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LOW-COST HYBRID DESIGN STRATEGIES: LARGE-SCALE SHAKING TABLE TESTS AND CHALLENGES OF IMPLEMENTATION

Anastasios Tsiavos[1], **Anastasios Sextos**[2]

[1] Lecturer, ETH Zurich, Switzerland
tsiavos@ibk.baug.ethz.ch

[2] Professor, University of Bristol, United Kingdom
a.sextos@bristol.ac.uk

Abstract

The complexity of design, the high transportation cost and the use of materials of high carbon footprint inhibit the sustainable implementation of response modification strategies, such as seismic isolation systems and tuned mass dampers to a large number of countries worldwide. This study presents novel, low-cost response modification strategies that are constructed based on materials, which can be easily resourced. These strategies comprise low-cost engineering measures for the protection of the superstructure from seismic damage at the design hazard level and low-cost seismic isolation techniques for the seismic protection of structures for intensities that exceed the design one. These methods are based on the inclusion of a thin layer of sand or roller bearings between two rigid and smooth surfaces in a sandwich configuration, which facilitates the sliding of the upper surface against the bottom surface at an attractively low, yet reasonably configurable, friction coefficient. The efficiency of the aforementioned response modification strategies is demonstrated based on large-scale testing performed at University of Bristol that paved the way for the design and construction of a new building.

Keywords: seismic isolation, low-cost response modification strategies, large-scale shaking table tests

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1 INTRODUCTION

The design of strategies that modify the dynamic response of structures aims to utilize the attractive mechanical characteristics, the energy dissipation and the recentering ability of highly engineered devices to reduce the seismic demand during an earthquake excitation. These strategies, defined as response modification strategies, entail a wide range of seismic isolation devices and tuned mass dampers, which are extensively implemented worldwide in developed countries ([1], [2], [3], [4]).

However, the high transportation cost, the project-specific qualification testing, the use of materials of high embodied carbon footprint and the highly engineered construction of these devices inhibit their extensive application in regions of low- to moderate income, as well as in deprived areas in higher income countries. This is because owners and stakeholders have limited access to highly technology seismic protection systems or lack the resources to enforce compliance to modern codes, including those associated with seismic isolation [5]. Moreover, the lack of technical equipment and/or access to certified laboratories for project-specific testing of isolation devices and the potential absence of quality control in the field, increase the uncertainties related to the mechanical properties of the seismic isolation system that is constructed on site compared to a standard, highly engineered seismic isolation system. These uncertainties may impede the activation and the efficiency of the seismic isolation system and lead to severe damage to a superstucture that was not designed for the 'non-activated' seismic isolation configuration. This is of particular importance for the case of seismic motion intensities that exceed the design one as these structures would be lacking the adequate ductility.

In light of these challenges, the design of structures to develop different dynamic response mechanisms for different seismic intensity levels emerges as an engineering solution that is highly aligned with the context of countries or regions with limited financial resources, characterized by inadequate quality control and insufficient measures for ductile design. According to this design approach, defined as Low-Cost Hybrid Design (LC-HD) by Tsiavos et al. [6], the building is designed to respond in a 'fixed-based' mode for the design seismic intensity, and respond in a ductile manner according to the performance objectives outlined in the seismic code. For earthquake ground motions beyond the design level, the system is expected to slide on the low-cost foundation surface, thus introducing a "fuse" that is aimed to protect the structure in case of insufficient detailing, lack of code compliance or poor material properties. Essentially the Low-Cost Hybrid Design (LC-HD) refers to new buildings that are expected to be designed by the code, but given the lack of confidence on its implementation, it offers an additional safety factor against collapse.

