3rd International Conference on Natural Hazards & Infrastructure
5-7 July 2022, Athens, Greece

Large-scale field experiments on the geotechnical seismic isolation capability of gravel-rubber mixtures

Athanasios Vratsikidis[1], Anastasios Kapouniaris, Dimitris Pitilakis, Anastasios Anastasiadis
Aristotle University of Thessaloniki

ABSTRACT

We present the first large-scale experimental campaign performed on the prototype structure of EuroProteas in Thessaloniki, Greece, to assess the effectiveness of gravel-rubber mixture (GRM) layers placed underneath shallow foundations as a means of geotechnical seismic isolation (GSI). The paper aims to provide insight into the response of the GSI-structure systems in the forced vibration experiments. Three GRM with different rubber content per mixture weight (0%, 10%, and 30%) were used as foundation soil layers. Before the execution of the field experiments, laboratory tests were carried out to determine the physical, mechanical, and dynamic properties of the three GRM. A large number of instruments were installed to fully monitor the response of the structure and the GRM layer. An eccentric mass shaker applied harmonic forces at the top of the structure over a wide range of frequencies and force amplitudes. The field test results showed that a GSI layer of 0.50 m thickness composed of a GRM of 30% rubber content reduces the fundamental frequency of vibration of the GSI-structure system and thus its stiffness, whereas the structure tends to oscillate as a rigid body over soft soil. Additionally, the increased material damping of the mixtures leads to an increase in the system's damping. Overall, the recorded motion at the top of the structure is effectively reduced indicating that a thin GRM layer of 30% rubber content per mixture weight can be an efficient and affordable seismic isolation scheme.

Keywords: geotechnical seismic isolation, gravel-rubber mixtures, experimental soil-structure interaction, large-scale testing

INTRODUCTION

Over the past 40 years, seismic isolation systems in the form of laminated elastomeric bearings, sliding bearings and friction-pendulum systems were extensively studied and widely used in civil engineering practice to reduce earthquake-induced structural damage (Naeim & Kelly, 1999; Banović et al., 2019). However, due to the increased cost of their installation and maintenance, the adoption of such solutions is almost prohibited for conventional buildings, especially in developing countries. Recently, researchers have investigated the exploitation of the soil's deformability underneath the foundations as a natural passive isolation mechanism (Anastasopoulos et al., 2010; Gazetas et al., 2013). Although the studies have demonstrated that the concept of rocking isolation is quite effective in reducing the seismic demand certain drawbacks associated with the residual differential settlement of the structure may arise.

Over the past decade, several researchers have examined geotechnical seismic isolation (GSI) as an innovative alternative technique to control the structural response (Tsang, 2009). Various materials have been proposed for the improvement of the foundation soil, however, much of the current literature on GSI and geostructures has paid attention to the use of soil-rubber mixtures (SRM) or gravel-rubber mixtures (GRM) due to their favorable physical and dynamic properties (Kim & Santamarina, 2008; Tsang, 2008; Anastasiadis et al., 2012a; Anastasiadis et al., 2012b; Senetakis et al., 2012a; Senetakis et al., 2012b; Senetakis & Anastasiadis, 2015;

[1] avratsik@civil.auth.gr

Tsinaris, 2018). Several numerical studies thus far have investigated the use of SRM or GRM as a geotechnical seismic isolation (GSI) system in the form of a layer underlying the foundation of a structure (Tsang, 2008; Mavronicola et al., 2010; Pitilakis et al., 2015; Brunet et al., 2016; Tsang & Pitilakis, 2019; Dhanya et al., 2020; Pistolas et al., 2020). However, very few studies, focused mainly on laboratory and small-scale testing, have investigated experimentally the seismic isolation potential of the SRM/GRM (Xiong et al., 2014; Tsiavos et al., 2019; Tsang et al., 2021).

Moreover, rubber grains used in the mixtures are derived from scrap tires, the accumulation and disposal of which has become a severe global environmental issue (Torretta et al., 2015). Therefore, the use of GRM as a construction material has advantageous ecological effects. Considering that most of the developing and agricultural countries have not yet explored alternative uses of scrap tires, the use of GRM in the seismic isolation of conventional structures in developing countries can be considered an affordable and sustainable alternative.

The present study presents the first experimental campaign conducted to assess the effectiveness of gravel-rubber mixture (GRM) layers placed underneath shallow foundations as a means of geotechnical seismic isolation (GSI). Ambient noise was recorded, and free- and forced-vibration tests were performed on the prototype structure of EuroProteas (http://euroseisdb.civil.auth.gr/sfsi) after replacing the foundation soil with three different GRM. The experimental findings show that a thin GSI layer with a height of 0.50 m and composed of a GRM with 30% rubber content per mixture weight could effectively isolate the structure.

