GRAVEL-RUBBER MIXTURES UNDERNEATH FOUNDATIONS FOR AN ECO-FRIENDLY MITIGATION OF THE SEISMIC RISK OF STRUCTURES: LARGE-SCALE TESTS

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Abstract

The paper shows the results of the first experimental campaign performed on a large-scale prototype structure on gravel rubber mixtures (GRM) in the framework of the Transnational Access Project "SOFIA: Soil Frame-Interaction Analysis through large-scale tests and advanced numerical finite element modeling" funded under the European project "Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe – SERA-TA – H2020 (Grant Agreement 730900)". The large-scale prototype structure was the EuroProteas structure in Thessaloniki, Greece. The experimental campaign aimed to assess the effectiveness of GRM layers underneath shallow foundations as a new eco-sustainable solution for mitigating the seismic risk of structures. The rubber used in the mixtures was obtained from the recycling of end-of-life tires (ELTs).

The EuroProteas structure is a steel frame structure on an RC slab supporting two RC slabs, having the same size as the foundation slab (3.00x3.00x0.40 m). The subsoil consists mainly of silty sand with an average shear wave velocity equal to 200 m/s. As for the foundation soil, a soil pit was excavated down to a depth of 0.50 m and backfilled with GRM of different rubber content per weight. Forced-vibration tests were carried out using an eccentric mass shaker on the roof of the structure. The structure response was recorded by accelerometers located both at the roof and at the foundation; the soil response was recorded by seismometers installed on the soil surface in horizontal directions and inside the GRM layers beneath the foundation. The study investigated the rubber content effect of the GRM layer on the dynamic response of the EuroProteas structure and the overall performance of the GRM as a geotechnical seismic isolation (GSI) system.

1. Introduction

Rubber grains for the mixtures are usually manufactured from scrap tires, the disposal of which has become a severe environmental problem worldwide over the last years. So, in the last decades, many geotechnical projects have devoted to recycling rubber mixed with granular soils (soil rubber mixtures, SRM) in innovative manners. SRM, which have been recently included in ASTM and CEN standards (ASTM D6270, 2008; CEN/TS14243, 2010), are characterized by low specific weight, high elasticity, low shear modulus, and high damping. Therefore, the use of SRM could be advantageous due to their excellent static and dynamic properties. Recently SRM have attracted significant research interest as a new technique of geotechnical seismic isolation (GSI); the main idea is to improve the foundation soil so that seismic energy will be partially dissipated within it before being transmitted to the structure. SRM represents a low-cost seismic isolation system alternative to the traditional seismic isolation systems (Naeim & Kelly, 1999), whose installation and maintenance are considered quite expensive economically and technically for conventional buildings; these solutions are almost prohibited in developing countries where the financial resources are limited.

SRM suitability and advantages as GSI in the form of a layer underlying the foundation of structures have been widely investigated numerically over the recent years (Tsang et al. 2012; Tsang and Pitilakis 2019; Pistolas et al. 2020), demonstrating the decrease of the foundation's seismic response. On the other hand, only a few experimental studies on this subject are available in the literature, and they are mainly limited to laboratory and small-scale testing (Xiong and Li, 2013; Bandyopadhyay et al. 2015; Tsiavos et al., 2019; Tsang et al., 2020). Although these experiments provide significant insight concerning the behavior of SRM as a GSI strategy, there are certain limitations in reproducing realistic boundary conditions and stress fields. Therefore, large-scale field tests of SRM as a seismic isolation layer beneath large-scale structures are necessary to investigate the SRM-foundation-structure systems' response.

This study shows the first experimental campaign results on a full-scale prototype structure on gravel-rubber mixtures (GRM). The large-scale prototype structure was the EuroProteas one in Thessaloniki, Greece (http://euroseisdb.civil.auth.gr). It was used after replacing the foundation soil with three different GRM for a thickness of 0.5m. Forced-vibration tests were performed. The study investigated the rubber content effect of the GRM layer on the dynamic response of the EuroProteas structure and the overall performance of the GRM as a geotechnical seismic isolation (GSI) system.