Different alternatives have been proposed for the above foundation sliding interface. Tsiavos et al. [6,7,8] demonstrated experimentally, at large scale, the efficiency of a novel 'sand-wich' seismic isolation, based on the encapsulation of a thin sand layer (PVC sand-wich) or a layer of roller bearings (PVC-Rollers Sandwich) between two PVC surfaces below the foundation of a structure. The sliding of the superstructure at a configurable low friction coefficient that may vary in the range of 0.1 to 0.25 is enabled by the rolling motion of sand grains (PVC sand-wich [6]) or glass/steel roller bearings (PVC-Rollers Sandwich [8]). A similar system was explored by Banovic et al. [9], who investigated numerically and experimentally at large scale the sliding of structures founded on a layer of pebbles.

Several researchers have further investigated experimentally low-cost seismic isolation methods [10, 11] based on the use of fiber-reinforced, unbonded elastomeric isolators. Nevertheless, the vulcanization required for the production of rubber in these bearings inhibits their use in countries where this vulcanization cannot be performed, leading to high carbon footprint values and high transportation costs. Another group of low-cost seismic isolation methods comprises a class of Geotechnical Seismic Isolation (GSI) methods [12], which are based on the use of flexible soil-based materials below the structure that modify its seismic response. Tsang [12] and Brunet et al. [13] investigated numerically and showed the efficiency of the use of a 2m thick, flexible sand-rubber foundation layer for the seismic isolation of structures in developing countries.

Tsiavos et al. [14] investigated experimentally the seismic response of structures founded on a sand-rubber layer. Gatto et al. [15] explored the injection of flexible polyurethane foam into the soil below the foundation of a building to create a low-cost seismic isolation system that reduces the seismic acceleration of the building during an earthquake excitation. However, this method requires a deep excavation below the structure and the deposition of a flexible GSI layer [16]. The main problem though of the implementation of rubber-based mixtures for the GSI of structures is the induced rocking motion that may be manifested during the excitation [7]. Within this context, the hybrid low-cost response modification strategies emerge as a promising combination of efficient seismic protection for a wide spectrum of intensity levels, that does not require significant resources of the use of materials that are not accessible in low-income regions. This paper presents a summary of the large-scale shaking table tests that demonstrate the efficiency of these low-cost response modification strategies and discusses the challenges related to the implementation of these strategies in real life structural design and construction.

2 LARGE-SCALE SHAKING TABLE TESTS

The conceptual design of a prototype, masonry building using the Low-Cost Hybrid Design method (LC-HD) is presented in Fig. 1. The design of the superstructure, which in this case is a masonry one, comprises the attachment of steel wire mesh and steel ties to the facade walls of the building. The latter is expected to increase substantially the in-plane and out-of-plane seismic strength and deformability of the building. The design of these engineering measures aims at the seismic protection of the building from seismic damage for the design seismic hazard level, as per the provisions of seismic codes for masonry construction. If this seismic hazard level is exceeded by a strong earthquake ground motion excitation, a secondary ‘fuse’ mechanism is designed to get activated at the foundation of the building. This mechanism comprises the novel, low-cost ‘sand-wich’ seismic isolation system, that was described previously. The RC foundation slab of the building is casted above the upper PVC surface. A 10-20 cm thick excavation further enables the construction of a hardcore layer, typically of concrete as well, allowing for the formation of a flat, rigid base below the sliding surface of the structure. The sand layer was initially designed with a 5cm thick sand layer but was gradually reduced to achieve the desirable friction coefficient.

The large-scale shaking table investigation of a three-times scaled down model of the above masonry building at the 3mx3m, 6-degree-of-freedom shaking table of University of Bristol [6] is shown in Fig. 2a. The magnified acceleration response of the superstructure subjected to the Chi-Chi 1999 earthquake ground motion is shown in Fig. 2b.

As shown in Fig. 2b, the building subjected to an earthquake ground motion excitation of PGA=0.4g that represents the design acceleration in several countries worldwide, manifested sliding, thus capping the maximum acceleration acting on the superstructure to an acceleration level of 0.2g. This corresponds to a kinetic friction coefficient of approximately 0.2. It is noted that the acceleration demand of 0.2g did not cause any damage to the superstructure, since that was designed following efficient and low-cost engineering practices (well anchored steel mesh around the masonry walls and steel ties connecting opposite wall surfaces).