EXPERIMENTAL CAMPAIGN

Test Structure

EuroProteas prototype structure (Fig.1) was designed according to modern codes and constructed to function as a test structure in large-scale experiments for the investigation of soil-foundation-structure interaction phenomena and the wave propagation in soil due to the vibration of the structure. It is a stiff structure with a large superstructure mass founded on soft soil so that the soil's nonlinear behavior is activated during the excitation of the soil-structure system.

Two identical reinforced concrete slabs (C20/25) of dimensions 3.00x3.00x0.40 m and a mass of 9.16 Mg each represent the superstructure mass, which is supported by four steel columns of section QHS150x150x10 mm. The columns are clamped on a foundation slab similar to the superstructure slabs and are connected with steel X-braces of section L100x100x10 mm in all directions to increase the stiffness of the structure and ensure its symmetry. The total mass of the structure is calculated approximately at 28.5 Mg. More details on the prototype's design and construction can be found in Pitilakis et al. (2018). The fixed-base fundamental natural frequency of EuroProteas is estimated numerically at 9.13Hz.

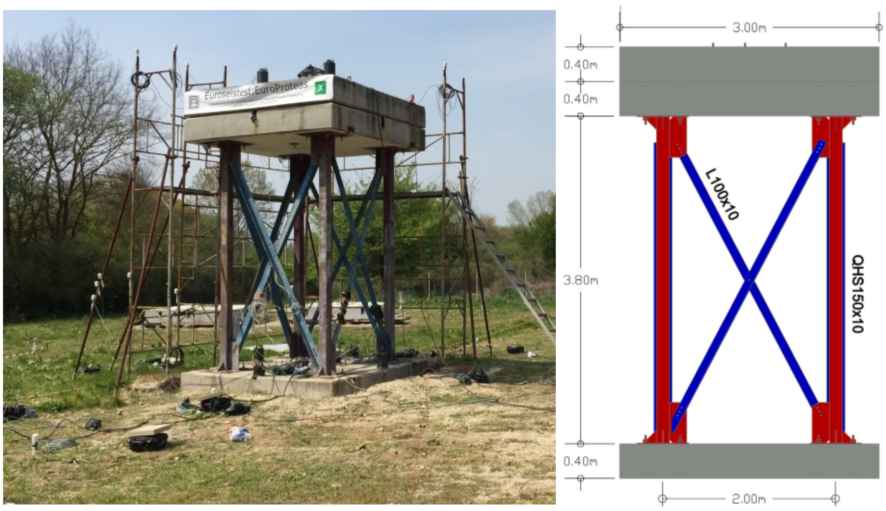

Figure 1. *A photo and a 2D sketch of EuroProteas prototype structure*

Foundation Soil

The soil formation and its physical and dynamic properties at EuroSeisTest experimental facility have been extensively investigated and presented in previously published geophysical and geotechnical studies (Pitilakis et al., 1999; Manakou et al., 2010). Furthermore, additional geotechnical and geophysical surveys were carried out before the construction of the structure, including drilling boreholes, down-hole tests, resonant column, and cyclic triaxial tests on undisturbed soil samples, to define in detail the soil profile immediately below the structure (Pitilakis et al., 2018). The foundation soil shear wave velocity varies from 100 to 150 m/s up to a depth of 5 m and then increases to more than 250 m/s at 25 m depth.

As this research seeks to investigate the influence of the rubber content of a GRM foundation layer in the dynamic response of a structure and its seismic isolation potential, three GRM with different fractions of rubber and gravel were considered as foundation soil materials. We defined the rubber content per mixture weight (p.w.) 0, 10, and 30% for the three foundation GRM (corresponding to 0, 25, and 75% per mixture volume, respectively).

Before installing the GRM in the field, a laboratory experimental program was carried out at the Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering of the Aristotle University of Thessaloniki in Greece, including sieve analysis, resonant column tests and cyclic triaxial compression tests, to determine the physical, mechanical and dynamic properties of the three GRM. Quarry gravel with ID C1D21 consisted of angular particles and classified as GP and synthetic granulated rubber material with ID R3 classified as GR according to ASTM-D2487-17 (2017) were mixed to create the mixtures. Due to the large grain sizes of C1D21 and R3 and the limitation of the maximum allowed dimensions of the specimens in the resonant column apparatus, an additional GRM composed of gravel with ID C1D9 and granulated rubber with ID R2 was also studied in the laboratory. The two additional materials have smaller medium grain sizes but the same mean grain size ratio ($D_{50,r}$ / $D_{50,g}$) so that their response in low-strain conditions could be considered approximately the same with the corresponding response of the GRM used in the field (Anastasiadis et al., 2012b; Senetakis et al., 2012b; Pistolas et al., 2018). The properties and the classification characteristics of the materials mixed to create the GRM are presented in Table 1, while the physical properties of the GRM used in the field experiments are presented in Table 2.

