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

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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

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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

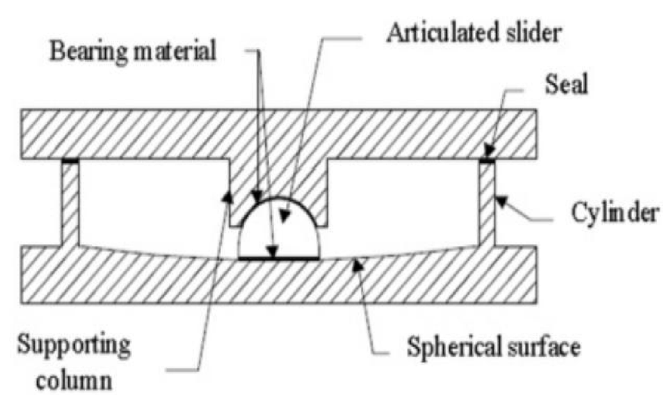

Fig. 1. Sliding concave bearing.