2. Experimental layout

EuroProteas is the first full-scale model structure in Europe (at the Euroseistest facility, 30km NE of Thessaloniki in Greece) designed and constructed as a simple test structure that promotes the SSI phenomena. It is a perfectly symmetric steel frame on an RC slab and supporting two RC slabs; steel X-braces connect the four steel columns in both directions. Over the last few years, many tests were performed on this structure. More details can be found in Pitilakis et al. (2015b; 2018) and Vratsikidis and Pitilakis (2018). Recently, both free- and forced-vibration tests were performed at different excitation levels, with and without rubberized soil underneath the foundation, in the framework of the European SERA Project (Pitilakis et al., 2021). This paper deals with the forced-vibration tests.

The input force was applied at the geometrical center of the structure's roof by an eccentric mass shaker. The produced harmonic force was applied along the structure's principal axis at approximately 30◦ angle with the magnetic North-South direction. The output force amplitude is adjusted by the eccentricity and the operating frequency according to the equation $F = E \cdot (2\pi f)^2$, where F is the shaker force (in N), E is the eccentricity of the shaker (in kg-m), and f is the rotational velocity of the shaker (in Hz). Just the tests characterized by the eccentricity equal to 6.93 kg-m are here shown for lack of space. The frequency range is 1-10 Hz to include the fixed- and flexible-base natural frequencies of all the three GSI-structure systems. The structure was shaken for a time window of 25s at each excitation frequency to reach a steady state.

The soil below EuroProteas was investigated using extensive geotechnical and geophysical surveys, including static and dynamic in-situ and laboratory tests (Pitilakis et al. 1999; 2018). The subsoil consists of a 7 m thick upper layer of silty clayey sand, which overlies a layer of clayey to silty sand with gravels between 7 and 22 m and, after that, a layer of marly silt to silty sand until the depth of 30 m. The shear wave velocity of the uppermost 5 m varies from 100 to 150 m/s and then increases to more than 250 m/s at 25 m depth. The uppermost 0.5m of the foundation soil was replaced with three different GRM backfills (Figure 1). The rubber content per mixture weight (p.w.) was fixed equal to 0%, 10%, and 30% for the three foundation mixtures labelled in the following as G/R 100/0, G/R 90/10, and G/R 70/30, respectively. The adopted gravel (G) was characterized by $D_{50,G}$ = 20.76 mm and $G_{s,G}$ = 2.67. The rubber (R) was recycled granulated rubber from car tires characterized by $D_{50,R}$ = 3.27 mm and $G_{s,R}$ = 1.10. Figure 2 shows their grain size curves and a detail of the three mixtures. As for the mixtures, the G/R 100/0 was characterized by $G_{s,G}$ = 2.67, D_r = 98%, γ_d = 16.2 kN/m^3; the G/R 90/10 was characterized by $G_{s,G}$ = 2.51, D_r = 98%, γ_d = 15.2 kN/m^3; the G/R 70/30 was characterized by $G_{s,G}$ = 2.19, D_r = 59-71%, γ_d = 11.8 kN/m^3.

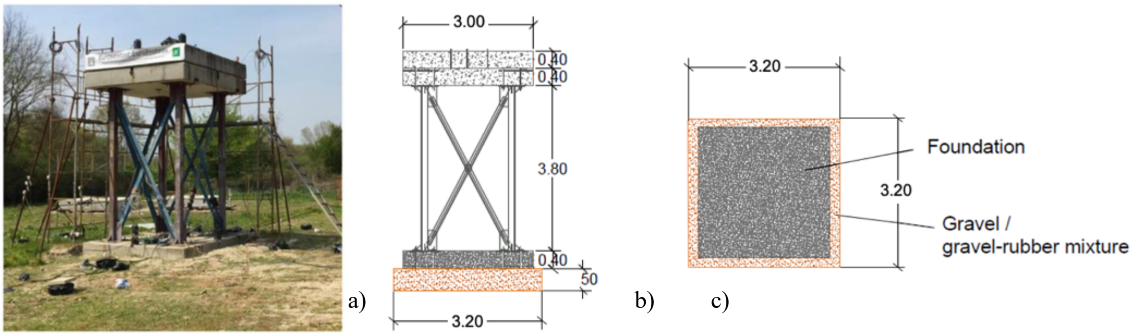

Fig 1. (a) Photo, (b) section and (c) plan view of EuroProteas with the adopted GRM underneath the foundation (lengths in meters).

