Geotechnical seismic isolation system based on rubber-soil mixtures: analytical modelling, experimental testing and field measurement

Un system d'isolation parasismique composée des mélanges du sous-sol avec du caoutchouc: simulation numérique et des essais expérimentales

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ABSTRACT: The innovative concept of geotechnical seismic isolation (GSI) with the use of a continuous layer of low-modulus rubber-soil mixtures (RSM) surrounding the foundation of the structure has attracted considerable research interest globally in the past decade. This paper presents a summary of the recent works completed by the authors. This includes an equivalent-linear lumped-parameter analytical model for explaining the isolation mechanism of the GSI system. On the other hand, the effectiveness of the isolation system has been validated by geotechnical centrifuge modelling. Its dynamic soil-structure interaction behaviour has also been demonstrated by using the Euroeseistest-EuroProteas model structure (http://euroseisdb.civil.auth.gr). It has been confirmed that the controlled stiffness and damping of the GSI-RSM foundation layer can reduce the rocking stiffness, thereby enhances the seismic isolation capability, whilst without having large permanent deformations due to the higher elasticity of the RSM material. Finally, a series of shaking table tests have also been conducted to examine the effectiveness of GSI-RSM system on isolating electrical transformers. Generally, it was found in these studies that a 30% to 60% reduction of structural demand can be achieved.

RÉSUMÉ: Nous proposons une conception originale de l'isolation parasismique géotechnique (GSI) a l'aide d'une couche de sous-sol de rigidité faible, composée d'un mélange du sol avec du caoutchouc. L'article présente un résumé des travaux de recherche faites par les auteurs sur ce sujet nouveaux qui attire l'intérêt les derniers années. Parmi les sujets présentés est le model analytique faite pour expliquer le mécanisme de l'isolation géotechnique, et différentes études expérimentales a la centrifugeuse et au Euroeseistest-EuroProteas structure experimental (http://euroseisdb.civil.auth.gr), pour mieux comprendre le comportement du system compose, les effets de l'interaction sol-structure et finalement pour valider la méthode. Les études faites et les résultats acquis ont prouvé que avec le contrôle de la rigidité et de l'amortissement du system sous-sol-caoutchouc qui affecte le rigidité de balancement du system, il est possible de prendre avantage de l'isolation sismique offerte ainsi, sans avoir en revanche des déformations irréversibles importantes. En conséquences le system offre des capacités d'isolation sismique assez intéressantes qui permet une réduction de demande structurale de 30% a 60%. Le system a été aussi teste au table vibrante pour étudier l'isolation d'un transformateur électrique de grand dimensions.

KEYWORDS: geotechnical seismic isolation, rubber-soil mixtures, waste tyre, soil-structure interaction, augmented rocking.

1 INTRODUCTION

Geotechnical seismic isolation (GSI) takes advantage of the dynamic interaction between structure and low-modulus foundation material (Tsang & Pitilakis 2019). The foundation natural soil material is replaced or modified down to a certain depth (e.g. 2–3 m) by well-controlled low-modulus materials such as rubber-soil mixtures (RSM) (initially proposed in Tsang 2008), in order that the soil-foundation-structure interaction (SFSI) favourably affects the overall structural response. The key advantage of the GSI system is that seismic energy is dissipated before it transmits into the structure, which is fundamentally different from conventional seismic isolation systems or other earthquake protection techniques (Tsang 2009, Karatzia & Mylonakis 2017). This is a paradigm shift.

Whilst the concept of GSI is not limited to a particular choice of materials, RSM were chosen because: (i) rubber has been widely used in vibration damping and isolation, and both the static and dynamic properties of RSM were available in the literature, and (ii) waste tyres are available in abundance with an urgent need of recycling, which also provides a green and economical source for RSM (Tsang 2012, Xiong & Li 2013, Tsiavos et al. 2019, Chiaro et al. 2019). Granulated RSM are characterised by nonlinearity and high damping in the medium-to-high strain range, with properties that can be adjusted via rubber content (Senetakis et al. 2012). With high shear resistance, low shear modulus (Anastasiadis et al. 2012), controllable stress-strain behaviour and increased damping, RSM are a desirable candidate for use in GSI system.