Table 1. Properties and classification of natural and synthetic materials

Properties \ Data	**Natural Materials**		**Synthetic Materials**	
Material	Gravel	Gravel	Rubber	Rubber
Material code	C1D21	C1D9	R3	R2
G_s	2.67	2.67	1.10	1.10
D_{50} *(mm)*	20.76	8.96	3.27	1.58
C_u	1.48	1.38	1.72	1.79
Classification	GP	GP	GR	GR

Table 2. Physical properties of the GRM installed as foundation soil layers

GRM ID	**Rubber content (%)**	$D_{50,r}/D_{50,g}$	D_r **(%)**	γ_d **(kN/m³)**	G_s
GRM100/0	0	-	98	16.2	2.67
GRM90/10	10	0.16	98	15.2	2.51
GRM70/30	30	0.16	59-71	11.8	2.19

The G/G_o-logγ-D curves of the three GRM as determined are presented in Fig.2 in four different mean effective isotropic confining pressures. It is apparent that an increase in the rubber content leads to more linear G/G_o-logγ curves due to the more rubber-like behavior of the mixture. In contrast, the increase of the rubber content results in an increase in the damping ratio and a more non-linear shape of the D-logγ curves.

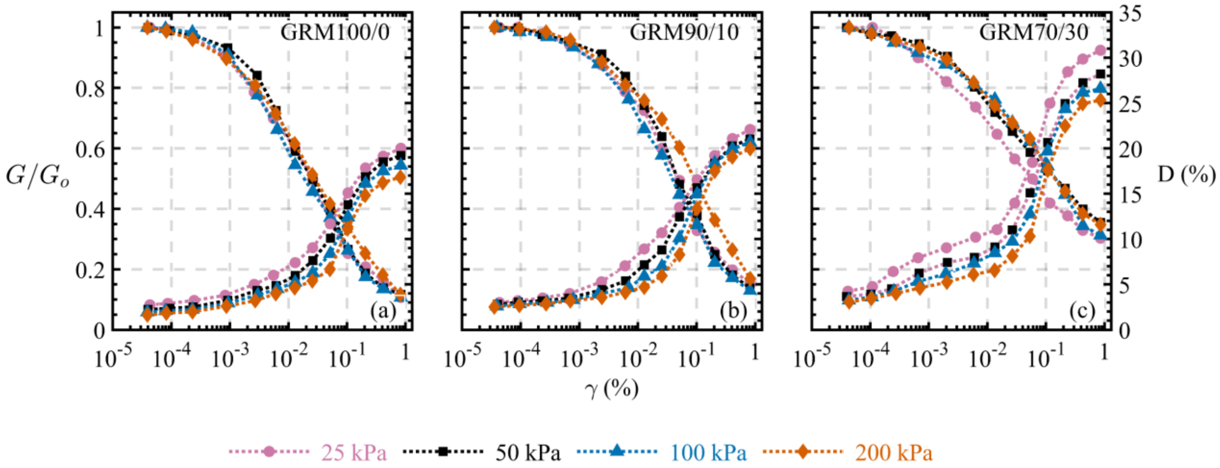

Figure 2. *Normalized shear modulus, G/G_o, and damping ratio, D (%), versus the shear strain γ (%), for (a) GRM 100/0, (b) GRM90/10 and (c) GRM 70/30*

Instrumentation

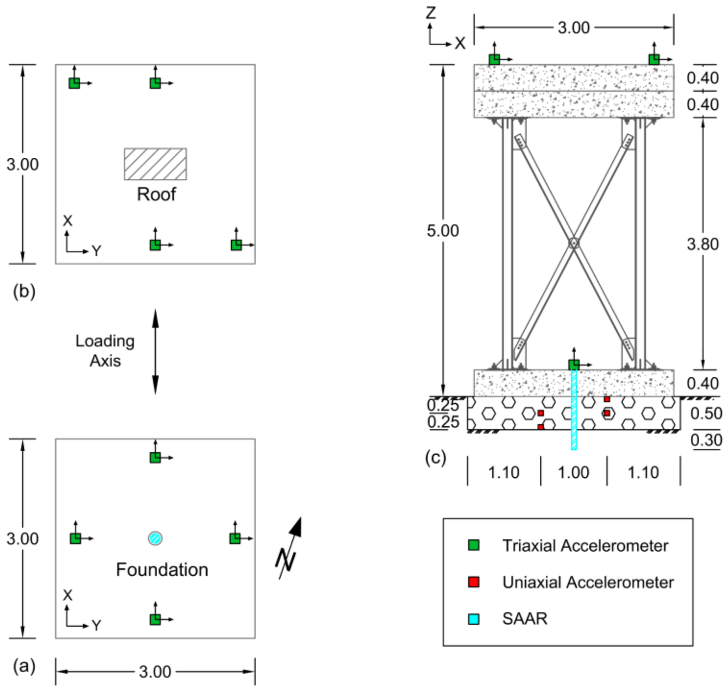

Figure 3. *Plan view of (a) the foundation and (b) the roof slabs instrumented with triaxial accelerometers (the hatched area represents the position of the eccentric mass shaker) and (c) a cross-section of the structure and the GRM foundation layer instrumented with the uniaxial accelerometers and the SAAR*

