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STATE OF THE ART OF INSULATED WATER STORAGE TANKS FOR POST-EARTHQUAKE EMERGENCIES

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Abstract: Guaranteeing the supply of water for human consumption immediately after a major earthquake is essential for the development of a resilient city. Unfortunately, in several cities around the world, this objective cannot be met due to the state of their distribution networks. One proposed solution is the use of isolated tanks for emergency response. This article presents an updated review of the state of the art of the seismic behavior of base-isolated water storage tanks. The topics reviewed were: studies on theoretical aspects of isolated water tanks, analytical and numerical analysis models used, experimental studies, among others. Finally, it is concluded that the introduction of isolators improves the dynamic response of the tanks; however, it is presented how several parameters affect this response. Aspects to be reviewed in future reports are also presented, in order to extend the research in this area.

Keywords: tanks, seismic isolators, resilient city, experimental studies, analytical models.

INTRODUCTION

The supply of water for human consumption, in the first moments after a major earthquake, is essential to attend to the affected population. Currently, several cities in the Latin American region with high seismic risk have a deficient water distribution system that could suffer serious damage in future seismic events.

A clear example of this was the collapse of the sewerage network in the city of Ica, Peru, as a result of structural damage caused by the 2007 earthquake, which had a magnitude of 8.0 on the moment magnitude scale (Mw) and a maximum intensity of IX on the Mercalli scale. According to the 2011 World Bank Water and Sanitation Program report [1], the earthquake caused a total of S/. 84 million in damages to drinking water and sanitation systems, a figure equivalent to 6.4 times the expenditure executed in that year by municipal authorities in such services. This caused 61% of homes to suffer water service cuts, generating a risk of spreading epidemiological diseases.

The same situation was witnessed in Ecuador thanks to the Mw 7.8 earthquake of 2016. According to the Inter-American Development Bank [2], "...with reduced access to public drinking water supply due to broken pipes and collapsed homes, the risk of water contamination and associated disease outbreaks was high." Subsequently, temporary measures were implemented, which were not sufficient to supply the cities with the same capacity prior to the event. For this reason, the use of water storage tanks could be an effective alternative for post-earthquake emergencies.

In general, storage tanks can be classified according to: geometry, the fluid they store and the material of which they are composed. They range from cylindrical to rectangular, buried and elevated tanks. The use of the material they are made of depends on the availability of resources in the workplace and the importance of the fluid they contain. Polyethylene is one of the most common materials used to store potable water. However, if the tank is located in a seismic city, reinforced concrete is mostly used.

Unlike other types of infrastructures, in the design of tanks, not only the behavior against external conditions (earthquakes) is important, but also the interaction of the fluid with the tank. Housner in 1963 [3] proposed a simplified mass and force model to analyze storage tanks. In the model, water is divided into convective and impulsive mass; this would be the main technical paper on which other research is based.

In past earthquakes, structural failures such as buckling, uplift, wall rupture, roof damage, support collapse in elevated tanks and cracks in buried tanks, among others, have been observed (Cooper [4]; Hamdan [5]). Because of this, the need for seismic protection of the tanks was realized to ensure their operability even in the most severe earthquakes. From a design-for-performance point of view, tanks must meet targets corresponding to essential infrastructure (SEAOC [6]). An alternative to achieve these performance objectives is the use of isolators. It should be noted that when evaluating their performance, conditions such as: soil type, earthquake conditions, the seismic protection system chosen, among other factors, should also be taken into account.

The objective of this study is to make a compilation of the investigations, carried out to date, regarding the performance of insulated water storage tanks. The review covers (i) investigations of insulated and non-insulated tanks to date, (ii) reference standards and (iii) influence of parameters on the responses of insulated and non-insulated tanks.

Based on this state of the art, conclusions and aspects for future research are presented, in order to provide information for the current practice of this type of systems.

STUDIES OF ISOLATED AND NON-ISOLATED TANKS TO THE PRESENT DAY

Seismic analysis of a water tank is complex due to the interaction between the fluid and the structure of the system. During an earthquake "...seismic energy is transferred from the ground to the fluid" (Asha & Glory [7]). The fluid is divided into two portions: one part of the water participates in the surface surge (convective mass) and the other part moves in conjunction with the tank (impulsive mass).

MODEL OF THE TANK-WATER SYSTEM

This is a lumped mass model for ground supported liquid storage tanks. The model assumes that the liquid is incompressible, irrotational, inviscid and that the tank walls are rigid. It also assumes that "...the contents of a buried reservoir are excited in the form of sloshing by an earthquake and that the amplitude of the surge is an indicator of the intensity of the ground motion" (Housner [3]). Thus, this model consists of two degrees of freedom as shown in Figure 1; one associated with the convective mass (Ml) and the other with the impulsive mass (Mo).

