

# Full-Scale Testing of a Structure on Improved Soil Replaced with Rubber–Gravel Mixtures



Athanasios Vratsikidis , Angelos Tsinaris, Anastasios Kapouniaris, Anastasios Anastasiadis, Dimitris Pitilakis , and Kyriazis Pitilakis 

**Abstract** We present the results of an extensive large-scale experimental campaign on the dynamic response of rubber–gravel mixtures as an innovative seismic isolation material. In the first series of experiments, the foundation soil immediately below the prototype structure of EUROPROTEAS was replaced only with gravel to serve as benchmark tests, while in the following tests two rubber–gravel mixtures with increasing rubber content per mixture weight were used. The experimental campaign included free- and forced-vibration tests. A large number of instruments of various types (accelerometers, seismometers, shape-acceleration arrays, and laser sensors) were installed on the structure, in the foundation soil and at the adjacent soil surface in order to obtain a well-instrumented 3D set of recordings to study the response of the structure and wave propagation in soil media. In this study, we seek to investigate the isolation capability of the rubber–gravel mixtures under dynamic loading. Our primary goal is to assess the effect of the rubber content of the improved foundation soil in the stiffness and the damping of the soil–structure system.

**Keywords** Experimental geotechnical engineering · Soil–rubber mixtures · Seismic isolation · Large scale · Field test

## 1 Introduction

Over the last years, the disposal of a large volume of used tires has become a severe environmental problem. A recent trend is the use of recycled tires in civil engineering projects [1, 2]. An application in earthquake engineering consists in placing a shallow and resilient layer of rubber–soil mixture (RSM) underneath a structural foundation, an improvement method known as geotechnical seismic isolation [3–5]. This emerging application is mainly based on theoretical and experimental studies that have proven that granulated RSM has attractive mechanical and dynamic properties [6–8].

---

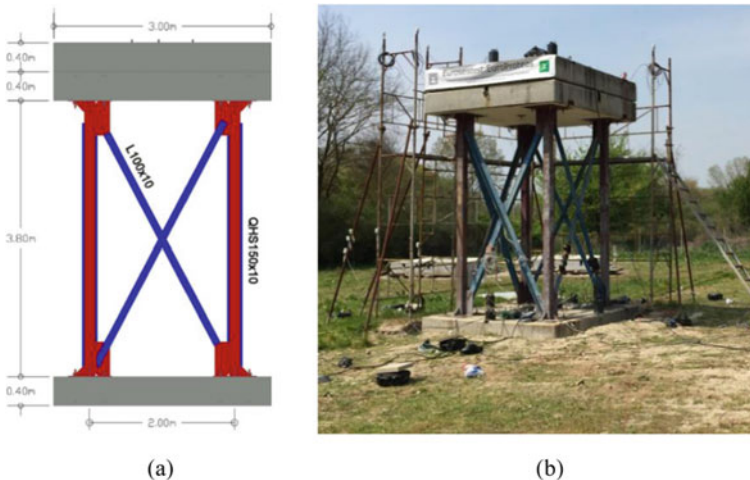
A. Vratsikidis (✉) · A. Tsinaris · A. Kapouniaris · A. Anastasiadis · D. Pitilakis · K. Pitilakis  
Aristotle University of Thessaloniki, Thessaloniki, Greece  
e-mail: [avratsik@civil.auth.gr](mailto:avratsik@civil.auth.gr)

In this paper, we present an extensive experimental campaign conducted on the large-scale prototype structure of EUROPROTEAS located in the EUROSEIS-TEST experimental facility (<https://euroseisdb.civil.auth.gr>). The experiments were conducted after replacing the foundation soil with three different rubber–gravel mixtures (RGM). The standard gravelly soil derived from coarse uniform gravel quarry, while the synthetic material (rubber) is derived from recycled used tires and, after appropriate processing, can be found in the form of various sizes. Free- and forced-vibration testing was performed over a wide range of load levels and input frequencies in order to investigate the response of the soil-structure system, evaluate the foundation soil damping behavior under the effects of different rubber content per mixture weight, and to determine the optimum rubber content.

## 2 EUROPROTEAS Facility

### 2.1 Structure

EUROPROTEAS prototype structure was particularly designed to promote soil-structure interaction phenomena (Fig. 1). It consists of three identical reinforced concrete slabs, each having a mass of 9 Mg, one representing the surface foundation and the other two the superstructure mass. The roof mass is supported by four steel columns QHS 150 × 150 × 10 mm which are connected with steel X-braces L 100 × 100 × 10 mm in all directions to ensure the symmetry of the structure [9, 10].