A significant amount of research works has been carried out to demonstrate the potential of GSI-RSM system (e.g. Tsang et al. 2009, Shimamura 2012, Tsang et al. 2012, Kaneko et al. 2013, Pitilakis et al. 2015, Brunet et al. 2016, Forcellini 2017, Nanda et al. 2018, Dhanya et al. 2020). However, the isolation mechanism has not been thoroughly investigated. Hence, an equivalent-linear lumped-parameter model was recently developed for dynamic SFSI analysis of the GSI system and for characterising its isolation mechanism (Tsang & Pitilakis 2019). This analytical model has been verified based on a 2-D finite element model. On the other hand, experimental research is indispensable for confirming its effectiveness in reducing structural response. To this end, centrifuge modelling with an earthquake shaker under an acceleration field of 50 g was conducted (Tsang et al. 2021) such that the actual nonlinear response characteristics of RSM and subsoil can be mimicked in scaled models. Also, shake table tests (in a 1-g environment) on scaled models of a coupled soil-structure system of the electrical transformer were also performed as a case study (Li et al. in preparation). This article briefly reports these recent works.

2 ANALYTICAL MODELLING

The performance of the GSI system has been studied through various numerical, physical and hybrid modelling techniques; but due to the complexity of the problem, the isolation mechanism has not been thoroughly investigated. Hence, Tsang & Pitilakis (2019) aimed at initiating this aspect of development. A simple and efficient lumped-parameter model has been developed for analysing the dynamic SFSI of the GSI system (Figure 1). Considering the importance of various nonlinearities involved, a theoretical approach for estimating effective shear strain has been derived to capture the nonlinearity of subsurface materials by the equivalent-linear method, which is widely used in practical geotechnical seismic analysis. The analytical model has then been verified based on numerical modelling of a coupled soil-structure system using a 2D finite element model. The effectiveness of the equivalent-linear lumped-parameter model has also been demonstrated through a representative case study, based on which the main features of the isolation mechanism are investigated.

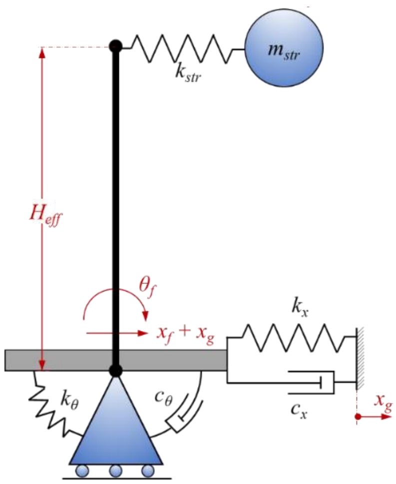


Figure 1. The mass-spring-dashpot model of a soil-shallow foundation-structure system adopted in the equivalent-linear analytical model (Tsang & Pitilakis 2019).

Figure 2(a) shows the reduction of structural displacement demand of GSI system with RSM layer of 2 m thick and 30% rubber by weight. It was concluded that the seismic isolation capability of the GSI system is founded on the reduced lateral stiffness of the RSM layer and the lower modulus of RSM that reduces the rocking stiffness, which leads to the amplification of foundation rotation as shown in Figure 2(b).

To a certain degree, this might be considered analogous to the traditional seismic isolation with the use of rubber bearings, which is further augmented by rocking foundation isolation. GSI system aims to redistribute seismic demand on the whole SSFS system to a well-controlled low-modulus foundation material, such that the demand on the superstructure can be reduced and the associated damage can be minimised.

