SHAKING TABLE TESTS ON FULL-SCALE LEGGED LIQUID STORAGE TANKS PROTECTED WITH A VERTICAL-ROCKING ISOLATION SYSTEM

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Abstract

Legged thin-walled liquid storage tanks have shown in many cases poor seismic performance during several strong earthquakes around the world. The damage and collapse of these containment structures lead to the loss of the liquid, such as milk, wine, and others, thus generating significant economic losses. This damage may also affect components along the production line of other food products, and hence, it is relevant to develop solutions to seismically protect these structures and ensure continuous operation. Consequently, this paper presents the dynamic performance evaluation of a new Vertical-Rocking Isolation system. This evaluation is done by shaking table tests performed on a full-scale legged storage tank. A comparison is presented between the numerical seismic behavior of the fixed-to-the-base configuration of the tank and the experimental one with vertical-rocking isolation. The isolation system setup consisted of four ISO3D-2G devices, each one placed on each leg of the tank. The ISO3D-2G device is vertically flexible and laterally stiff, which enables the isolation mechanism of the rocking motion of the tank. The experiments were carried out using a white noise input and three ground motions. The measurements included the acceleration and lateral displacement at the center of mass of the tank. Experimental results confirm the beneficial effects of using a vertical-rocking isolation system in this legged storage tank. Base shear reduction ratios between 5.5 and 8.4 were obtained, which demonstrates that the lateral isolation effect is satisfactory. The use of this device can also be extended to other systems sensitive to rocking motions.

Keywords: Legged storage tanks; seismic isolation; vertical-rocking isolation; shaking table test.

1. Introduction

Legged thin-walled liquid storage tanks have shown a deficient seismic performance during several earthquakes in the world, generating significant economic losses. For example, in the 2010 Mw 8.8 Maule Earthquake, approximately 125 million liters of wine were lost (equivalent to about 250 million U.S. dollars). This loss represented 12.5% of 2009´s year production even though the earthquake occurred a few weeks before the 2010 annual harvest [1]. The same poor performance of these type of tanks was observed in different seismic countries, such as the 2012 Emilia Earthquake in Italy [2], the 2011 Christchurch and 2013 Marlborough Earthquakes in New Zealand [3], the 2014 South Napa Earthquake in USA [4], and again in Chile during the 2015 Coquimbo Earthquake. Winery industries were severely affected in all these events, further demonstrating that seismic protection of thin-walled storage tanks was needed.

The collapse of these structures is due mainly to the low thickness of their walls, which permits local buckling of the mantle or legs of the tank. The latter is the most common failure during earthquakes because the legs are supporting the weight of the tank and must also directly support the lateral forces induced on them by the ground motion. This interaction between axial load and shear forces on the legs can be worsened by the simultaneous action of the vertical component of the earthquake, which has been shown to cause a reduction in the shear and flexural capacity of the supporting elements of a structure [5–7]. Thus, it is of great relevance to apply to these types of structures a three-dimensional seismic isolation system, which besides reducing the lateral demand, also isolates the vertical component of the earthquake.

The purpose of this research is to experimentally evaluate the dynamic performance of a new Vertical-Rocking Isolation (VRI) system using ISO3D-2G devices. This was done by 1D shaking table tests performed on a full-scale legged storage tank protected with the VRI system. The tank was subject to a white noise input scaled to three different intensities in order to perform the system identification and then to 21 consecutive shaking table tests within a time frame of about 8 hours (see Table 2 for the whole list of tests). However, only the results of the 6 underlined tests in the table are analyzed in this work. In all cases, the isolation system showed a highly non-linear behavior with a fundamental period for seismic demands of nearly 1 second. Although for this study, the structure was not taken to the usual 2-second-period spectral zone, the beneficial effects inherent to the seismic isolation were preserved.

2. The methodology of the experimental campaign

Given the limited extension of this article, only the most relevant aspects of the experimental campaign are presented.

Considered tank

Fig. 1 shows an overview of the test set-up, which corresponds to a typical 3,000-liter storage tank used in the winemaking process supported on 4 ISO3D-2G devices, each one welded below each leg of the tank. The liquid used inside during the tests is water, which has approximately the same density of wine. The tank was completely filled with water, so the sloshing effect due to a free surface may be neglected [8]. This no-free-surface condition is consistent with the practice of the winemaking process. The total mass of the liquid and the tank is nearly 3,200 kg, and their geometric properties are presented in Table 1.

