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Experimental study on the seismic response of liquid storage tanks with Sliding Concave Bearings

María E. Compagnoni, Oscar Curadelli*, Daniel Ambrosini

Engineering Faculty, National University of Cuyo, CONICET, Mendoza, Argentina

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ABSTRACT

It is known that, earthquakes have caused severe damages to a large number of industrial facilities, mainly storage tanks with extremely serious economic and environmental implications. Thus, it is extremely importance to use techniques for reducing the seismic vulnerability of such structures. Seismic base isolation as seismic protection technology is already known and its development continues to grow. The present paper focuses on the seismic performance of broad and slender atmospheric storage steel tanks base isolated by Sliding Concave Bearings (SCB). The performance study carried out through shaking table tests on a vertical cylindrical steel tank model allowed to determine quantitatively the efficiency of the SCB by analyzing two structural parameters: (a) sloshing height and (b) base shear force. Six real ground motions with different characteristics were considered. Results show the effectiveness of SCB in reducing the base shear force values for all studied cases without significantly affecting the sloshing displacements when compared with fixed-base support.

1. Introduction

Commonly, industrial accidents with chemical substances caused by natural phenomena such as floods, earthquakes, storms, etc. are referred to as NaTech accidents (Krausmann et al., 2011). The term “NaTech accident” was first used by Showalter and Myers in 1994 (Showalter and Myers, 1994) and it comes from the contraction of the words “natural” and “technological” with reference to the simultaneous occurrence and interaction between a natural disaster and a technological accident (Krausmann and Cruz, 2008). In this context, earthquake-triggered damage on facilities storing and processing dangerous materials can lead to the release of eco-toxic, flammable and/or explosive substances with potentially severe consequences. There are numerous examples for earthquake-triggered NaTech accidents on industrial facilities and transportation system as those reported in Lindell and Perry (1997) and Krausmann et al. (2010). Effects on the heavily industrialized Kocaeli region of Turkey after the August 17, 1999, earthquake are reviewed by Steinberg and Cruz (2004) and Girgin (2011). A detailed analysis on the area affected by the 12 May 2008, Wenchuan earthquake 2008, were reported by Wang (2008) and Krausmann et al. (2010). The impact of the 11 March 2011, Great East Japan earthquake on chemical industries and gaps in Natech risk management are reported by Krausmann and Cruz (2013). Particularly, atmospheric storage tanks are essential components of most industries, mainly in water supply, nuclear plants, oil refineries and petrochemical facilities. Thus, the importance of safe behavior goes beyond economic costs which include social and environmental consequences as mentioned by Phan et al. (2018) on risk analysis of process plants under seismic loading and in the study on storage tank accidents performed by Chang and Lin (2006). Several researchers have reported damages and failures of liquid storage tanks during past earthquakes, thereby revealing their vulnerability in almost every major seismic events including the following: in Valdivia, Chile 1960 (Steinbrugge and Flores, 1963), many elevated water tanks collapsed or were heavily damaged; in Niigata, Japan 1964 (Watanabe, 1966), along with the disaster caused by the earthquake, five crude oil storage tanks in a refinery caught fire and continued burning for two weeks, spreading into the surrounding area and burning down a total of 286 adjacent houses; in San Juan, Argentina 1977 (Manos, 1991), several tanks for fermentation and wine storage were damaged; in Livermore, California 1980 (Niwa and Clough, 1982), approximately 100 unanchored stainless steel tanks of Wente Brothers winery in Livermore were damaged by buckling; in Whittier, California 1987 (Knoy, 1995), gas supply was shut off for days because of leaking pipes. After Kocaeli earthquake, in Turkey 1999 (Phan et al., 2017; Korkmaz et al., 2011; Sezen et al., 2008; Persson and Lonnermark, 2004), severe damages were reported, particularly, on cylindrical tanks that caught fire immediately after the earthquake and continued for days; in Coalinga, California 1983 (Manos and Clough, 1985), the major damage was buckling and seepage of the containers; in Tokachi-oki, Japan 2003 (Persson and

* Corresponding author. Facultad de Ingeniería, Centro Universitario, Parque Gral, San Martín, 5500, Mendoza, Argentina.
E-mail addresses: oscar.curadelli@ingenieria.uncuyo.edu.ar, ocuradelli@fing.uncu.edu.ar (O. Curadelli).

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Lonnermark, 2004), the earthquake caused severe damage to seven large oil storage tanks with floating roof because of severe sloshing of oil; in Maule, Chile 2010 (EERI-Earthquake Engineering Research Institute, 2010 and Gonzalez et al., 2013), total wine losses were estimated at over 125M liters; in Emilia, Italy 2012 (Brunesi et al., 2014), the earthquake revealed the seismic vulnerability of storage steel tanks typical of the past Italian design practice, highlighting structural deficiencies related to lack of structural seismic design and detailing, lack of redundancy, and inadequate anchorage design and execution; finally, in American Canyon, California 2014 (Fischer et al., 2016) the damage was mainly focused on stainless steel storage tanks and fermentation tanks, as well as on wine storage barrels due to the collapse of the structures that supported them. Field reports on the structural performance of tanks during recent earthquakes indicate that the steel tanks, rather than concrete tanks, are more susceptible to damage and eventual collapse (Hamdan, 2000). Unlike buildings, liquid storage tanks have less redundancy and during a seismic excitation they are affected by hydrodynamic forces exerted on the tank's walls (Maity et al., 2009). Therefore, it is of critical interest to ensure operational reliability, since many of them are located in areas of high seismicity worldwide.