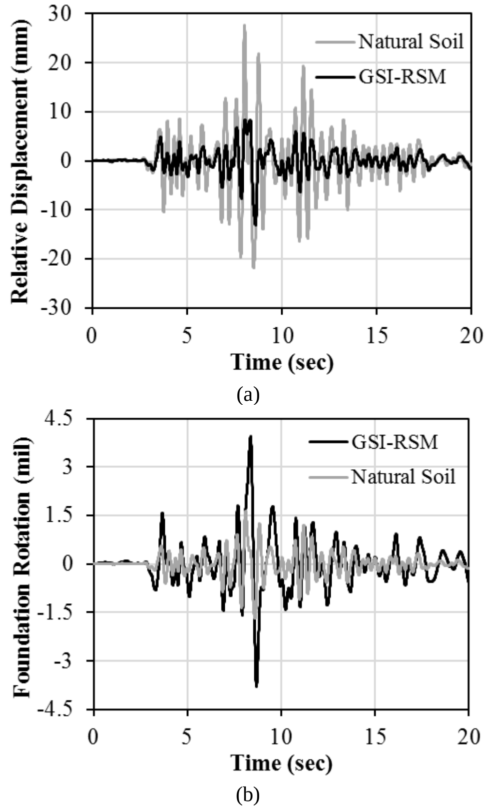


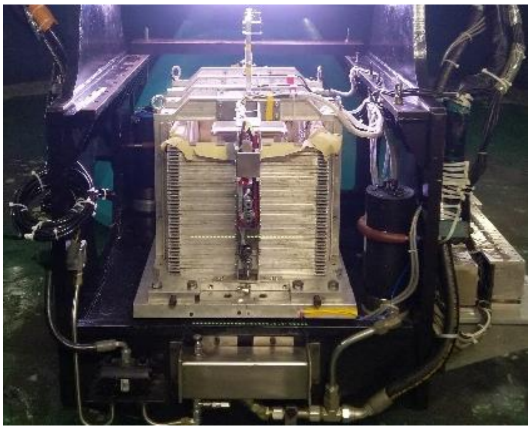
Figure 2. (a) Time histories of (a) the displacement response of the SDOF superstructure relative to the foundation, and (b) the rotation response of the foundation (in the unit of milliradian, i.e. mil) under the 1994 Northridge earthquake ground shaking (Tsang & Pitilakis 2019).

3 GEOTECHNICAL CENTRIFUGE TESTING

Centrifuge modelling with an earthquake shaker under an acceleration field of 50 g was conducted at National Central University in Taiwan (Figure 3) in order to mimic the actual nonlinear dynamic response characteristics of RSM and subsoil in a coupled soil-foundation-structure system (Tsang et al. 2021). RSM with 30% and 40% rubber by weight were used in the tests. It was found in previous studies (Sheikh et al. 2013; Mashiri et al. 2015; Disfani et al. 2017) that the skeleton of RSM is formed by both soil and rubber particles when rubber content is between 10–18% and 30–35% by weight. Hence, RSM-30% would behave as a true mixture, whilst RSM-40% is expected to exhibit rubber-like behaviour.

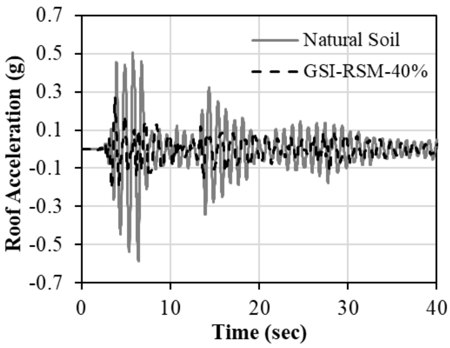
It is evidenced from the test results, as shown in Figure 4(a), that the structural demand can be reduced by as much as 40–60%. An increase was also observed in both the horizontal and rotation responses of the foundation. The increase in horizontal response of the foundation is analogous to the large shear displacement that is experienced by rubber bearings during an earthquake, whereas the increased yet reversible rotation response of the foundation due to the reduced rocking stiffness, as observed in Figure 4(b), leads to an augmented rocking mechanism. Importantly, the elasticity of the properly designed RSM layer can avoid soil failure/yielding and minimise the undesirable residual ground deformation due to rotation and sliding.

(a)

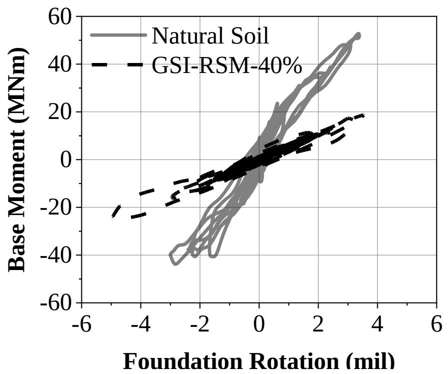


(b)

Figure 3. (a) Overview of the geotechnical centrifuge facility at National Central University in Taiwan (Hung & Liao 2020), and (b) the laminar box mounted in the swing basket.