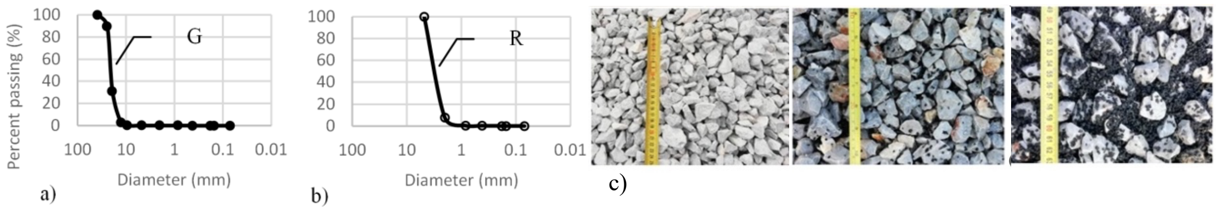

Figure 2. (a) Gravel grain-size curve. (b) Rubber grain-size curve. (c) A detail of the three mixtures.

2.1 Instrumentation

A particularly dense instrumentation scheme was designed to monitor and record the response of the structure, the foundation, the GRM layer, and the adjacent soil in the vertical “z” direction and in the two horizontal NS “n” and EW “e” directions (Figure 3).

The structure was instrumented with accelerometers installed both on the roof, along the direction of shaking (that is the “n” direction) and at the opposite corners of the slab to capture possible out-of-plane motion (Figure 3a), and on the foundation, forming a cross shape to capture the foundation’s translational, rocking, and possible out-of-plane motion (Figure 3b). Seismometers and one accelerometer were located on the soil surface to monitor the soil response, both along the loading axis and on the perpendicular axis (Figure 3c). The distance between those close to the structure was defined at 0.50 m = B/6, where B is the foundation’s width. The most distant instrument was installed at 5 m = 5B/3. Finally, a shape-acceleration array equipped with sensors every 0.15 cm was installed immediately below the foundation’s geometrical center to capture the GRM layer’s response and accelerometers were buried under the foundation to monitor the response of the GRM (Figure 3d).

3. Results

Due to the lack of space, the results are presented only about the horizontal accelerations in the “n” direction, which is the loading direction.

Figure 4.a shows the wave propagation in the system, in terms of maxima accelerations, for the frequencies near to the resonance frequencies of the GSI-structure systems (2.5Hz for G/R 70/30; 4Hz for G/R 100/0 and 90/10; Pitilakis et al., 2021) and the fixed-base structure (8 Hz; Pitilakis et al., 2021). For f = 2.5Hz, the highest maxima accelerations occur in the presence of G/R 70/30 since resonance occurs for this frequency. Comparing the acceleration at the roof with the one at the

foundation, an almost constant decrease is achieved for all the GRM, although the accelerations differ considerably for GR 70/30 on one side and GR 90/10 and GR 100/0 on the other side. Similar results are achieved comparing the accelerations at the foundation and at the soil surface (0.5 m far from the foundation). Finally, moving through the soil surface (from 0.5 m up 2.0 m far from the foundation), there is a different acceleration decreasing: the small value achieved in G/R 100/0 may be due to the higher stiffness and more negligible damping of G/R 100/0. Similar results are achieved for f = 4Hz and f = 8Hz. The motion's decay from the foundation to the soil next to the foundation, especially for G/R 70/30, confirms the supposed ability of the recycled rubber included in GRM to trap the dynamic wave, avoiding its passage from the foundation to the soil. So, the GSI of the structure is optimized by increasing the rubber content of the soil rubber mixture up to 30% per mixture weight.
Figure 4.b shows the R_a-input frequency relationship at the roof for all the three analyzed mixtures, where R_a is the ratio between the maximum acceleration of the system and the maximum acceleration of the eccentric mass shaker (evaluated as $E\omega^2/m_s$, being E the product between the eccentric mass m_e and the eccentricity e; ω the forcing frequency and m_s the mass of the structure). For a frequency close to 2.5Hz the response is amplified much more for G/R 70/10, while for G/R 100/0 and GR/90/10 the response is amplified at 4Hz. Moreover, the highest amplification is obtained for G/R 100/0 and the lowest one is for G/R 70/30, demonstrating once more the increase in the damping of the GSI-structure system due to the increase in rubber percentage in the GRM.