One of the most effective measures to protect structures against earthquakes is the seismic base isolation technique (Kelly, 1986; Buckle and Mayes, 1990; Jangid and Datta, 1995; Ibrahim, 2008). This technique, which is extensively used in civil structures, began to be implemented in liquid storage tanks two decades ago and several theoretical studies have been carried out (Chalhoub and Kelly, 1990; Wang et al., 2001; Shrimali and Jangid, 2002, 2004; Jadhav and Jangid, 2006; Shekari et al., 2009; Soni et al., 2011; Curadelli, 2013; Paolacci et al., 2013; Yazici, 2014; Paolacci, 2015; Saha et al., 2015). Particularly, about numerical analysis on sliding bearing isolation systems can be cited the following studies. Zayas et al. (1990) was a pioneering work in the development of Friction Pendulum System ™ (FPS). Fenz and Constantinou (2008) developed a simplified model based on discrete nonlinear elements to represent the behavior of Triple Friction Pendulum (TFP) bearings. Subsequently, Sarlis and Constantinou (2016) presented a revised model for the TFP bearing. A parametric study on the earthquake response of tanks isolated with variable friction pendulum system (VFPS) under near-fault ground motions was carried out by Panchal and Jangid (2008). They concluded that the seismic response can be controlled within a desirable range. Abali and Uçkan (2010) investigated the seismic performance of both broad and slender tanks base isolated by curved surface sliding bearings and focused on the dependence of overturning moment and vertical acceleration on the axial load variation at the bearings. Phan et al. (2016) demonstrated the effectiveness of a concave sliding bearing system for the seismic protection of liquefied gas storage tanks through a seismic fragility analysis.

However, few documented experimental works on earthquake performance of seismically isolated liquid storage tanks, especially with sliding bearings, have been published. Calugaru and Mahin (2009) conducted experimental and analytical studies on seismically isolated tanks with Triple Pendulum Bearings. Experimental results showed significant reductions in base shear, tank uplift, tank deformation, and acceleration amplification for the isolated configuration as compared to fixed base. De Angelis et al. (2010) particularly studied two base isolation alternatives: high-damping rubber bearings devices and steel sliding isolation devices with c-shaped elasto-plastic dampers. Results showed that both isolator typologies reduced the total pressure generated on the tank wall. On the other hand, a slight increase of the oscillation amplitude of the liquid surface and consequently of the floating roof was observed. A recent study conducted by Colombo and Alamazán (2017) assesses by simulation, the seismic reliability of two typical stainless steel legged wine storage tanks (with capacities of 3000 L and 17,100 L) isolated by a non-linear isolation system. Results show that the isolation system would reduce the limit state probability in the order of 90%.

Rubber-type bearings, such as lead-rubber bearings or high-damping-rubber bearings, are not recommended for seismic isolation of storage tanks because their fundamental vibration period changes when their mass changes over time. However, as mentioned by Wang et al. (2001), pendulum bearings have properties that considerably benefit the seismic isolation of industrial tanks. Thus, particularly for medium and high liquid storage levels, when the isolation system is most effective, the fundamental period of a tank isolated by Sliding Concave Bearings (SCB) merely depends on the radius of curvature of the sliding interface, making dynamic characteristics of the isolated tanks invariant and fully controllable. Being made of stainless steel, SCB are also resistant to chemicals, fires, temperature extremes and adverse environmental exposure. Given the above advantages, this type of isolation system is preferred for industrial tank applications (Zayas and Low, 1995).

This paper assesses the effectiveness of Sliding Concave Bearings (SCB) for controlling the seismic response of atmospheric vertical cylindrical liquid storage tanks. The reduced scale (1:8) model corresponds to a typical steel tank used in wine industry. In the study, the structural response in terms of sloshing wave height and base shear force of a steel tank model is experimentally determined. Both structural parameters are the most important in the liquid storage tank design. The first one aims to prevent liquid spill or the impact of sloshing waves on the tank roof and the latter to ensure a safe behavior. To provide a broad overview and robust results, three aspect ratios including broad to slender cylindrical tanks subjected to real ground acceleration time-histories with markedly different characteristics and intensities are considered.

2. Concept of Sliding Concave Bearings (SCB)

From the combination between sliding bearing concept and pendulum type response concept it is possible to infer an interesting seismic isolation system denoted in this work as Sliding Concave Bearing (SCB) (Fig. 1). A SCB isolator basically consists of one main spherical surface on which slides one articulation allowing relative rotation. This sliding movement generates friction which provides considerable energy dissipation. The system tank-isolation support works as follows: when earthquake-induced force is lower than the static value of friction force, the system behaves as fixed base, otherwise, the upper part slides over the concave sliding surface and the bearing develops a lateral force equal to the combination of the dynamic friction force and the horizontal component of weight (restoring force) that results of the induced rising of the structure along the spherical surface. Neglecting the friction and under the hypothesis that the structural response of isolated tanks is heavily dominated by the impulsive component (short-period vibration modes), especially for medium and high liquid storage levels, the equation of motion of the system is similar to that of a simple pendulum and its natural period is controlled exclusively by the

