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Mitigation of seismic vibrations using gravel–rubber mixtures: a geotechnical seismic isolation application for heritage structures

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ABSTRACT: Urban environments face increasing challenges related to both seismic hazards and anthropogenic vibrations (from traffic, machinery, etc.), particularly in densely built historic areas where infrastructure is highly vulnerable. There is a growing need for sustainable, effective ground isolation systems capable of addressing these dynamic stresses without compromising the integrity of heritage structures. This study explores the use of well-graded gravel–rubber mixtures (*wg*GRMs), composed of ELT-derived granulated rubber and natural aggregates, as a Geotechnical Seismic Isolation (GSI) system designed to meet this emerging demand. The elastic and high-damping characteristics of rubber grains make *wg*GRMs a promising geo-material for attenuating a wide range of vibrations while promoting circular economy practices. Laboratory results have demonstrated their good dynamic behaviour under both seismic and anthropogenic loading conditions. To assess their practical application, a historical masonry bell tower in Bronte (Catania, Southern Italy) was selected as a case study. Finite Element Method (FEM) simulations were performed considering the soil foundation improved with a *wg*GRM. Advanced constitutive models (HSsmall and Generalized Hoek–Brown) were adopted to accurately capture the nonlinear behaviour of both the soil and the *wg*GRMs layer. Key parameters, such as rubber content and input ground acceleration, were varied to evaluate system performance under different loading scenarios. The findings highlight the effectiveness of *wg*GRMs in reducing vibration transmission and protecting sensitive structures, supporting their use as a sustainable GSI solution for enhancing resilience in urban heritage areas, while promoting environmentally responsible reuse of tyre waste.

1 INTRODUCTION

The conservation of historical buildings in seismic regions poses a dual challenge: safeguarding cultural value while ensuring structural safety. Italy—especially eastern Sicily—is among Europe's most seismically active zones, repeatedly struck by moderate to severe earthquakes that threaten its dense asset of unreinforced masonry buildings (Abate et al., 2022; Fiamingo and Massimino, 2025). Many heritage structures predate modern design codes and were built on volcanic soils that could amplify ground motion (Di Filippo et al., 2023).

Emerging research explores the use of Geotechnical Seismic Isolation (GSI) systems for isolating structures from seismic motion (Tsang, 2008). Unlike conventional methods that focus on strengthening the structure itself, GSI strategically takes advantage of the Soil-Structure Interaction (SSI) by introducing a low-modulus and high-damping material layer between the building's foundation and the natural soil (Tsang, 2025). GSI can lengthen the structure's natural period and increase energy dissipation, reducing transmitted forces to the structure (Pitilakis et al., 2021; Abate et al., 2023a; Forcellini et al. 2024). This approach could be suitable for heritage sites because it avoids intrusive modifications to walls or façades. In this context, soil-rubber mixtures have emerged as a highly effective and sustainable material for GSI applications. These mixtures are typically obtained by blending cohesionless soil, such as gravel and/or sand, with granulated rubber derived from End-of-Life Tires (ELTs) (Pasha et al., 2019; Chew et al., 2022; Abate et al. 2023b; Fiamingo and Chiaro, 2025). The incorporation of rubber grains, a material known for its high damping capacity and deformability, results in a significantly lower shear modulus and higher energy dissipation compared to natural soil (Anastasiadis et al., 2012). Recent experimental and numerical studies on well-graded Gravel-Rubber Mixtures (*wg*GRMs) have demonstrated their effectiveness in reducing seismic demands (Fiamingo et al., 2025a, 2025b, 2026). The laboratory tests demonstrate that *wg*GRMs possess a high shear strength angle, exceeding 35°, in addition to favourable energy absorption characteristics.