Table 1
Geometric properties of the tank

Tank mantle radius [cm]	Mantle height [cm]	Length of the legs [cm]	Center of mass height [cm]	Upper width of the legs [cm]	Lower width of the legs [cm]	Thickness of steel plates [cm]
80	158.5	90	168.3	22	10	0.2

Fig. 1: Experimental set-up for the tested tank

VRI system and ISO3D-2G device

The VRI is a three-dimensional isolation system inspired in the rocking motion of structures. It can be materialized by placing devices that are vertically flexible and laterally stiff at the base of the structure. This system does not allow the lateral translation of the base of the structure as it occurs with conventional isolation systems. However, the vertical flexibility of the devices permits rotation of the base that generates the lateral displacement of the center of mass of the structure. Fig. 2a presents a schematic view rocking isolation mechanism.

It is important to mention that in the VRI system, the devices are simply supported on the ground, so uplifting and sliding are allowed. These characteristics are of great value for this type of industrial structure since, besides allowing their easy relocation inside the facilities (there is no need to anchor the structure to the floor), the forces transmitted to the foundations are considerably reduced, lowering their cost.

The ISO3D-2G device was specifically developed to materialize the VRI system and meet its kinematic requirements—to be vertically flexible while being laterally stiff. This device is composed of an assembly of steel pieces and high-damping rubber bearings that are deformed under uniaxial tension and compression. The steel components have a kinematic relationship that amplifies the deformation of the rubber under tension. Fig. 2b shows the ISO3D-2G device in undeformed and deformed positions. For additional information about the isolation system and the properties of the ISO32D-2G device, please refer to [9].

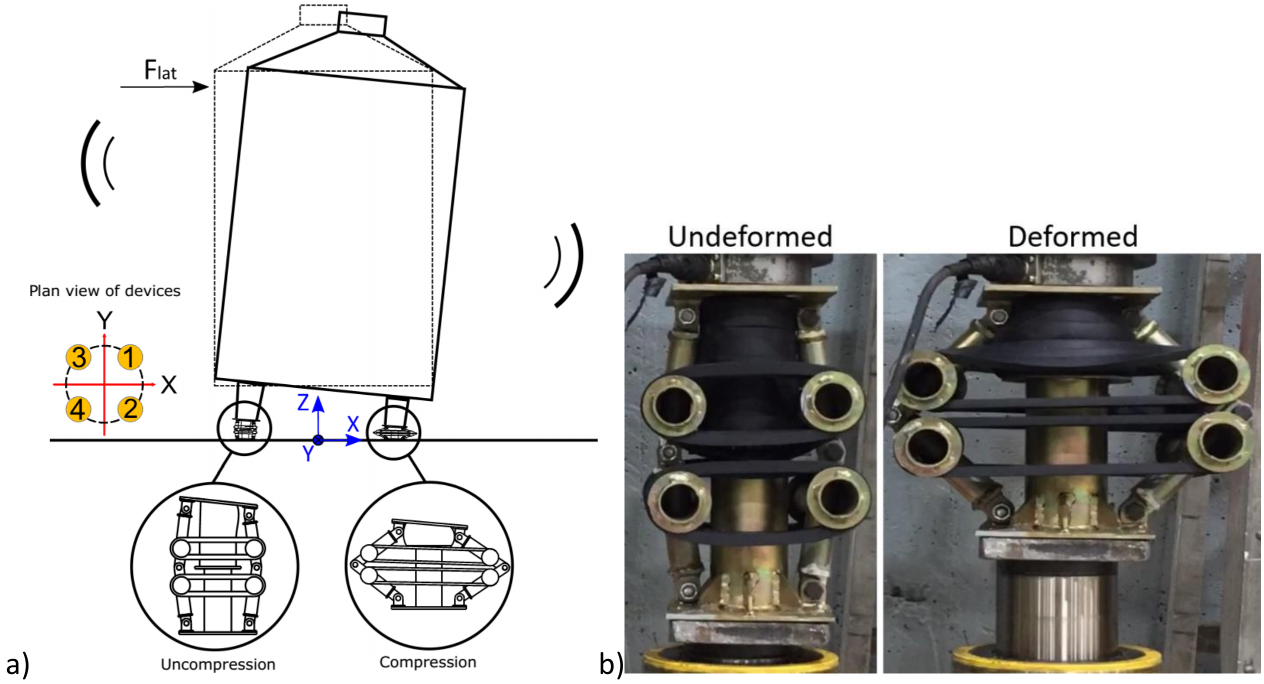

Fig. 2: a) Rocking isolation mechanism of the VRI system; and b) undeformed and deformed position of the ISO3D-2G device.

