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SEISMIC ISOLATION USING A GEOSYNTHETIC LINER. SHAKING TABLE TESTS APPLIED TO A SEMI-REAL SCALE STORAGE TANK

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Abstract

Within the last 20 years, seismic isolation systems and seismic protection devices have had an outstanding performance during major earthquakes providing many structures with operational continuity and lowering the probability of undergoing large damage after severe ground shaking. Likewise, seismic isolation systems are able to keep the content of the buildings reasonably intact by means of energy dissipation mechanisms, i.e., elasto-plastic deformation, damping, friction, etc. Based on the principle of friction, seismic isolation with geosynthetics uses a controlled sliding surface along an interface liner to dissipate energy input from an earthquake. An experimental analysis of a seismic isolation system using geosynthethics is introduced. A high strength, non-woven geotextile placed over an ultrahigh molecular weight polyethylene (geotextile/UHMWPE interface) constitutes a synthetic liner that can provide seismic protection throughout energy dissipation by means of slip deformations. A series of shaking table tests applied to a semi-real scale storage tank were carried out. The dynamic response of the system isolation-liquid-tank is registered and studied in a semi-real scale. Instrumentation consisting of LVDT's, accelerometers and pressure transducers were placed at specific points of interests at the storage tank as well as at the shaking table to measure accelerations, displacements and water pressures. During each test, time histories of acceleration, displacements and water pressures were recorded, i.e., transmitted accelerations from the table to the tank, relative displacements of the tank with respect to the table and water pressures at the tank's inner wall. Both, harmonic and 2D earthquake excitations (bidirectional simultaneously) were used to analyze the dynamic response of the system tank-liquid-isolation and to prove the seismic performance of the interface as seismic isolation. One of the main results from the shaking table tests was a remarkable reduction of transmitted accelerations from the shaking table to the tank (verified for all tests). In addition, for the isolated condition, lower water pressures at the tank's inner wall were measured during dynamic excitation in comparison to those measured for a fixed-base condition (no isolation). One of the benefits of using geosynthetics as a seismic isolation is when threshold acceleration is exceeded, which limits the maximum acceleration transmitted to the superstructure from the excitation. Also, lower levels of seismic demand produces lower values of seismic output parameters i.e., base shear, seismic overturning moments, sloshing effects and water pressures. This experimental research demonstrates the technical feasibility of using an interface of geosynthetics as a seismic protection system, and shows its advantages to be used in earthquake hazard mitigation.

Keywords: seismic isolation; geosynthetic liner; shaking table tests; dynamic response; earthquake protection system.

1. Introduction

In the past two decades, seismic isolation systems have had an outstanding performance in protecting structures during severe ground shaking on major earthquakes. The number of infrastructure designed with devices which provide seismic protection increases every year, and specially, after major earthquake events. Some of the recent major earthquakes, Japan (2011), Chile (2010), Nepal (2015), Ecuador (2016), and Taiwan (2016), to mention some of them, have left not only human losses but also invaluable damage to critical infrastructure. This critical infrastructure rarely can be put back in operation after minutes or several hours following a major event due to large structural damage but above all, due to the extensive damage to its content, utilities and vital components. Infrastructure projects from public and private sectors are increasingly requiring not only structures do not collapse after a major earthquake event, but also that the structural design incorporates some degree of seismic protection to the building which guarantees protection of its vital lines and allowing prompt reestablishing of operations. Thus, owners are nowadays more familiar with the possibility of providing seismic protection to the structures. Seismically isolated structures exhibit very limited damage and almost immediate restart of operations after a significant seismic event; in addition, building content is protected preventing damage on critical equipment.

Seismic isolation devices define the overall dynamic response of a foundation-structure system by means of energy dissipation (elasto-plastic deformation, viscous damping, friction, etc). Under seismic forces, seismic isolation devices allow large deformations take place at the level where the isolators are located reducing the impact of the earthquake's input energy on the overlying structure. Based on one of these principles, seismic isolation with geosynthetics uses a controlled sliding surface along an interface liner comprised of a geotextile and a geomembrane to dissipate input energy from earthquakes. Current research has furnished promising results when an interface of a geotextile placed over a geomembrane is used as an interface liner to be used as a seismic isolator. It has been shown that an interface comprised of a high-strength nonwoven geotextile type (Non wovens), placed on a polymer of ultra-high molecular weight (UHMWPE), can provide seismic protection by energy dissipation through sliding. This interface can be materialized at the bottom of the building's footings or slab [6]. Likewise, this same interface can be placed within the soil of foundation in order to generate an upper protected zone between the soil and the structure foundations [5].