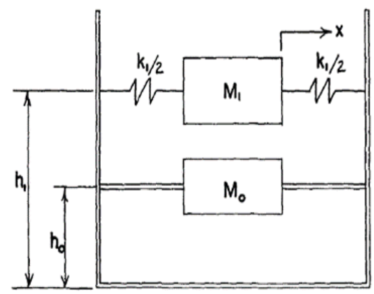

Fig. 1 - Equivalent dynamic system for a water tank. Taken from "The Dynamic behavior of water tanks" (Housner, 1963).

The mass MI, corresponding to the wave, can oscillate horizontally with respect to a restraining spring of stiffness Ki/2. The mode corresponding to this mass is the fundamental mode of oscillation, which is the most important for solving the seismic analysis.

Housner observed that "the liquid pressure generated due to earthquake ground motion is very important for seismic design of tanks" (Shrimali & Jangid [8]). This is because, the accelerated liquid (impulsive and convective), is capable of inducing large hydrodynamic pressures on the tank walls, which generates lateral pressures and overturning moments. The impulsive pressure is associated with the inertial forces of the part of the liquid rigidly attached to the tank wall; the convective

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pressure is that associated with the pressure produced by the oscillation of the liquid.

However, in the 1964 Alaska earthquake, it was observed that tanks designed with the previous model suffered significant surface damage (U.S. Department of the Interior [9]). As a result of that earthquake, almost 20,000 barrels of aviation fuel were lost due to the rupture of a storage tank, and several steel tanks were toppled and destroyed. This is due to the fact that the Housner model underestimates the values of the impulsive pressures because it considers the tank walls to be rigid.

To overcome this drawback, Veletsos in 1974 analyzed a "modal method considering the effects of tank flexibility and only impulsive pressure" (Zhao & Zhou [10]). Subsequently, Haroun and Housner in 1981 [11] introduced a model that also considered wall flexibility; in 1983 Haroun [12] developed a 3-degree-of-freedom design of a ground-supported cylindrical tank. In this model, it is assumed that the liquid contained in the tank is incompressible with irrational flow; also, the flexibility of the tank walls is considered. During a seismic motion the liquid mass vibrates in 3 different patterns:

a) Convective mass (mc): Corresponds to the portion of the liquid that behaves as sloshing on the free surface of the tank.

b) Impulsive mass (mi): intermediate liquid mass that vibrates together with the tank walls.

c) Rigid mass (mr): lower liquid portion that moves rigidly with the tank.

Although there are several modes in which the sloshing and impulsive masses vibrate, "...the response can be predicted only by considering the first sloshing mode and the first impulsive mode" (Seleemah & El-Sharkawy [13]). With such consideration, the tank-water system can be modeled as three lumped masses as in Figure 2.

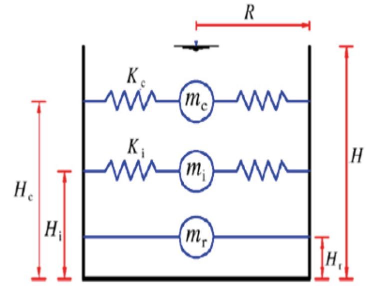

Fig. 2 - Mechanical analogy proposed by Haroun and Housner for flexible cylindrical tanks. Taken from "Seismic response of base isolated liquid storage ground tanks" (Seleemah & El-Sharkawy, 2011).

On the other hand, in 2000 Malhotra made a model in which he "combined the largest impulsive modal mass with the first impulsive mode and the largest convective modal mass with the first convective mode" (Bagheri & Farajian [14]). In this way, it is possible to represent the system by means of only two modes. The representation of this model is shown in the following image:

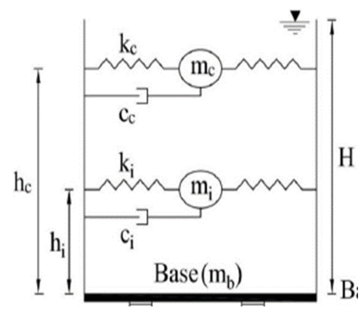

Fig. 3 - Simplified mass-spring model. Taken from "Seismic Response of Base Isolated Liquid Storage Tanks under Near Fault Ground Motions" (Bagheri & Farajian, 2016).

In this model, the convective and impulsive masses are connected to the tank walls by springs with stiffnesses Kc and Ki respectively. Also, the damping coefficients of both masses are denoted Cc and Ci.

