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Dynamic testing of a seismically isolated deep foundation: insights from the ERIES-GISIS project

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ABSTRACT: The ERIES-GISIS (Geotechnical Innovative Seismic Isolation System) project, aligned with the goals of the ERIES initiative (Engineering Research Infrastructures for European Synergies), aims to test and validate an innovative seismic base isolation system designed to mitigate inertial forces transmitted to superstructures during earthquakes. The system is particularly appealing for the foundation retrofitting of existing buildings, especially masonry ones with historical and cultural significance. A key component of the study is the use of the EuroProteas full-scale model to simulate the dynamic response of a structure resting on a seismically isolated foundation. The experimental research investigates the increase in its fundamental natural period, the dynamic behaviour of the entire system, and the effects of soil-structure interaction. Building on extensive expertise in earthquake engineering and detailed knowledge of the existing full-scale model's dynamic behaviour, the study introduces a new micropiles foundation system integrating the isolation devices. This system involves a newly cast-in-place reinforced concrete foundation slab, installed directly above a set of isolation micropiles embedded in the soil. The resulting configuration features a superstructure supported by a deep seismically isolated foundation. A comprehensive campaign of forced-vibration tests has been conducted on the upgraded structural prototype structure, covering a wide range of input excitation amplitude and frequencies. The results aim to provide valuable insights into the effectiveness of the GISIS concept in enhancing seismic performance, with potential implications for the protection and preservation of vulnerable historical heritage.

1 INTRODUCTION

Seismic isolation is widely recognized as one of the most effective strategies to mitigate the effects of earthquakes on structures. Over the past decades, extensive research and numerous practical applications have demonstrated its potential in reducing seismic demand on buildings. Despite its widespread use, the technique continues to evolve, as new devices and installation concepts are developed to meet increasingly complex structural and geotechnical requirements.

The concept of separating a structure from ground motion dates back over a century (Reitherman, 2008), and even earlier forms of isolation can be found in ancient construction practices, where the idea of reducing the connection between the ground and the superstructure was applied intuitively (Carpani, 2014). The fundamental objective of base isolation is to modify the dynamic characteristics of a building by introducing a soft interface between the foundation and the superstructure. This allows the isolated structure to move independently from the ground, resulting in reduced accelerations and inertial forces during seismic event (Patil & Reddy, 2012).

Different technologies have been developed for this purpose, including laminated rubber bearings, high-damping rubber bearings, lead–rubber bearings, and sliding or pendulum systems (Sonawane, 2016). While each device offers specific mechanical behaviour and energy dissipation capacity, their practical effectiveness strongly depends on installation feasibility and the structural typology of the building.

For newly designed reinforced concrete buildings, the insertion of an isolation layer can be integrated directly into the structural design. However, for existing structures – especially those built in masonry– the application of conventional isolation systems is considerably more complex. The creation of a continuous separation plane and the need to temporarily support the superstructure make the process invasive and often impractical (Islam et al., 2011). Masonry buildings, in particular, do not present discrete bearing elements such as columns, which limits the applicability of traditional isolators designed for frame structures.

Given the extensive presence of existing and historical constructions in seismic regions, there is a growing interest in alternative isolation solutions that can be installed at the foundation level with limited intervention on the superstructure. In recent years, several studies have explored hybrid systems that combine geotechnical elements – such as micropiles or soil–foundation interfaces – with mechanical isolation or damping devices (Pitilakis et al., 2021, Vratsikidis et al., 2023). These approaches aim to extend the benefits of base isolation to structures where conventional techniques are difficult to implement, providing a promising direction for future developments.

2 SMART-GAP ISOLATION DEVICE

Although base isolation is among the most effective strategies to reduce seismic forces on structures, its practical implementation often faces limitations related to the type and configuration of the superstructure. In particular, pre-existing and masonry buildings pose major challenges, since conventional devices require invasive interventions at discrete bearing points or along well-defined structural interfaces. To overcome these constraints, a new foundation-based isolation system – named Smart-Gap – has been developed, with the aim of enabling a continuous and non-invasive installation beneath existing structures. The system is patented by the European Patent Office.