The effectiveness of the seismic isolation using an interface of geosynthetics has been proven using shaking table tests and analyzing the dynamic response of single-degree of freedom systems, i.e., assuming that the structure and the earthquake excitations act in one horizontal direction. However, it is of practical importance in order to this seismic isolation system is applied in real structures that multi-degree of freedom response analysis is carried out. This present study intends to continue the research to date, verifying the effectiveness of the seismic isolation using geosynthetics, performing shaking table tests (earthquake excitations) on a semi-real scale sotorage tank, where multi-degree of freedom dynamic response are analyzed (shaking table-isolation-tank-liquid system). One of the main findings of this study is that using geosynthetics as a seismic isolation it limits the maximum acceleration transmitted to the superstructure from the earthquake excitation; thus, lower levels of seismic demand were recorded in the superstructure, i.e., the tank. (Lower values of base shear, seismic overturning moments, sloshing effects and water pressures. In addition, a potential benefit of using geosynthetics is a reduction of the undesirable effects from surficial liquefaction through a limitation of the subsurface settlement. This is accomplished because of the flexible nature of the geosynthetics to accommodate seismic deformations. Promising results from this research provides an outstanding starting point for the geosynthetics' industry in seeking the applicability of this seismic isolation system in real structures. Seismic isolation with geosynthetics is presented as a technically feasible and viable alternative to the conventional rubber isolators and frictional devices at a much lower cost.

2. Composition of the Interface of Geosynthetics

The interface of geosynthetics, used as a seismic isolation, can be typically comprised of a geotextile, woven or non-woven; placed over a HDPE or UHMWPE geomembrane. This geosynthetic interface can be placed underneath the foundation of a structure, or directly within the soil underneath the foundations. Different geosynthetic interfaces have been tested on single-degree of freedom shaking table tests by several authors on previous research. The different interfaces tested on previous studies and this research, and their respective friction coefficients are summarized in Table 1.

Table 1 – List of interfaces of geosynthetic suitable for seismic isolation

Interface	Description	Friction Coefficient[a]
Geotextile/HDPE	High strength non-woven geotextile, heat-bonded, polypropylene.	0.14 [4]
	High strength woven geotextile, slit-film, polypropylene.	0.18 [4]
	High strength non-woven geotextile, heat-bonded, polyester.	0.18 [4]
	High strength woven geotextile, polyester.	0.16 [4]
	High strength non-woven geotextile, needle punched, polypropylene.	0.10-0.12 [3]
	High strength non-woven geotextile against 1.5 mm smooth HDPE.	0.15-0.30 [6]
HDPE/HDPE	High density polyethylene	0.10-0.12 [3]
PTFE/PTFE	PTFE Polypropylene	0.08-0.15 [6]
UHMWPE/UHMWPE	Two layers 6.4 mm thick (ultra high molecular weight polyethylene).	0.09-0.25 [2], [6]
Geotextile/UHMWPE	High strength non-woven geotextile, heat-bonded, polypropylene against UHMWPE (ultra high molecular weight polyethylene).	0.06-0.08 [6]
Geotextile/UHMWPE[b]	High strength non-woven geotextile, needle punched, polyester against UHMWPE	0.15-0.28 [2]

[a] Range depends on number of cycles, normal stress, and sliding velocity.
[b] This Study. [1], [2].