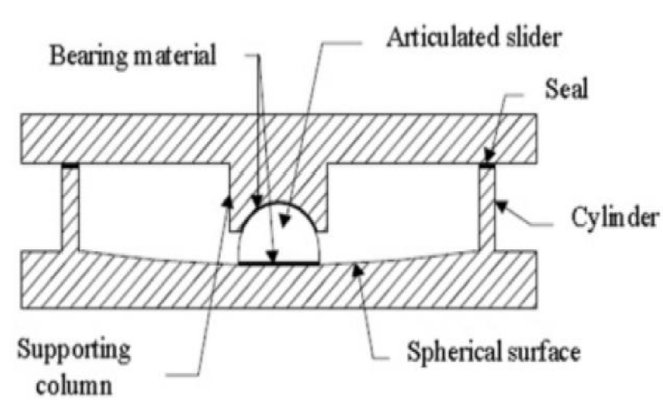

Fig. 1. Sliding concave bearing.

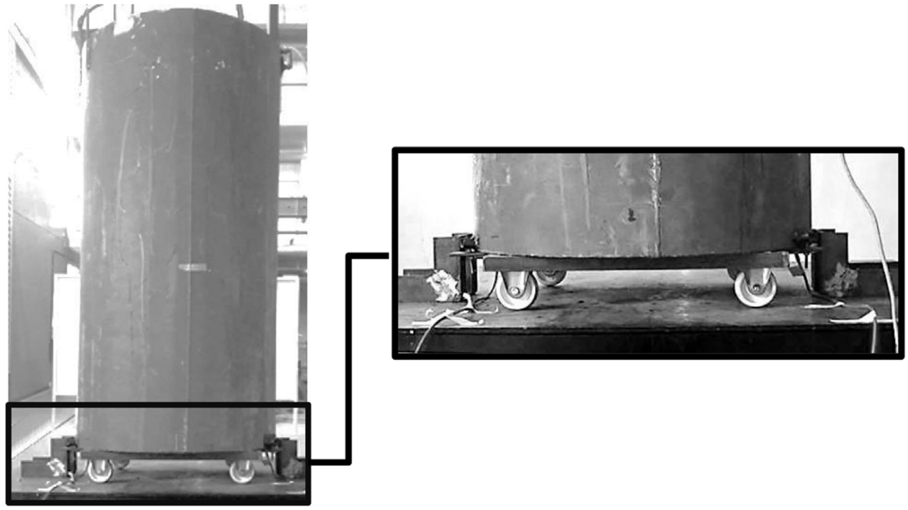

Fig. 2. Experimental model of fixed base cylindrical tank.

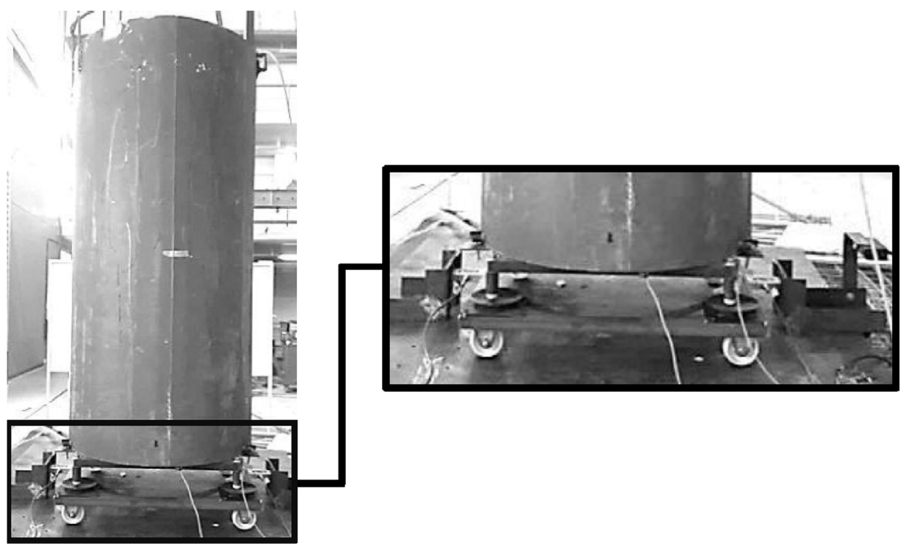

Fig. 3. Experimental model of base isolated cylindrical tank.

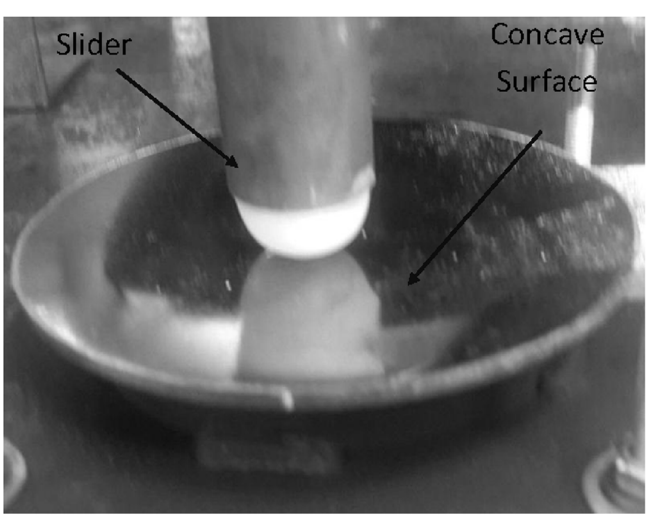

Fig. 4. Sliding concave bearing.