This study shows finite element method (FEM) dynamic analyses to investigate the seismic behaviour of *wg*GRMs as a GSI system in a historical bell-tower in Bronte, Italy. The dynamic analyses employ advanced constitutive models, namely the Hardening Soil with Small Strain Stiffness (HSsmall) and the Generalised Hoek-Brown (GHB), to capture the nonlinear behaviour of the *wg*GRMs and surrounding soils. The mechanical and dynamic parameters adopted in the numerical simulations are derived from laboratory tests previously performed on *wg*GRMs. The study evaluates the influence of rubber content and input ground motion on the tower's response, ultimately demonstrating the effectiveness of *wg*GRMs for seismic isolation.

2 THE CASE STUDY

2.1 The St. Giovanni Evangelista bell-tower

The St. Giovanni Evangelista bell-tower, a notable 16th-century masonry structure within Bronte's historic centre (Figure 1a), serves as the benchmark structure for this investigation into the effect of *wg*GRMs as a GSI system. Built in 1614, the tower rises 25.80 m from a quadrangular base measuring approximately 6.00 m per side (Mondello, 2020). While direct survey data is unavailable, its foundations are inferred to be continuous masonry footings, extending ~1.50 m below grade. The structure's walls, faced with lava stone, exhibit a progressive tapering in thickness, diminishing from 2.00 m at ground level to 1.03 m at the upper levels. The numerical analysis for this paper is based on a 2D FEM model, focusing on section A–A (Figures 1b-c), as explained in Section 3.

2.2 Soil Foundation and adopted mixtures

The subsoil of the studied Bronte area consists predominantly of volcanic soils (Branca and Ferrara, 2013). Site characterisation includes Multichannel Analysis of Surface Waves (MASW) tests (Figure 2a) and borehole investigations. A linearly interpolated V_s profile from the MASW data (Figure 2a) indicates a conventional seismic bedrock ($V_s \geq$ 800 m/s) at 54 m depth, consistent with regional models (Cavallaro et al., 2016). Based on this profile, the resulting weighted average value of the shear wave velocity up to 30 m ($V_{s,30}$) is 484.30 m/s, which corresponds to a Soil Type B classification under the current Italian building code (NTC, 2018). The investigation delineates two geological units: a superficial "LC" unit of volcanic sand (extending to ~22.5 m) and a deeper "SFALS" unit of fractured basalt lava. The dynamic soil properties are derived from the literature. For the LC unit (Figure 2b), reference is made to curves from similar volcanic soils in Catania (Cavallaro et al., 2001). The behaviour of the SFALS basalt is inferred from studies on Etnean volcanic rocks (e.g., Heap et al., 2020).

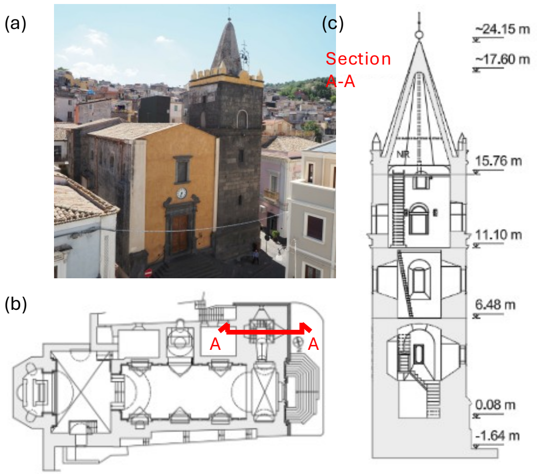

Figure 1. (a) St. Giovanni Evangelista church and its bell-tower; (b) Plan view of the St. Giovanni Evangelista church; (c) Bell-tower cross-section (modified by Mondello 2020).

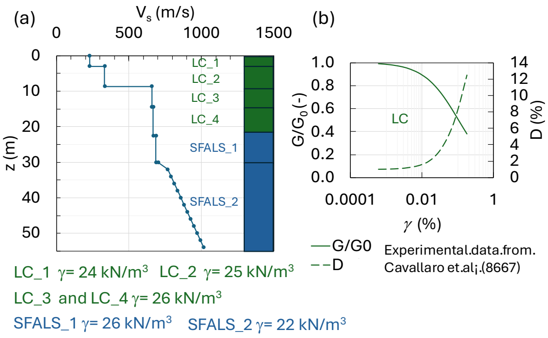

Figure 2. (a) $V_s(z)$ profile from MASW tests; (b) $G(\gamma)/G_0$ and $D(\gamma)$ curves for the LC soil (modified by Cavallaro et al. 2001).