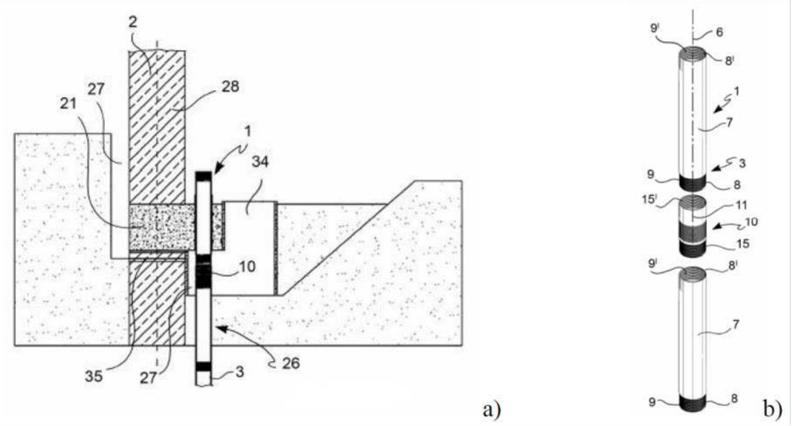

Figure 1 Possible final configuration of the base seismic isolation system for perimetral vertical bearing elements (a) and Micropiles+Seismic Isolation Device (b)

The conceptual basis of the Smart-Gap system (Figure 1) stems from the need to introduce seismic isolation where traditional methods cannot be applied, by exploiting elements that are already common in geotechnical practice. The solution combines the use of micropiles, serving as both structural and installation elements, with compact isolation devices placed among micropile segments. This configuration allows the isolation components to be distributed diffusely beneath the foundation, creating a separation layer that decouples the superstructure from ground motion while maintaining the necessary static load transfer. In the proposed system, in real seismic conditions, ground motion is transmitted to the superstructure via soil–micropiles interaction. The presence of the seismic isolator decouples the substructure from the superstructure allowing a large reduction of inertial forces. Furthermore, this system allows to reach large fundamental period of vibration maximising the superstructure inertial mass

A possible installation process is designed to be carried out with minimal disruption to the existing building. Initially, a new foundation system is created by installing micropiles directly below the existing structure, guided by reinforced concrete support elements rigidly connected to the building. These supports ensure correct alignment of the micropiles and allow the static load to be progressively transferred. After installation and grouting, the upper segment of each micropile is temporarily left unconnected, so that the isolation device can be positioned between the lower and upper sections. Once the isolators are in place, the upper micropile segments are reattached and the load from the superstructure is gradually transferred to the new system using hydraulic jacks. The final step consists of cutting the vertical structural element below the support, effectively separating the original foundation from the new isolated one and allowing controlled horizontal displacements during seismic events.

One of the key advantages of the Smart-Gap system lies in its versatility. The modular nature of the micropile–isolator devices allows for a high degree of flexibility in terms of spatial distribution and number of devices themselves, making it possible to adapt the isolation layout to different foundation geometries and stiffness conditions. By properly calibrating the position of each device, the dynamic response of the building can be optimized – aligning the centres of mass and stiffness and thus reducing torsional components in the fundamental vibration modes.

Overall, the Smart-Gap system merges well-established geotechnical techniques with innovative isolation principles, providing a practical and adaptable solution for seismic protection of both new and existing structures, including those with masonry foundations or irregular layouts.

The ERIES-GISIS project aims to evaluate the effectiveness of the Smart-Gap by means of forced vibration tests on an isolated slab. In order to quantify the benefits of the isolation system on structures, a well-studied prototype has been used: the EuroProteas prototype structure at the EuroSeisTest site (Figure 2).