A dense instrumentation scheme was designed to monitor and record the response of the structure, the foundation and the GRM layer. Four triaxial accelerometers (Etna2, Kinemetrics Inc. and CMG-5TCDE, Guralp Systems Ltd) were mounted on the foundation slab forming a cross shape to record the foundation's translation, rocking, and possible out-of-plane motion (Fig.3a), while four more were mounted on the upper roof slab; two along the axis parallel to the direction of shaking (in-plane) and the other two at the opposite corners of the slab to capture possible out-of-plane motion (Fig.3b). Moreover, the GRM layer response was captured by four uniaxial accelerometers (Kistler Holding AG) buried inside the GRM layer along the loading axis at three different levels (Fig.3c); one was installed approximately at the top of the GSI layer (0.09m), two of the uniaxial accelerometers were installed in the middle of the layer (0.25m), and one at the base of the layer (0.50m). In addition, the GRM layer was also monitored with a 1.2-m shape-acceleration array equipped with eight triaxial MEM sensors every 0.15 cm that was installed immediately below the foundation's geometrical center (Fig.3c). The positive x-axis of the instruments was oriented parallel to the positive x-direction of the structure, which forms an angle of 30^{o} with the magnetic North and is parallel to the loading axis.

Experimental Program

The experimental program involved ambient noise measurements, free-vibration tests, and forced-vibration tests. The results of the system identification based on the ambient noise recorded by all the instruments while the structure was sitting on top of each GRM layer before the free- and forced vibration experimental series were carried out as well as the findings of the free-vibration experiments are reported in Pitilakis et al. (2021). This study focuses on the results of the forced-vibration experiments which can provide an insight into the response over a wide frequency range of interest.

A portable eccentric mass shaker provided by ITSAK-EPPO was installed at the geometrical center of the roof slab to serve as a source of harmonic excitation. The modification of the shaker's eccentricity with the use of four pairs of steel plates (configuration A, B, C, and D) and the excitation frequency allow the adjustment of the amplitude of the output force. Three identical series of forced-vibration experiments were performed on each GSI-structure system covering a wide range of excitation amplitude varying from 0.07 to 28.50 kN in a frequency range of 1–10 Hz (Table 3).

Table 3. *Summary of the forced-vibration experiment per each GSI-structure system*

Test ID	Mass/Plates	Eccentricity (kg-m)	Frequency Range (Hz)	Force Amplitude (kN)
1	A	1.85	1-10	0.07-7.30
2	A + B	3.93	1-10	0.15-15.50
3	A + B + C	6.93	1-10	0.30-27.30
4	A + B + C + D	11.31	1-8	0.50-28.50

DYNAMIC RESPONSE OF THE GSI-STRUCTURE SYSTEM

The analysis of the ambient noise measurements recorded by all the instruments for the tree GSI-structure systems is reported in Pitilakis et al. (2021). The fundamental natural frequencies of the system founded on the GRM100/0 and the GRM90/10 were estimated almost equal, while this value was decreased significantly in the case of the GRM70/30 foundation soil layer showing a remarkable decrease in the system's stiffness. Another important finding was the increase in the estimated damping ratio of the GRM70/30-EuroProteas system.

The peak acceleration amplitude recorded at the roof versus the shaker frequency for the forced-vibration experiments 3 and 4, in which the largest harmonic forces are applied to the structure, is presented in Fig.4. It is apparent that the response of the GSI-structure system founded on the GRM100/0 is almost similar to this founded on the GRM90/10 layer. The motion is amplified when both systems are excited at 4Hz defining the structure's resonant frequency at approximately this value. On the other hand, the amplification of the response of the structure founded on the GRM70/30 layer is noticed when the excitation frequency is set at 2.5Hz. These findings indicate the decrease in the stiffness of the system due to the increase in the rubber content. Another important observation is the significantly reduced values of the recorded acceleration in the case of the

GRM70/30 over a wide frequency range compared to those corresponding to the other GRM layers showing the contribution of the rubber content in the damping of the system.