As introduced, this study examines a benchmark case that includes the bell-tower placed on the original soil and a second case in which *wg*GRMs fully isolate the bell-tower's foundation. The mechanical behaviour of the *wg*GRMs was previously characterised by Fiamingo et al. (2025a, 2025b) through a comprehensive testing program including monotonic consolidated drained triaxial tests, bender element tests, and drained cyclic triaxial tests. These experiments constitute the basis for the calibration of the HSsmall constitutive model parameters adopted in the numerical analyses (Fiamingo et al., 2026). The mixtures adopted in this study include two different volumetric rubber contents (VRC)—25% and 40%—denoted as *wg*GRMs 75/25 and *wg*GRMs 60/40, respectively. Figures 3a and 3b show the experimental data for the secant shear modulus (G_{sec}) and hysteretic damping ratio (D). The figures also show the fitted curves for G_{sec} versus shear strain (γ) based on the Darendeli (2001) model, and for D versus γ based on the Yokota et al. (1981) model. Both the initial shear modulus (G_0, at γ = 0.00001%) and G_{sec} decrease with higher VRC. Furthermore, the reduction of G_{sec} with increasing strain levels becomes less pronounced at higher VRC, indicating a more linear material response. D increases with VRC for γ < 0.03% but decreases with VRC for strains above this threshold. Generally, the damping values of the tested mixtures are higher than those typically found in natural soils.

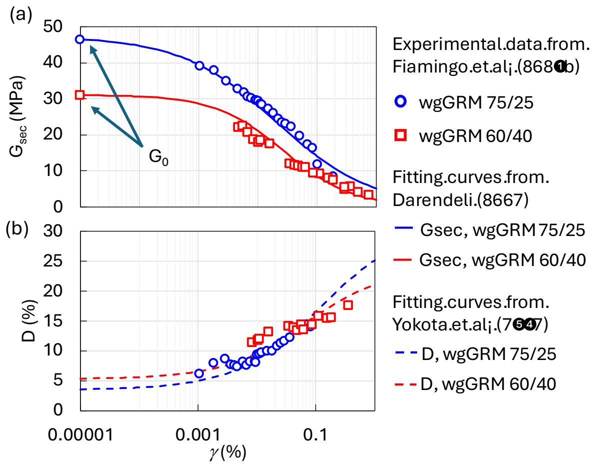

Figure 3. (a) Secant shear modulus (G_{sec} vs γ) curves and (b) hysteretic damping ratio (D vs γ) curves for the investigated well-graded gravel-rubber mixtures with a volumetric rubber content (VRC) of 25% and 40% (modified by Fiamingo et al. 2025b).

2.3 Seismic inputs

The dynamic analyses employ a set of seven spectrum-compatible accelerograms, selected according to NTC (2018). These motions are consistent with the seismic hazard disaggregation for the investigated area (Stucchi et al., 2011), with moment magnitudes (M_w) ranging from 4.0 to 7.0 and epicentral distances (R) ranging from 0 to 30 km. The selection is performed using the Rexel WEB code to ensure compliance with the average spectral compatibility criteria of the NTC (2018). The latter is developed according to the following parameters: Soil type: A, Topographic category: T1, Nominal Life (V_N): 50 years, Functional Type: III, and Limit State of interest: Limit State of Life Safety. The elastic response spectra of the seismic motions are presented in Figure 4.

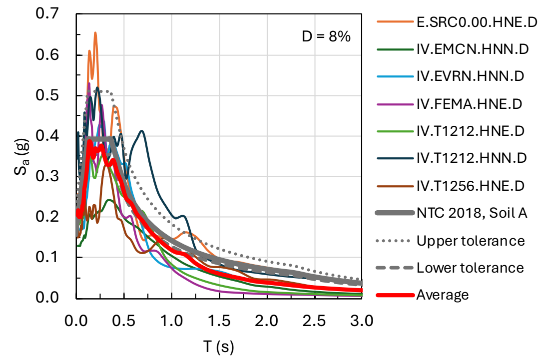

Figure 4. Elastic response spectra for the adopted seismic motion. Damping ratio (D) is equal to 8%.