In this study, the tested interface consisted of two geosynthetics. The first is a high strength geotextile nonwoven type and the second is a polymer of ultra-high-molecular-weight polyethylene (UHMWPE) (Fig. 1). The geotextile utilized in this research, as well as others used in previous research are readily available and manufactured in a regular basis. The polymer UHMWPE has a distinctive property not to change their physical and mechanical properties before high humidity environments and before temperatures below 80° C. In addition, UHMWPE materials are highly durable and resistance to chemical attacks. Both materials also stand out for their varied uses and engineering applications as well as their wide presence in the geosynthetics' market. The most important mechanical property for a interface of geosynthetics to be used as a seismic isolation liner is the coefficient of friction of the interface. The lower this coefficient of friction, the more the isolation effect will be and the more energy will be dissipated along the interface. The isolation effect provided by the geosynthetic interface was verified in the previous research for shaking table tests carried out in a single degree of freedom system (one dimensional movement of the shaking table, deformation and displacements of a rigid block). The latest dynamic tests in rigid blocks were presented by Yegian and Kadakal 2004. These tests proved the effectiveness of the interface in reducing accelerations transmitted from the vibrating table to the rigid block. The concept of the seismic isolation using a sliding interface of geosynthetics for a single degree of freedom is very simple and addresses to the frictional characteristics of the interface. If a rigid block is considered to slide along the geosynthetic's interface, a balance of horizontal forces must occur in the system. It is known that when the vibrating table accelerates it transmits a frictional force F to the block (Eq. 1), which cannot exceed the shear strength of the interface between geosynthetics.

$$F = W \tan(\phi) \tag{1}$$

Where W is the weight of the block and Φ is the angle of friction of the interface between geosynthetics. This force F causes the block to move with acceleration a_b, such that:

$$W \tan(\phi) = \frac{W}{g} a_b \tag{2}$$

$$a_b = \tan(\phi) \cdot g \tag{3}$$

Eq. 2 and Eq. 3 show that during a dynamic test, when the acceleration of the table is less than the limit acceleration of the block (or yield acceleration), the vibrating table and the block move together, i.e., there is no relative displacement of the block with respect to the shaking table; thus, no sliding occurs at the interface. On the other hand, when acceleration exceeds the yielding acceleration, there is relative sliding of the block with respect to the table. This theoretical reasoning allows obtaining the friction coefficient of the interface as:

$$\phi = \arctan\left(\frac{a_b}{g}\right) \tag{4}$$

During a real seismic event, this process of energy dissipation becomes more complex as the system will present multi-degree of freedom' dynamic response. However, this study verified that the multi degree of freedom dynamic response has little effect on the isolation effect of the interface of geosynthetic. The most important property of the interface is the dynamic friction coefficient. The immediate effect of this controlled sliding along the interface of geosynthetics is that the superstructure experiences a dramatic reduction in the seismic forces and the transmitted accelerations to the structure; thus, reducing the seismic demand over the structural elements and components. This situation was verified for all shaking table tests performed to the system table-isolation-tank-liquid.

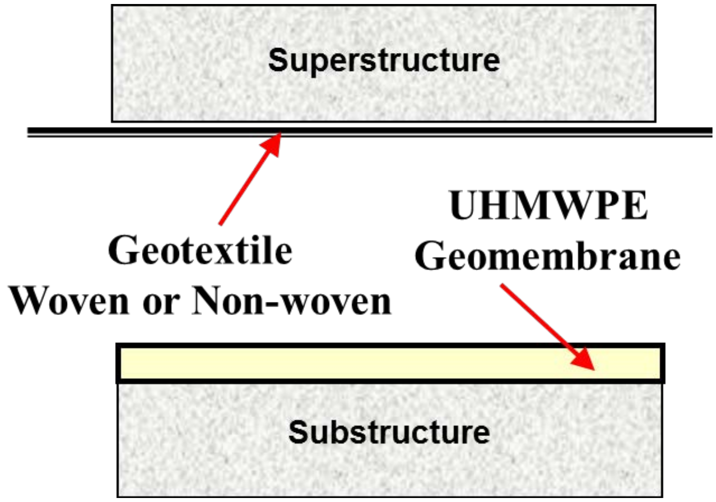

Fig. 1 – Schematic of the seismic isolation with geosynthetics.