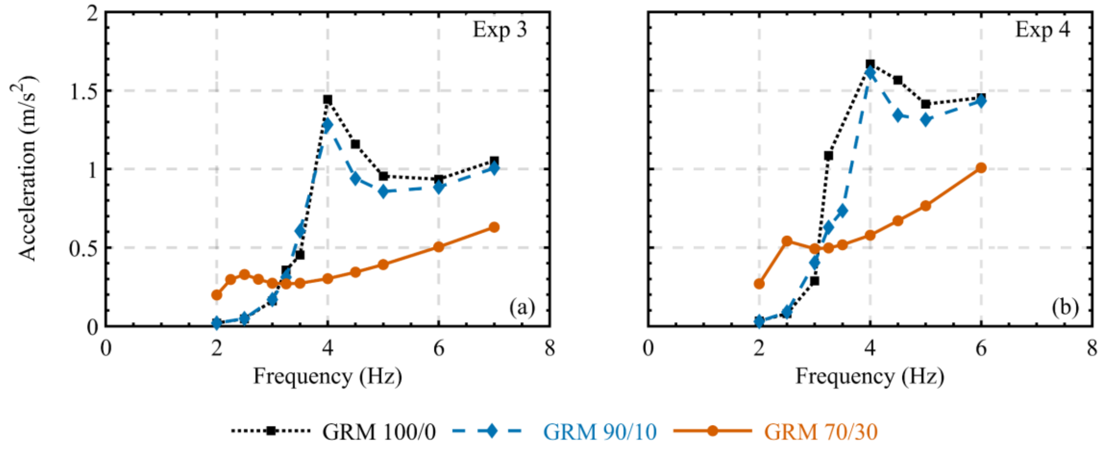

Figure 4. *Maximum amplitude of the acceleration recorded at the top of EuroProteas at different excitation frequencies in the forced-vibration experiments (a) 3 and (b) 4*

Furthermore, Fig.5 illustrates the peak acceleration values recorded by the uniaxial accelerometers that were installed in the GRM layers after normalizing them by the horizontal component of the motion recorded at the top of the foundation slab. When the structure is founded on the GRM100/0 the motion at the bottom of the layer is decreased by almost 65% for excitation frequencies over 4Hz. Moreover, when the rubber content is increased to 10%, a slightly more significant decline in the acceleration amplitude is noticed at the bottom of the layer. This discrepancy can be attributed to the modest contribution of the rubber content to energy dissipation. The high values of the normalized acceleration observed for frequencies less than 3Hz in both GRM layers are the result of the very low motion amplitude recorded by the accelerometers combined with the meager signal-to-noise ratio of the recordings at those frequencies. In the case of the GSI-structure system with the 30% rubber fraction, the motion recorded at the middle and the bottom of the GRM layer is reduced by approximately 75% and 90% respectively, indicating the increase in the material damping with increasing rubber content.

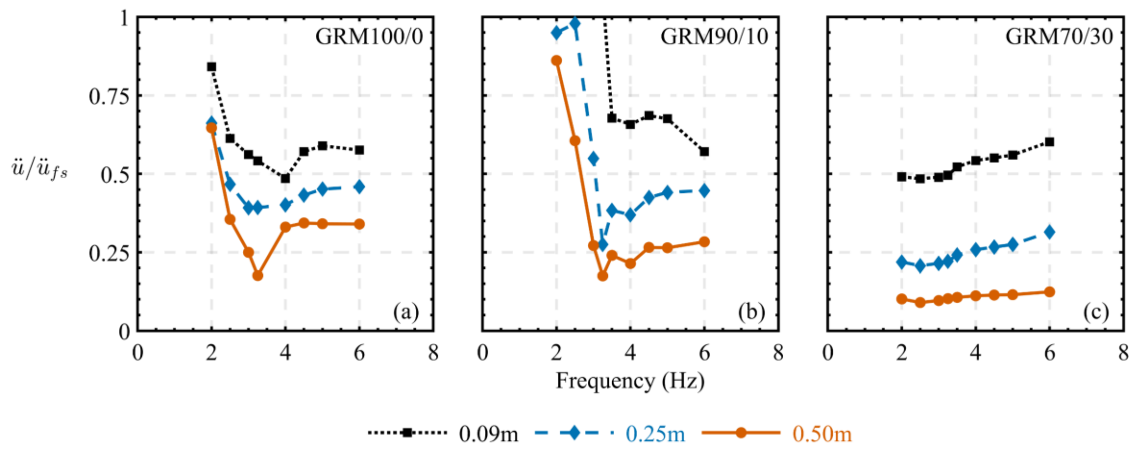

Figure 5. *Maximum acceleration recorded in the (a) GRM100/0, (b) GRM90/10 and (c) GRM70/30 at 0.09m, 0.25m, and 0.50m below the foundation slab normalized by the horizontal acceleration recorded at the top of the foundation slab in the forced-vibration experiment 4*