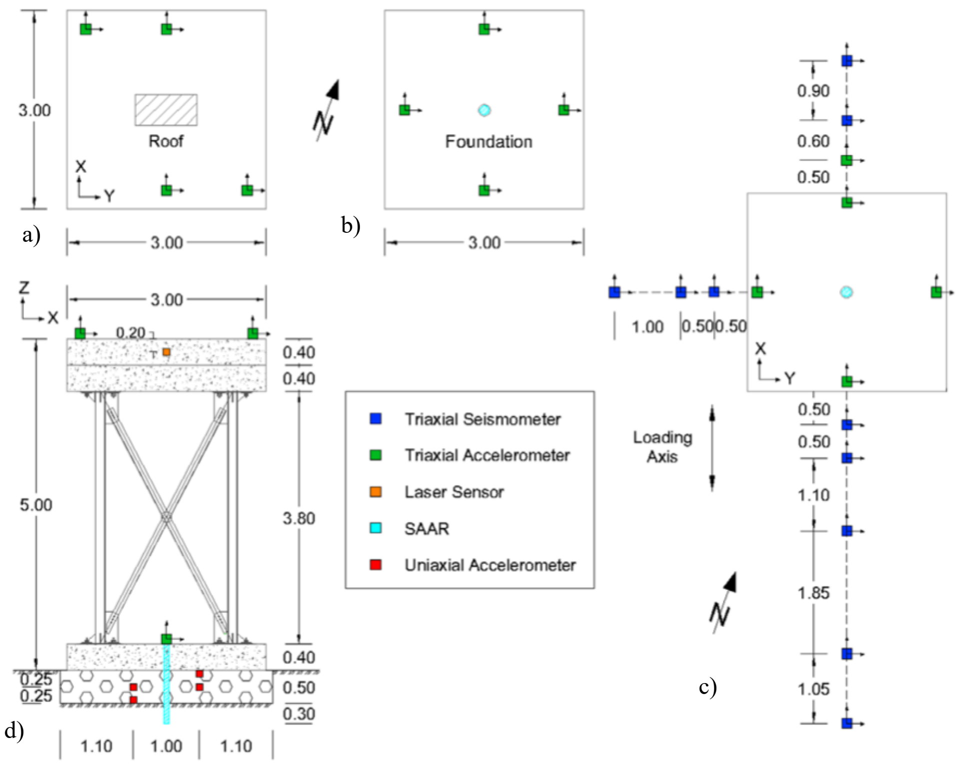

Fig 3. (a), (b) and (c) Plan view and (d) cross-section of the instrumentation layout of the tests.

Figure 5 shows the maxima horizontal accelerations at the roof, the foundation, and the soil surface versus the input frequency. As for the roof, G/R 100/0 and G/R 90/10 exhibit the same trend; the first peak for f = 4Hz is always evident, as well as the second peak for f = 9Hz at the foundation and on the soil for G/R 90/100. Instead, G/R 70/30 has higher values in the first part as the resonant frequency is lower (f = 2.5Hz), then the accelerations are consistently lower than those for G/R 100/0 and G/R 90/10; this means that the energy introduced into the system was consumed due to the damping of the rubber. The same trend is visible at the foundation and the soil, even if the values are much lower.