3. Two-dimensional Shaking Table Tests on Isolated Tank

In order to test the effectiveness of the seismic isolation on a multi degree of freedom system, dynamic tests were prepared in a shaking table. In this study, a high strength, non-woven geotextile placed over an ultrahigh molecular weight polyethylene (geotextile/UHMWPE interface) constitute the synthetic liner that can provide seismic protection throughout energy dissipation by means of slip deformations. The dynamic response and interaction of the system isolation-liquid-tank, on a semi-real scale is recorded and studied. Adequate instrumentation consisting of LVDT's, accelerometers and pressure transducers were placed at specific points of interests at the storage tank as well as at the shaking table to measure accelerations, displacements and water pressures with time. The shaking table tests were carried out considering isolated and non-isolated conditions, as well as tests with and without liquid. Both, harmonic and 2D earthquake excitations (bidirectional simultaneously) were used to analyze the dynamic response of the system tank-liquid-isolation and to verify the interface effectiveness as seismic isolation. Figure 2 to Figure 4 show schematics of the experimental arrangement.

Fig. 2 - General view of the instrumented isolated tank mounted on the shaking table.

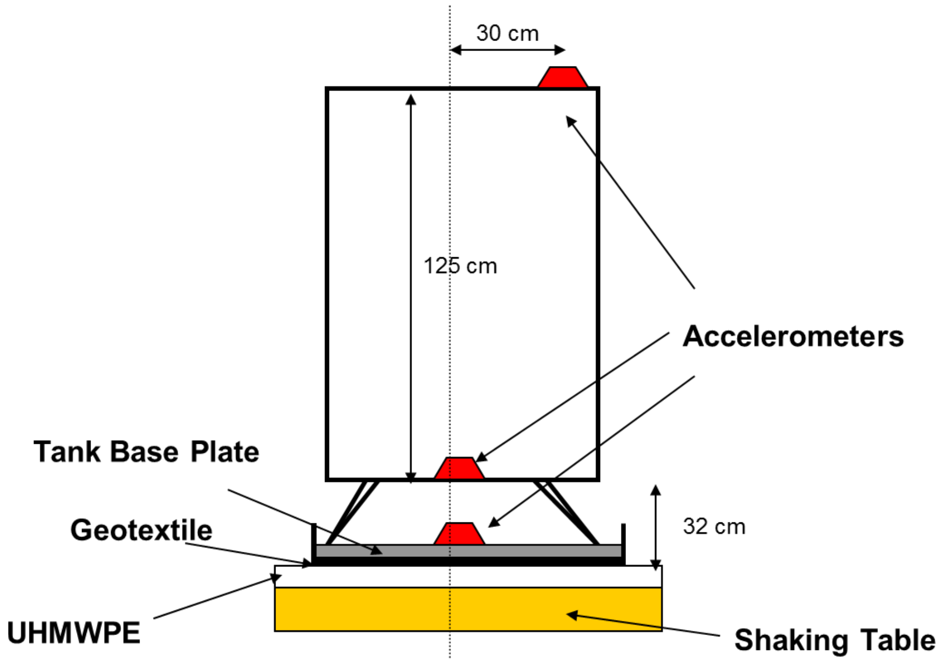

Fig. 3 - Location of accelerometers within the isolated tank and the shaking table.

