proposed isolation system in legged wine storage tanks, reducing the shear and axial forces on the tank legs in comparison with the fixed base configuration.

Keywords: Wine storage tanks; Seismic isolation; Shaking table test

1. INTRODUCTION

Legged stainless steel tanks are used in the winery industry for fermentation and storage since the 1950s in USA (Cooper 2004), and since the 1980s, approximately, in Chile and Argentina (González et al. 2013). The use of this material, i.e. stainless steel, over other material for fermentation and wine storage tanks is due to its: (i) ease cleaning; (ii) noble chemical inertness; (iii) better control of the fermentation process; and (iv) aesthetically attractive appearance. However, several earthquakes have affected many of these tanks. For instance, many reports of damage provide evidence of failure and extensive damage in wine storage tanks such as during the 1977 Caucete earthquake in Argentina (Manos 1991), the 1980 Livermore earthquake (Niwa and Clough 1982), the 1983 Coalinga earthquake (Manos and Clough 1983), the 1989 Loma Prieta earthquake (EERI Reconnaissance Team 1990) and the 2003 San Simeon earthquake (EERI Reconnaissance Team 2004) (all in California, USA), the 2007 Pisco earthquake in Peru (González et al. 2013), the 2010 Maule earthquake in Chile (González et al. 2013), and the 2014 South Napa earthquake again in California, USA (Fischer et al. 2016). Therefore, the seismic vulnerability of these structures is evident.

The most common types of damage observed in legged liquid storage tanks are: buckling of the tank legs caused by large axial loads coupled with lateral loads and failure of the anchorage system caused by the high overturning moment transmitted to the base. Among these causes, the failures that are responsible for a large or total loss of the liquids contained in legged storage tanks is buckling of the tank legs (see Figure 1). For instance, in the past 2010 earthquake in Chile the losses reached approximately 125 million litres of wine (250 million U.S. dollars) representing 12.5% of production in 2009 (González et al. 2013). The earthquake struck a week before the start of the harvest, when

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only 50% of storage capacity was in use. This indicates that more than 25% of tanks with wine lost all or part of their content.

![Image]

Figure 1. Typical buckling failures in the tank legs.

On the basis of the above-mentioned observations, and due to the successful of the wine industry in some seismic countries such as the US, Italy, New Zealand, Chile and Argentina among others, seismic protection of wine storage tanks in the face of earthquake hazards is of paramount economic importance.

Recently numerous studies have been carried out in this field in order to improve seismic behaviour and to reduce the risk of damage or failure of liquid storage tanks (Kelly 1986, Soong 1997). In these studies two major alternatives are presented: seismic isolation and external energy dissipation. Some examples of seismic protection in liquid storage tanks using isolation systems are given by Shriml and Jangid (2004), Cho et al. (2004), and Almazán et al. (2007). Similarly, examples of seismic protection in liquid storage tanks using external energy dissipation devices are published by Maleki and Ziyaefar (2007, 2008), Pirner and Urushadze (2007), Liu and Lin (2009), Malhotra (1998), Curadelli (2011), Ormeño et al. (2015) and Colombo and Almazán (2015). However, only a few works have been found in the technical literature concerning the seismic performance and protection of legged tanks. For instance, Almazán et al. (2007) investigated numerically the seismic response of a typical wine legged tank with seismic isolation in the bottom of its legs.

Therefore, in this work the effectiveness of a novel isolation system on a legged wine storage tank has been investigated through shaking table test on full-scale of a real tank, typically used in the wine industry for fermenting and storing relatively small volumes of high quality wines. More precisely, with the purpose of evaluating the effectiveness of using a novel seismic isolation system in this structure, the seismic response of this tank with the isolation system was compared to that of fixed-base configuration. The isolation system was consisted of one multi-spring central leg, acting as a restoring element (i.e. the element responsible for the self-centring capacity), and one flat sliding bearing below each tank leg. The force-displacement relationship of the multi-spring central leg was numerically established by means of an ANSYS model and the respective pushover analysis. The tests, which have been performed at the Laboratory of the Department of Structural and Geotechnical Engineering of the Pontificia Universidad Católica de Chile, demonstrated the effectiveness of the herein proposed seismic protection system.