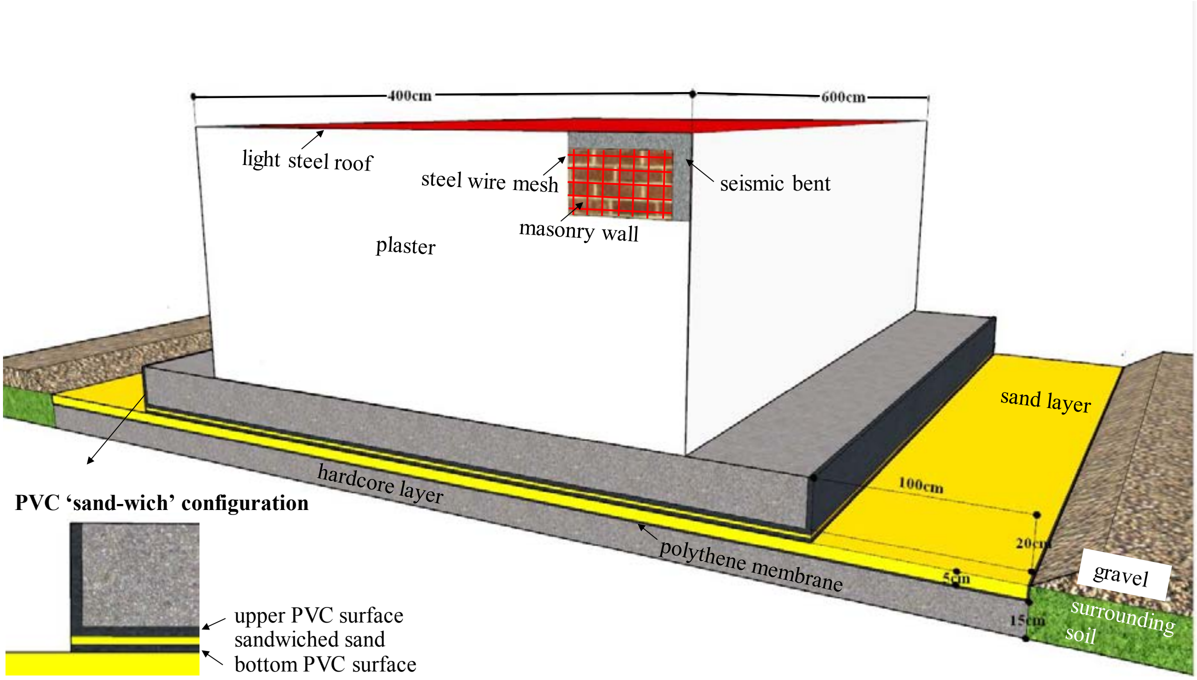
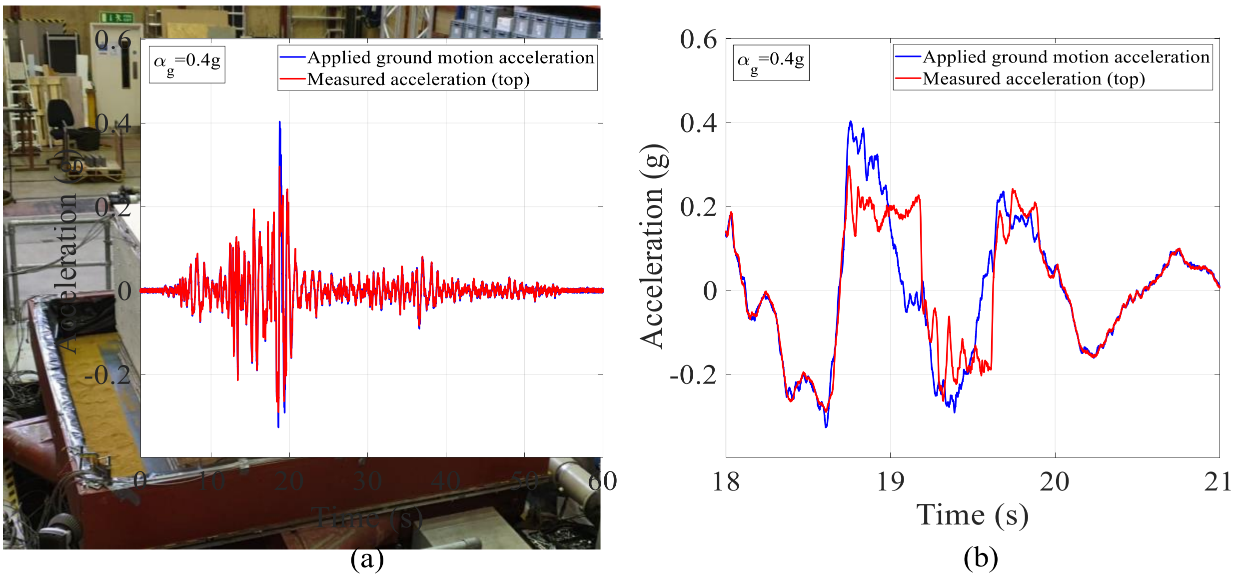