Thanks to the development of finite element programs, studies of tank-water interaction have been developed. For example, Drosos [15] developed a finite element model (FEM) in which the seismic response of the tank with arbitrary geometry and liquid height is studied.

In summary, at first the fluid-structure interaction is studied by a simplified method with the fluid modeled by the spring mass system and the hydrodynamic pressure represented by the additional mass. However, to obtain the seismic response of tanks accurately, FEM is being widely used in recent years. The structure and the fluid can be simulated by finite elements and their interaction can be easily considered by the contact algorithm. Such a method offers an effective way to handle seismic studies of liquid storage tanks.

TANK INSULATION

The traditional method to protect tanks is generally to stiffen them by increasing the width of their walls (Shrimali and Jangid [8]). However, in recent years, studies have been conducted to evaluate the effectiveness of seismic isolators at the base of tanks. Thus, the concern is not only on the interaction of the fluid with the tank, but also on how the inclusion of these devices affects the maximum responses.

One of the pioneering studies was that of Liang and Tang in 1994 [16], in which they performed a FEM analysis of a steel tank isolated at the base with elastomeric isolators (LRB). The results obtained described an improvement in the response to seismic stress, since the hydrodynamic pressure (60%), accelerations (93%) and displacement (67%) of the tank were greatly reduced, these results are presented in Table 1. However, there is also an increase in the convective mass response. The same happens in the case of triple pendulum isolators (FPS) according to the study of Wang et al [17].

	Maximum displacement (m)	Maximum acceleration (m/s2)	Hydrodynamic pressure (KN)
Insulated tank	0.0004	0.16	48
Uninsulated tank	0.0012	2.4	120
Reduction (%)	**67**	**93**	**60**

Table 1: FEM analysis results of tank of H=12 m and R =18 m with LRB insulators.

*Adapted from Liang and Tang 1994 [16].

Since isolators are capable of reducing the maximum responses of tanks, it is possible to reduce the size of their sections, especially in the case of friction isolators which are more effective in controlling the response of liquid storage tanks compared to elastomeric isolators (Shrimali & Jangid [8]). Such reductions are reflected in the graph in Figure 4.

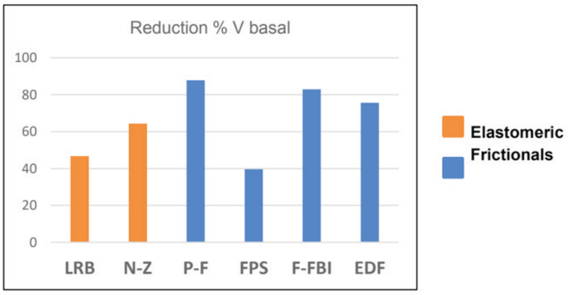

Fig. 4 - Basal shear reduction by type of isolator. *Adapted from Shrimali & Jangid [8].

Some experimental studies have also been carried out to compare the behavior of tanks with fixed base and isolated tanks. In 1995, Kim and Lee [18] performed a pseudodynamic test for the seismic evaluation of liquid storage tanks with LRB isolators at the base. In the pseudodynamic model, the tank is represented as a discrete system and its seismic response is solved using numerical integration.

The authors observed that the hydrodynamic forces of the impulsive and short-period components have a dominant effect on the basal shear force. Furthermore, they observed that the acting basal shear is significantly reduced when the tank is isolated and the dominant frequency is in the effective frequency range of the base isolation system. The test was performed on two cylindrical tanks, one slender and one wide (3700 m^3 and 12840 m^3). The results indicated that, due to the introduction of the isolators, on average the impulsive force was reduced by 59%, the convective force increased by 10% and the basal shear was reduced by 36%. The individual results are shown in Table 2.

	Force reduction (%)		
	Convective force	Impulsive force	Basal shear
High tank and flexible system	-33	**81**	65
High tank and rigid system	-6	56	19
Wide tank and flexible system	-2	75	67
Wide tank and rigid system	-1	27	-1

Table 2: Pseudodynamic test results for 4 types of tanks

*Adapted from Kim and Lee [18].

Finally, Park et al [19] performed scale model tests with shaking table to verify the previously mentioned numerical methods to study the dynamic behavior of the isolated tanks. It was shown that careful selection of the mechanical properties of the isolators with a certain lower limit on the effective frequency of the system could guarantee the reduction of the dynamic responses of the storage tanks. This frequency tends to be 3 to 4 times the fundamental sloshing frequency.

REFERENCE STANDARDS

At present, there are international codes and standards for designing and determining the dynamic actions of reinforced concrete water storage tanks, which differ in terms of how tanks are classified, the allocation of the response modification factor for different types of tanks, etc.