(a)



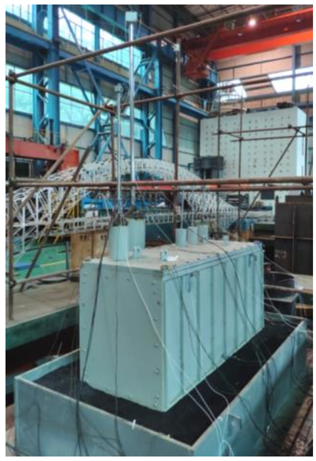
(b)

Figure 4. (a) Time histories of the total acceleration response recorded at the roof, and (b) the foundation moment-rotation response under the 1940 El Centro earthquake ground shaking.

4 SHAKING TABLE TESTING

Electrical transformers were repeatedly damaged in recent earthquakes, causing tremendous loss to power infrastructure (Li et al. 2017, 2018). GSI-RSM system can be a promising candidate for mitigating structural responses caused by both horizontal and vertical ground motions. A shaking table test was carried out by Li et al. (in preparation) to investigate the performance of GSI-RSM system for protecting electrical transformers on a shallow foundation. A prototype 1000 kV electrical transformer is shown in Figure 5(a), whilst the 1:5 scaled transformer model sitting on RSM is shown in Figure 5(b). Steel was used for fabricating the scaled bushings of the transformer model.

(a)



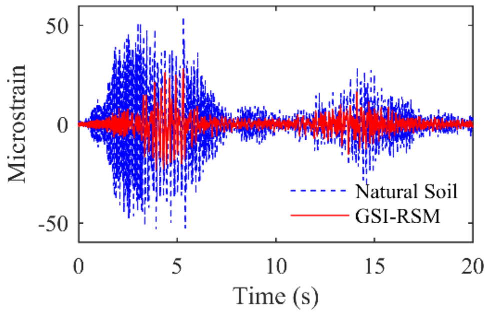
(b)

Figure 5. (a) A prototype 1000 kV electrical transformer selected for the case study, and (b) the shaking table test set-up for the isolated case where prototype transformer is placed on RSM with 35% rubber by weight (Li et al. in preparation) (55% in 1:5 scaled model in order to achieve the target elastic modulus that satisfies Cauchy condition as recommended in Moncarz & Krawinkler 1981 and Meymand 1998).

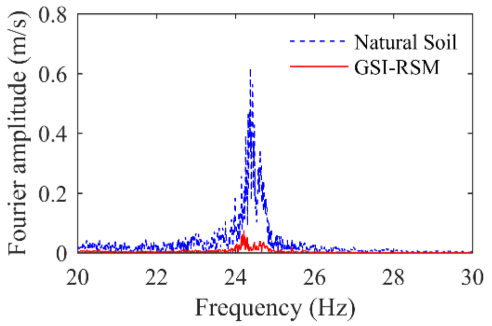
The bushings on the transformer model had different fundamental frequencies, which provided a chance to investigate the performance of GSI-RSM system on a wide range of natural frequencies. It was observed in the shake table test that the reduced horizontal and rotational stiffnesses of the RSM foundation layer were the key attributes to the isolation effectiveness. The results show that the GSI-RSM system was able to effectively reduce the seismic responses of all three sizes of bushings on the transformer model by an average of 35-40% when it was subjected to either horizontal-only or combined horizontal-and-vertical ground motions. The vertical acceleration response of various components also decreased when the transformer model was subjected to the combined horizontal-and-vertical actions. Figure 6(a) shows the reduction of strain response, which is the most important performance indicator for the bushings of the transformer. The Fourier amplitude spectra of the acceleration response of the non-isolated and the GSI-isolated cases are shown in Figure 6(b).

5 FULL-SCALE TESTING WITH EUROESEISTEST-EUROPROTEAS MODEL STRUCTURE

An extensive large-scale experimental campaign on RSM as an innovative seismic isolation material was conducted on the existing large-scale model structure EuroProteas built in the Euroseistest (sdgee.civil.auth.gr/facilities/europroteas.html) in the framework of the SERA project (http://www.sera-eu.org/).