3 THE FEM MODELS

The 2D FEM models developed for the analyses are generated using MIDAS FEA NX (2024). Figure 5a and 5b depict the soil-bell-tower and soil-*wg*GRMs-bell-tower systems, respectively. To minimise the influence of artificial boundaries, the soil deposit in all models has dimensions of 168.00 m in width and 54.00 m in depth. The soil stratigraphy is discretised into six layers (Figure 2a), with the structure placed at the centre. Details of the *wg*GRMs layer are shown in Figure 5b. The analyses employ a simplified model where the pyramidal cusp geometry is linearised, an approach that maintains the overall mass and stiffness of the primary walls. The model uses plane-strain four-node solid elements for the soil and *wg*GRMs layer and plane-stress four-node solid elements for the structure. To simulate the in-plane stiffness provided by the internal floors, rigid links are defined at each story (Figure 5a). Furthermore, the mesh is refined to ensure that all element sizes are smaller than one-eighth of the shortest wavelength of the input signal (Lanzo and Silvestri, 1999). Free-field boundary conditions are applied to the vertical sides of the model to represent the effect of an infinite lateral extent and absorb outgoing seismic waves. These boundaries are linked to the main mesh via viscous dampers (Lysmer and Kuhlemeye, 1969). The base of the models is fully fixed. At the model base, the seismic motions described in Section 2.3 are applied. To simulate potential nonlinear interface behaviour such as sliding and uplift, contact surfaces with normal (k_n) and shear (k_t) stiffness springs are implemented at the soil-foundation (or *wg*GRMs-foundation) boundary. The stiffness of these springs is derived from the properties of the adjacent materials (Abate et al., 2023b).

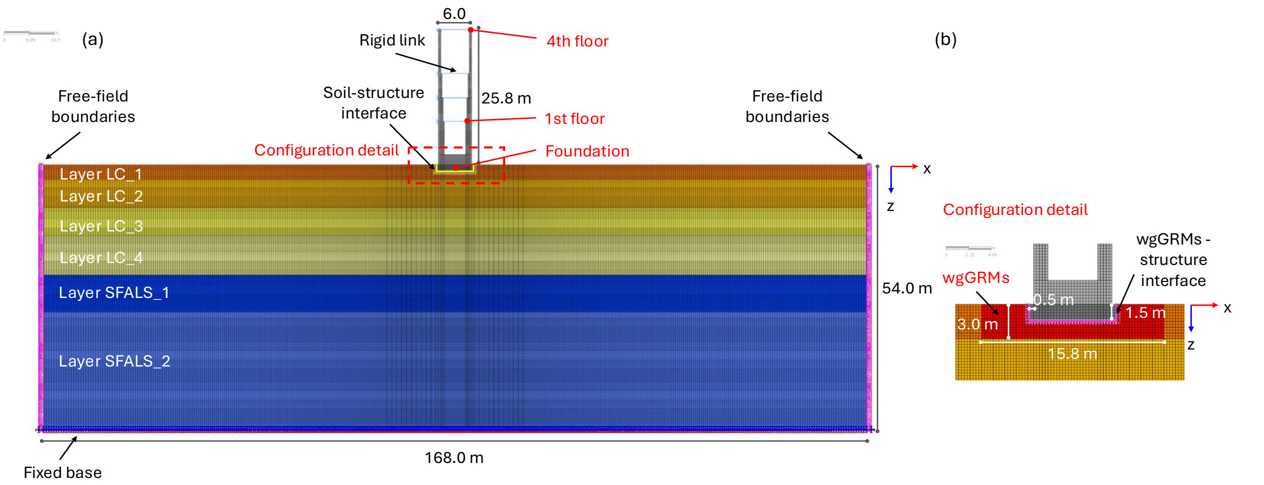

Figure 5. 2D FEM models: (a) soil-structure system; (b) detail of the soil-wgGRMs-structure system.

