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VOLUME-2

Editor

Prof. Dr. Orhan ÇAĞLAYAN

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INVESTIGATION OF SEISMIC BEHAVIOR OF REINFORCED CONCRETE STRUCTURES INSULATED WITH SEISMIC META-MATERIALS IN EARTHQUAKE ENGINEERING

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ABSTRACT

Located on multiple active fault lines, Turkey frequently experiences devastating earthquakes. In recent years, seismic metamaterials have emerged as an innovative isolation technique in earthquake engineering due to their ability to create band gaps that prevent the propagation of seismic waves within specific frequency ranges. Periodic foundations composed of such materials can reduce structural responses by dissipating in seismic energy before it reaches the structure. This study experimentally investigated the damping performance of metamaterial-based periodic foundations. A uniaxial shaking table capable of horizontal motion along the x-axis, driven by a 0.75 kW servo motor, was used as a vibration source. The motor's motion was simulated through Arduino IDE programming. Servo motor control signals with step counts of 5000, 4000, and 3000—representing three different vibration frequency profiles—were applied to three test specimens for 20.667 seconds. Accelerometers placed on the top layer of each specimen recorded acceleration responses at 80-millisecond intervals. The recorded data were analyzed in the time domain (acceleration-time) and the frequency domain (via Fast Fourier

Transform). The test specimens consisted of: (i) a conventional foundation made of reinforced concrete plates, (ii) a one-dimensional periodic foundation composed of rubber and concrete plates, and (iii) a one-dimensional periodic foundation embedded with piezoelectric sensors. All specimens were scaled to represent soil-structure interaction, with each 30×30×4 cm layer bonded using a polyurethane-based adhesive. Experimental results revealed that periodic foundations were more effective in suppressing vibration energy than conventional ones. Furthermore, the piezoelectric sensor-integrated foundations exhibited vibration-induced energy harvesting potential, offering multifunctional benefits for structural applications in seismic environments.

Keywords: Earthquake engineering, Dynamic analysis, Metamaterial, Shaking table, Vibration attenuation.

INTRODUCTION

Turkey is in a seismically active region with multiple fault lines that generate frequent destructive earthquakes. In civil engineering, numerous scientific efforts have been devoted to minimizing the material and human losses associated with seismic events.

Early studies by Sigalas (1992) and Kushwaha (1993) demonstrated that phononic crystals can create band gaps that inhibit the propagation of electromagnetic and acoustic waves within specific frequency ranges. Khelif et al. (2015) showed that geometric configurations and boundary conditions can manipulate these band gaps. Sanchez-Perez (1998) and Montero (1998) experimentally demonstrated the attenuation of sound waves using arrays of rigid cylinders. Chen (2019) noted that even disordered or semi-periodic phononic crystals could form band gaps. Pennec (2010) further explored application areas such as sound control, negative refraction, and wave-blocking capabilities.

Given their wave-attenuating potential, metamaterials and phononic crystals have attracted attention as innovative seismic isolation tools in earthquake engineering. A growing body of experimental and theoretical research has emerged in this context. Witarto (2018) investigated one-dimensional periodic foundations extending along the z-axis and demonstrated their seismic isolation performance using a scaled nuclear reactor model. Yan et al. (2013, 2015) explored two- and three-dimensional periodic foundations, providing design insights for generating high-frequency band gaps. Xiang (2012) experimentally validated composite systems' damping performance from commonly available materials with differing densities, such as rubber and concrete. Jia and Shi (2010) used computational models to analyze the effects of physical and geometric parameters, such as elastic modulus, density, and filling ratio, on band gap formation. Casablanca (2018) evaluated the damping capacity of periodic foundations based on displacement responses. In another study, Witarto (2019) examined unit cells based on local resonance and Bragg scattering, concluding that Bragg-type designs exhibited superior damping performance.

Field-scale applications have also begun to emerge. Brûlé et al. (2014) conducted a large-scale experiment in France using vertically drilled seismic metamaterial-based barriers. Although the viscoelastic properties and heterogeneity of the soil were neglected in that study, energy maps revealed that the seismic wells contributed significantly to wave attenuation. Çelebi et al. (2009) compared the effectiveness of four wave barriers—hollow, water-filled, concrete-filled, and bentonite-filled—regarding horizontal and vertical displacement, incorporating soil-structure interaction effects. Miniaci (2016) aimed to develop remote seismic shielding systems by integrating phononic crystals with varying mechanical properties and considering soil effects.

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Despite the promising findings in the literature, experimental applications of seismic metamaterials in building foundations remain limited. This indicates a notable research gap, particularly in developing foundation systems that function as passive seismic energy absorbers or isolators.