Test program and sensors

Several dynamic tests have been carried out on the tank using the 1D 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 was subject to a white noise input scaled to three different intensities to perform the system identification, and then to 21 consecutive shaking table tests with natural and artificial records from the 2010 M_w 8.8 Maule Earthquake within a time frame of about 8 hours. Table 2 presents all the records used and their respective scaling. However, only six of the tests are analyzed herein. Table 3 shows the measured peak ground acceleration of the six motions at the center of the shaking-table.

Since the tested structure was on a real scale, no time scaling operation was necessary. All the acceleration records (the drive signal for the table) were filtered using a high-pass (HP) filter with a cut-off frequency of 0.1 Hz and a low-pass (LP) filter with a cut-off of 40 Hz. The displacement output-signal was filtered too, using an HP filter with a cut-off of 0.2 Hz to avoid undesired large-impulsive displacement on the table that could cause the tank to overturn.

Table 2

Records used on the shaking-table tests in the same order they were performed

# Test	Record	Scaling	# Test	Record	Scaling
1	**White noise**	**33%**	13	Artificial record 1	75%
2	**White noise**	**67%**	**14**	**Artificial record 1**	**100%**
3	**White noise**	**100%**	15	Artificial record 1	120%
4	Talca	50%	16	Artificial record 2	75%
5	Talca	75%	17	Artificial record 2	100%
6	**Talca**	**100%**	18	Artificial record 2	120%
7	Talca	120%	19	Artificial record 3	75%
8	Harmonic (1 Hz)	65%	20	Artificial record 3	100%
9	Hualañé	75%	21	Artificial record 3	120%
10	Curicó	75%	22	Hualañé	80%
11	**Curicó**	**100%**	23	Hualañé	85%
12	Curicó	120%	24	Hualañé	90%

Table 3

Measured Peak Ground acceleration of the records during the experimental campaign.

Record	PGA (g)
White noise - 33%	0.096
White noise - 67%	0.183
White noise - 100%	0.262
Talca - 100%	0.596
Curicó - 100%	0.384
Artificial record 1 - 100%	0.450

The sensor set-up for the acquisition of the structural response consisted of seven Linear Variable Differential Transformer (LVDT), four strain gauges, four accelerometers, and two pressure transducers. Four of the seven LVDTs were used to measure the vertical deformation of each device with respect to the shaking table and the other three LVDTs were used to measure the lateral displacement of the tank wall at three different heights—at the isolation level, at the base of the mantle, and at the neck. 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 horizontal acceleration of the tank at a different height, while 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. The pressure transducers were located inside the tank at the base of the mantle. In spite of the complete instrumentation carried out, in this article only results associated with the lateral displacement of the center of mass and base shear of the structure are presented.

3. Results of the system identification

The three white noise inputs were used to perform the dynamic identification of the system. Fig. 3 shows the amplitude of the total acceleration empirical transfer function H(f), measured at halfheight of the tank wall in the frequency domain. The results from three different base motion intensity are shown: 33%, 67%, and 100%. As it can be seen, there are two main issues to highlight about these results: (i) the period of the fundamental mode increases for higher intensities (i.e., 0.50 s at 33%, 0.60 s at 67% and 0.81 s at 100%); and (ii) the maximum amplitude of H(f) decreases for higher intensities (i.e., 2.47 at 33%, 1.80 at 67% and 1.6 at 100%). These results show the highly non-linear behavior of the system in terms of stiffness and damping.

The first issue can be explained by the reduction of the effective vertical stiffness of the ISO3D-2G device at larger deformations. Larger intensity demands on the tank cause this higher deformation. The demands obtained with the white noise inputs are lower than those expected during a seismic event, so it would be expected that the fundamental period of the structure during an earthquake be higher than 0.8 seconds. In fact, in the following section, it will be noted that the fundamental period of the structure under the analyzed seismic demand levels is close to 1 second. The second issue is due to the fact that the device increases its energy dissipation capacity as its deformation increases.

A second mode with a period close to 0.05 seconds was also identified. However, the period and the H(f) amplitude for that mode seem to be relatively unaffected by the intensity of the motion.