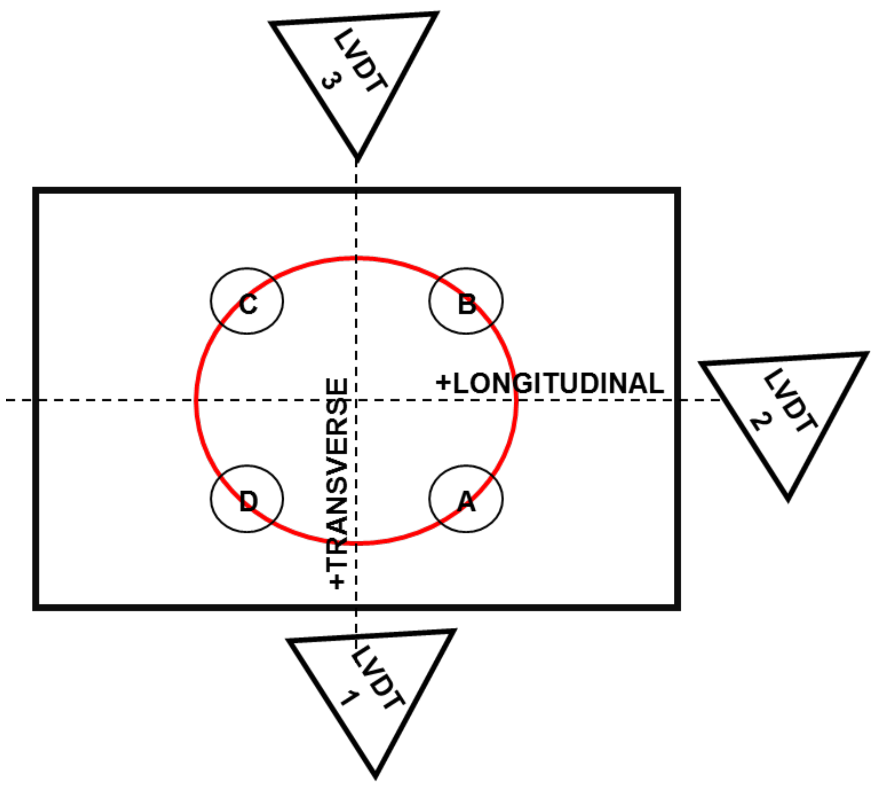

Fig. 4 – Plan view of the shaking table arrangement and instrumentation. Direction of analyses able addressed in the results. A, B, C, D: pressure transducers. LVDT-1 and LVDT-2.

For each test, accelerations transmitted from the shaking table to the tank, relative displacements of the tank with respect to the table, and water pressures generated at the tank inner wall were recorded. These measurements were obtained through accelerometers placed on the vibrating table and the tank (Fig. 3), pressure transducers attached to the tank inner wall mantle and displacement transducers (LVDT) which recorded the movement of the table and the tank in two directions simultaneously (Fig. 4).

In order to run a general testing for the system table-isolation-tank, a first dynamic excitation consisting of a one-dimensional random signal with different frequency contents, with an average peak acceleration of 0.4g. was applied to the isolated tank. Figure 5 shows a comparison between the history of accelerations imposed by the random signal and the time history recorded by the accelerometer placed immediately at the base plate of the tank.