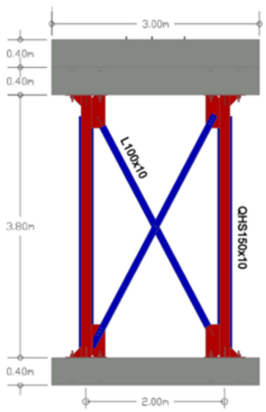
(a)



(b)

Figure 6. (a) Flexural strain response recorded at the bottom of the low voltage bushing, and (b) the Fourier amplitude spectra of acceleration response at the top of the bushing under the 2008 Wenchuan earthquake ground shaking with PGA of 0.4 g (Li et al. in preparation).

The EuroProteas model structure is a perfectly symmetric and reconfigurable structure that is particularly designed to mobilise strong interaction with its foundation soil as it is a stiff structure with a large superstructure mass founded on soft foundation soil (Pitilakis D. et al. 2018). It is founded on a square reinforced concrete slab (C20/25) with dimensions 3.0m x 3.0m x 0.4m which rests on the ground surface. The superstructure mass consists of two reinforced concrete slabs identical to the foundation slab that are supported on four square hollow steel columns (QHS 150mm x 150mm x 10mm), which are clamped on the foundation. L-shaped (100mm x 100mm x 10mm) X-braces connect the steel columns on all sides of the structure, ensuring its perfect symmetry. The total mass of the structure is calculated approximately at 28.5Mg where its outer dimensions are 3.0m x 3.0m x 5.0m (Figure 7).



(a) (b)

Figure 7. (a) A 2D sketch and (b) a photo of the large-scale EuroProteas model structure at Euroseistest site.

The foundation soil stratigraphy and its dynamic characteristics are well investigated in a comprehensive in-situ and laboratory geotechnical and geophysical testing program and validated via an extensive seismic recording program reported in earlier studies (Pitilakis K. et al. 1999). The foundation soil was replaced up to a depth of 0.5m with three different rubber-gravel mixtures (RGM) backfills (with rubber contents 0%, 25%, and 75% by volume, respectively) (Figure 8) to investigate the response of the soil-structure system under the effects of different rubber contents.

(a)

(b)

(c)

Figure 8. The three soil pits (of dimensions 3.2m x 3.2m x 0.5m) filled with rubber-gravel mixtures (RGM): (a) 0%, (b) 25% and (c) 75% rubber contents by volume.

Laboratory resonant column and cyclic triaxial tests, as well as conventional granularity and compaction tests, were performed to determine the characteristics of different RGM (Pistolas et al. 2018; Vratsikidis et al. 2020). The first test pit named 0% was replaced only with gravel to serve as benchmark test, while in the following pits two RGM with different rubber contents were used (25% and 75% by volume). The EuroProteas model structure was placed at the surface of the replaced foundation soil, and extensive experimental free and forced-vibration tests were performed (Vratsikidis et al. 2020). A dense instrumentation scheme comprising high-resolution accelerometers, seismometers, and non-contact laser displacement sensors was designed and installed to fully monitor and record the response of the structure and the foundation soil in three-dimensions (Figure 9).

A characteristic result is portraited in Figure 10, which depicts a representative comparison of the response in terms of recorded acceleration at the top of the structure during a free-vibration test where the foundation soil is composed of gravels only and mixed with 25% rubber content by volume. A significant decrease in the frequency content and amplitude is noticed in the recorded structural response with increased rubber content. More results and comparisons are reported in Vratsikidis et al. (2020) that an increase in the rubber content affects significantly, and favourably, the predominant frequency and the damping of the soil-structure system and enhances in that way the seismic isolation capability of RGM material.