2. TANK AND ISOLATION SYSTEM

The dimensions of the tank are: radius $R = 0.8$ m, wall height $H_w = 1.70$ m, and length of the legs $L_g = 0.9$ m. The wall, base and legs are realized with stainless steel plates having a thickness of 2 mm. The tank is supported on four legs with upper width $w_u = 22$ cm, and lower width $w_l = 10$ cm. The liquid used in the experimental campaign is water, which has the same density of wine. The tank is completely filled due to the fact that these tanks are completely filled in the wine industry. The total mass of the liquid and the tank is about 3,300 kg.
Three different configurations were analysed in the experimental campaign (see Figure 2). The first configuration was the tank without the isolation system, in which the tank was just anchored to the foundation. The second configuration was the tank with the isolation system (i.e., the multi-spring central leg and the flat sliding bearings). The third configuration was the tank isolated only with the flat sliding bearings (i.e., without the multi-spring central leg). In the configuration with the multi-spring central leg, this central leg was anchored to the tank base and the shaking table. Additionally, it is important to remark that the multi-spring central leg did not receive weight load from the tank, i.e., the weight of the tank was resisted by the original tank legs.

![Figure 2. Sketch of the analysed configuration: (a) fixed base, (b) isolated with the central leg and (c) isolated only with the flat sliding bearings.](image)

The isolation system consisted of one multi-spring central leg, responsible of the restoring force, and one flat sliding bearing below each tank leg (see Figure 3). Due to the simplicity of the construction and the common use of spring as restoring element, compression springs were used for the central leg. Moreover, the springs used at the bottom and the top of the central leg acted as spherical ball joints as well, i.e., the pattern in which the springs were used allows the tank to move horizontally in any direction. The multi-spring central leg was made with five spring, two big square plates, two small square plates and one tube. The side length of the big plates and the small plates were 50 cm and 27 cm, respectively. The thicknesses of these plates were 1 cm. The dimensions of the tube were: internal diameter $\phi_i = 16$ cm, external diameter $\phi_e = 18$ cm, and length $l = 44.6$ cm. The dimensions of the springs were: free length $l_s = 13.7$ cm, wire diameter $d_w = 1.8$ cm, pitch $p = 3.7$ cm and external diameter $\phi_{es} = 16.2$ cm. The material of the springs was SAE 9254 steel. The central leg had the linear approximation for the lateral force-displacement relationship shown in Figure 4. This relationship was obtained by the method described in the section below. The isolation period, calculated with the linear approximation of the lateral force-displacement and the total mass of the structure, was about of 2 s. In this context, it is worth mentioning that this is a novel approach to use these types of springs, i.e., using the flexural, shear and axial stiffnesses of compression springs.

With respect to the flat sliding bearings used in the proposed isolation system, four stainless steel plates of size 500 mm x 500 mm and thickness 2 mm were used. Each plate was placed below each leg of the tank. Additionally, three Teflon pads were embedded on the bottom of each leg of the tank (see Figure 3). The diameter and length of each Teflon pads were 10 mm and 5 mm, respectively.

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3. MULTI-SPRING CENTRAL LEG MODEL

In order to obtain the force-displacement relationship of the multi-spring central leg, and to ensure that the multi-spring central leg will work correctly without failure, a 3D finite element model was used. This model was developed in ANSYS, and the force-displacement relationship and stress verification were carried out with the aid of non-linear static pushover analysis. The stress-strain relation was determined by means of a bilinear isotropic hardening model, where the material parameters of the stress-strain relation for the plates and the tube were as follows: the Young modulus of elasticity and the yielding stress were 193 GPa and 310 MPa, respectively; the Poisson ratio was 0.3; and the tangent modulus was 1.8 GPa. However, the material used for the springs was SAE 9254 steel which had a Young modulus of elasticity of 205 GPa and a yielding stress of 1470 MPa. The device was discretized using a 3-D 20-node solid element exhibiting a quadratic displacement behaviour (SOLID186). This element has three degrees of freedom per node (i.e. translation in the x, y and z directions of the nodal) and makes it possible to perform a non-linear analysis. Large displacement and deformation effects, such as large deflection, large rotation and large strain, were accounted for by using the non-linear geometry option in ANSYS.
Horizontal rollers located above the top plate were used to simulate the surrounding tank structure. These rollers kept the top plate horizontal during the lateral displacement of the tank. The bottom plate was fixed to the foundation (see Figure 5).