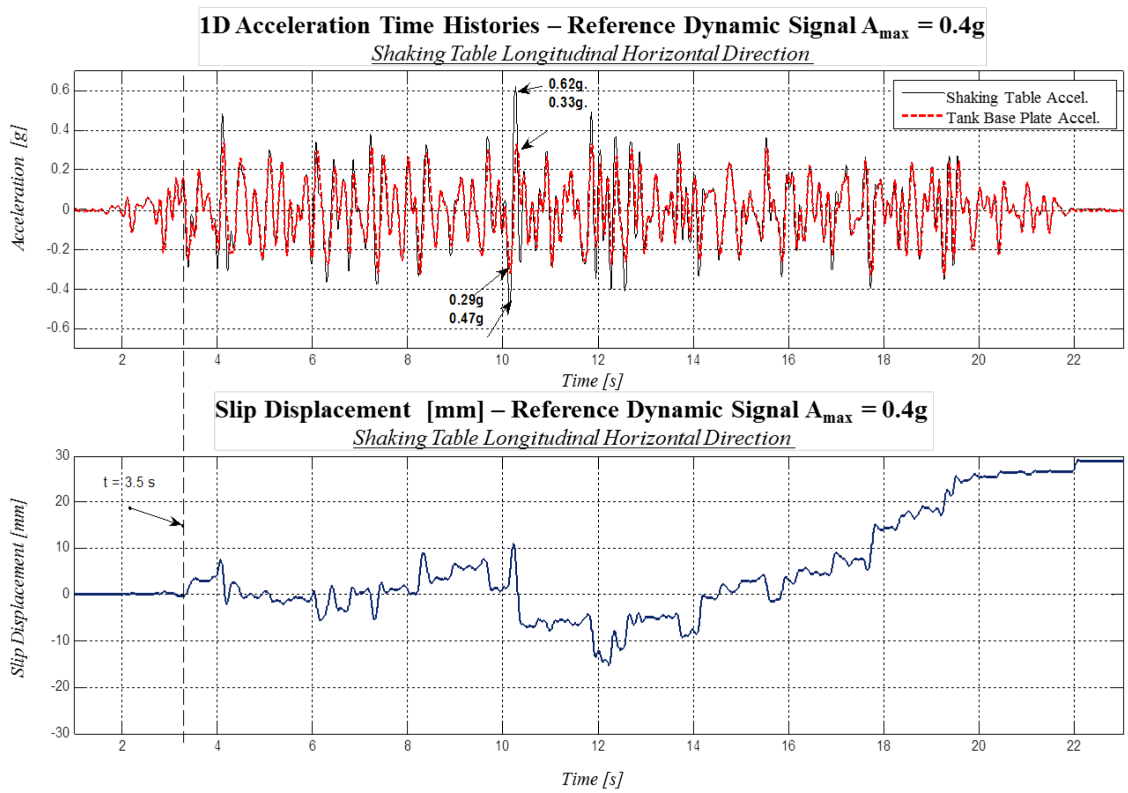

Fig. 5 - Effectiveness of the isolation system on reducing recorded accelerations at the tank base plate for a random input signal with frequency content ranging from 1 Hz to 10 Hz, and peak acceleration of 0.4 g. As sliding occurs, slip deformation along the interface develops.

The results from this one dimensional excitation confirmed the concept of block sliding exhibited on the previous research. At the time 3.5 seconds, it can be observed that the relative movement of the tank with respect to the table initiates. As sliding occurs along the interface of geosynthetics, the maximum peak acceleration recorded in the tank was 0.33g., whereas de maximum acceleration of the shaking table was 0.62g. This difference in the excitation and the transmitted acceleration to the tank represents a 47% of reduction of the excitation. In addition, it can be observed that a permanent deformation of about 30 mm was measured at the end of the excitation.

Two dimensional shaking table tests confirmed the effectiveness of the interface of synthetics as a seismic isolation. As a main result from the two dimensional shaking table tests can be noted a remarkable reduction of transmitted accelerations from the shaking table to the tank, for all tests carried out. In addition, for the isolated condition, lower water pressures at the tank inner wall were measured during dynamic excitation in comparison to those measured for a fixed-base condition (no isolation). Figure 6 to Figure 9 summarizes the most important results from all performed tests and the principal reductions in accelerations transmitted to the tank and water pressures recorded at the tank inner wall.

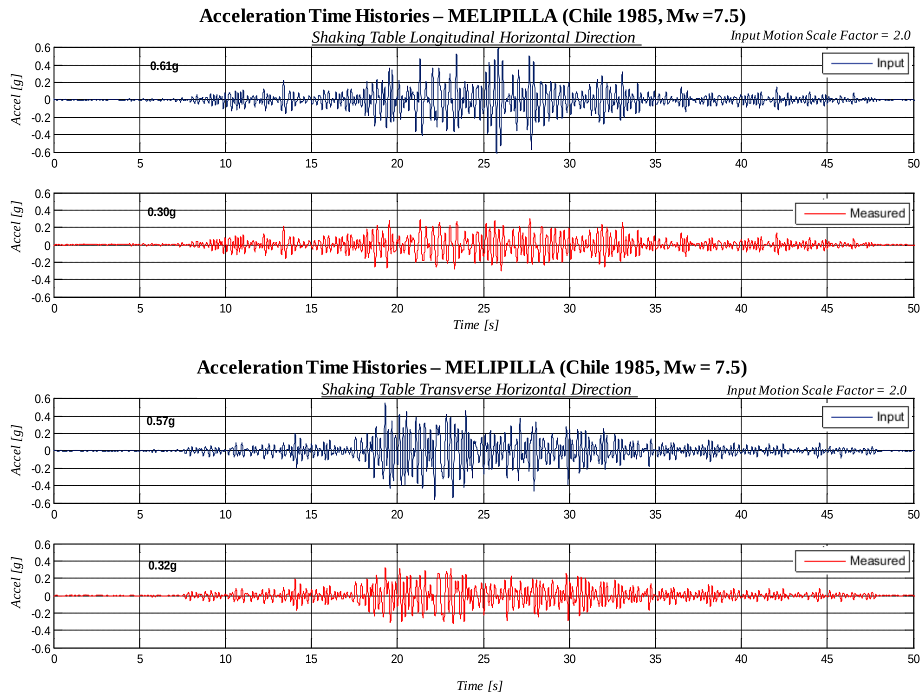

Fig. 6 – Dynamic response of the system table-isolation-tank for a typical subduction earthquake excitation.