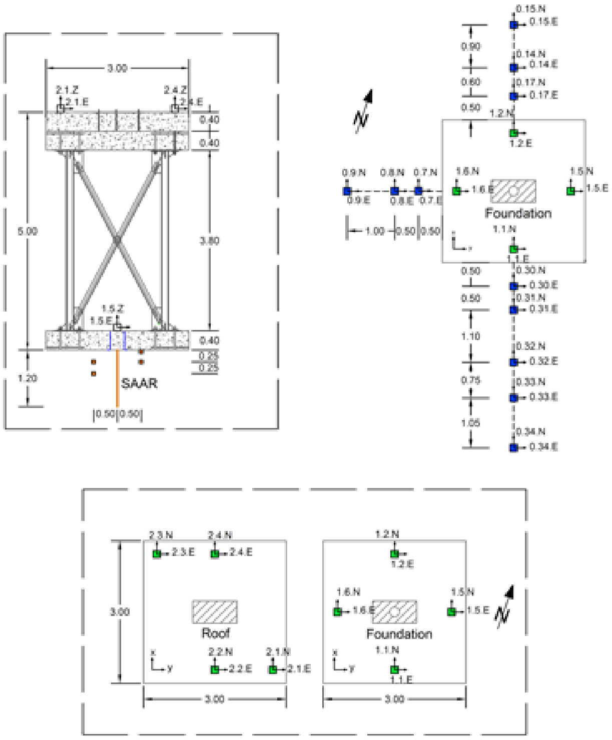


Figure 9. Instrumentation layout of the EuroProteas structure and the foundation soil.

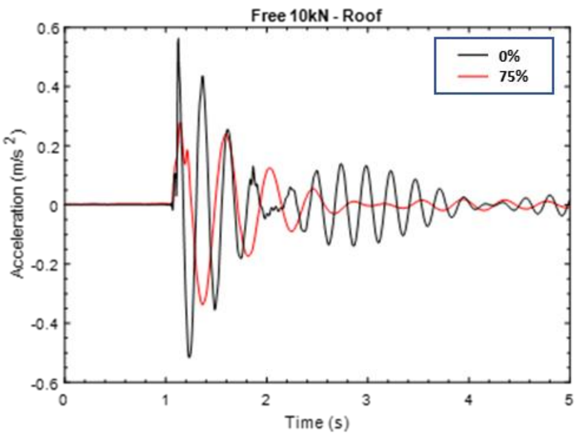


Figure 10. Acceleration response recorded at the top of the structure during a free-vibration test for cases of 0% and 25% rubber content by volume in the mixture.

6 CONCLUSIONS

Geotechnical seismic isolation (GSI) is an emerging technology for protecting structures from earthquake ground shaking by exploiting the beneficial effects of soil-foundation-structure interaction (SFSI). GSI system aims to redistribute seismic demand on the whole soil-foundation-structure system to a well-controlled low-modulus foundation material, such that the demand on the superstructure can be reduced and the associated damage can be minimised.

A lumped-parameter analytical model has been developed for GSI system, which has taken into account the nonlinearity of subsurface materials in the soil-foundation-structure model. A new theoretical approach for estimating effective shear strain as part of the equivalent-linear method has been proposed, whilst detailed derivation can be found in Tsang & Pitilakis (2019). The isolation mechanism of GSI system has been demonstrated and explained through a case study, of which some results are presented in the first part of this paper.

The second part of this paper briefly presents a dynamic centrifuge test on the performance of GSI system that is founded on the use of rubber-soil mixtures (RSM) as a well-controlled low-modulus foundation material. An average of 40–60% reduction of structural demand in terms of roof acceleration, inter-storey drift and base moment was achieved. The increased yet reversible horizontal and rotation responses of the foundation were evidenced, which also highlights the unique “augmented rocking mechanism”. The observed elasticity of GSI-RSM foundation layer can avoid soil failure/yielding and minimise the undesirable residual ground deformation due to rotation and sliding. More detail can be found in Tsang et al. (2021).

On the other hand, a shaking table test has been conducted on GSI-RSM system for protecting electrical transformers. An average of 35-40% reduction of bushing responses has been achieved. It has further been confirmed that the reduced stiffness of RSM layer is the key attribute to isolation effectiveness. The performance was comparable when vertical excitation was jointly applied (Li et al. in preparation).