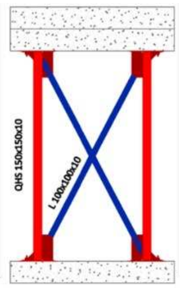

Figure 2 EuroProteas prototype structure at EuroSeisTest site, Thessaloniki, Greece

Tests will be carried out by applying different forced inputs to various system configurations, in order to evaluate the dynamic response of the seismically isolated structure with the Smart-Gap devices. Details regarding the site conditions, structural characteristics as well as testing procedures are presented in the following sections.

3 SITE AND PROTOTYPE PROPERTIES

EuroProteas is located at the TST site of EuroSeisTest, a major European facility dedicated to full-scale investigations in earthquake engineering and soil–structure interaction (Vratsikidis et al., 2022). The site, situated about 30 km northeast of Thessaloniki, has been extensively characterized through decades of geotechnical and geophysical campaigns, making its subsurface conditions one of the best documented worldwide (Pitilakis et al., 2018). The stratigraphy consists of a sequence of soft alluvial deposits with low stiffness in the near-surface layers.

Within this well-characterized setting, the EuroProteas prototype was conceived as a simple but versatile full-scale structure. It consists of a reinforced-concrete foundation slab (3.0×3.0×0.4 m) supporting a symmetric steel frame with X-braces on all sides and adjustable mass. In the configuration adopted in this study, two reinforced-concrete roof slabs were installed, resulting in a fixed-base fundamental frequency of approximately 9.1 Hz.

For the present experimental campaign, a new purpose-built foundation slab was constructed (Figure 3). The slab was cast in situ and rigidly connected to four micropiles which incorporate the isolation devices. Each device consists of an elastomeric isolator with a diameter of 250 mm and a height of 197 mm, characterized by a nominal shear dynamic stiffness modulus $G_{\mathrm{dyn},\gamma=1} = 0.4\,\mathrm{MPa}$ — this configuration allowed to reach the lowest horizontal stiffness available from the provider factory. The stiffness implications are discussed in the next sections.

Overall, the combination of extensively documented site conditions and the modular EuroProteas structure creates an optimal full-scale environment for evaluating the performance of innovative seismic isolation systems such as the Smart-Gap system.

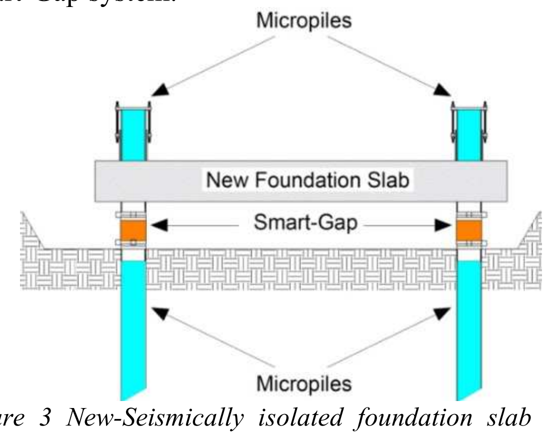

Figure 3 New-Seismically isolated foundation slab on Smart-Gap devices

4 TESTING PROGRAM

The test campaign consists of several forced vibration tests, by means of a mass shaker, covering input frequencies between 0.5 Hz and 9 Hz. The system is modified in each test. Basically, three different configurations have been tested:

- Isolated foundation slab only + shaker on the slab foundation;
- Isolated foundation slab + EuroProteas structure + shaker on the slab foundation;
- Isolated foundation slab + EuroProteas structure + shaker on the slab roof.

4.1 Mass vibrator shaker

To generate controlled harmonic excitations during the forced-vibration tests, the MK-500U eccentric mass vibrator (Figure 4) was employed. The equipment, owned by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK-EPPO), consists of a dual counter-rotating unidirectional shaker designed to induce well-defined horizontal dynamic loads on test structures.