The bell-tower is simulated as a linear visco-elastic material. The properties assigned are Young's modulus of 2850 MPa, Poisson's ratio of 0.3, and unit weight of 17 kN/m³, based on typical values for stone block masonry (Liberatore et al., 2000) and the NTC (2018), with a damping ratio of 8%. The soil and *wg*GRMs responses are reproduced using advanced nonlinear constitutive models. The stress-strain behaviour of the LC layers (volcanic sand) and of the *wg*GRMs is simulated with the HSsmall model (Benz et al., 2009). In contrast, the SFALS layers (fractured basalt) are reproduced by the GHB model (Hoek and Brown, 1980). Details about the interpretation and validation of the model parameters for LC, SFALS, and *wg*GRMs layers are provided in Fiamingo et al. (2026). All parameters for the soil and *wg*GRMs layers are provided in Tables 1-3. A summary of the key HSsmall model parameters includes: G_0^{ref}, the reference initial shear modulus at a reference confining pressure (p^{ref} = 100 kPa); m, a material constant; $\gamma_{0.7}$, the shear strain level where the secant shear modulus reduces to 70% of its initial small-strain value (G_0); E_{50}^{ref}, E_{oed}^{ref}, E_{ur}^{ref}, the reference stiffnesses for triaxial loading, primary oedometric loading, and unloading/reloading, respectively; ν_{ur}, the Poisson's ratio for unloading/reloading; k_0, the coefficient of earth pressure at rest; R_f, the failure ratio; c', φ, ψ, the effective cohesion, friction angle, and dilatancy angle; D_0, the small-strain damping ratio.

For the GHB model, the primary parameters are the Young's Modulus (E), Poisson's ratio (ν), uniaxial compressive strength of the intact rock (σ_{ci}), and the material constants m_i, GSI_{rock}, and D_{factor}, which are used to calculate the strength parameters m_b, s, and a. The dilatancy angle (ψ) and small-strain damping ratio (D_0) are also defined.

Table 1. HSsmall model parameters for the LC soil layers.

Parameters	Layer			
	LC1	LC2	LC3	LC4
G_0^{ref} (kPa)	127848	282083	1147858	1183361
m (-)	0	0	0	0
$\gamma_{0.7}$ (%)	0.044	0.044	0.044	0.044
E_{50}^{ref} (kPa)	30440	67163	273299	281753
E_{oed}^{ref} (kPa)	30440	67163	273299	281753
E_{ur}^{ref} (kPa)	91320	201488	819898	845257
ν_{ur} (-)	0.25	0.25	0.25	0.25
k_0 (-)	0.45	0.45	0.45	0.45
R_f (-)	0.9	0.9	0.9	0.9
p_{ref} (kPa)	100	100	100	100
c (kPa)	0	0	0	0
ϕ (°)	33.5	33.5	33.5	33.5
ψ (°)	0	0	0	0
D_0 (%)	1	1	1	1

Table 2. GHB model parameters for the SFALS layers.

Parameters	Layer	
	SFALS1	SFALS2
E (kPa)	2992521	4174184
ν (-)	0.20	0.20
σ_{0ci} (kPa)	80600	80600
m_i (-)	25	25
GSI_{rock} (-)	55	55
D_{factor} (-)	0	0
m_b (-)	5.01	5.01
s (-)	0.007	0.007
a (-)	0.504	0.504
ψ (-)	0	0
D_0 (%)	1	1

Rayleigh damping is applied to all materials in the model. The assigned damping ratios are 8% for the structure, as specified by NTC (2018), and 1% for the LC and SFALS soil layers (Cavallaro et al., 1999). Furthermore, damping ratios of 4% and 5% are assumed for the *wg*GRMs 75/25 and *wg*GRM 60/40 materials, respectively (Fiamingo et al., 2025b).