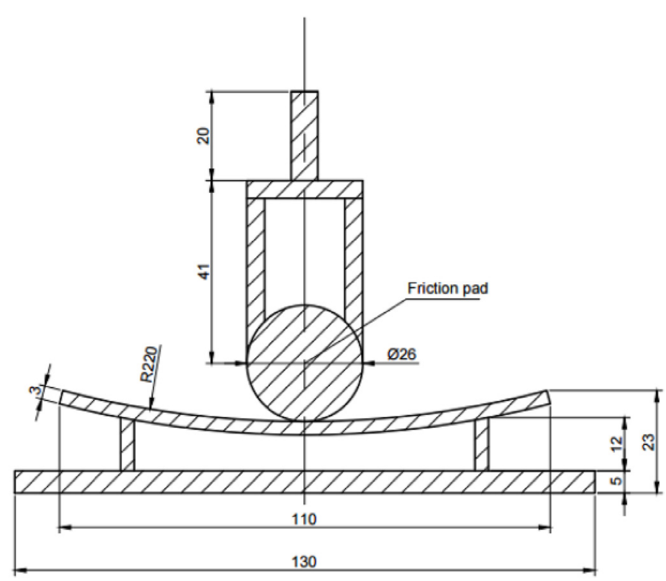

Fig. 5. Cross-section of sliding concave bearing.

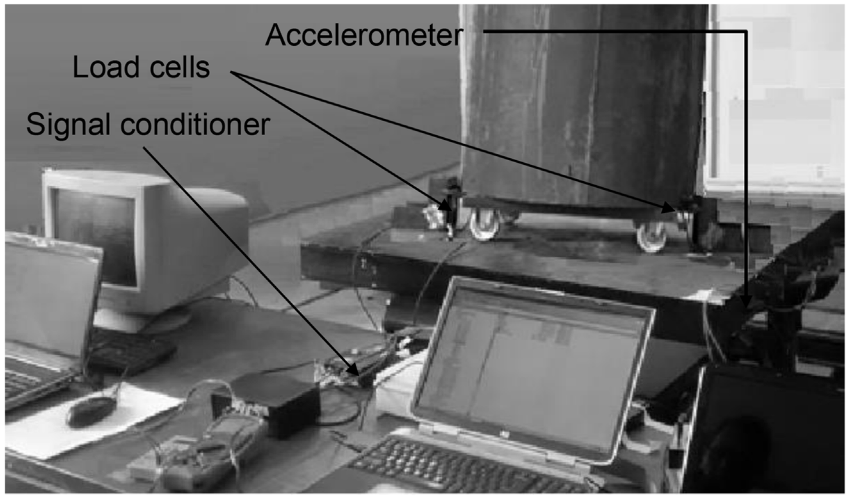

Fig. 6. Measuring system for the fixed base case.

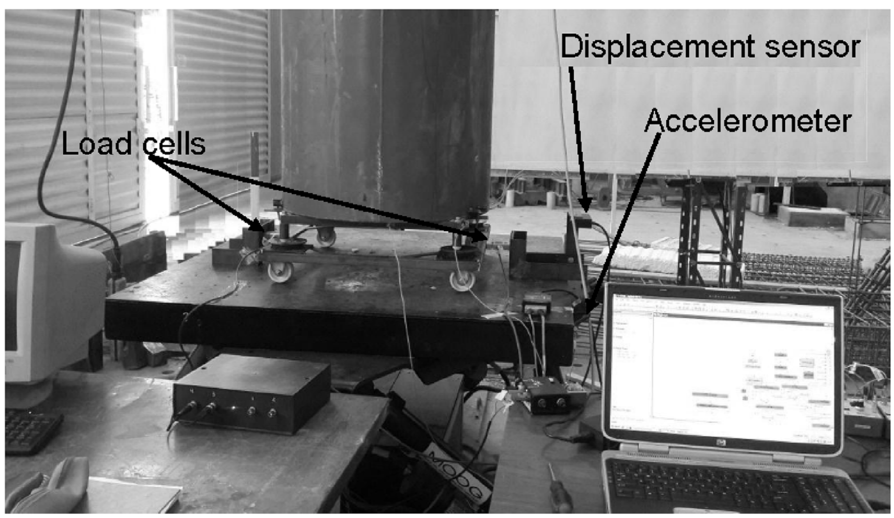

Fig. 7. Measuring system for the base isolated case.

Table 1
Natural frequencies of fixed base tank.

Tank	Mode	Fixed Base Model		
		EXP [Hz]	SM [Hz]	FEM [Hz]
S = 0.5	1º	1.00	0.99	1.00
	2º	2.02	–	1.98
S = 1.0	1º	1.16	1.15	1.16
	2º	2.03	–	2.02
S = 1.5	1º	1.18	1.17	1.18
	2º	2.03	–	2.03

Table 2
Details of earthquake ground motions.