The acceleration recorded at the top of the structure includes the translational acceleration component due to the bending of the structure, $\ddot{u}_s$, and the translational acceleration component related to the foundation rotation, $h\ddot{\theta}_f$, where h is the height of the structure (Tileylioglu et al., 2011; Vratsikidis et al., 2021). The latter is associated with the rocking motion of the structure. As can be seen in Fig.6, $\ddot{u}_s$ is almost equal to $h\ddot{\theta}_f$ when the structure sits on the GRM100/0 and GRM90/10 over the whole range of excitation frequencies. Besides, only a modest difference in the acceleration components is detected with the increase of the rubber content by 10%. In the case where these two GSI-structure systems are excited at 4Hz, close to their resonant frequency, the component associated with the foundation rotation is becoming greater due to the rocking of the structure. On the other hand, when the structure is oscillating on the GRM70/30 the horizontal acceleration due to rocking dominates the structure's response irrespectively of the shaker frequency. More importantly, the values of $h\ddot{\theta}_f$ are decreased compared to those corresponding to the other two GSI systems for frequencies over 3Hz. In addition, $\ddot{u}_s$ is significantly reduced demonstrating the rigid body-like response of the structure when the rubber content is increased to 30% due to the decrease in the stiffness of the foundation layer.

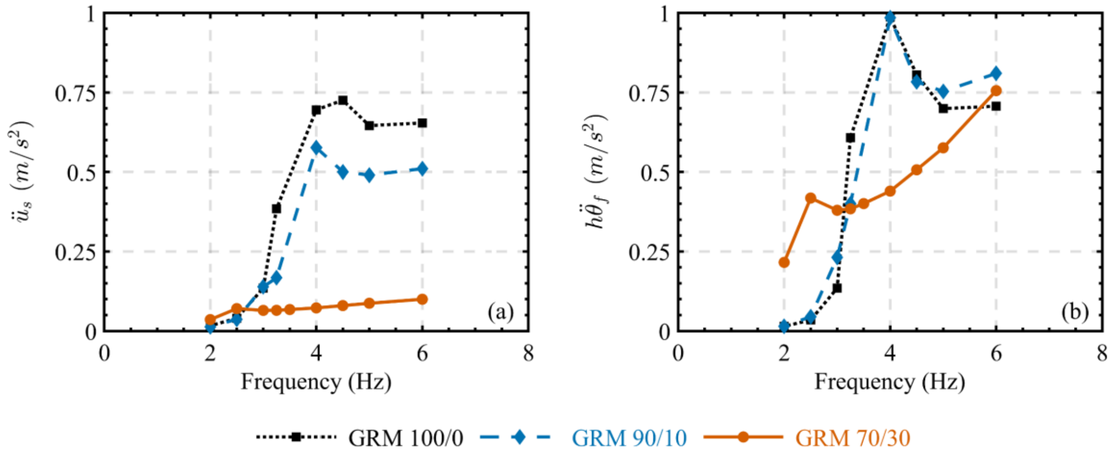

Figure 6. *Maximum amplitude of the translational acceleration component due to (a) structural bending, $\ddot{u}_s$, and (b) foundation rotation, $h\ddot{\theta}_f$, for each excitation frequency in experiment 4*

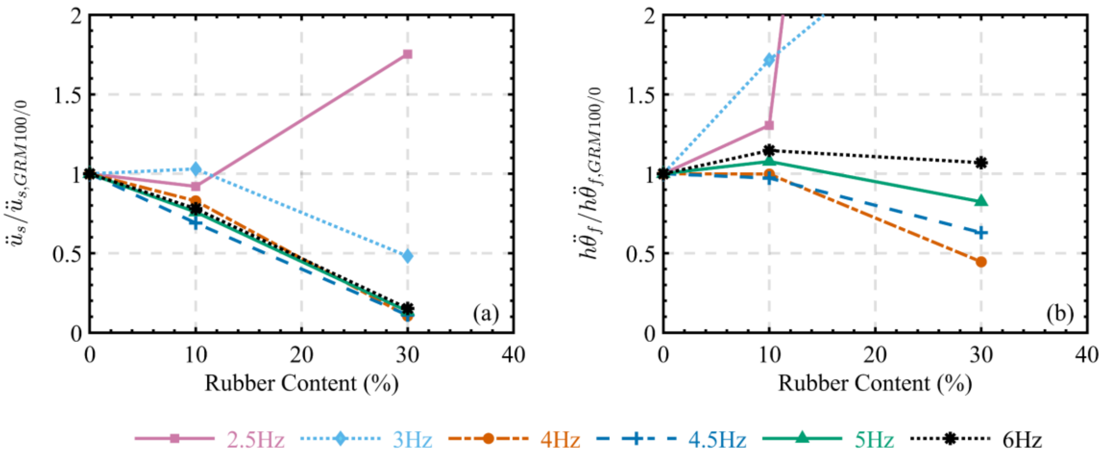

Figure 7. *Effect of the rubber content of the GRM layer on the amplitude of the translational acceleration component due to (a) structural bending, $\ddot{u}_s$, and (b) foundation rotation, $h\ddot{\theta}_f$, in experiment 4. The values of the acceleration are normalized by the value recorded for the structure on the GRM100/0*