**Fig. 1** **a** A 2D sketch and **b** a photograph of the EUROPROTEAS structure (<https://euroseisdb.civil.auth.gr>)

The outer dimensions of the structure are  $3 \times 3 \times 5$  m, while its total weight is approximately 28.5 Mg. The X-bracings and upper roof slab are removable allowing four different configurations of structure's mass and stiffness covering a wide range of natural frequencies between 1.78 and 13.06 Hz. For the experiments described herein the configuration of EUROPROTEAS involved bracing in all four sides and two reinforced concrete slabs on the roof.

## 2.2 Foundation Soil

The foundation soil stratigraphy and its dynamic properties are well documented from extended geophysical and geotechnical tests reported in earlier studies [11, 12]. In the series of experiments presented herein, the uppermost 0.5 m of the foundation soil was replaced with RGM backfills.

Prior to the modification of the foundation soil, a preliminary study was carried out at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of the Aristotle University of Thessaloniki to define the physical properties of the mixtures of gravel with granulated rubber at a percentage of 0, 10, and 30% per mixture weight to be used for the foundation soil improvement. The small strain dynamic response of RGMs is characterized by low values of stiffness and high values of damping. Additionally, the stiffness degradation and the damping increase exhibit a more linear behavior in the medium and high strain range as the rubber content increases [13–15].

According to [16], the relative ratio of the mean grain size of the soil–rubber mixture is a determinant parameter for the behavior of the mixture. Herein, we studied a uniform quarry gravel with angular particles fraction of mean grain size  $D_{50}$  equal to 20.76 mm as primary physical material ( $G$ ), whereas a granular fraction of rubber of mean grain size  $D_{50}$  equal to 3.27 mm was studied as primary synthetic material ( $R$ ). The rubber grain is tire-derived materials and has been included in ASTM and CEN standards in recent decades [17, 18]. The specific gravity of soil solids,  $G_s$ , was determined according to the ASTM D854-02 specification [19] and was found equal to 2.67 for the gravel fraction and 1.10 for the rubber fraction, respectively.

According to [20, 21], it is seen that in a range of the axial deformation up to 20%, the examined specimens of pure gravel fraction as well as the mixtures of gravel with rubber content exhibited “loose sand behavior” without reaching positive values of volumetric strain. The majority of the examined specimens present a contractive behavior with a tendency of reduction as the axial deformation increases, regardless of the uniformity of the sample, the particle size, and the relative ratio  $D_{50,s}/D_{50,r}$  of the mean diameter of its granules. However, as the rubber percentage in the mixture increases or as the level of the applied envelope stress increases the specimens exhibit a more intense contractive behavior, which means that the addition of the rubber in the mixture leads to a reduction of the dilation angle values. This is because of the high compression and contraction of the soil structure during the consolidation stage

**Table 1** Properties and classification of natural and synthetic examined materials

Properties	Gravel	Rubber
Material ID	G	R
$G_s$	2.67	1.10
$D_{10}$ (mm)	14.69	2.07
$D_{30}$ (mm)	18.80	2.67
$D_{50}$ (mm)	20.76	3.27
$D_{60}$ (mm)	21.67	3.56
$C_u$	1.48	1.72
$C_c$	1.11	0.97
$e_{max}$	1.385	1.616
$e_{min}$	0.844	1.075
USCS classification	GP	Granulated rubber

due to the high level of the applied radial stress and the high deformability of the rubber granules. Therefore, during the failure stage, the rubber grains, as part of the sample solid structure, have a small margin of deformation left, while the solid structure, in which the soil grains are participated, is partly rearranged.

Table 1 summarizes the physical characteristics of the natural soil and the synthetic material used in this research, while Fig. 2 shows the grain size distribution of the above materials that were used in this research and affect the mechanical properties of the examined samples. The above parameters were determined according to the specification ASTM C136 [22]. The classification of the used physical soils and synthetic materials were performed adopting the D2487-00 [23] and D6270-98 [17] of ASTM specifications respectively.

Three soil pits having dimensions  $3.2 \times 3.2 \times 0.5$  m were excavated (Fig. 3). The first soil pit was filled only with gravel to serve as a benchmark foundation type. The other two pits were filled with RGM of different rubber content by mixture weight. Table 2 summarizes the properties of the RGM (G/R), for different percentages of rubber content (0%, 10%, and 30%) per mixture weight ( $\sim$  0%, 25%, and 75% per volume mixture, respectively), used as foundation material in the experimental program. For the definition of the properties, two samples were taken from the bottom and the top layer of each mixture. The same values of the properties were estimated in both samples; however, there was a discrepancy in the determination of the relative density of the third mixture, which had a higher value at the bottom layer despite the fact that the compaction tests conducted were identical and the energy of the compaction was the same. We believe that this is attributed to the poor compaction of the foundation soil and that proper layering of mixtures consisted of such materials is an important factor to achieve uniform relative density.