### 3.1 Stress Verification of the Multi-spring Central Leg

Non-linear static pushover analysis for the multi-spring central leg was carried out (displacement control analysis) using the multi-spring central leg model described above. Horizontal displacement history was applied to the top plate following a ramp-shaped function, i.e. linear and monotonic increasing. The horizontal displacement was raised up to 15 cm. This value was the maximum desirable displacement in order to maintain safety the compression springs. Nevertheless, in order to maintain the safety of the surrounding structures and piping connections, the maximum allowed displacement was of 10 cm. The displacement step was equal to 15 mm.

The Von Mises stress distribution of the structure subjected to horizontal displacement was calculated for each displacement step. The maximum Von Mises stress value in the springs was 1168 MPa (Figure 6). In the other parts of the central leg, i.e. the tube and the plates, the maximum Von Mises stress value was 137 MPa. In both cases, the structure is shown in the deformed configuration (Figure 7). As expected, the stresses were highly concentrated at some coils of the springs, where the maximum effective stress reached 1168 MPa. Hence, comparing these maximum stress values with the yielding stresses indicated above, i.e. 310 MPa for steel of the plates and the tube and 1470 MPa for SAE 9254 steel used in the springs, it can be concluded that the multi-spring central leg will remain without failure. As mentioned above, the lateral force-displacement relationship of the central leg is shown in Figure 4.

Figure 5. The multi-spring central leg model with the boundary conditions and applied loading.

Figure 6. Von Mises stress distribution (in MPa) of springs at the maximum displacement condition.
4. BASE MOTION AND SENSOR SETUP

A series of dynamic tests have been accomplished on the tank using the shaking table installed at the Laboratory of the Department of Structural and Geotechnical Engineering of the Pontificia Universidad Católica de Chile. During the experimental campaign the tank has been tested in three different configurations: isolated base with the multi-spring central leg and the flat sliding bearings (referred as case CL), isolated just with the flat sliding bearings (referred as case SB), and fixed to the shake table (referred as case FB).

A set of six different base motion histories have been utilized in each configuration. More precisely, the horizontal component of three natural (see Table 1) and three artificial records (ART1, ART2 and ART3), in accordance with the Chilean code spectrum for 5% damping and soil classified as type II (NCH INN 2003), were scaled to different intensity levels. Due to the fact that the tested structure was on the real scale, no time scaling operation was necessary. All the records were filtered using a high-pass filter with a cut-off frequency of 0.1 Hz. The different intensity levels used for the natural and artificial records were: 100%, 120% and 150% for case CL (i.e. scale factor of 1, 1.2 and 1.5, respectively); 50%, 70%, 90% and 100% for case SB (i.e. scale factor of 0.5, 0.7, 0.9 and 1, respectively); and 30%, 40% and 50% for case FB (i.e. scale factor of 0.3, 0.4 and 0.5, respectively). The records selected are shown in Table 1.

Table 1. Characteristics of the natural accelerograms used during the experimental campaign (recorded at $M_w$ 8.8 2010 Maule, Chile Earthquake).

<table>
<thead>
<tr>
<th>Accelerogram</th>
<th>PGA (g)</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curicó</td>
<td>0.470</td>
<td>180</td>
</tr>
<tr>
<td>Hualañe</td>
<td>0.461</td>
<td>144</td>
</tr>
<tr>
<td>Talca</td>
<td>0.477</td>
<td>148</td>
</tr>
</tbody>
</table>

The sensor setup for the acquisition of the structural response consisted of: two LVDTs, four strain gauges, four accelerometers and three pressure transducers. The type and location of the sensors to test the isolated system are shown in Figure 8. The two LVDTs were used to measure the displacement of the tank with respect to the shaking table in cases CL and SB. The four strain gauges were used to compute the axial and shear forces of one leg of the tank. Three of the four accelerometers were used to measure the wall tank horizontal acceleration, and the fourth accelerometer was used to measure the horizontal acceleration of the shaking table. All the accelerometers were orientated in the direction of the applied motion.
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Response of the base-isolated tank with the multi-spring central leg and the flat sliding bearings