Finally, an extensive large-scale experimental program on the innovative GSI-RSM system conducted on the existing large-scale model structure EuroProteas is briefly discussed. The foundation soil was replaced up to a depth of 0.5m with three different rubber-gravel mixtures (RGM) backfills (with rubber contents 0%, 25%, and 75% by volume, respectively). Free vibration and forced-vibration tests were performed. A significant decrease in the frequency content and amplitude is noticed in the recorded structural response with increased rubber content. More results are reported in Vratsikidis et al. (2020).

GSI is aligned perfectly with the low-damage seismic design strategy, which is increasingly being used to enhance public safety and to build a more resilient society. Further experimental and theoretical investigation is required to improve and optimise the GSI system for different structural typologies and soil conditions.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Anastasiadis A., Senetakis K. and Pitilakis K. 2012. Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures. *Geotech Geol Eng* 30 (2), 363–382.

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

Chiaro G., Palermo A., Granello G., Tasalloti A., Stratford C. and Banasiak L.J. 2019. Eco-rubber seismic-isolation foundation systems: a cost-effective way to build resilience. *Proceedings of the 2019 Pacific Conference on Earthquake Engineering*, Auckland, New Zealand, 4-6 April 2019.

Dhanya J.S., Boominathan A. and Banerjee S. 2020. Response of low-rise building with geotechnical seismic isolation system. *Soil Dynamics and Earthquake Engineering* 136, Article no. 106187.

Disfani M.M., Tsang H.H., Arulrajah A. and Yaghoubi E. 2017. Shear and Compression Characteristics of Recycled Glass-Tire Mixtures. *ASCE Journal of Materials in Civil Engineering* 29 (6), Article no. 06017003.

Forcellini D. 2017. Assessment on geotechnical seismic isolation (GSI) on bridge configurations. *Innovative Infrastructure Solutions* 2, 9. DOI: 10.1007/s41062-017-0057-8

Hung W.Y. and Liao T.W. 2020. LEAP-UCD-2017 Centrifuge Tests at NCU. In: Kutter B., Manzari M., Zeghal M. (eds) *Model Tests and Numerical Simulations of Liquefaction and Lateral Spreading*. Springer, Cham.

Kaneko T., Orense R.P., Hyodo M. and Yoshimoto N. 2013. Seismic response characteristics of saturated sand deposits mixed with tire chips. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 139 (4), 633-643.

Karatzia X. and Mylonakis G. 2017. Geotechnical isolation of pile-supported bridge piers using EPS geofoam. *Proceedings of the 16th World Conference on Earthquake Engineering*, Santiago, Chile, January 9-13, 2017.

Li S., Tsang H.H., Cheng Y. and Lu Z. 2017. Effects of sheds and cemented joints on seismic modelling of cylindrical porcelain electrical equipment in substations. *Earthquakes Struct* 12, 55–65.

Li S., Tsang H.H., Cheng Y. and Lu Z. 2018. Seismic testing and modeling of cylindrical electrical equipment with GFRP composite insulators. *Compos Struct* 194, 454–67.

Li S., Cheng Y., Tsang H.H., Lu Z. and Pitilakis K. Shaking table test on the performance of electrical transformer on geotechnical seismic isolation (in preparation).

Mashiri M.S., Vinod J.S., Sheikh M.N. and Tsang H.H. 2015. Shear Strength and Dilatancy Behaviour of Sand-Tire Chip Mixtures. *Soils and Foundations* 55 (3), 517-528.

Meymand P. 1998. *Shaking Table Scale Model Tests of Nonlinear Soil-Pile-Superstructure Interaction in Soft Clay*, Ph.D. Dissertation, University of California, Berkeley.

Moncarz P. and Krawinkler H. 1981. *Theory and Application of Experimental Model Analysis in Earthquake Engineering*. Rpt. No. 50, John Blume Earthquake Eng. Ctr., Stanford Univ.

Nanda R.P., Dutta S., Khan H.A. and Majumder S. 2018. Seismic Protection of Buildings by Rubber-Soil Mixture as Foundation Isolation. *International Journal of Geotechnical Earthquake Engineering* 9 (1), 99-109. DOI: 10.4018/IJGEE.2018010106

Pistolas G.A., Anastasiadis A. and Pitilakis K. 2018. Dynamic Behavior of Granular Soil Materials Mixed with Granulated Rubber: Influence of Rubber Content and Mean Grain Size Ratio on Shear Modulus and Damping Ratio for a Wide Strain Range. *Innovative Infrastructure Solutions* 3 (47).