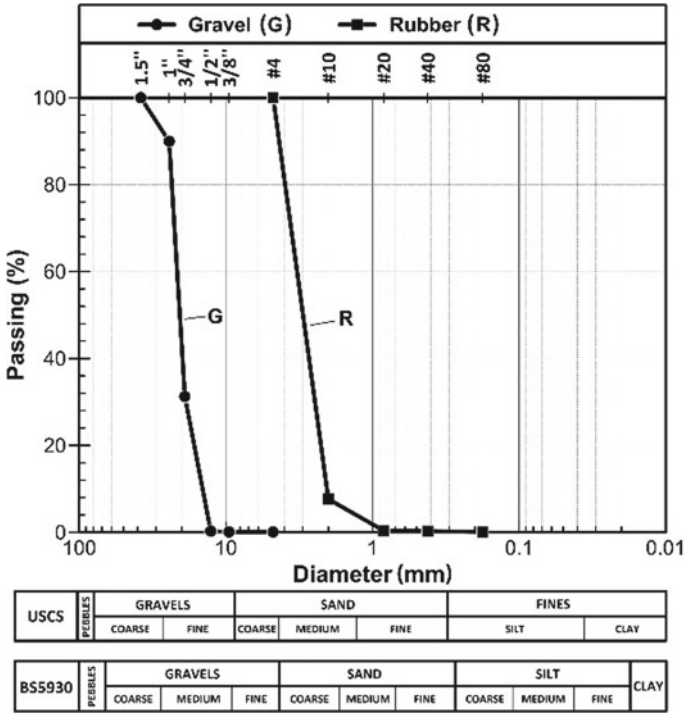


Fig. 2 Sieve analysis of the gravel and rubber materials used in the experiments

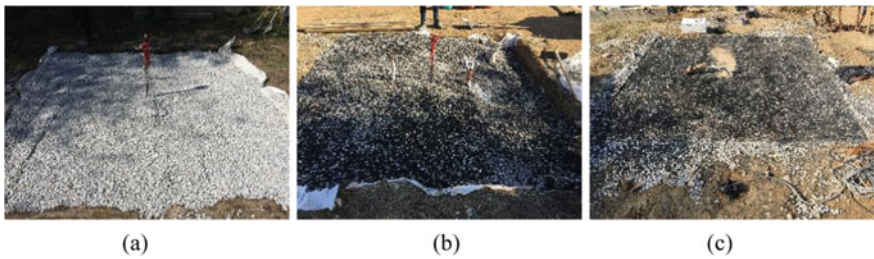


Fig. 3 Three soil pits filled with the rubber–gravel mixtures, a G/R 100/0, b G/R 90/10, and c G/R 70/30

Table 2 Foundation soil types used in the experiments

Foundation ID	Rubber by mixture weight (%)	$D_{50,r}/D_{50,s}$	$G_s$	$D_r$ (%)	$\gamma_d$ (kN/m <sup>3</sup> )
G/R 100/0	0	–	2.67	97.81	16.2
G/R 90/10	10	0.16	2.51	98.49	15.2
G/R 70/30	30		2.19	58.52–71.03	11.8

### **2.3 Instrumentation Layout**

A dense instrumentation scheme was designed in order to fully monitor and record the response of the structure, the foundation soil, and the adjacent soil in three dimensions (Fig. 4).

The structure was instrumented with nine triaxial accelerometers. Five of them were mounted on the roof, whereas the foundation was instrumented with four accelerometers. Moreover, laser sensors were installed to record the vertical displacement of the foundation slab.

Eleven seismometers were installed on the soil surface buried at the level of the foundation base. Eight of them were placed along the axis of loading, while the others were placed on the perpendicular axis. A 1.2 m shape-acceleration array equipped with 8 triaxial MEM sensors having an intermediate distance of 0.15 cm was installed immediately below the geometrical center of the structure to capture the response of the RGM mixture. Additionally, four uniaxial accelerometers were buried in specific locations under the foundation in order to fully monitor the response of the foundation soil.