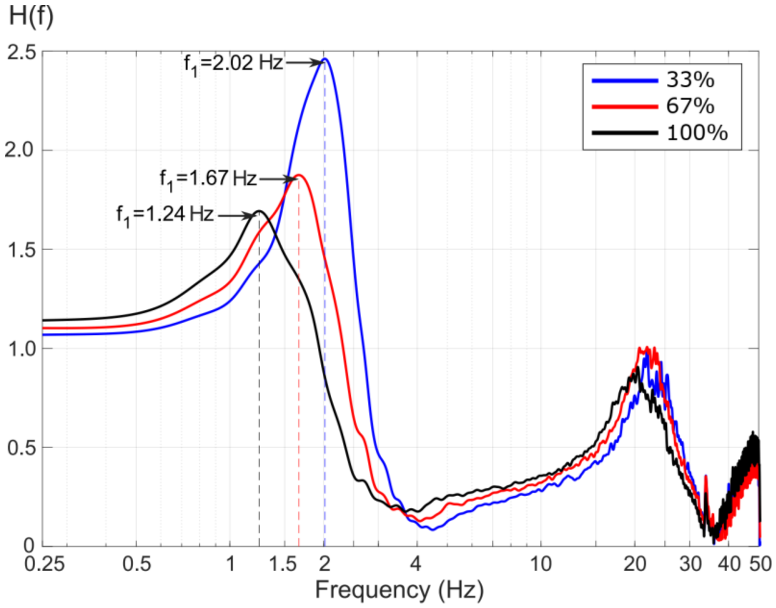

Fig. 3: Results of the system identification for the white noise input.

4. Seismic records results

The response at the center of mass of the structure was measured for Talca, Curicó, and Artificial records. Fig. 4 presents the measured relation between the total base shear of the structure and the lateral displacement of the center of mass for the three records. The effective stiffness and damping ratio were identified for the largest deformation cycle of each test. For the three records, the observed behavior is similar to that of conventional isolation systems. The effective period is nearly 1 second for the three records, and the effective damping ratio varies between 0.14 and 0.20.

Before the shaking table tests, all the ISO3D-2G devices were individually tested and scragged to maximum deformation before installation, so no significant softening effect was expected during the tests. Thus, stable hysteretic cycles were expected for the global behavior of the system. Regarding the stiffness of the structure, it effectively remained stable during the tests as the structure period of 1 second did not vary during the tests. However, the effective damping ratio did change. The conditions under which the devices were subjected were extreme (21 consecutive seismic records of more than 100 seconds of duration most of them), so the reduction in the effective damping ratio observed in Artificial Record 1 may be due to rubber degradation from a large number of deformation cycles before that specific record (about 1,000 cycles).

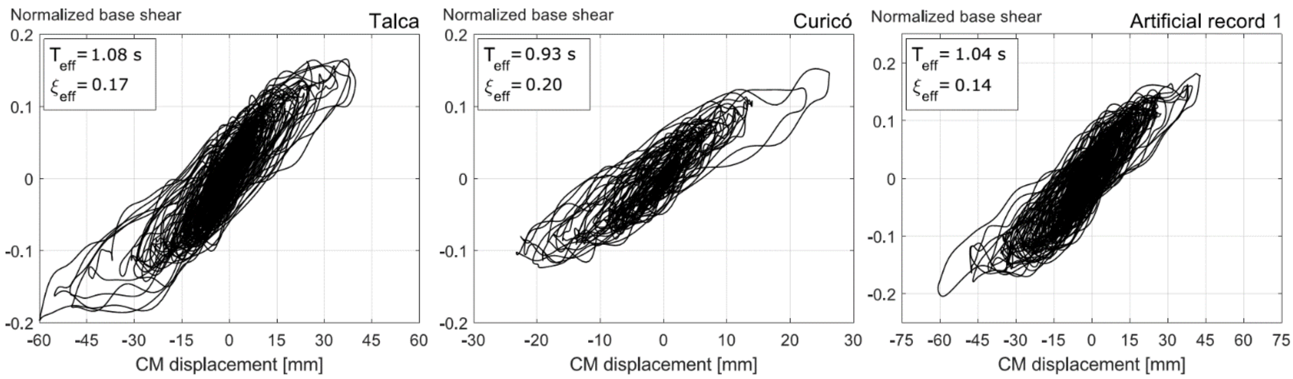

Fig. 4: Normalized total base shear and displacement of the center of mass of the structure for the three considered records.

Table 4 presents a summary of the maximum base shear and lateral displacement for the tank with the VRI system and with a fixed base (FB). The maximum values for the VRI system were obtained directly from those measured in the test, while the values for the fixed base tank were obtained from the response spectrum of the acceleration measured in the table. For the fixed base tank, a period of 0.27 seconds and damping of 2% were considered [10]. For these records, no uplift was observed, nor did the devices slide on the shaking table. It can be seen that the average reduction factor for the base shear is 6.7, i.e., in the same order as the conventional lateral isolation systems, while the lateral displacement of the isolated tank is approximately twice that of the fixed base one.