Table 3 lists the available standards for reinforced concrete storage tanks:

Code/Standards	Type of tanks to be considered	Seismic strength level
NZSEE	1, 2, 3	DR
AWWA D-110 (1995)	1	EP
AWWA D-115 (1995)	1	EP
Eurocode 8 (1998)	1, 2, 3	DR
ACI 371 (1998)	2	DR
ACI 350.3 (2001)	1, 2	EP
AWWA D-100 (2005)	1, 2, 3	EP
2006 IBS & ASCE 7	1, 2, 3	DR

Table 3: Detail of codes and standards for reinforced concrete storage tanks

*Adapted from Jaisawl, O. et al [20].

NOTATION

DR = Design by resistance

EP = Allowable Stress Design

1 = Reinforced concrete ground-supported tank

2 = Elevated tank on tower with shafts

3 = Elevated tank on frame type tower

All of the exhibited codes use the rigid-walled mechanical tank model, which represents the tank-liquid system as a two-mass model (Housner [3]; Veletsos and Yang [21]). The impulsive mass vibrates along with the tank wall, and the convective mass vibrates with respect to the tank wall and undergoes sloshing motion.

The design acceleration corresponds to the period of the impulsive mode, which depends on the wall flexibility. Because of this, the wall flexibility is only neglected in the evaluation of the impulsive and convective masses, but is included in the evaluation of the time period.

Although the information necessary to design tanks with seismic isolation is available, there is no formal technical documentation that regulates the design of these tanks.

INFLUENCE OF PARAMETERS ON THE RESPONSE OF INSULATED AND NON-INSULATED TANKS

When analyzing the behavior of an isolated tank, some of the response parameters to be evaluated are the following: Maximum displacement (impulsive and convective), basal shear force, sloshing height, overturning moment, wall pressure, etc.

These parameters can be affected by several factors specific to the tank, such as its geometry, type of insulation chosen, as well as by external agents such as soil and movement characteristics, among others. The following is a description of how these agents influence the responses obtained in analyses carried out by different researchers.

INFLUENCE OF TANK AND INSULATION SYSTEM CHARACTERISTICS ON RESPONSE

As seen in the previous chapter, the inclusion of isolators in the system generates an improvement by significantly reducing the basal shear and the impulsive displacement. This improvement can be more effective depending on the characteristics of the tank and the isolation system.

Bagheri and Farajian [14] conducted a study to evaluate the effect of different parameters on the response of cylindrical tanks with FPS (friction pendulum system) type isolators at the base, including the effect of H/R (Height/Radius) ratio. The responses of 5 insulated tanks with H/R ratio ranging from 0.5 to 2.5 were compared. The result of the analysis indicated that the more slender the tank is the convective and impulsive periods decrease. Thus, as the H/R (Height/Radius) ratio increases, the peak impulsive displacement tends to decrease significantly whether isolated or not. Therefore, base isolation tends to be more effective in slender tanks.

On the other hand, the basal shear in isolated tanks is not influenced by the H/R aspect (Seleemah and El-Sharkawy [13]). The displacement related to the convective mass is larger in isolated tanks, because the period associated with the convective mass approaches that of the isolation system. This increase is more relevant when the tank is more slender. Therefore, the free space above the liquid surface should be increased in the case of insulated tanks.

Another important characteristic to consider is the period of the isolation system being included. As the period of the isolator increases, the shear, overturning moment and displacement responses decrease. This is because the more flexible structure transmits less seismic acceleration to the tank.

INFLUENCE OF EXTERNAL CONDITIONS ON RESPONSE

The seismic response of tanks is influenced by soil and ground motion characteristics. For example, soil stiffness increases the dynamic behavior of tanks without isolation. This is reflected in the study by Kumar and Saha [22], where the basal shear, overturning moment and displacement of the tank without isolators increase with soil stiffness, especially in the lower ranges of shear modulus (G). However, for the case of tanks with isolated base the effect of soil on the maximum responses is negligible in the range considered for the shear moduli.

The wave height is more affected by the motion characteristics than by the soil type (Kumar and Saha [22]). The wave motion (convective displacement and consequently the vertical displacement of the free surface) is sensitive to the long-period components of near-fault motions (Bagheri and Farajian [14]). This result was obtained by analyzing slender and wide tanks, with and without isolation, subjected to 4 near and far source seismic records. According to this research, the reduction of these parameters due to isolation is 5% and 12% for far-fault motions in wide and slender tanks, respectively, while for near-fault motions it is -12% and -4%. These results are shown in the graph in Figure 2.