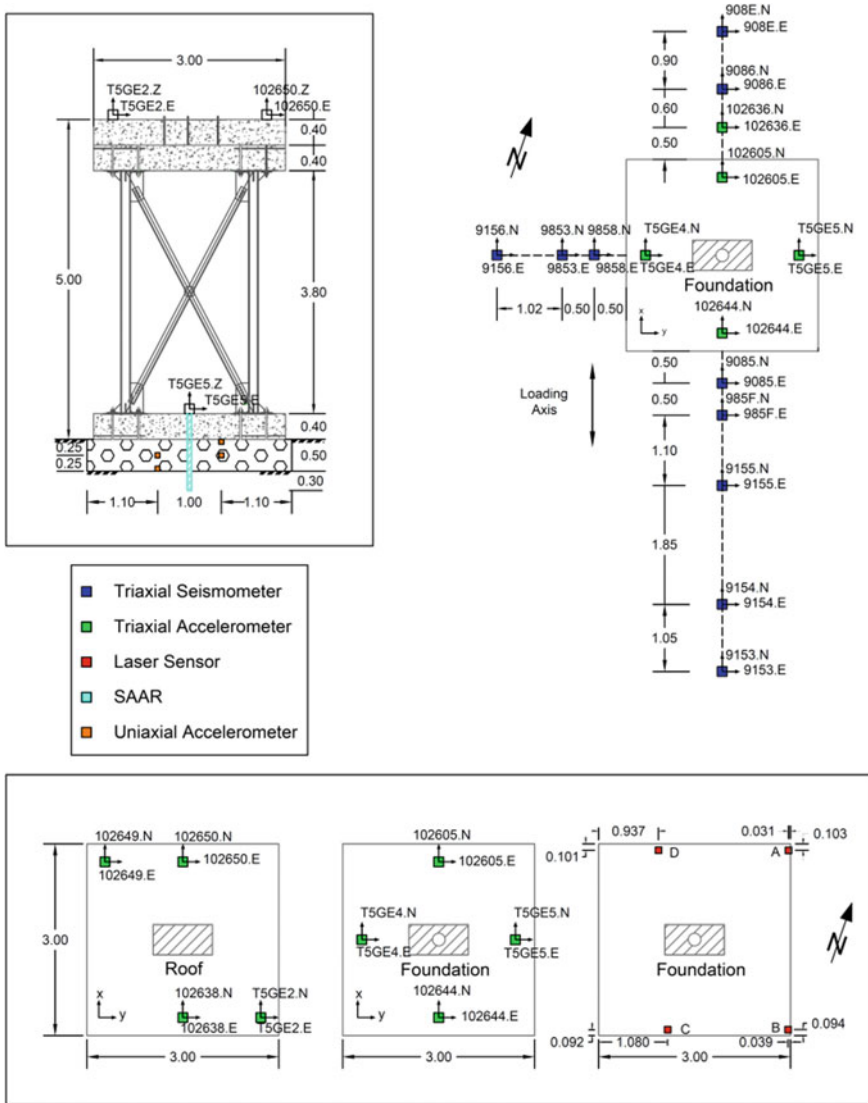
## **3 Experimental Campaign**

### **3.1 Free-Vibration Experiments**

We carefully designed the free-vibration experiments to capture the response of the structure for a wide range of pull-out force amplitudes. The forces were applied to the superstructure by a wire rope of 14 mm diameter. The one end of the wire rope was clamped at a 3 ton reinforced concrete counterweight buried in the soil 20 m away from EUROPROTEAS (Fig. 5a). The other end of the rope along with a load cell that measured the applied tension force was fastened on a special steel hook installed on the top roof slab (Fig. 5b). Tension was applied by a pulling hoist and when the desired level of force was reached, the wire rope was cut loose and the structure oscillated freely until rest. In total, 15 pull-out force amplitudes varying between 1.35 and 15.20 kN were applied (Table 3).

### **3.2 Forced-Vibration Experiments**

An eccentric mass vibrator system was installed at the geometrical center of the roof slab as a source of harmonic excitation (Fig. 6a). The axis of the produced harmonic force was applied along the main axis of the structure forming an angle of approximately 30 degrees with the magnetic north–south direction (Fig. 4). The shaker has four pairs of plates (A, B, C, and D) in four different sizes that can be used



**Fig. 4** Cross section of the foundation soil and structure instrumentation (top left), plan view of the foundation and soil surface instrumentation (top right), and plan view of the roof slab instrumentation (bottom left), the foundation slab instrumented with the accelerometers (bottom center) and with the laser sensors (bottom right)