Table 3. HSsmall model parameters for the wgGRMs layer.

Parameters	Layer	
	***wg*GRM 75/25**	***wg*GRM 60/40**
G_0^{ref} (kPa)	46500	31000
m (-)	0.7	0.4
$\gamma_{0.7}$ (%)	0.0046	0.0088
E_{50}^{ref} (kPa)	6186	2922
E_{oed}^{ref} (kPa)	4949	2922
E_{ur}^{ref} (kPa)	14227	10227
ν_{ur} (-)	0.3	0.3
k_0 (-)	0.32	0.38
R_f (-)	0.7	0.7
p_{ref} (kPa)	100	100
c (kPa)	0	0
ϕ (°)	43	38
ψ (°)	2	0
D_0 (%)	4	5

4 RESULTS

The performance of the proposed *wg*GRMs 75/25 and *wg*GRMs 60/40 is evaluated by examining the maximum horizontal accelerations (η_a, shown in Figures 6a-b) and maximum drifts (η_d, shown in Figure 6c-d) recorded at the foundation and at various floors. These parameters serve as indicators of structural response, following the approach of Somma et al. (2022). They are expressed as:

$$\eta_a = 1 - \left(\frac{a_{max,GSI}}{a_{max,NO\ GSI}}\right) \quad (1)$$

$$\eta_d = 1 - \left(\frac{u_{d,max,GSI}}{u_{d,max,NO\ GSI}}\right) \quad (2)$$

where $a_{max,GSI}$ is the peak horizontal acceleration for the model incorporating the GSI layer (i.e., the *wg*GRMs 75/25 or *wg*GRMs 60/40 case) and $a_{max,NO\ GSI}$ is the corresponding value for the reference model without any isolation material. Similarly, $u_{d,max,GSI}$ and $u_{d,max,NO\ GSI}$ refer to the maximum drift with and without the GSI system, respectively. Drift is defined as:

$$u_d = u_{x,dyn,floor} - u_{x,dyn,found} - \theta h \quad (3)$$

where $u_{x,dyn,floor}$ is the dynamic horizontal displacement of a given floor, $u_{x,dyn,found}$ is the dynamic horizontal displacement of the foundation, θ is the rocking rotation (derived from the vertical displacement of the foundation corners), and h is the inter-story height.

Figures 6a-b demonstrate that the GSI layer provides a substantial reduction in seismic accelerations—around 60%—a trend that remains consistent across the foundation, the first level, and the fourth level of the bell tower for the *wg*GRM 75/25 and *wg*GRM 60/40. A comparable behaviour is observed for drift (Figures 6c-d), with an average reduction of approximately 30% for both investigated mixtures.

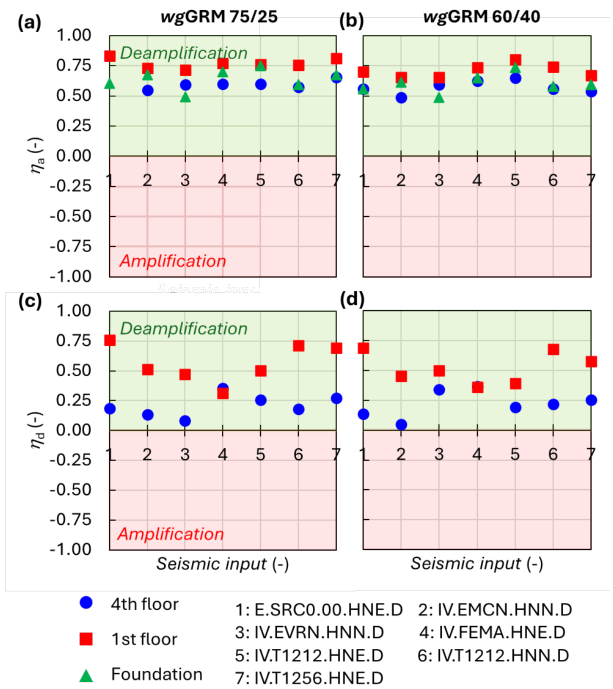

Figure 6. Efficiency in terms of maximum horizontal accelerations (η_a): (a) wgGRM 75/25; (b) wgGRM 60/40. Efficiency in terms of maximum drift (η_d): (c) wgGRM 75/25; (d) wgGRM 60/40.