Table 4
Experimental results for the VRI system and numerical results for a fixed base (FB) condition

Record	VRI - experimental		FB – numerical		Ratio FB/VRI	
	$\frac{V}{W}$	u_{max} [mm]	$\frac{V}{W}$	u_{max} [mm]	$\frac{V}{W}$	u_{max}
Talca	0.20	60.2	1.67	30.2	8.35	0.50
Curicó	0.15	26.2	0.83	15.1	5.50	0.58
Artificial 1	0.20	60.7	1.25	22.6	6.25	0.37
				Mean	6.7	0.48

Fig. 5 presents the Sa-Sd spectra using the measured acceleration in the table for tests 6, 11, and 14. The spectra were computed for 2%, 10%, and 20% of damping ratio. The periods T=1s and T=0.27s are specified since those are the periods of the isolated tank and the fixed-to-the-base tank, respectively. In red circles are the spectral values associated with the fixed-to-the-base tank and the isolated tank considering their equivalent effective properties, where the reduction of seismic demand can be visually observed. It can be concluded that the maximum values obtained experimentally for the isolated system coincide with those obtained by equivalent linear properties. So it is expected that this system can be well-approximated by equivalent linearization, as long as there is no uplifting of the devices.

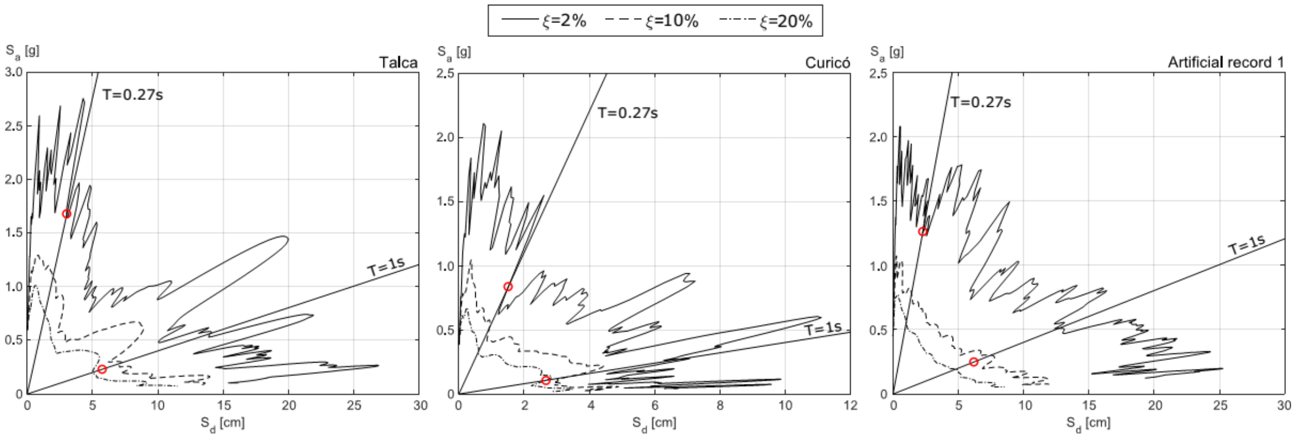

Fig. 5: Sa-Sd spectra of the measured acceleration in the table for the records.

5. Conclusions

In this work, the performance of the Vertical Rocking Isolation System was experimentally analyzed. A 3000-liter capacity legged storage tank was supported on four ISO3D-2G devices to generate the vertical rocking isolation mechanism. The tank was subject to three white noise inputs of different intensities to perform the system identification and to three seismic records of higher intensity to evaluate its performance as an isolation system.

The results showed a highly non-linear behavior of the system; however, for the demands levels presented herein, the system can be well-represented by equivalent linearization. The fundamental period of the system increases for larger demands, and varied between 0.5s and 0.8s for the white noise inputs, and it was close to 1.0s for the seismic inputs. On the other hand, the second mode remained practically unaffected by the intensity of the motion.

The observed performance of the VRI system is similar to that of conventional lateral isolation systems. For the seismic records, horizontal base shear reduction ratios between 5.5 and 8.35 were obtained, while the maximum lateral displacement of the isolated tank was in average twice that of the fixed-to-the-base tank. In three cases the maximum base shear of the isolated system remained below 20% of the total weight of the structure, which is consistent with the target performance of isolated structures.

Finally, it is concluded that the use of vertically flexible devices at the base of some structures to generate a rocking isolation mechanism is an effective way to reduce the seismic demand on the structure, even though the isolated modes and periods of the structure are less than 2.0 sec. Although there is not a complete lateral translation at the base, the VRI system isolates the structure by allowing the lateral displacement of the center of mass.

Future work will consider the analysis of the whole set of ground motions on the performed tests and a design procedure will be developed in order to effectively design the VRI system.

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7. References

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