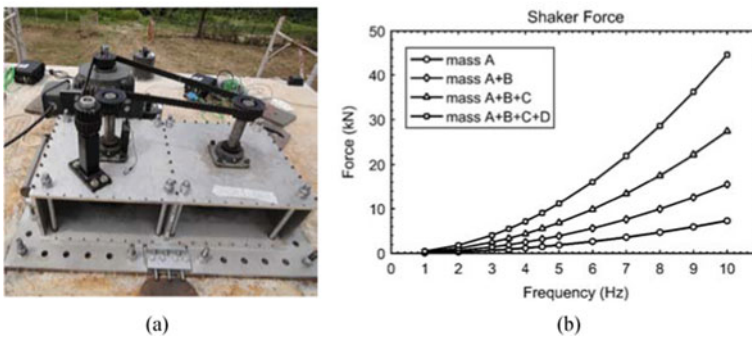




**Fig. 5** **a** Pulling hoist clamped on the counterweight and **b** the load cell attached to the roof slab

**Table 3** Summary of the free-vibration experiments per each foundation soil mixture

Foundation soil type	G/R 100/0	G/R 90/10	G/R 70/30
Experiment ID	Force (kN)		
A	1.60	1.90	1.35
B	10.40	5.40	2.90
C	15.20	10.60	6.28
D	2.10	3.50	9.80
E		7.50	15.00
F		2.80	



**Fig. 6** **a** Eccentric mass shaker installed on the upper roof slab and **b** the force-frequency relationship governing its function

to adjust the vibrator’s eccentricity. The amplitude of the output force can be adjusted according to the eccentricity and the operating frequency (Fig. 6b). The performed forced-vibration experiments covered a wide range of excitation amplitude varying between 0.07 and 28.50 kN in a frequency range of 1–10 Hz (Table 4).



**Table 4** Summary of the forced-vibration experiments

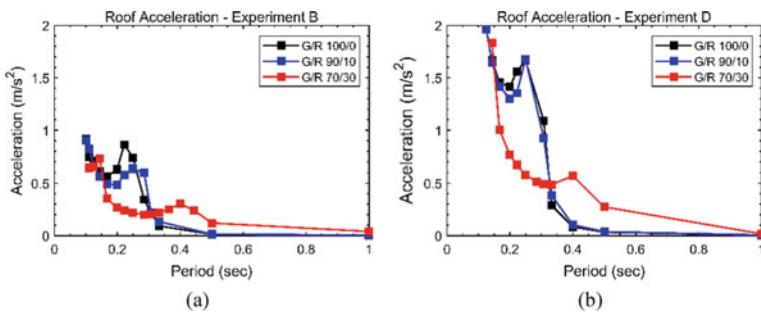
Experiment ID	Mass/Plates	Eccentricity (kg m)	Frequency range (Hz)	Force amplitude (kN)
A	A	1.85	1–10	0.07–7.30
B	A + B	3.93	1–10	0.15–15.50
C	A + B + C	6.93	1–10	0.30–27.30
D	A + B + C + D	11.31	1–8	0.50–28.50

## 4 Experimental Results

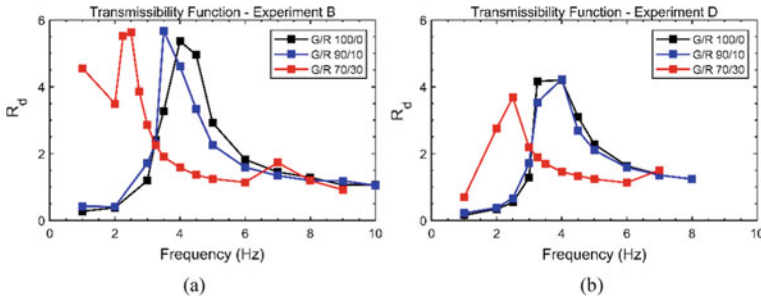
### 4.1 Period Elongation

The maximum amplitude of the acceleration recorded at the roof versus the period of the input signal during the forced-vibration Experiments B and D for each foundation soil mixture are reported in Fig. 7. The natural period of the soil-structure system for the benchmark test, in which the foundation soil is replaced only by gravel, is estimated at 0.25 s in both the experiments. The effect of the 10% rubber content per mixture weight does not seem to significantly affect the natural period of the system which remains approximately the same. However, it appears to slightly increase the damping of the system as the values of the recorded roof acceleration for the same input frequencies are reduced. On the other hand, in the case of the G/R 70/30 foundation soil mixture, the period is clearly shifted to 0.4 s implying a strong effect of the increased rubber content in the stiffness of the soil mixture-structure system.