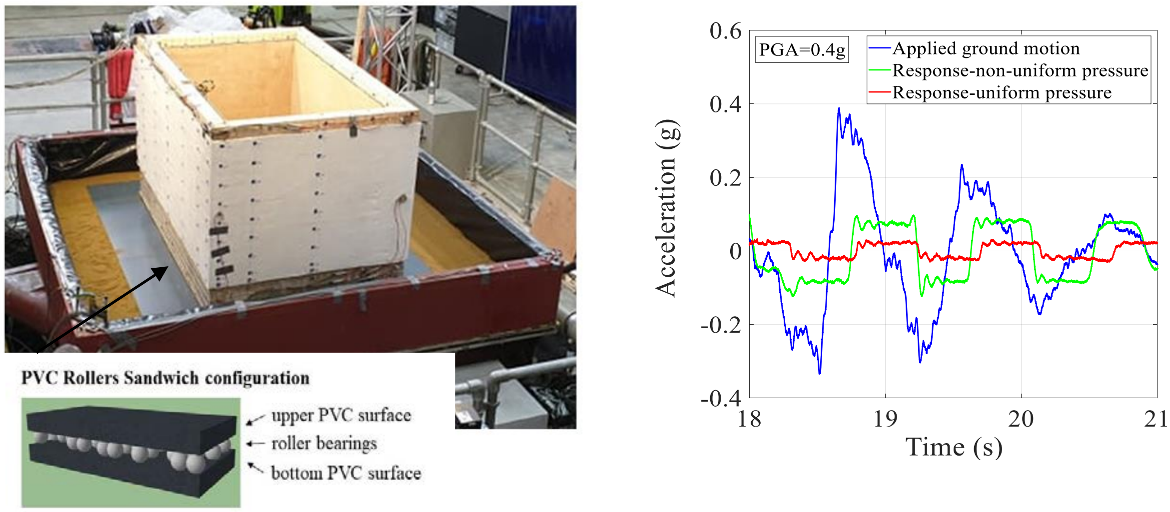
Fig. 1. Prototype building designed with the Low-Cost Hybrid Design (LC-HD) method.



(a) (b)

Fig. 2. (a) Large-scale shaking table test of scaled masonry building designed using the LC-HD method at University of Bristol (b) Magnified acceleration response at sliding due to the activation of the PVC-sandwich seismic isolation for the Chi-Chi 1999 recorded earthquake ground motion excitation.

As a means to introduce a lower friction coefficient rolling elements were also encapsulated into the sliding surface. It was observed [8] that the replacement of sand with steel or glass bearings can decrease the friction coefficient of the interface, due to the smoother rolling motion of the spherical encapsulated elements, to 0.1 or below (Fig. 3).