Earthquake	x- direction component	Year	PGA [g]	SD (scaled) [s]
San Fernando	CDMG279	1971	0.21	10.49 (3.71)
Kocaeli, Turkey	SKR090	1977	0.38	9.86 (3.49)
Maule, Chile	EO canal 1	2010	0.48	33.76 (11.93)
Caucete, San Juan, Argentina	–	1977	0.46	36.64 (12.95)
Irpinia, Italia	ENEL/SEA99	1980	0.36	15.22 (5.38)
Erzincan, Turkey	ERZ-EW	1992	0.50	7.34 (2.59)

selection of radius of curvature of the concave sliding surface (Wang et al., 2001; Abali and Uçkan, 2010). This feature makes it very attractive to use on tanks with variable liquid level. The enclosing cylinder of the isolator provides a lateral displacement restraint and protects the interior components from environmental contamination.

3. Experimental model and preliminary tests

3.1. Tank model

Dimensions of real industrial tanks do not allow conducting direct dynamic tests using a laboratory shaking table (maximum capacity: 10 kN). Thus, a scaled cylindrical steel tank model was built according to similitude laws, from the following primary scales: length 1:8, density 1:1 and acceleration 1:1 (Fig. 2). Their characteristics are: radius $R = 0.325\ m$, height $L = 1.36\ m$ and wall thickness $e = 3.00\,mm$. It is worth noting that, the wall thickness does not meet the length scale because it would result extremely thin (unrealistic local buckling of the wall). Thus, for the isolated tank, wall deformations may be ignored. The following steel properties were assumed, Young's modulus $E_s = 200\ GPa$, Poisson ratio $\nu = 0.3$ and density $\rho_s = 7850\ Kg/m^3$. The liquid used was water with density $\rho_l = 1000\ Kg/m^3$ and bulk modulus $\beta_l = 2.2\ GPa$. The tank was fixed to an auxiliary support fitted with wheels so that the motion transmission between shaking table and tank

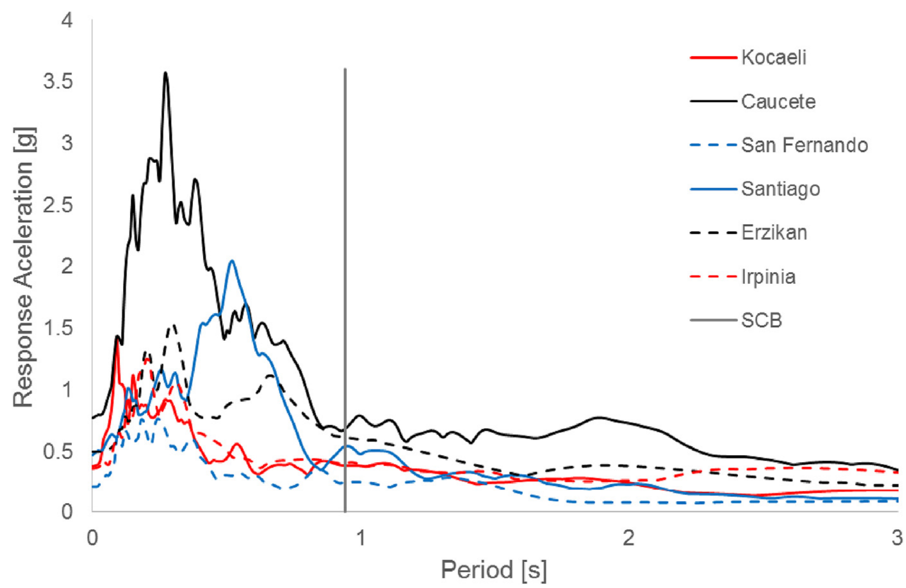

Fig. 8. Response spectra of seismic records.

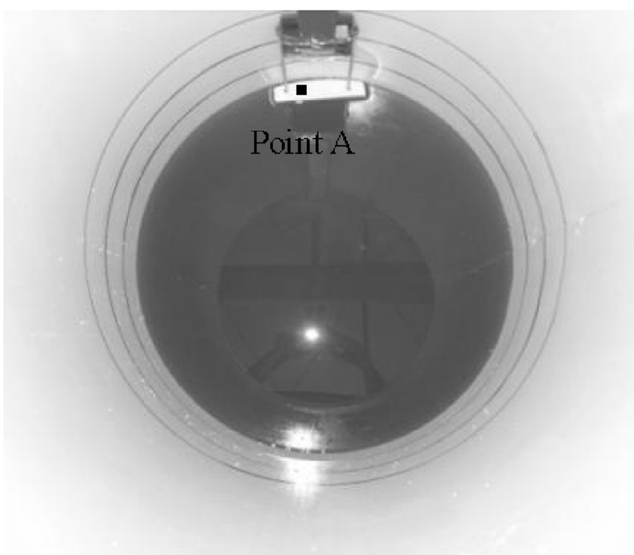

Fig. 9. Measuring point of sloshing wave vertical displacement (top view).

is through two load cells (Fig. 2).

3.2. Isolation system prototype

The isolation system prototype consisted of a set of four isolators (Fig. 3) composed of a Teflon® (polytetrafluoroethylene, PTFE) spherical slider that moves on a spherical polished steel surface with a radius of 0.22 m which results in a vibration period of the system equal to 0.94 (Fig. 4). The outline of an isolator is shown in Fig. 5. Spherical surfaces of the isolation system prototype are mounted on the same auxiliary support to enable base shear force measurement.