Similar conclusions are drawn by looking at the transmissibility functions (Fig. 8) of the three different soil-structure systems, which are estimated according to [24]. The acceleration response factor  $R_d$  is calculated as the ratio of the acceleration recorded at the roof to the shaker force normalized by the superstructure mass. The acceleration response function is decreased in the case of the G/R 70/30 foundation soil mixture indicating an increase in the value of damping. This is attributed to



**Fig. 7** Maximum amplitude of the acceleration recorded at the roof during the forced-vibration **a** experiment B and **b** experiment D at different excitation frequencies

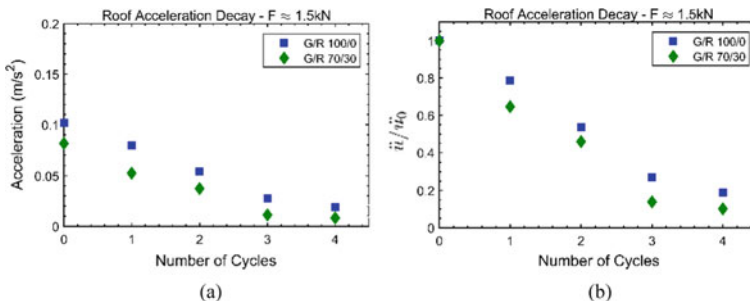


**Fig. 8** Transmissibility functions estimated for the forced-vibration **a** experiment B and **b** experiment D

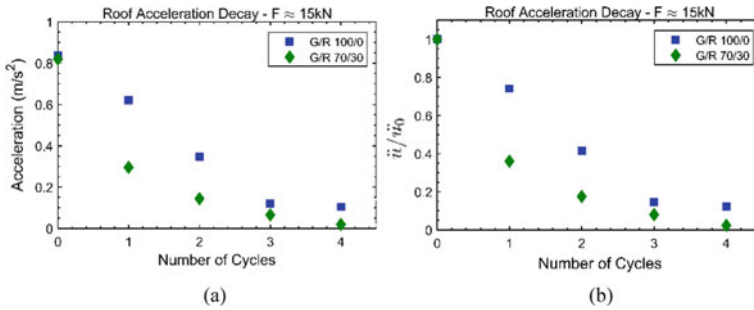
the strong effect of the increased rubber content in the mixture. Additionally, the acceleration response function is decreased for large amplitude forces for the same foundation soil mixture (e.g., in Experiment D) indicating an increase in the damping due to possible nonlinearities introduced in the response of the system.

### 4.2 Roof Response Decay

In Fig. 9a, we compare the decay of the amplitude of the acceleration recorded at the roof of the structure during the two free-vibration experiments labeled A in the case of the foundation soil mixture G/R 100/0 and G/R 70/30 (Table 3). The amplitude of the applied pull-out force in both experiments was approximately 1.5 kN. The acceleration values normalized by the initial maximum recorded acceleration in each test are presented in Fig. 9b. A decrease of more than 70% in the amplitude is noticed after three cycles of oscillation in both tests. This pronounces the large amount of energy dissipated in only the first few cycles of oscillation. However, the rate of



**Fig. 9** Decay of the roof response **a** as it was recorded and **b** normalized by the initial acceleration value with respect to the number of cycles of oscillation during the free-vibration experiment A (Table 3) for G/R 100/0 and G/R 70/30



**Fig. 10** Decay of the roof response **a** as it was recorded and **b** normalized by the initial acceleration value with respect to the number of cycles of oscillation during the free-vibration experiment C in the case of the G/R 100/0 mixture and experiment E in the case of G/R 70/30 mixture (Table 3)

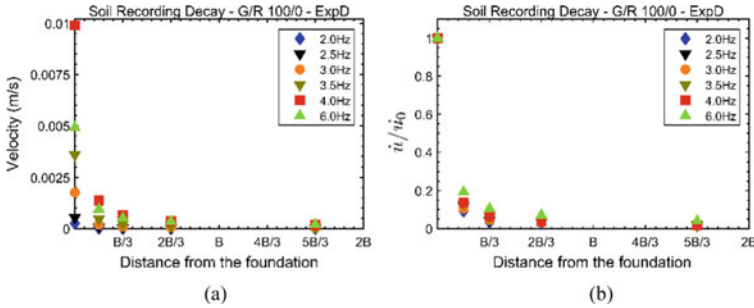
the decrease of the acceleration seems to be slightly greater in the case of the G/R 70/30 mixture indicating the contribution of the rubber content in the damping of the system.