(a) (b)

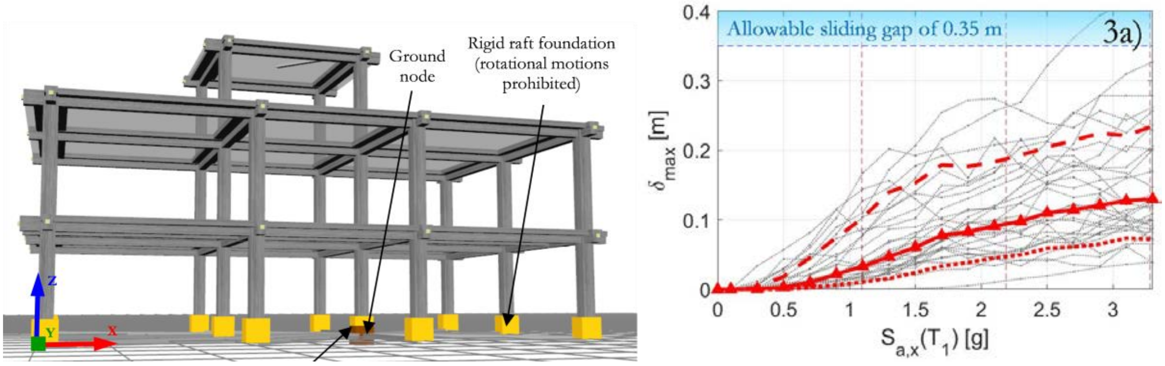
Fig. 3. (a) Large-scale shaking table test of scaled masonry building designed using the LC-HD method at University of Bristol (b) Magnified acceleration response at sliding due to the activation of the PVC Rollers sandwich seismic isolation for the Chi-Chi 1999 recorded earthquake ground motion excitation.

This is shown in more detail in the magnified acceleration response of the superstructure subjected to the Chi-Chi 1999 earthquake ground motion of Fig. 3b: the building subjected to an excitation of PGA=0.4g manifested sliding at an attractively low acceleration level of 0.05g for a density of 800 rollers/m^2 facilitating uniform vertical pressure on the bearings. The use of 200 rollers/m^2 increased the sliding acceleration level to 0.1g due to the non-uniform pressure on the bearings, which inhibits the smoothness of their rolling motion. The masonry structure, which was designed following efficient and low-cost engineering practices (steel mesh, steel ties), was protected from seismic damage in this case as well, both in the state before sliding as well as during sliding.

3 CHALLENGES OF IMPLEMENTATION

The modern code provisions for the inelastic, seismic design of structures focus on the concentration of seismic damage at pretetermined locations, which are designed to behave in a ductile manner and dissipate seismic energy during an earthquake event. However, the ductile design of structures to satisfy displacement-based performance objectives related to their expected seismic damage is not always feasible in regions with limited financial resources, as observed in some areas during the recent 2023 Kahranmaras earthquake in Turkey. Within this frame, the fundamental performance objective for the design of structures located in these regions is the prevention of their collapse, not only for the design earthquake, but also for seismic intensites exceeding the design hazard level.

The efficiency of the LC-HD approach was demonstrated in the previous section. However, a major drawback of such a low-cost protective system is the inevitable lack of recentering capability. This was also observed during the large-scale shaking table tests performed by Tsiavos et al. [6,7,8] that indicated a residual sliding displacement of the isolated superstructure after the end of the ground motion excitation, of the order of 5cm-15cm. Detailed probabilistic assessment for the case of a 3-storey R/C building have also shown [5] a mean value of residual displacement of the order of 10cm, with the maximum predicted transient displacement being approximately 30cm in the extreme case of motions twice as strong as the design acceleration (i.e., for Sa(T)=2g), see Fig. 4. Note that the PVC-s residual-to-maximum displacement ratio was found of the order of 2/3 [5].



(a) (b)

Fig. 4. (a) Overview of the building numerically studied and (b) maximum PVC-s sliding displacement δ_{max} [m] [5].