On the other hand, the reduction of impulsive displacement, overturning moment and basal shear of isolated structures is greater when subjected to movements far from failure. From the study it was obtained that, when isolators were introduced, the impulsive displacement, overturning moment and basal shear were reduced by 85% when subjected to a movement far from the failure; whereas, when subjected to movements close to the failure, a reduction of 64-65% was obtained (Bagheri and Farajian [14]).

Thus, it is understood that the introduction of isolators is more effective when the tank will be subjected to far-from-fault motions due to the sensitivity of the response parameters to the long-period components of the motion.

CONCLUSIONS

An updated state-of-the-art review of the seismic behavior of water storage tanks with base isolation is presented. From the information reviewed, it is concluded that the use of isolators in this type of infrastructure generates better responses to seismic stresses, which fulfills the objective of building fully operational tanks after an emergency. However, certain considerations must be taken into account for their design, which involve the tank geometry, type of isolator to be considered and susceptibility to external considerations such as soil type.

A summary of the conclusions drawn based on the literature reviewed is presented:

- All codes and standards for storage tank design use the mechanical model of a rigid-walled tank, but consider the flexibility of the walls through an amplification factor. Also, there is no formal technical documentation that regulates the design of these tanks.

- Currently, the finite element method allows obtaining the seismic responses of tanks more accurately than simplified mass methods.

- By introducing isolators in the tank system, the responses corresponding to the impulsive mass are reduced. The reduction is greatest when the dominant frequency is in the effective frequency range of the base isolation system. However, the convective mass response is slightly increased.

- When the tank is slender the maximum impulsive displacement decreases, regardless of whether it is insulated or not.

- The shear, overturning moment and displacement responses decrease in greater magnitude when the isolator period is greater; because when the structure is more flexible it transmits less seismic acceleration to the tank.

- Friction isolators are more effective in controlling response compared to elastomeric isolators.

- The introduction of isolators is most effective when the tank is subjected to far-from-fault motions due to the sensitivity of the responses to long-period components of the motion.

However, the studies conducted so far still require further research related to the following aspects:

- Most research has studied the benefits of introducing isolation systems in large storage tanks; however, there is no study that delimits, structurally and economically, the minimum dimensions required for the use of isolators.

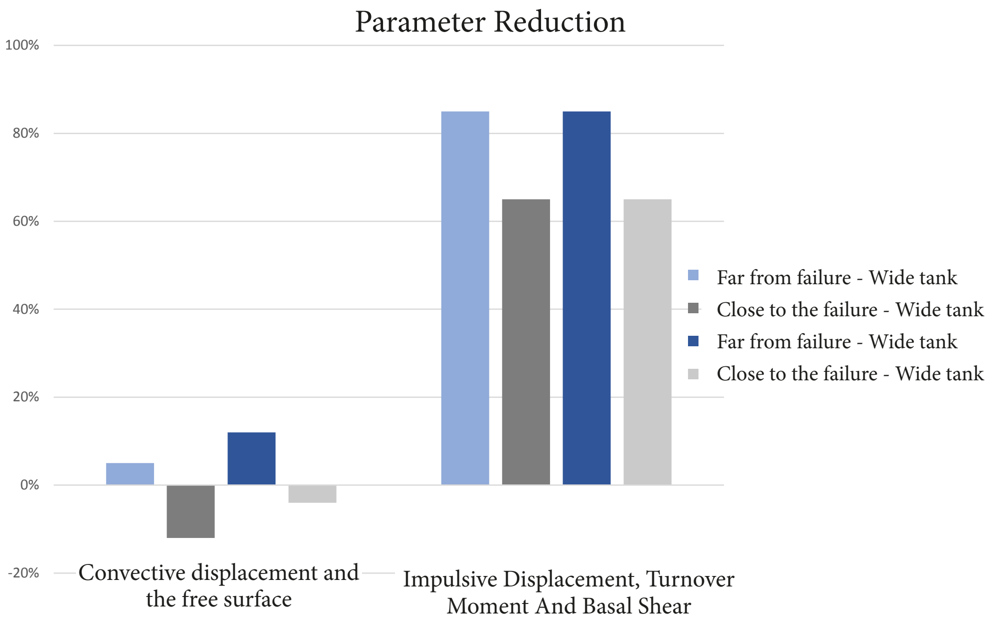

Fig. 4 - Parameter reduction according to motion characteristics. *Adapted from Bagheri and Farajian [14].

- It is necessary to develop a greater number of experimental tests, because most of the research evaluates results from numerical models.

- It is necessary to study with more emphasis the effect of the following conditions in obtaining response parameters: free edge and thickness of the tank walls.

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