While the rate of the decrease of the response appears almost similar in the case of the gravelly foundation soil irrespectively of the amplitude of the applied pull-out force, we notice a much steeper decline when the rubber content is present and the amplitude of the pull-out force is much greater (Fig. 10). A decrease in the acceleration by 50% is shown in the first cycle of oscillation, whereas in the next cycle the response is almost negligible demonstrating the increased damping of the system due to the increased rubber content.

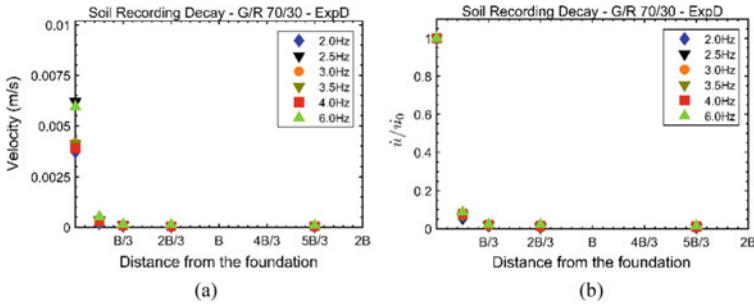
### 4.3 Adjacent Soil Motion Decay

We investigated the wave propagation in the soil and specifically the decay of the amplitude of motion with increasing distance from the structure when it was subjected to harmonic sinusoidal forces during the forced-vibration Experiment D, in which the greatest forces are applied at the roof of the structure (Table 4).

In the case of the G/R 100/0 foundation soil mixture, the amplitude of the response recorded at the soil surface is greater when the structure is excited close to its resonant frequency indicating that the foundation soil and the structure respond to the loading as a whole system (Fig. 11). A reduction in the motion by 80% is noticed at a distance equal to B/6 (B = foundation width) compared to the response recorded at the top of the foundation, whereas the amplitude of the response can be considered negligible at a distance equal to 2B/3 irrespectively of the excitation frequency. In the presence of the rubber in the foundation soil, the decrease is greater at the same distances as the foundation soil contributes to the dissipation of a bigger portion of energy (Fig. 12). At a distance equal to B/6, the decrease of the recorded velocity is approximately



**Fig. 11** Decay of the recorded soil surface response **a** as it was recorded and **b** normalized by the velocity value recorded on the foundation at increasing distance from the foundation in forced-vibration experiment D in the case of the G/R 100/0 foundation soil



**Fig. 12** Decay of the recorded soil surface response **a** as it was recorded and **b** normalized by the velocity value recorded on the foundation at increasing distance from the foundation in forced-vibration experiment D in the case of the G/R 70/30 foundation soil

90%, while at distance equal to B/3 the amplitude of the motion is decreased by almost 98% irrespectively of the excitation frequency.

## 5 Conclusions

We performed a series of free- and forced-vibration experiments to study the behavior of RGM as an alternative and innovative foundation soil improvement. We specifically focused on the effect of the rubber content per mixture weight by investigating the dynamic response of the prototype structure of EUROPROTEAS founded on three different RGM mixtures. The results pronounced that a 10% rubber content per mixture weight has a slight and almost negligible effect in the response of the structure. On the other hand, an increase in the rubber content to 30% per mixture weight affects significantly the predominant frequency and the damping of the soil-structure system. Additionally, it is evident that there is a significant decline in the

amplitude of the recorded response at the adjacent soil surface indicating a greater dissipation of energy in the foundation soil.

**Acknowledgements** This study was performed in the framework of the European project “Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe—SERA-TA—H2020 (Grant Agreement 730900).”