From a practical viewpoint, for low-rise, low-weight structures, the recentering of the superstructure after the earthquake can be performed by means of trucks that are able to apply the necessary pulling force. Additionally, appropriate design measures should be considered for the accommodation of this sliding displacement in the design phase, by providing flexible connections for the pipes and sewage system and the implementation of a buffer zone in the form of a sacrificial parapet in the perimeter of the structure to inhibit pounding. Sextos et al. [5] report that given an allowable sliding gap of 0.35 m, the probability of pounding between the raft foundation of the PVC-s base-isolated building and the non-structural perimeter parapet wall is less than 2% at the extreme case of three times the design-level (see also Fig. 4b). In case the design requirements for the structure do not allow a residual sliding displacement or the weight of the structure does not allow the recentering by trucks, a recentering system that minimizes this residual sliding displacement has been proposed by ETH Zurich. Tsiavos et al. [17] demonstrated through large-scale shaking table tests at ETH Zurich the efficiency of a low-cost and sustainable recentering system based on low-cost steel springs and deformable timber plates [18]. This system, which is based on a ‘sandwich’ seismic isolation strategy, can be used either as low-cost seismic isolation with recentering or a low-cost tuned mass damper, leading to residual sliding displacement lower than 5mm. Alternative, low-cost recentering systems are also currently explored at the University of Bristol under the UKRI-funded project LASSIE (Low life cycle cost Sand-wich Isolation System for Seismic Risk Reduction, PI: N. Alexander, Co-Is: A. Sextos, A. Diambra).

The aforementioned novel engineering techniques for the combination of low-cost seismic isolation with recentering systems will increase substantially the potential of application of low-cost hybrid design and low-cost seismic isolation to a wide range of countries worldwide. It is the authors’ position though that for case that the construction quality of the superstructure cannot be assured, the protective sliding ‘fuse’ mechanism is deemed critical to at least prevent collapse. This observation essentially paves the way for a wider discussion of rethinking what are the *desirable* and *feasible* performance objectives in the context of housing safety in the developing world.

4 CONCLUSIONS

This paper focuses on the presentation of the results of large-scale shaking table tests and the challenges of implementation of low-cost response modification strategies to developing countries. The uncertainties related to the implementation of ductile seismic design measures and highly engineered seismic isolation methods in low-income countries emerge from the lack of quality control, the improper inspection of the construction site and the inadequate application of the latest code provisions in these countries. These uncertainties require rethinking and contextualization of the conventional performance-based design approaches to align with the aforementioned construction limitations. Along these lines, this study aims to trigger a discussion on the feasibility of conventional performance-based design approaches in regions of low income raising the question of focusing on a single performance objective: Collapse Prevention. In this context, large-scale shaking table tests performed at University of Bristol [6,7,8] are demonstrated and the Low-Cost Hybrid Design (LC-HD) method is presented in detail. According to this method, the structure is designed as normal to modern seismic codes, however, in case these measures are not implemented or the design seismic intensity is exceeded, the low-cost seismic isolation located at the foundation level will act as an additional seismic protection mechanism.

REFERENCES

[1] M.C. Constantinou, A. Kartoum, A.M. Reinhorn, P. Bradford, Sliding isolation system for bridges: Experimental study. *Earthquake Spectra*, **8**, 321–344, 1992.

[2] P. Castaldo, G. Amendola, Optimal DCFP bearing properties and seismic performance assessment in nondimensional form for isolated bridges. *Earthquake Engineering and Structural Dynamics*, **50**(9), 2442–2461, 2021.

[3] M. Furinghetti, A. Pavese, V. Quaglini, P. Dubini, Experimental investigation of the cyclic response of double curved surface sliders subjected to radial and bidirectional sliding motions. *Soil Dynamics and Earthquake Engineering*, **117**, 190–202, 2019.

[4] A. Tsiavos, D. Schlatter, T. Markic, B. Stojadinovic, Experimental and analytical investigation of the inelastic behavior of structures isolated using friction pendulum bearings. *Procedia engineering*, **199**, 465-70, 2017.