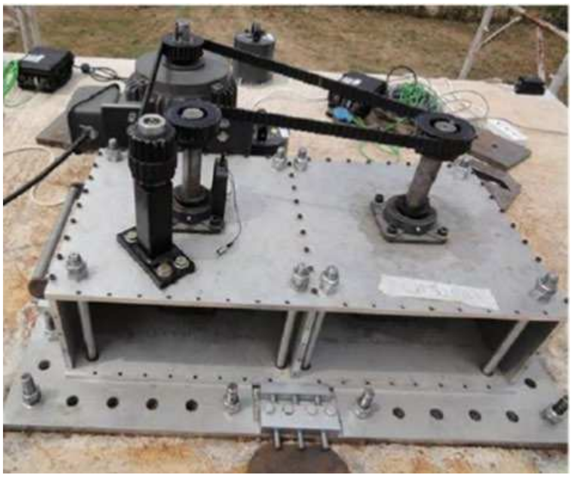

Figure 4 Mass vibrator shaker MK-500U

The vibrator can deliver sinusoidal horizontal forces up to approximately 50 kN, with an adjustable operating frequency ranging from 0.1 to 20 Hz in steps of 0.1 Hz. Its excitation characteristics can be modified by varying the eccentricity, achieved through interchangeable pairs of eccentric plates (types A, B, C, and D), covering a total range between 0.15 and 11.31 kg·m. The amplitude of the generated force (F) depends on the selected eccentricity (E) and the operating frequency (f), and is expressed by the relation:

$$F = E(2\pi f)^2 \quad (1)$$

where F is the resulting sinusoidal force (in newtons), E is the eccentricity (in kg·m), and f is the rotational frequency (in Hz).

This excitation system enabled the application of well-controlled horizontal harmonic loads to the test foundation and superstructure. In Figure 5 the dependency of the sinusoidal forces as a function of frequency and applied masses is reported.

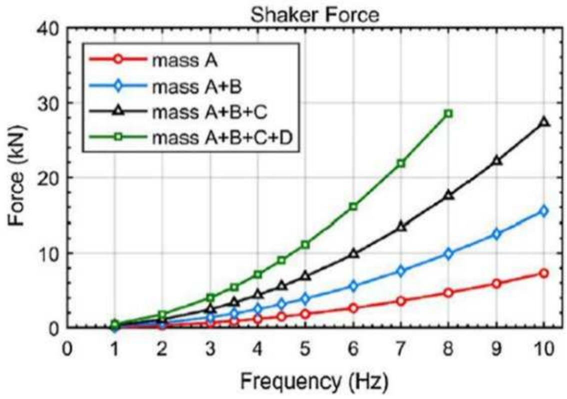

Figure 5 Mass vibrator shaker: generated forces as a function of frequency and applied masses

It can be readily noted that, at low excitation frequencies — expected to be ranging between 0.5 Hz and 2 Hz for base-isolated structures — the resulting forces are relatively small. This condition may pose some challenges in accurately identifying the fundamental vibration period of the isolated system. Nevertheless, this aspect will be further addressed and discussed in detail in the following sections.

4.2 Recording instrumentations

In order evaluate and quantify the dynamic response of the system, as well as assess its foundamental natural period, several recording instruments have been installed.

In particular, the following instrumentaions have been used: triaxial accelerometers for the structure, triaxial seismometers for the soil surface, displacement lasers for the foundation slab and uniaxial accelerometers at specific locations above and beneath the isolators. In Figure 6 and Figure 7 the instruments locations and their description are briefly reported.

The analysis primarily focused on acceleration measurements recorded at both the foundation and roof levels. Displacement readings from laser sensors – installed to monitor the horizontal movement of the foundation slab – were also collected during the testing phase; however, these data are not discussed in the present contribution.