Fig.7 presents the effect of the rubber content of the GRM layer on the components of the motion for each frequency that excited the structure in the forced vibration experiment 4. A decrease in the acceleration due to structural bending by almost 90% is noticed for most of the excitation frequencies in the case of the GRM70/30. Regarding the effect of the rubber content on the rocking component, although favorable for frequencies over 3Hz, is not as much significant. However, the sum of these components is reduced with increasing rubber content indicating the beneficial effect of the rubber in the overall response of the structure. The increased values for low frequencies are attributed to the resonant frequency of the GSI system with 30% rubber content which amplifies the overall motion recorded at the top of the structure and specifically the rocking component.

CONCLUSIONS

We performed the first large-scale experimental campaign on the prototype structure of EuroProteas to assess and evaluate the seismic isolation capabilities of GRM layers placed underneath shallow foundations. The design of the GSI-structure systems was based on laboratory experiments which demonstrated that the increase in the rubber content leads to a decrease in the small-strain shear modulus and a rise in the damping ratio of the GRM, while the degradation of the shear modulus is becoming more linear for a rubber fraction of 30%. The experiments were carried out on the structure founded on three GRM layers with rubber content of 0, 10%, and 30% per mixture weight to study the effect of rubber content in the system's response.

A 10% rubber content in the GRM layer has a negligible effect on the structure's dynamic characteristics. On the other hand, a decrease in the system's stiffness is noticed when a GRM layer of 30% rubber content is placed underneath the structure and the resonant frequency is shifted to lower values. Moreover, the material damping is increased as indicated by the significantly reduced acceleration recorded at the bottom of the GSI layer. Another important result is the remarkable decline in the component of the horizontal acceleration due to structural stiffness and the rigid body-like response of the structure with increasing rubber content. Considering the fact that seismic waves are transmitted from the ground to the structure, these experimental findings indicate that a GSI layer composed of a GRM with 30% rubber content per mixture weight effectively isolates the structure.

ACKNOWLEDGEMENTS

This research was carried out as part of the project «RiskSchools: Innovative smartphone application for the rapid pro-seismic checking and the vulnerability and risk assessment of the school buildings in the Region of Central Macedonia» (Project code: KMP6-0077243) under the framework of the Action «Investment Plans of Innovation» of the Operational Program «Central Macedonia 2014 2020», that is co-funded by the European Regional Development Fund and Greece".

REFERENCES

Anastasiadis, A., Senetakis, K., & Pitilakis, K. (2012a). Small-Strain Shear Modulus and Damping Ratio of Sand-Rubber and Gravel-Rubber Mixtures. *Geotechnical and Geological Engineering*, *30*(2), 363–382. h

Anastasiadis, A., Senetakis, K., Pitilakis, K., Gargala, C., Karakasi, I., Edil, T., & Dean, S. W. (2012b). Dynamic Behavior of Sand/Rubber Mixtures. Part I: Effect of Rubber Content and Duration of Confinement on Small-Strain Shear Modulus and Damping Ratio. *Journal of ASTM International*, *9*(2), 103680.

Anastasopoulos, I., Gazetas, G., Loli, M., Apostolou, M., & Gerolymos, N. (2010). Soil failure can be used for seismic protection of structures. *Bulletin of Earthquake Engineering*, *8*(2), 309–326.

ASTM. (2017). *D2487 - 17e1 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. ASTM International, West Conshohocken, PA.

Banović, I., Radnić, J., & Grgić, N. (2019). Geotechnical Seismic Isolation System Based on Sliding Mechanism Using Stone Pebble Layer: Shake-Table Experiments. *Shock and Vibration*, *2019*, 1–26.

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

Dhanya, J. S., Boominathan, A., & Banerjee, S. (2020). Response of low-rise building with geotechnical seismic isolation system. *Soil Dynamics and Earthquake Engineering*, *136*, 106187.

Gazetas, G., Anastasopoulos, I., Adamidis, O., & Kontoroupi, T. (2013). Nonlinear rocking stiffness of foundations. *Soil Dynamics and Earthquake Engineering*, *47*, 83–91.

Kim, H.-K., & Santamarina, J. C. (2008). Sand–rubber mixtures (large rubber chips). *Canadian Geotechnical Journal*, *45*(10), 1457–1466.