[5] A. Sextos, Z. Zhang, N. Alexander, Large-Scale Testing for Enhancing the Resilience of Schools in Seismic Regions: Challenges and Cost-Efficient Solutions, R. Vacareanu and C. Ionescu (Eds.): Progresses in European Earthquake Engineering and Seismology Third European Conference on Earthquake Engineering and Seismology – Bucharest, 433–448, 2022. https://doi.org/10.1007/978-3-031-15104-0_26.

[6] A. Tsiavos, A. Sextos, A. Stavridis, M. Dietz, L. Dihoru, F. Di Michele, A. Nicholas, Low-cost hybrid design of masonry structures for developing countries: shaking table tests. *Soil dynamics and Earthquake Engineering*, **146**, 106675, 2021.

[7] A. Tsiavos, A. Sextos, A. Stavridis, M. Dietz, L. Dihoru, N.A. Alexander, Large-scale experimental investigation of a low-cost PVC 'sand-wich' (PVC-s) seismic isolation for developing countries. *Earthquake Spectra*, **36(4)**, 1886–1911, 2020.

[8] A. Tsiavos, A, Sextos, A. Stavridis, M. Dietz, L. Dihoru, N.A. Alexander, Experimental investigation of a highly efficient, low-cost PVC-Rollers Sandwich (PVC-RS) seismic isolation. *Structures*, **33**, 1590-1602, 2021.

[9] I. Banović, J. Radnić, N. Grgić, Geotechnical seismic isolation system based on sliding mechanism using stone pebble layer: shake-table experiments, *Schock and Vibration*, **1-26**, 9346232, 2019.

[10] S. Galano, A. Calabrese, State of the Art of Seismic Protection Technologies for Non Engineered Buildings (N-EBs) in Developing Regions of the World, *Journal of Earthquake Engineering*, 2023.

[11] D. De Domenico, D. Losanno, N. Vaiana, Experimental tests and numerical modeling of full-scale unbonded fiber reinforced elastomeric isolators (UFREIs) under bidirectional excitation. *Engineering Structures*, **274**, 115118, 2023.

[12] H.H. Tsang, Seismic isolation by rubber–soil mixtures for developing countries. *Earthquake Engineering and Structural Dynamics*, **37**, 283–303, 2008.

[13] S. Brunet, J.C. de la Llera, E. Kausel. Non-linear modeling of seismic isolation systems made of recycled tire-rubber. *Soil Dynamics and Earthquake Engineering*, **85**, 134–145, 2016.

[14] A. Tsiavos, N.A. Alexander, A. Diambra, E. Ibraim, J.P. Vardanega, A. Gonzalez-Buelga, A. Sextos. A sand-rubber deformable granular layer as a low-cost seismic isolation strategy in developing countries: experimental investigation, *Soil Dynamics and Earthquake Engineering*, **125**, 105731, 2019.

[15] M.P.A Gatto, L. Montrasio, L. Zavatto. Experimental Analysis and Theoretical Modelling of Polyurethane Effects on 1D Wave Propagation through Sand-Polyurethane Specimens, Journal of Earthquake Engineering, 2021.

[16] A. Tsiavos, Methodologies and design parameters that influence the efficiency and sustainability of geotechnical seismic isolation systems, Proceedings of the Third European Conference on Earthquake Engineering and Seismology (3ECEES), Bucharest, 2022.

[17] A. Tsiavos, D. Kolyfetis, G. Panzarasa, I. Burgert, B. Stojadinovic, Shaking table investigation of a low-cost and sustainable timber-based energy dissipation system with recentering ability. Bulleting of Earthquake Engineering, 2022.
https://doi.org/10.1007/s10518-022-01464-2

[18] J. Sun, H. Guo, J. Ribera, C. Wu, K. Tu, M. Binelli, G. Panzarasa, F. Schwarze, Z. Wang, I. Burgert, Sustainable and biodegradable timber sponge piezoelectric nanogenerator for sensing and energy harvesting applications. *ACS Nano,* **14**, 14665–16474, 2020.