The reduction in acceleration obtained in this study (≈60%) is consistent with experimental observations reported in the literature. Laboratory and large-scale tests on gravel–rubber mixtures (e.g., Anastasiadis et al., 2012; Pitilakis et al., 2021) show that rubber inclusion increases damping and reduces shear stiffness, resulting in effective vibration attenuation.

These decreases confirm that the *wg*GRMs function effectively in dissipating seismic energy and in partially isolating the structure from ground motion. Notably, this improvement in seismic response is achieved without modifying the structural fabric, which is crucial for preserving heritage constructions. The findings suggest that GSI can enhance seismic safety while preserving the building's historical integrity and promoting sustainability by utilising recycled materials.

Figure 7 presents the ratio between the fundamental frequency of the system—including SSI—and the input frequency at the foundation ($f_{SSI}/f_{input,found}$) for each ground motion. The outcomes distinctly show that the presence of *wg*GRMs consistently lowers the $f_{SSI}/f_{input,found}$ values relative to the scenario with no mixture. This reduction implies that the *wg*GRMs increase the overall deformability of the soil–structure system. The added flexibility moves the system away from resonance-prone frequency ranges, resulting in a more favourable seismic response. The shift in frequency thus highlights the dual function of *wg*GRMs: they not only dissipate energy but also alter the dynamic characteristics of the system to promote safer separation between ground and structural frequencies.

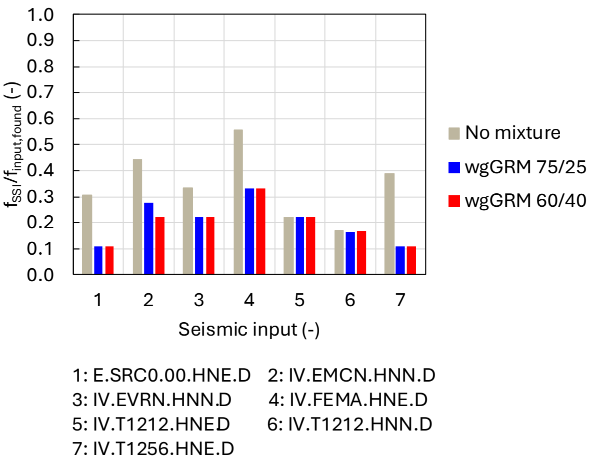

Figure 7. Variation of the frequency ratio $f_{SSI}/f_{input,found}$ with ground motion for each mixture.

Figure 8 compares the acceleration response spectra at the foundation level for two representative seismic inputs, with and without the *wg*GRM layer. The spectra clearly show that the introduction of the *wg*GRMs leads to a marked reduction in spectral accelerations across a wide range of periods. This attenuation is more pronounced in the short-to-intermediate period range, where the bell tower's predominant frequencies are located. For both input motions analysed—E.SRC0.00.HNE.D (Figure 8a) and IV.EVRN.HNN.D (Figure 8b)—the isolated configuration exhibits a consistent downward shift of the spectral accelerations, confirming that the mixture effectively reduces the acceleration demand transmitted to the structure. This behaviour aligns with the trends observed in Figures 6 and 7, in which the *wg*GRMs decrease both acceleration and drift demands by increasing the overall flexibility and damping of the soil–structure system. The reduction in spectral accelerations is directly linked to the softer and more dissipative mechanical response introduced by the *wg*GRM layer, which filters high-frequency components and shifts the system's response away from resonance conditions. These results reinforce the capability of *wg*GRMs to provide an effective seismic isolation mechanism at the foundation level, even under different ground-motion characteristics.