Manakou, M. V., Raptakis, D., Chávez-García, F. J., Apostolidis, P. I., & Pitilakis, K. (2010). 3D soil structure of the Mygdonian basin for site response analysis. *Soil Dynamics and Earthquake Engineering*, *30*(11), 1198–1211.

Mavronicola, E., Komodromos, P., & Charmpis, D. C. (2010). Numerical Investigation of Potential Usage of Rubber-Soil Mixtures as a Distributed Seismic Isolation Approach. *Civil-Comp Proceedings*, *93*.

Naeim, F., & Kelly, J. M. (1999). *Design of Seismic Isolated Structures*. John Wiley & Sons, Inc.

Pistolas, G. A., Anastasiadis, A., & Pitilakis, K. (2018). Dynamic Behaviour of Granular Soil Materials Mixed with Granulated Rubber: Effect of Rubber Content and Granularity on the Small-Strain Shear Modulus and Damping Ratio. *Geotechnical and Geological Engineering*, *36*(2), 1267–1281.

Pistolas, G. A., Pitilakis, K., & Anastasiadis, A. (2020). A numerical investigation on the seismic isolation potential of rubber/soil mixtures. *Earthquake Engineering and Engineering Vibration*, *19*(3), 683–704.

Pitilakis, D., Anastasiadis, A., Vratsikidis, A., Kapouniaris, A., Massimino, M. R., Abate, G., & Corsico, S. (2021). Large-scale field testing of geotechnical seismic isolation of structures using gravel-rubber mixtures. *Earthquake Engineering & Structural Dynamics*, *50*(10), 2712–2731.

Pitilakis, D., Rovithis, E., Anastasiadis, A., Vratsikidis, A., & Manakou, M. (2018). Field evidence of SSI from full-scale structure testing. *Soil Dynamics and Earthquake Engineering*, *112*, 89–106.

Pitilakis, K., Karapetrou, S., & 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-Vassilikou, T., & Jongmans, D. (1999). Geotechnical and geophysical description of euro-seistest, using field, laboratory tests and moderate strong motion recordings. *Journal of Earthquake Engineering*, *3*(3), 381–409.

Senetakis, K., & Anastasiadis, A. (2015). Effects of state of test sample, specimen geometry and sample preparation on dynamic properties of rubber–sand mixtures. *Geosynthetics International*, *22*(4), 301–310.

Senetakis, K., Anastasiadis, A., & Pitilakis, K. (2012a). 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*(1),38-53.

Senetakis, K., Anastasiadis, A., Pitilakis, K., & Souli, A. (2012b). Dynamic behavior of sand/rubber mixtures, part II: Effect of rubber content on G/Go-γ-DT curves and volumetric threshold strain. *ASTM Special Technical Publication*, *1540 STP*(February), 248–264.

Tileylioglu, S., Stewart, J. P., & Nigbor, R. L. (2011). Dynamic Stiffness and Damping of a Shallow Foundation from Forced Vibration of a Field Test Structure. *Journal of Geotechnical and Geoenvironmental Engineering*, *137*(4),344-353.

Torretta, V., Rada, E. C., Ragazzi, M., Trulli, E., Istrate, I. A., & Cioca, L. I. (2015). Treatment and disposal of tyres: Two EU approaches. A review. *Waste Management*, *45*, 152–160.

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

Tsang, H. (2009). Geotechnical seismic isolation. *Earthquake Engineering: New Research. Nova Science Publishers, Inc., New York, US*, 55–87.

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

Tsang, H., Tran, D., Hung, W., Pitilakis, K., & Gad, E. F. (2021). Performance of geotechnical seismic isolation system using rubber-soil mixtures in centrifuge testing. *Earthquake Engineering & Structural Dynamics*, *50*(5), 1271–1289.

Tsiavos, A., Alexander, N. A., Diambra, A., Ibraim, E., Vardanega, P. J., Gonzalez-Buelga, A., & 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*, 105731.

Tsinaris, A. (2018). *Experimental and numerical investigation of improving the seismic response of retaining structures with backfill of mixtures of lightweight materials, Phd Dissertation (in Greek)* [Department of Civil Engineering, Aristotle University of Thessaloniki]. http://ikee.lib.auth.gr/record/300573

Vratsikidis, A., Pitilakis, D., Anastasiadis, A., & Kapouniaris, A. (2021). Evidence of soil-structure interaction from modular full-scale field experimental tests. *Bulletin of Earthquake Engineering*.

Xiong, W., Yan, M. R., & Li, Y. Z. (2014). Geotechnical Seismic Isolation System - Further Experimental Study. *Applied Mechanics and Materials*, *580–583*, 1490–1493.