Processing of the acceleration data plays a key role in determining the fundamental vibration period of the isolated system, while the detailed elaboration of displacement measurements, as well as the other recorded data, will be addressed in future work.

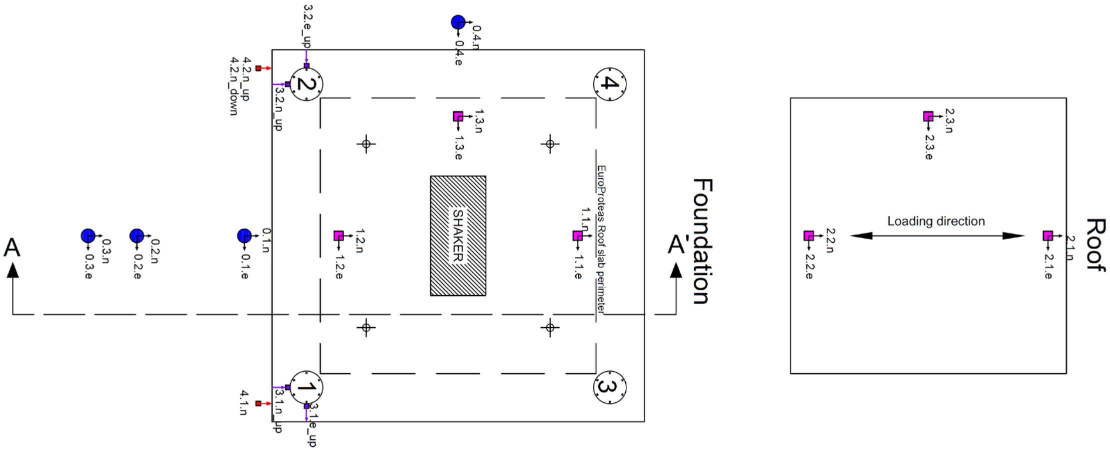

Figure 6 Instrumentations locations - Planimetric view

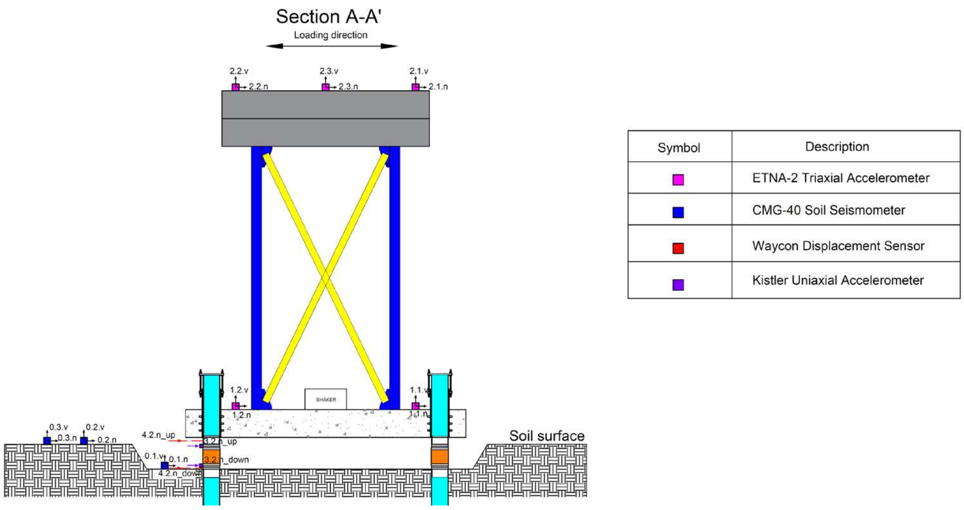

Figure 7 Instrumentations locations - A-A' Section

4.3 Experimental Program and Methodology

Table 1 summarizes the performed tests. As previously mentioned, three different test configurations were investigated. The first configuration refers to the forced-vibration tests conducted on the isolated foundation slab only. For this configuration, the shaker masses were varied from test to test, resulting in a total of three setups. The second and third configurations, instead, were tested using only the highest shaker mass.