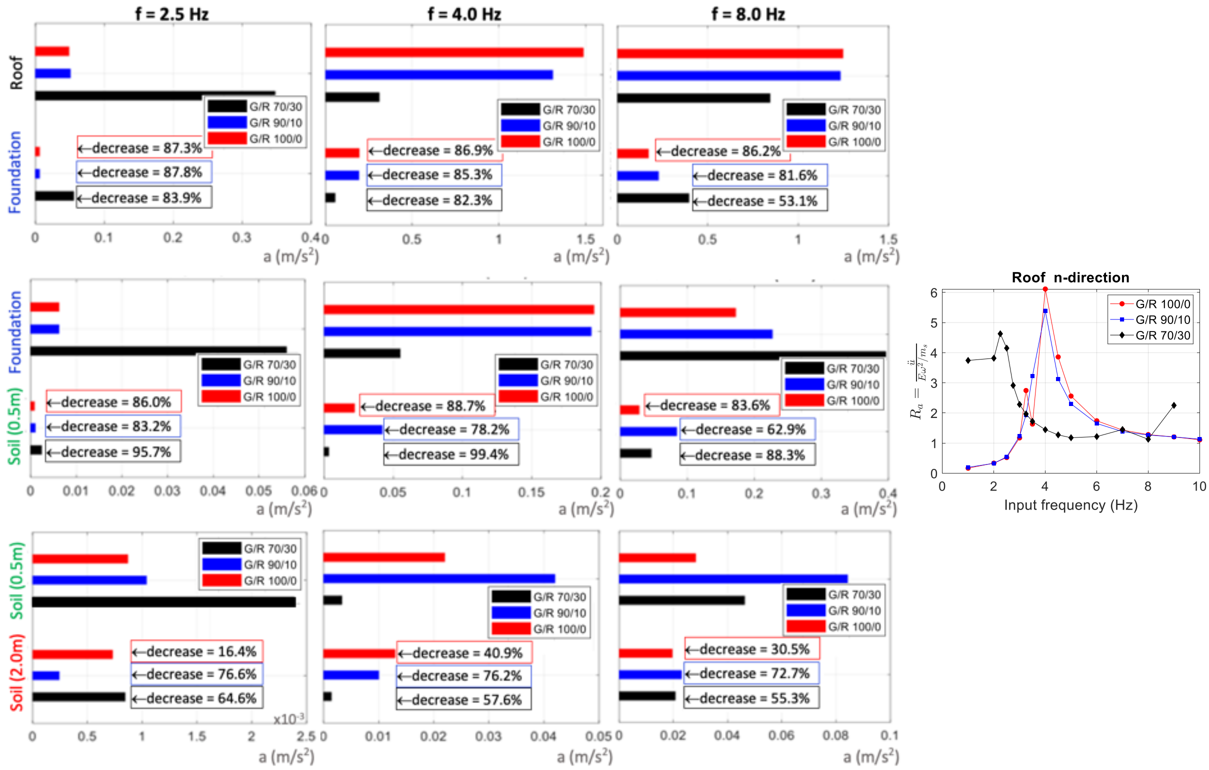

Figure 4. (a) Comparison among maxima horizontal accelerations for the frequencies near to the resonance frequencies of the GSI-structure systems; (b) Acceleration response factor R_a at the roof.

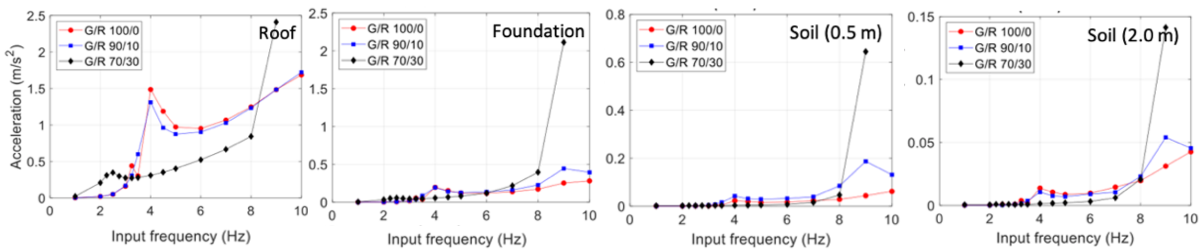

Figure 5. Maximum acceleration vs input frequency for the three mixtures.

4. Conclusions

The paper deals with the first extensive experimental field campaign in the full-scale prototype structure of EuroProteas to investigate the potential of GRM as a means of GSI.

The structure was placed on three GRM layers with different rubber content per mixture weight (0%, 10%, and 30% for the three mixtures labeled as G/R 100/0, G/R 90/10, and G/R 70/30) for a thickness of 0.5m. A dense instrumentation was used to record the wave propagation in the system.

The main results of three sets of forced-vibration tests (applying the input force on the roof of the structure), performed at different excitation levels, showed that a GSI layer composed of a gravel-rubber mixture with 30% rubber content per weight effectively isolates the structure. Even 0.5m thickness (i.e., *B*/6 of the foundation width *B*) of the GSI system cut off successfully all emitted waves at 0.5m from the foundation.

The signal suffers a significant deamplification due to the increase in the rubber content inside the mixture, making softer the soil in the presence of G/R 70/30 compared to G/R 100/0 and 90/10.

Moreover, it is possible to see an energy "entrapment" in the structure, at whose roof the input was applied; in other words, a significant portion of the energy is dissipated in the GRM layer before its radiation to the surrounding soil, proclaiming the beneficial effects of the GRM as a geotechnical seismic isolation system of the structure.

So, considering a real seismic input following the opposite path, from the ground to the structure, the great advantage of the GRM is that seismic energy is dissipated before it transmits into the structure.

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