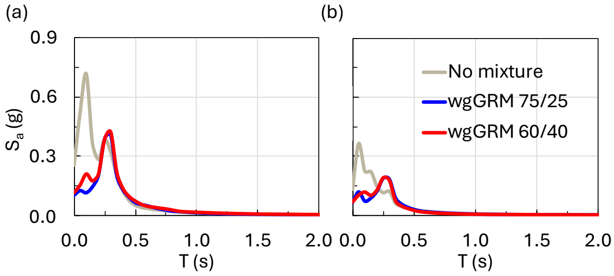

Figure 8. Acceleration response spectrum for the configuration with and without wgGRMs for the seismic motion: (a) E.SRC0.00.HNE.D; (b) IV.EVRN.HNN.D.

Finally, Figure 9 presents the total vertical displacement ($u_{z,tot}$) of the bell-tower foundation, which combines both the static component and the dynamic component.

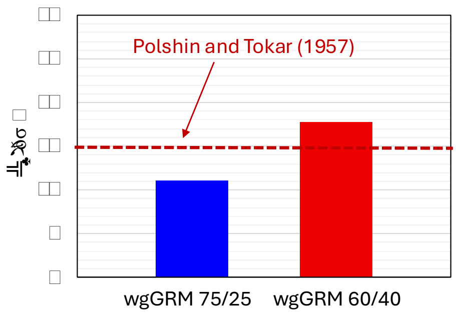

Figure 9. Total vertical displacements ($u_{z,tot}$) of the foundation bell tower and comparison with the allowable vertical displacement value by Polshin and Tokar (1957).

The computed vertical displacements are compared with the maximum allowable value of 15 cm recommended by Polshin and Tokar (1957) for masonry structures. Increasing the VRC results in a greater total vertical displacement, with a nearly linear relationship between VRC and $u_{z,tot.}$ The settlements obtained for the *wg*GRM 60/40 exceed the recommended threshold. This behaviour is attributed to the substantially higher compressibility of mixtures containing larger proportions of rubber, which contrasts with the stiffer *wg*GRM 75/25 layer. Such excessive settlement can be mitigated by incorporating geosynthetic reinforcement—such as geogrids—which have been shown to improve vertical stiffness, as suggested by Dhanya et al. (2020).

5 CONCLUSIONS

This study investigates the application of well-graded gravel–rubber mixtures (*wg*GRMs) as a Geotechnical Seismic Isolation (GSI) system for the preservation of historical masonry structures, using the 16th-century bell tower of St. Giovanni Evangelista in Bronte (Italy) as a case study. Advanced nonlinear FEM analyses are performed to evaluate how different rubber contents influence the seismic response of the soil–structure system. Although the two mixtures have different rubber contents, the dynamic analyses show very similar reductions in both accelerations and drifts, with each mixture lowering transmitted accelerations by about 60% and drifts by roughly 30% compared to the case without *wg*GRMs. The introduction of the *wg*GRM layer increases the system's deformability and shifts the fundamental frequency away from resonance with the input motions. This frequency separation further contributes to lowering the seismic demand on the structure. Response spectra analyses indicate a consistent reduction in spectral accelerations over the relevant period range for the bell-tower. This confirms that *wg*GRMs act as an effective seismic filter, validating their performance across various seismic inputs. While higher rubber content (60/40) enhanced deformability and damping, it also led to larger vertical settlements, exceeding standard allowable limits for masonry structures. In contrast, the 75/25 mixture provided a better balance between seismic isolation and acceptable compressibility. Potential settlement issues associated with high rubber content mixtures can be mitigated through the use of geosynthetic reinforcement. The GSI solution using *wg*GRMs offers a non-invasive intervention that does not alter the original structural fabric—an essential requirement for heritage conservation. Additionally, the reuse of recycled tyre rubber promotes environmentally sustainable engineering practices.

Overall, the numerical results highlight the potential of *wg*GRMs as a cost-effective, sustainable, and minimally intrusive GSI technology capable of significantly enhancing the seismic resilience of historical masonry structures. Future developments should focus on 3D modelling, full-scale validation tests, and refined design guidelines to support practical implementation in heritage contexts.

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