At this stage, an important consideration must be made: since the shaker output force varies with the excitation frequency, the direct identification of the system's fundamental period is not straightforward.

Table 1 Experimental program

Configuration	Structure	Mass shaker position	Test No.	Shaker masses	Frequency range
			1	A+B	0.5-8
1	No	Foundation	2	A+B+C	0.5-10
			3	A+B+C+D	0.5-9
2	Yes	Foundation	4	A+B+C+D	0.5-9
3	Yes	Roof	5	A+B+C+D	0.5-8

In other words, the maximum acceleration recorded by any instrument is not necessarily associated with the natural frequency of the system. This occurs because, within the expected frequency range of the isolated system – approximately between 0.5 and 2 Hz – the applied excitation force is relatively low, leading to acceleration amplitudes significantly lower than those observed at higher frequencies.

Consequently, the measured accelerations should always be interpreted in relation to the input frequency and, therefore, to the corresponding excitation forces.

Thus, the proposed methodology to consider the aforementioned factors is:

- Identify the applied input frequency, (f_i), to process data at that specified frequency (Figure 8);
- Calculate the elastic acceleration response spectra (S_a,T) (Figure 9);
- Normalise the elastic acceleration response spectra with respect to the recorded PGA and the frequency dependent input force, F_{input} (Figure 10).

In other words, an amplification factor per unit applied force, AF_1, is calculated as:

$$AF_1 = \frac{S_a(f_i)}{PGA \cdot F_{input}(f_i)} \qquad (2)$$

As illustrated as an example in the following figures, this methodological approach is required to capture the actual influence of the isolators on the system's fundamental period. Otherwise, considering only the conventional acceleration response spectra would lead to an apparent resonance frequency of about 8 Hz.

Conversely, when the results are normalized, a different—and more realistic—natural frequency is identified, approximately equal to 1.5 Hz. This value is consistent, as order of magnitude, with the expected natural frequency of the isolated system.

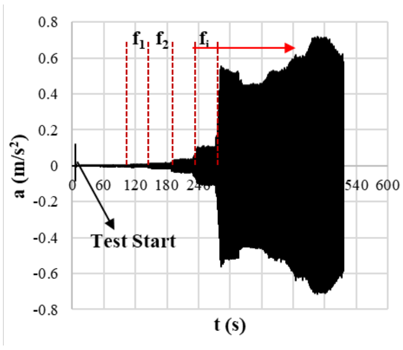

Figure 8 Recorded acceleration

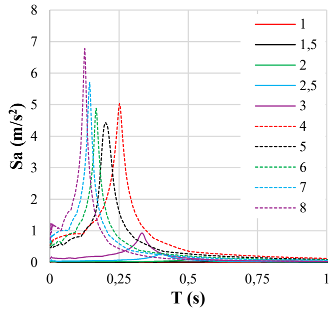

Figure 9 Elastic response spectra

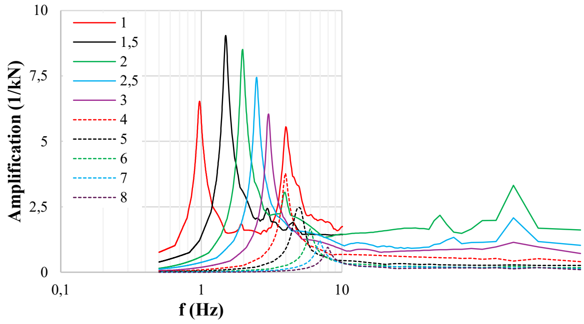

Figure 10 Normalised response spectra

Regarding the isolator devices, it is possible to estimate a theoretical foundamental period starting by the knowledge of the theoretical lateral stiffness of the single isolator itself, equal to 250 kN/m. If a value of the viscous damping, ξ, equal to 15% is considered, the theoretical natural frequency of the system can be estimated as:

$$f_N = \sqrt{\frac{k_h}{M}} \cdot \sqrt{(1-\xi)^2} \qquad (3)$$

where M is the mass and k_h is the horizontal stiffness (stiffness of the single isolator times the number of isolators). In Table 2 the estimation of the natural frequency is reported, as a function of two strain levels (thus taking into account the dependency of G_{dyn} with γ - shear strain of rubber); G_{ref} is a reference shear modulus for γ=100%.