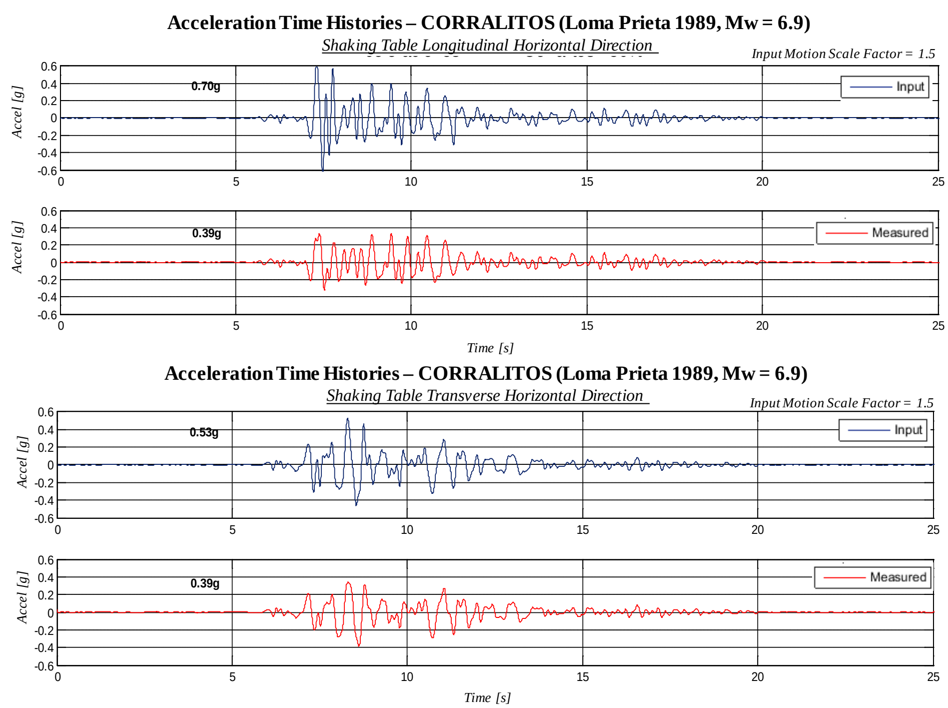

Fig. 7 – Dynamic response of the system table-isolation-tank for a typical strike-slip earthquake excitation.