## References

1. Edeskär, T., Westerberg, B.: Tire shreds used in a road construction as a lightweight and frost insulation material. In: Oriz de Urbina, G., Guomans, H. (eds.) 5th International Conference on the Environmental and Technical Implications of Construction with Alternative materials, pp. 293–302, INASMET, San Sebastian (2003)
2. Humphrey, D.: Tire derived aggregate as lightweight fill for embankments and retaining walls. In: Hazarika, H., Yasuhara, K. (eds.) Proceedings of the International Workshop on Scrap Tire Derived Geomaterials-Opportunities and Challenges, pp. 59–81, Yokosuka, Japan (2007)
3. Tsang, H.-H.: Seismic isolation by rubber-soil mixtures for developing countries. *Earthq. Eng. Struct. Dynam.* **37**(2), 283–303 (2008)
4. Senetakis, K., Anastasiadis, A., Trevlopoulos, K., Ptilakis, K.: Dynamic response of SDOF systems on soil replaced with sand/rubber mixture. In: Proceedings of the ECOMAS Thematic Conference on Computation Methods in Structural Dynamics and Earthquake Engineering, Rhodes, Greece (2009)
5. Ptilakis, K., Trevlopoulos, K., Anastasiadis, A., Senetakis, K.: Seismic response of structures on improved soil. In: De Roeck, G., Degrande, G., Lombaert, G., Muller, G. (eds.) Proceedings of the 8th International Conference on structural dynamics (EURODYN2011), pp. 72–81, Leuven, Belgium (2011)
6. Anastasiadis, A., Senetakis, K., Ptilakis, K.: Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures. *Geotech. Geol. Eng.* **30**(2), 363–382 (2012)
7. Anastasiadis, A., Senetakis, K., Ptilakis, K., Gargala, C., Karakasi, I.: Dynamic behavior of sand/rubber mixtures. Part I: Effect of rubber content and duration of confinement on small-strain shear modulus and damping ratio. *J. ASTM Int.* **9**(2), 221–247 (2012)
8. Tsinaris, A., Anastasiadis, A., Ptilakis, K.: Mechanical behavior of lightweight soil/rubber mixtures in a wide shear strain range. In: Proceedings of the 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece (2018)
9. Ptilakis, D., Rovithis, E., Anastasiadis, A., Vratsikidis, A., Manakou, M.: Field evidence of SSI from full-scale structure testing. *Soil Dyn. Earthq. Eng.* **112**, 89–106 (2018)
10. Vratsikidis, A., Ptilakis, D.: Full-scale free- and forced-vibration experiments at the Euro-Proteas SSI facility: experimental data exploitation. In: Proceedings of the 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece (2018)
11. Ptilakis, K., Raptakis, D., Lontzetidis, K., Tika-Vasillikou, T., Jongmans, D.: Geotechnical and geophysical description of EUROSEISTEST, using field, laboratory tests and moderate strong motion records. *J. Earthq. Eng.* **3**(3), 381–409 (1999)
12. Raptakis, D., Chávez-García, F.J., Makra, K., Ptilakis, K.: Site effects at Euroseistest-I. Determination of the valley structure and confrontation of observations with 1D analysis. *Soil Dyn. Earthq. Eng.* **19**(1), 1–22 (2000)
13. Anastasiadis, A., Senetakis, K., Ptilakis, K., Gargala, C., Karakasi, I.: Dynamic behavior of sand/rubber mixtures. Part I: Effect of rubber content and duration of confinement on small-strain shear modulus and damping ratio. *J. ASTM Int.* **9**(2), 1–19 (2012)
14. Pistolas, G.A., Anastasiadis, A., Ptilakis, K.: 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. *Innov. Infrastruct. Solutions* **3**(47) (2018)

15. Pistolas, G.A., Pitilakis, K., Anastasiadis, A.: A numerical investigation on the seismic isolation potential of rubber/soil mixtures. *Earthq. Eng. Eng. Vibr.* **19**, 683–704 (2020)
16. Senetakis, K.: Dynamic properties of granular soils and mixtures of typical sands and gravels with recycled synthetic materials. Ph.D. dissertation, Department of Civil Engineering, Aristotle University of Thessaloniki Greece (in Greek) (2011)
17. ASTM Standard Test Methods for Use of Scrap Tires in Civil Engineering Applications: D6270-98. *Annual Book of ASTM Standards*, ASTM International (1998)
18. CEN: Materials Produced from End of Life Tyres-Specification of Categories Based on Their Dimension(s) and Impurities and Methods for Determining Their Dimension(s) and Impurities, European Committee for Standardization, CEN/TS 14243:2010, Brussels (2010)
19. ASTM Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer: D854-02. *Annual Book of ASTM Standards*, ASTM International (2002)
20. Pistolas, G.A.: Experimental and numerical investigation of the implementation of recycled materials mixtures in the foundation of structures for the improvement of seismic behavior. Ph.D. dissertation. Department of Civil Engineering, Aristotle University of Thessaloniki, Greece (in Greek) (2015)
21. Tsinaris, A.: Experimental and numerical investigation of improving the seismic response of retaining structures with backfill of mixtures of lightweight materials. Ph.D. Dissertation. Department of Civil Engineering, Aristotle University of Thessaloniki, Greece (in English & Greek) (2018)
22. ASTM: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates: C136-06. *Annual Book of ASTM Standards*, ASTM International (2006)
23. ASTM Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System): D2487-00. *Annual Book of ASTM Standards*, ASTM International (2000)
24. Chopra, A.: *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, 2nd edn. Prentice Hall Inc., New Jersey (2001)