The f_N of the system can be reasonably between 1.24 Hz and 1.95 Hz for the configuration 1 (only the slab foundation) and between 0.84 Hz and 1.32 Hz for the configurations 2 and 3 (slab foundation + EuroProteas structure).

Table 2 Estimated natural frequency of the isolated system for two different strain levels

		$G_{dyn(\gamma)}=G_{ref}$		$G_{dyn(\gamma)}=2.5\ G_{ref}$	
Conf. N°	**M (kg)**	**f_N (Hz)**	**T_N (s)**	**f_N (Hz)**	**T_N (s)**
1	16320	1.24	0.81	1.95	0.51
2 - 3	35680	0.84	1.20	1.32	0.76

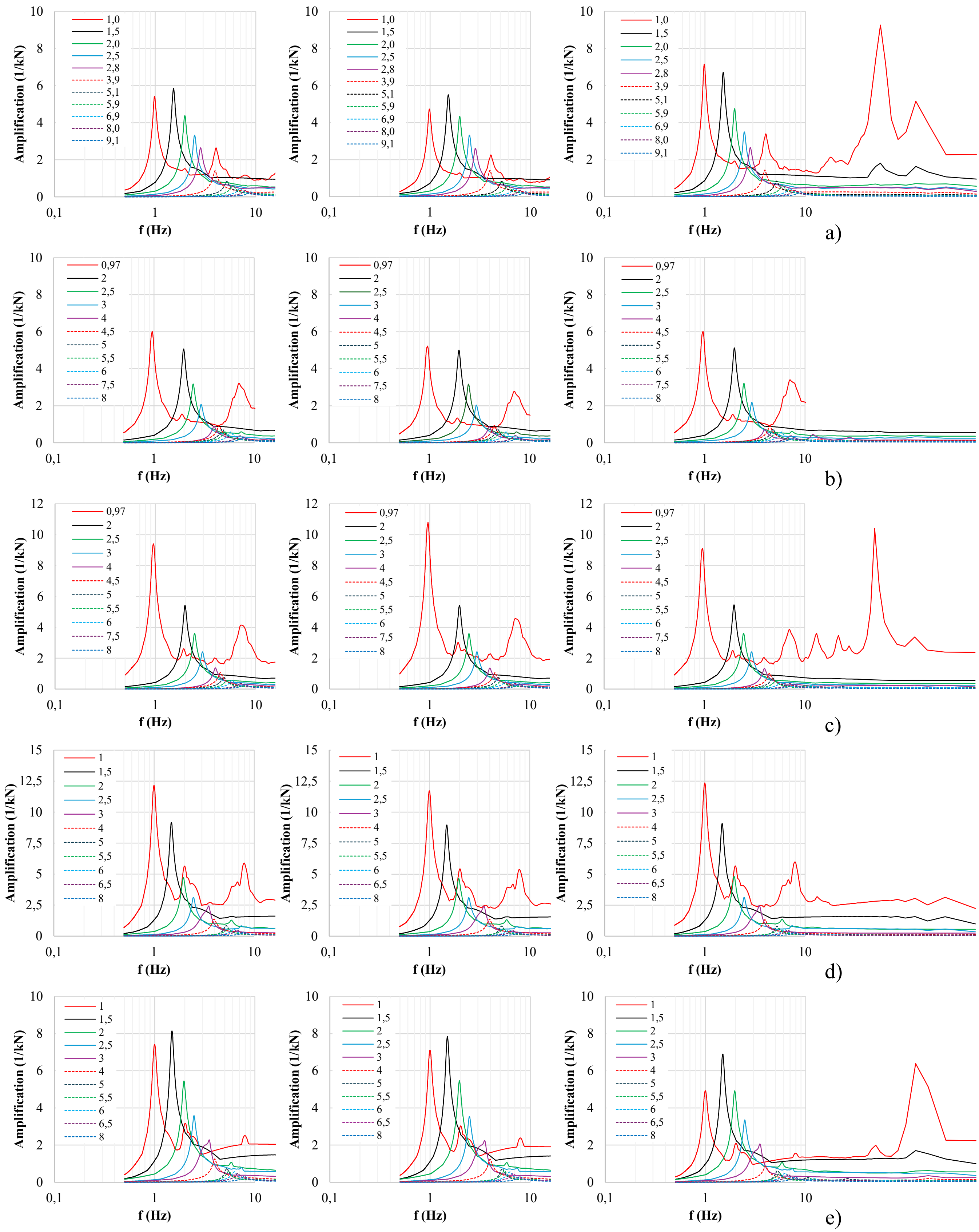

Figure 11 Tests results: a) Conf. n°1, Test 3; b) Conf. n°2, Test 4, recording on the slab; c) Conf. n°2, Test 4, recording on the roof; d) Conf. n°3, Test 5, recording on the slab; e) Conf. n°3, Test 5, recording on the roof

5 RESULTS AND DISCUSSION

Figure 11 presents the experimental results in terms of the amplification ratios defined by (2) plotted against the input excitation frequency. The curves refer exclusively to the configuration where the shaker was equipped with the full set of masses (A+B+C+D), as this arrangement provides the highest excitation force attainable with the available equipment and therefore allows a more reliable identification of the system's resonant response. The accelerations used in the analysis were acquired from sensors 1.1n, 1.2n, and 1.3n installed on the foundation slab, and from sensors 2.1n, 2.2n, and 2.3n positioned at the roof level, thus ensuring a consistent comparison between the response at the base and at the top of the structure.

The results clearly demonstrate that, when the isolated foundation slab is tested alone – without the superstructure – the system exhibits a natural frequency of approximately 1.5 Hz. Once the superstructure is placed on the isolated foundation, the effective mass of the system increases, producing a corresponding decrease in the natural frequency to roughly 1.0 Hz. This shift