The experimental program included two series of forced vibration test, one of them used as baseline in which the tank model is supported on a fixed base and the other one, the same experimental model supported on the SCB. To cover broad and slender tanks, three liquid levels, H, (or aspect ratio S = H/R) were studied: (a) $H = 0.16\ m\ S = 0.5$, (b) $H = 0.32\ m\ S = 1.0$, and (c) $H = 0.48\ m, S = 1.5$.

As mentioned in the Introduction, the structural response was measured in terms of two parameters: sloshing wave height and base shear force.

3.3. Instrumentation

To determine the vertical movement of the free surface of fluid an assembly of buoy and laser displacement sensor Micro Epsilon opto NCDT LD1607 was employed. A similar laser sensor was used to measure the displacement of the isolation system. The acceleration records imposed by the laboratory shaking table were measured by a PCB Piezotronics accelerometer (accel. max. 3 g, 700 mV/g). The shear force was measured using two aluminum "S" beam load cells with a capacity of 500 N mounted in series with the auxiliary support mentioned before (Figs. 2 and 3). Sensor signals were digitalized by a PCM-DAS16D/16 data acquisition board at 500 sps per channel during $t = 100$ s and processed by HP VEE 5.0 software (Hewlett Packard, 1998). Figs. 6 and 7 show an overview of the measuring system for each case.

3.4. Free vibration tests

In order to determine natural frequencies of the experimental model, preliminary free vibration tests were performed on both support configurations, fixed base and isolated base. Table 1 show the two-first frequencies of the convective or sloshing components (low frequency components) which represent the effect of the portion of liquid mass localized at the top of the container measured in the experimental model and those obtained numerically by a simplified model (SM) (Haroun and Housner, 1981) and a finite element model (FEM). Frequency of impulsive component (extremely high frequency) representing the intermediate liquid mass vibrating along with the tank wall is not showed. Both numerical models are not detailed in the present work because of space limitations. It is important to highlight that the fundamental frequency of isolated tank was 0.94 Hz.

Since the SM has only one degree of freedom to represent the sloshing component, it was only possible to determine the first natural frequency of that component. The differences among the frequencies measured and calculated are below 2%.

3.5. Ground motions

In order to take a broader view and draw general conclusions about the seismic performance of based isolated tanks by Sliding Concave Bearing System, an input set of six time-scaled real earthquake ground

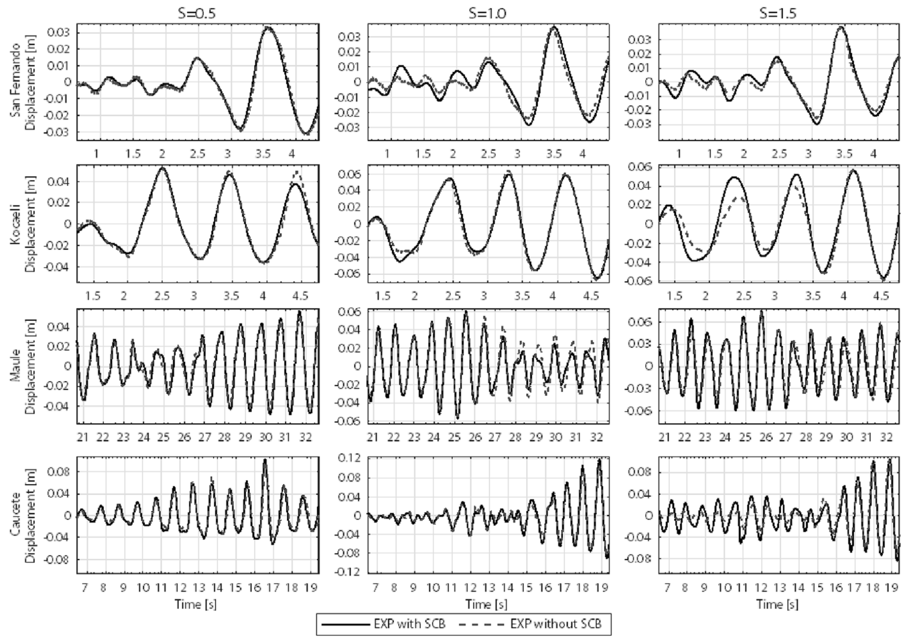

Fig. 10. Time history of sloshing wave height.

Table 3
Sloshing wave height.

Earthquake	[a,b] $\frac{h_w - h_{wo}}{h_w}100$	
	Max. Value Dif. [%]	RMS value Dif. [%]
S = 0.5		
San Fernando	0.40	−1.14
Kocaeli	1.03	−3.86
Maule	9.28	9.68
Caucete	4.54	8.31
Average	**3.81**	**3.25**
S = 1.0		
San Fernando	1.01	10.49
Kocaeli	−2.33	0.25
Maule	4.13	−5.06
Caucete	4.55	10.98
Average	**2.50**	**6.91**
S = 1.5		
San Fernando	1.23	13.17
Kocaeli	−3.04	13.45
Maule	2.79	5.31
Caucete	2.57	23.17
Average	**2.30**	**16.39**

[a] h_w: sloshing height of isolated tank with SCB.
[b] h_{wo}: sloshing height of fixed base tank.

motions detailed in Table 2 was used. It was verified that, the first 4 ground motions do not cause breaking wave while the rest do. Additionally, to visualize the "decoupling" of the fundamental period of isolation system (SCB) from principal components of ground motions, the response spectra of seismic records are shown in Fig. 8. For a better comparison and visualization, only the significant duration (SD) of the structural response to each record is displayed. Trifunac and Brady (1975) defined the SD of a ground motion record as the time elapsing between the 5% and 95% of the total Arias Intensity (Arias, 1970). This value represents the period of time at which the greatest amount of energy is provided by the earthquake. Table 2 includes the scaled significant duration, according to time scale.