The tank configuration using the multi-spring central leg and the flat sliding bearings (case CL) was seismically tested using the previous described set of six records. The tests were conducted by scaling each record, starting from an intensity of 100% and repeating the test with increasing intensity up to 150%. The results of the most significant quantities that were acquired during the tests are compared with the results obtained in the other tank configurations, i.e. cases SB and FB. In particular, we focus on: the displacement of the tank relative to the shaking table, the shear and axial forces at the tank leg, and the total shear.

The shear and axial forces are ones of the most important quantities because the most common failure on legged tanks occurs when the combined effect of both forces provokes the buckling failure of the legs. The shear and axial forces can be easy calculated because of the elastic behaviour of the stainless steel using two pairs of strain gauges that are located at one of the tank legs (Figure 8).

![Location of sensors on the tank.](image)

The maximum values of the shear and axial forces at the tank leg are listed in Table ## for the maximum scale factors used. The maximum shear force at the tank leg was bounded by the mobilized
frictional force, and presented an average of 1.5 kN. In reference to the maximum axial force at the tank leg, it was also bounded to 12.8 kN (compression force), approximately. This bound was also consequence of the mobilized frictional force. More precisely, as the maximum total shear transmitted to the tank was bounded by the mobilized frictional force, the maximum overturning moment was bounded by this maximum total shear. Therefore, as the responsible of the dynamic increment on the axial force at the tank legs is the overturning moment, the maximum axial force was also bounded. The bounds on the maximum values of the shear and axial forces were also noticeable in the time history of all the tests. For brevity only the results of the Hualañe record, scaled with a scale factor of 1.5, are shown (Figure 9).

In conclusion, the results presented herein show that the tank with the multi-spring central leg and the flat sliding bearings remained without failure for a scale factor up to 1.5. More precisely, the tank remained without failure for the six records scaled up to the maximum intensity level of 0.72g of PGA.

![Graph](image)

Figure 9. (a) Shear and (b) axial forces due to Hualañe accelerogram with a scale factor of 1.5 in the case CL.

4.2 Response of the base-isolated tank with the flat sliding bearings

Similarly to the section above, the tank configuration using the flat sliding bearings (case SB), i.e. without the multi-spring central leg, was seismically tested using the previous described set of six records. The tests were conducted by scaling each record, starting from an intensity of 50% and repeating the test with increasing intensity up to 100%.

The values of the maximum displacement varied from 2 cm and 5 cm, approximately, for a scale factor of 0.5, up to 6 cm and 17 cm, approximately, for a scale factor of 1. We consider that this maximum value of 17 cm would provoke failure at the piping connections and the surrounding structures. With respect to the residual displacement, this varied from 1 cm and 3 cm, approximately, for a scale factor of 0.5, up to 15 cm, approximately, for a scale factor of 1. These results show that a restoring force is needed in order to guarantee lower residual displacements and to avoid failure of the
piping connections and the surrounding structures.

Finally, it is important to remark that, concerning the maximum shear and axial forces, no significant different were obtained between cases CL and SB. This was a consequence of the bound imposed by the mobilized frictional force, which value was very similar in both cases due to the flat sliding bearings were the same in both cases.

4.3 Response of the fixed-base tank

The tank configuration with the fixed-base (case FB), i.e. fixed to the shaking table, was seismically tested using the previous described set of six records. The tests were conducted by scaling each record, starting from an intensity of 30% and repeating the test with increasing intensity up to 50%.

The values of the maximum shear force varied from 1 kN and 1.2 kN, approximately, for a scale factor of 0.3, up to 1.6 kN and 1.9 kN, approximately, for a scale factor of 0.5. At the same time, the values of the maximum axial force varied from 12.5 kN and 13.5 kN, approximately, for a scale factor of 0.3, up to 15.5 kN and 16.5 kN, approximately, for a scale factor of 0.5.

Table 2. Maximum responses of the legged wine storage tank for the three different analysed cases subjected to the six selected records.