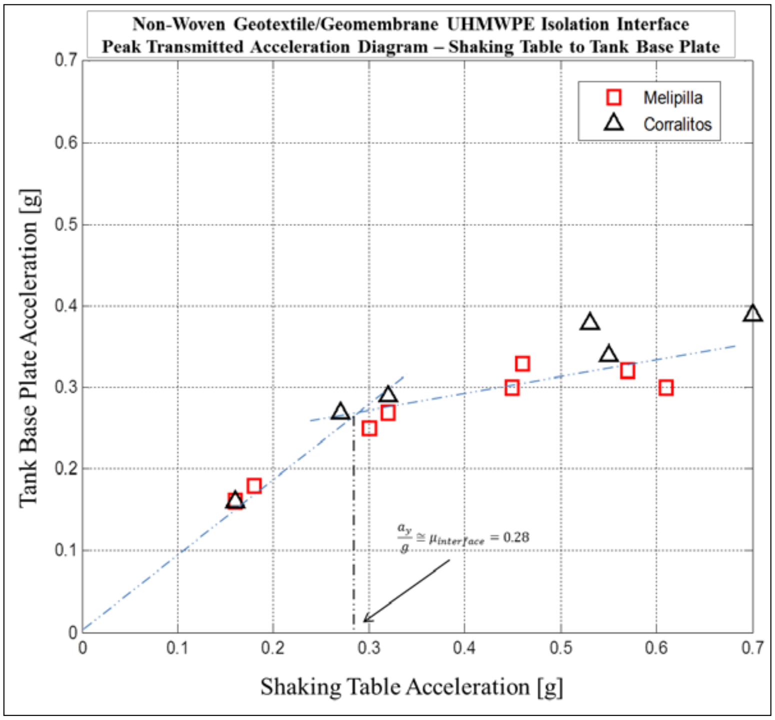

Fig. 8 – Peak transmitted acceleration diagram, shaking table to tank base plate.

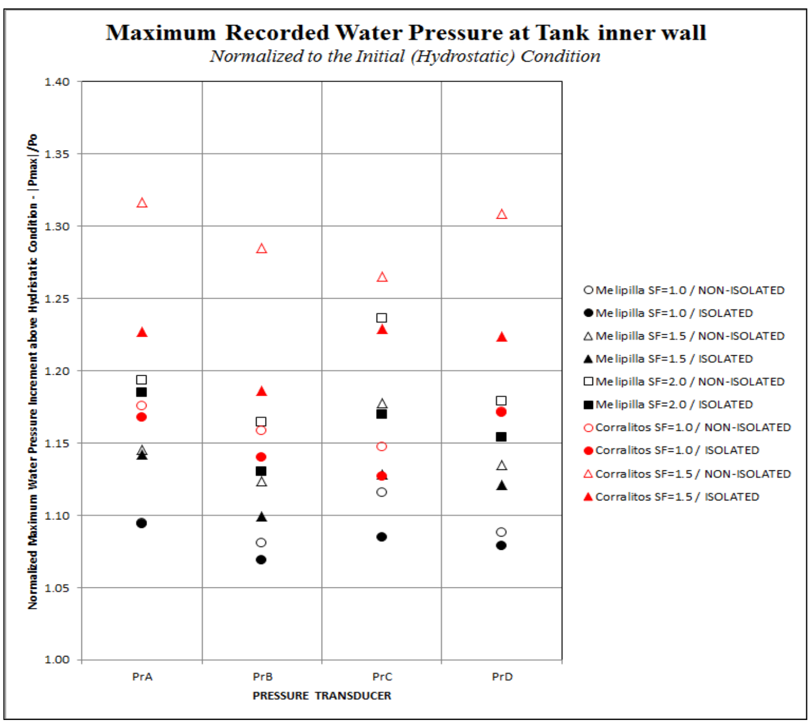

Fig. 9 – Maximum recorded water pressure at the tank inner wall, for conditions with and without isolation.

3. Constructability of the Interface

The applicability of this seismic isolation system using geosynthetics in real structures is in the process to be studied in deep. The flexibility in using the different materials, i.e., geotextiles and geomembranes HDPE or UHWPE and their availability makes this isolation system a cost-effective real alternative to the conventional rubber and frictional isolators. Future research will consider constructability aspects to materialize this isolation system between the structure's foundation and the soil. Several constructive solutions involve the use of helical piles and/or anchored grids to install the geomembrane (HDPE/UHMWPE) on grade, at the subbase level, or at the bottom of the foundation. On the other hand, due to the great variability of available geotextiles coefficients of friction as low as 0.09 can be achieved selecting the adequate geosynthetic interface.

3. Conclusions

The analysis of the results showed significant reductions in accelerations transmitted from the vibrating table to the tank and lower water pressures in the inner wall of the tank. These reductions were recorded for all the dynamic excitations used in this study. It was verified that, despite how complex the study of a system involving nonlinear forces and mechanical contact between two surfaces, the reduction rates of both acceleration and water pressure were significant (on the order of 40% to 60%), establishing clear differences between isolated and non-isolated conditions. This experimental research demonstrates the technical feasibility of using an interface of geosynthetics as a seismic protection system, and opens the discussion about its advantages to be used as seismic protection system. In addition, interfaces with lower coefficients of friction exist and can be tested in order to increase reductions on transmitted accelerations to the superstructure and the effectiveness of the interface as isolation system.

4. Acknowledgements

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