4. Results of shaking table tests

With the aim of showing the effectiveness of sliding concave isolators to control the seismic response of the liquid storage tanks in terms of maximum and rms (root mean square) value of sloshing height and base shear force, experimental test results on the experimental model are presented in this section.

4.1. Sloshing wave height

The vertical displacement of the sloshing wave is measured at point A, located on the free liquid surface very close to the tank wall where the liquid height displays the greatest change (Fig. 9).

It is important to clarify that the study was carried out on those four cases where the liquid surface did not show breaking waves.

Fig. 10 show the significant duration (SD) of time histories of sloshing wave height measured on the model tank with fixed base and isolated with SCB for the different aspect ratios and acceleration records.

Qualitatively, as can be seen from Fig. 10, there are no significant differences in amplitude and phase for sloshing wave height between both support systems.

Table 3 quantitatively shows that the displacement amplitude of the free liquid surface is slightly increased (an average in the maximum value equal to 2.9% and 8.8% in the rms value) with the installation of isolation system, presumably because of the resonant effect (proximity between first frequency of sloshing component and that of isolation system).

Thus, it can be concluded that, from an engineering point of view, the implementation of SCB does not increase the sloshing wave height significantly and therefore the height of the tank wall should not be modified when the isolation system is installed.

Under intense ground motions, such as Irpinia and Erzikan earthquakes, there were breaking waves which precluded the height measurement and therefore both tests were discarded.

4.2. Base shear force

This section presents base shear force measured in experimental tests on both support systems. Results from non-breaking and breaking

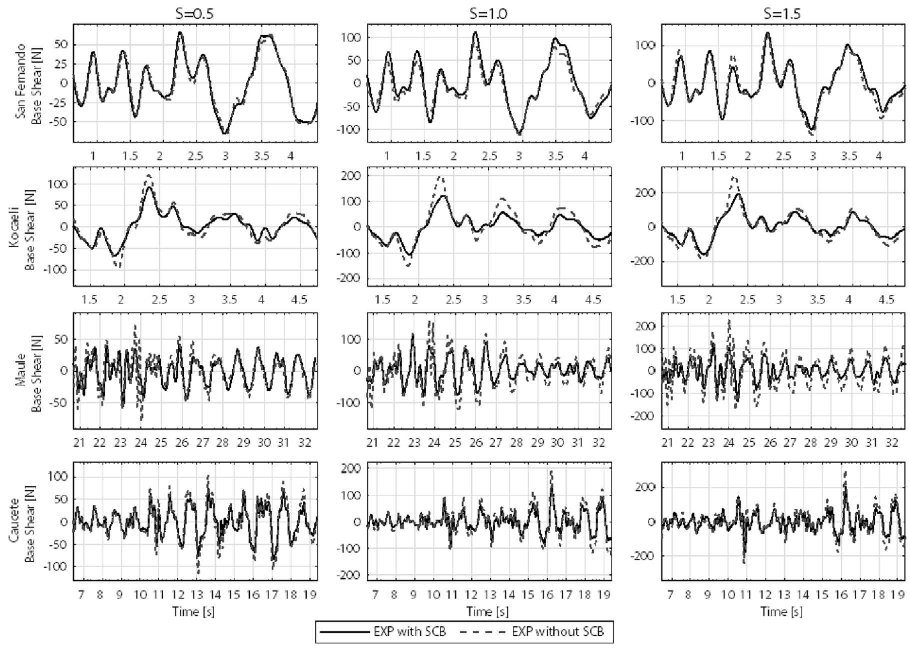

Fig. 11. Time history of base shear force (non-breaking wave case).

Table 4
Base shear force (non-breaking wave case).

Earthquake	[a,b] $\frac{f_w - f_{wo}}{f_w}100$	
	Max. Value Dif. [%]	RMS value Dif. [%]
S = 0.5		
San Fernando	1.61	4.64
Kocaeli	−23.21	−22.38
Maule	−29.94	−17.89
Caucete	−26.08	−22.60
Average	**−19.42**	**−14.56**
S = 1.0		
San Fernando	0.04	12.60
Kocaeli	−39.68	−34.04
Maule	−29.32	−27.36
Caucete	−30.52	−31.17
Average	**−24.87**	**−20.01**
S = 1.5		
San Fernando	−0.90	−4.49
Kocaeli	−36.71	−24.69
Maule	−29.32	−27.42
Caucete	−31.42	−22.35
Average	**−24.59**	**−19.74**

[a] f_w: base shear force of isolated tank with SCB.
[b] f_{wo}: base shear force of fixed base tank.

Table 5
Base shear force (breaking wave case).