<table>
<thead>
<tr>
<th>Record</th>
<th>Case</th>
<th>Maximum values of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>used scale factor</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td>Curicó</td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td>Hualañe</td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
<tr>
<td>Talca</td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td>ART1</td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td>ART2</td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>1.5</td>
</tr>
<tr>
<td>ART3</td>
<td>SB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.5</td>
</tr>
</tbody>
</table>

CL = tank with the multi-spring central leg and the flat sliding bearings
SB = tank with flat sliding bearings
FB = tank with fixed base

It should be noted that higher values of scale factor were not used in this configuration (case FB) because the aim of this investigation was to compare the seismic intensity level required to reach a
similar force demand on the tank leg for the three analysed cases, i.e. cases CL, SB and FB. In other words, in order to maintain the mock tank safety, the aim of this investigation was to obtain a similar force demand on the tank leg for the three analysed configurations, and compare the intensity level required to reach that demand and the lateral tank displacement.

4.4 Comparison between cases CL, SB and FB

A considerable increase in the capacity against failure of the structure was observed with the proposed seismic isolation system, i.e. case CL (see Table 2). For instance, in order for the tank with fixed-base configuration to reach a force demand on the tank leg similar to the one reached on cases CL and SB, a scale factor of 0.4 was necessary, which can be expressed as a PGA average of 0.17g. On the other hand, for the tank with the isolation system with the multi-spring central leg and the flat sliding bearings, in order to reach a similar force demand on the tank leg, a scale factor of 1.5 was necessary, i.e. a PGA average of 0.63g. As can be seen, a three times higher PGA was reached and no failure on the structure occurred. Therefore, comparing the PGA needed for a similar force demand on the tank leg in cases CL and FB, the reduction of the seismic demand on the tank leg in case CL was about 70%, compared to case FB. In other words, the force demand on the tank leg in case CL with a scale factor of 1.5 (PGA average = 0.63g) was similar to the one in case FB with a scale factor of 0.4 (PGA average = 0.17g).

For the tank with the flat sliding bearings and without the multi-spring central leg (case SB), the force demand on the tank leg was very similar to the one reached on case CL. However, as mentioned above, the large displacements will provoke failures of the piping connections and the surrounding structures (see Table 2). For instance, the average of the maximum displacement of case CL, and a scale factor 1.5, was 6.8 cm. This shows that even with an increase of 50% on the seismic intensity level (e.g. PGA), the maximum displacement of the tank was 34% less for case CL. Therefore, case SB would failure for a PGA of 0.42g, while case CL would remain without failure for a PGA of 0.63g.

This increase in the capacity against the failure of the tank in case CL was achieved due to 1) the bound on the maximum shear force transmitted to the tank by the effect of the mobilized frictional force, 2) the increase in the energy dissipated as a result of the friction at the bottom of the tank legs, 3) the changes on the period of the dynamic response of the structure and 4) the effectiveness of the multi-spring central leg acting as a restoring element.

5. CONCLUSION

Using a shaking-test campaign, the effectiveness of an isolation system design for the seismic protection of a typical legged wine storage tank was studied. The proposed isolation system is based on compression springs and flat sliding bearings. The tests have been performed using different experimental configurations: fixed base, isolated base with the multi-spring central leg and the flat sliding bearings, and isolated base only with the flat sliding bearings. During the tests, the tank has been subjected to six different accelerograms, which reproduce records of natural and artificial seismic events (3 natural and 3 artificial records). The results show the effectiveness of the proposed isolation system in reducing the maximum shear and axial forces at the tank legs. In particular, by focusing on the shear and axial forces at the tank legs and the lateral tank displacement, the following conclusions can be drawn:

- For legged wine storage tanks, this novel seismic isolation system can significantly reduce the seismic force demand on the tank legs.
- The use of just flat sliding bearings (without any restoring element) for seismic isolation of legged wine storage tanks provokes larger displacements of the tank, and these would provoke failure of the piping connections and the surrounding structures.
- The flexural, shear and axial stiffnesses of compression springs can be used to develop
efficient restoring elements for the seismic isolation of legged wine storage tanks.

- The restoring force provided by the multi-spring central leg was effective in reducing the lateral tank displacement and the residual tank displacement.

6. ACKNOWLEDGMENTS

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