Pitilakis D., Rovithis E., Anastasiadis A., Vratsikidis A. and Manakou M. 2018. Field evidence of SSI from full-scale structure testing. *Soil Dynamics and Earthquake Engineering* 112, 89–106. DOI: 10.1016/j.soildyn.2018.04.024

Pitilakis K., Karapetrou S. and Tsagdi K. 2015. Numerical investigation of the seismic response of RC buildings on soil replaced with rubber–sand mixtures. *Soil Dynamics and Earthquake Engineering* 79, 237–252.

Pitilakis K., Raptakis D., Lontzetidis K., Tika-Vasillikou T. and Jongmans D. 1999. Geotechnical and geophysical description of EUROSEISTEST, using field, laboratory tests and moderate strong motion records. *Journal of Earthquake Engineering* 3 (3), 381-409.

Senetakis K., Anastasiadis A. and Pitilakis K. 2012. Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. *Soil Dynamics and Earthquake Engineering* 33, 38–53.

Sheikh M.N., Mashiri M.S., Vinod J.S. and Tsang H.H. 2013. Shear and Compressibility Behaviors of Sand-Tire Crumb Mixtures. *ASCE Journal of Materials in Civil Engineering* 25 (10), 1366-1374.

Shimamura A. 2012. *Study on Earthquake Response Reduction by Improved Composite Geo-material using Rubber Chips and Fibrous materials* (translated from Japanese). PhD Thesis, Osaka University, Japan. (in Japanese)

Tsang H.H. 2008. Seismic isolation by rubber–soil mixtures for developing countries. *Earthquake Engineering and Structural Dynamics* 37 (2), 283–303.

Tsang H.H. 2009. Geotechnical seismic isolation. In: *Earthquake Engineering: New Research*, New York, U.S.: Nova Science Publishers Inc; p. 55–87.

Tsang H.H. 2012. Uses of scrap rubber tires. In: *Rubber: Types, Properties and Uses*, New York, U.S.: Nova Science Publishers Inc; p. 477-492.

Tsang H.H. and Pitilakis K. 2019. Mechanism of geotechnical seismic isolation system: Analytical modeling. *Soil Dynamics and Earthquake Engineering* 122, 171–184.

Tsang H.H., Lo S.H., Xu X. and Sheikh M.N. 2012. Seismic isolation for low-to-medium-rise buildings using granulated rubber–soil mixtures: numerical study. *Earthquake Engineering and Structural Dynamics* 41, 2009–2024.

Tsang H.H., Lam J.Y.K., Yaghmaei-Sabegh S. and Lo S.H. 2009. Protecting underground tunnel by rubber–soil mixtures. *Proceedings of the 7th International Conference on Lifeline Earthquake Engineering*, ASCE-TCLEE, Oakland, California, U.S., June 28 – July 1, 2009.

Tsang H.H., Tran D.P., Hung W.Y., Pitilakis K. and Gad E.F. 2021. Performance of geotechnical seismic isolation system using rubber-soil mixtures in centrifuge testing. *Earthquake Engineering and Structural Dynamics* 50, 1271-1289.

Tsiavos A., Alexander N.A., Diambra A., Ibraim E., Vardanega P.J., Gonzalez-Buelga, A. and Sextos, A. 2019. A sand-rubber deformable granular layer as a low-cost seismic isolation strategy in developing countries: Experimental investigation. *Soil Dynamics and Earthquake Engineering* 125, Article no. 105731.

Vratsikidis A., Tsinaris A., Kapouniaris A., Anastasiadis A., Pitilakis D. and Pitilakis K. 2020. Full-Scale Testing of a Structure on Improved Soil Replaced with Rubber-Gravel Mixtures, *1st Int. Symposium on Construction Resources for Environmentally Sustainable Technologies* (CREST2020) March, 2021 Fukuoka, Japan (Shiiki Hall, Kyushu University).

Xiong W. and Li Y. 2013. Seismic isolation using granulated tire–soil mixtures for less-developed regions: experimental validation. *Earthquake Engineering and Structural Dynamics* 42, 2187–2193.