Earthquake	[a,b] $\frac{f_w - f_{wo}}{f_w}100$	
	Max. Value Dif. [%]	RMS value Dif. [%]
S = 0.5		
Irpinia	−47.85	−61.17
Erzikan	−53.24	−49.06
Average	**−50.55**	**−55.11**
S = 1.0		
Irpinia	−50.70	−71.21
Erzikan	−56.31	−63.15
Average	**−53.51**	**−67.18**
S = 1.5		
Irpinia	−52.20	−70.47
Erzikan	−60.58	−60.35
Average	**−56.39**	**−65.41**

[a] f_w: base shear force of isolated tank with SCB.
[b] f_{wo}: base shear force of fixed base tank.

wave cases are presented separately to determine the influence of the liquid behavior.

4.2.1. Non-breaking wave case

The significant duration (SD) of measured time histories of the base shear force for those cases with non-breaking waves are plotted in

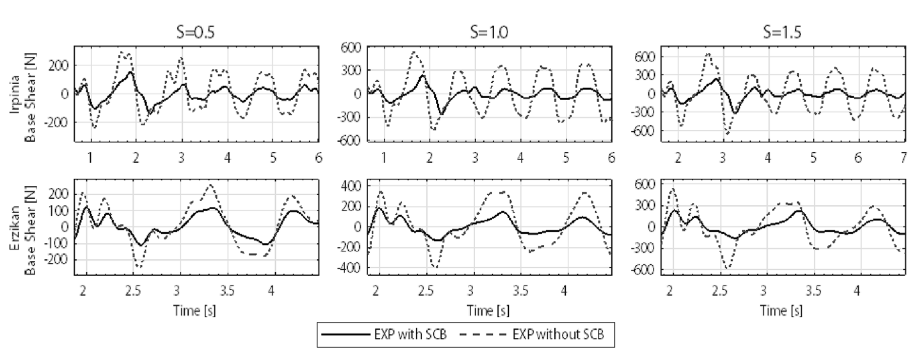

Fig. 12. Time history of base shear force (breaking wave case).

Fig. 11. In all cases it can be observed that there is almost no phase shift between both support systems but, the amplitude reached with the isolated tank is always lower than for fixed base tank in different degrees depending on aspect ratio and earthquake record.

In Table 4, base shear force for both types of support are quantitatively compared. As can be seen, SCB reduced the maximum and RMS value in all cases, except for San Fernando earthquake, in which the isolator did not slide because the maximum base shear force induced by the earthquake did not exceed the friction force and the system behaved as that with fixed base. The average reduction in base shear force was 23% and 18% for maximum and RMS value respectively, excluding San Fernando earthquake.

4.2.2. 2 Breaking wave case

Results from Fig. 12 show clearly that the use of SCB significantly reduced the base shear force for strong earthquakes with breaking waves.

Reductions of base shear force of isolated tank compared with the fixed base tank are summarized in Table 5. For breaking wave cases, the reduction was in average 53% and 63% in the maximum and RMS value, respectively.

Clearly, the isolated tank undergoes base shear forces considerably lower (in the order of 50%) than that system with fixed base. Additional reductions can be achieved by using a lower friction coefficient at the expense of increased displacement of isolation system, which would lead to adjustments of pipe connections.

It is important to point out that, regardless of the liquid behavior (breaking and non-breaking waves), the SCB is highly effective for reducing base shear force of liquid storage tanks under seismic excitation without modifying significantly the sloshing wave height. In contrast to other protection methods, SCB provides the protection level required (limit of base shear force) by carefully setting the friction force of the isolation system. This feature, in conjunction with the invariance of fundamental vibration period of the system with the liquid level makes the SCB ideal for seismic protection of liquid storage tanks.

5. Conclusions

The purpose of this study is to experimentally assess the efficiency of the Sliding Concave Bearing (SCB) System on atmospheric liquid storage steel tanks by analyzing two structural parameters: (a) sloshing wave height and (b) base shear force. To provide a broad overview and robust results during experimental test, three aspect ratios including broad and slender cylindrical tanks under real ground motions with different characteristics and intensities (breaking and non-breaking waves) were used.

From the study it is worth mentioning the following results:

- From an engineering point of view, SCB System does not increase the sloshing wave height significantly. This is because the long vibration period associated with the sloshing vibration mode is almost not affected with the inclusion of the isolation system.
- SCB system is very effective in reducing the base shear response for broad and slender cylindrical tanks. The reduction in maximum base shear force in the cases of breaking waves was higher than for the case with non-breaking waves (in the order of 50% and 25%, respectively). Further reductions can be achieved by using a lower friction coefficient at the expense of increased displacement of isolation system.
- The fact that, the designer can easily set the friction force to achieve a required protection level in conjunction with the invariance of the system fundamental period with the liquid level makes the SCB the most attractive isolation system for preventing damages in liquid storage tanks under earthquakes. These characteristics result in a greater certainty on the behavior and the structural response estimation of the system.
- For earthquakes of low intensity, where the SCB does not slide, the results shown, as expected, a structural behavior similar to fixed base case.

As concluding remarks it is important to emphasize that, the sharp drop obtained in the shear force by the inclusion of SCB (lower seismic demand) implies a significant increase in structural reliability or a reduction in the tank wall thickness at the time of the design (lower cost). On the other hand, no major changes in the sloshing wave height should be expected compared to fixed-base support.

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