is fully consistent with the determined theoretical predictions. It is also important to remark that the range of mass variations achievable in the experimental setup is inherently limited by the capacity of the structural constraints of the test facility. If a larger mass would be introduced, a further reduction of the natural frequency would be expected.

Overall, the results confirm the effectiveness of the Smart-Gap isolation devices. Their installation leads to a substantial reduction of the natural frequency of the system, decreasing it from the fixed-base value of approximately 9.1 Hz to about 1.0 Hz under isolated conditions. This significant shift places a structure in a frequency range where the seismic input is typically much lower – if compared to non-isolated systems – resulting in significantly reduced accelerations transmitted to the superstructure and, ultimately, in marked improvements in its dynamic performance.

6 CONCLUSIONS

This work reports a set of preliminary findings obtained from the full-scale experimental facility developed within the ERIES project, named GISIS. The investigated system consists of deep micropiles foundations incorporating seismic isolation devices directly embedded within the micropiles elements. The experimental evidence confirms that the proposed isolation concept is operational and capable of producing a substantial elongation of the fundamental vibration period of the soil–foundation–structure system, thereby resulting in a marked improvement in its dynamic performance. The beneficial effects of isolation become increasingly significant as the isolated inertial mass increases.

Furthermore, the configuration demonstrates particular suitability for application to existing structures, offering reduced installation demands and minimal intervention on the superstructural system.

ACKNOWLEDGEMENTS

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