This study investigates the damping performance of a periodic foundation system composed of seismic metamaterials and piezoelectric elements. The research uses a small-scale experimental approach to evaluate the system's ability to attenuate seismic energy without inducing structural or non-structural damage. Accordingly, this work contributes to the limited number of experimental studies assessing piezoelectric-enhanced seismic metamaterial-based structural systems.

METHODOLOGY

Vibration Source and Shake Table Design

The experimental setup is built around a shaking table that enables the transfer of artificially generated ground motions to structural components. A 0.75 kW servo motor powers the system. A linear motion module, designed to operate with the servo motor, facilitates movement along the x-axis and has a carrying capacity of approximately 80 kg. The vibration platform is constructed from ST35 steel and measures 40 × 40 cm.

The shake table can achieve a maximum displacement of 7.5 cm along the x-direction. The motion of the servo motor is controlled using Arduino IDE software, and the system was programmed to operate autonomously within the laboratory environment.

The general configuration of the control and measurement units used in the experimental setup and the data flow diagram is illustrated in Figure 1.

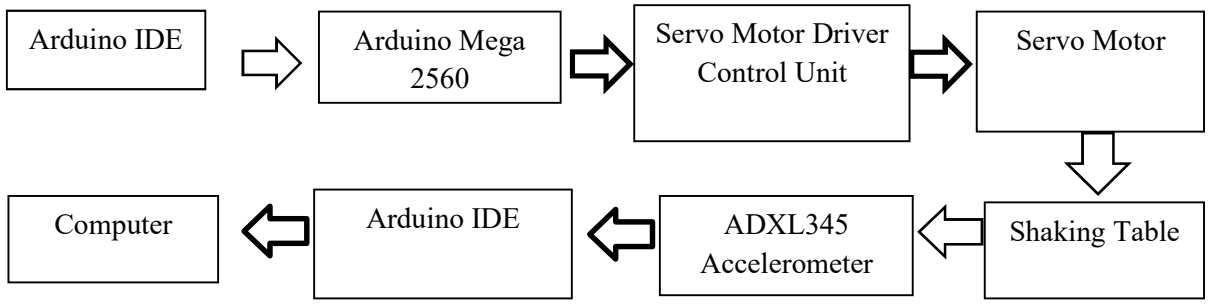


Fig 1. Schematic representation of the experimental system and the Arduino-IDE-based control and measurement flow diagram.

The schematic layout showing the spatial configuration of key components, such as the servo motor acting as the vibration source, the linear motion module, the steel plate, and the specimen layers, is presented in Figure 2. This layout supports visualization of the physical relationships between the components in the experimental setup.

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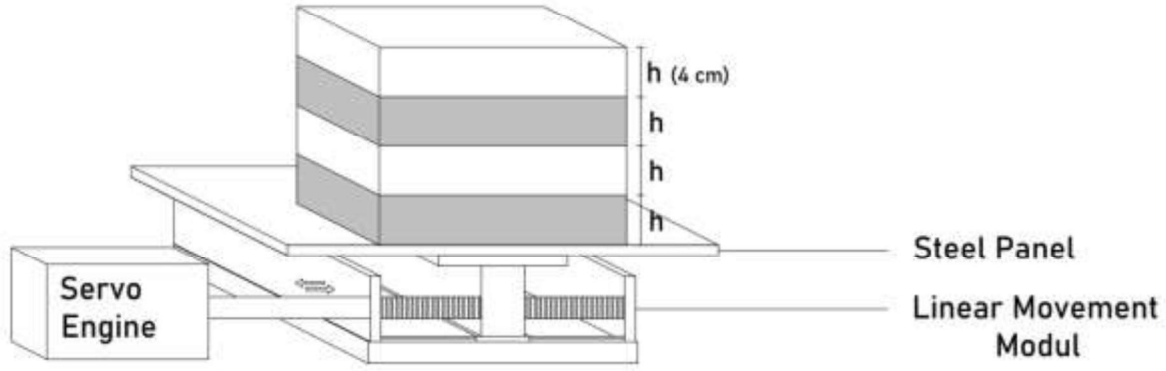


Fig 2. Schematic layout of the system, showing the servo motor, linear motion module, steel panel, and specimen layers positioned along the x-axis.

The actual appearance of the constructed shaking table and the integrated test specimen is presented in Figure 3. This figure includes two views: (a) the connection details of the shaking table system, and (b) the overall appearance of the shaking table with the test specimen positioned on top. The layout offers a clear visual context of the physical setup and experimental configuration.



(a) (b)

Fig. 3. (a) The connection details of the shaking table system, (b) The overall appearance of the shaking table with the test specimen placed on top.

Test Specimen Material Properties

Three different models were developed for experimental investigations. The reference system consisted of a conventional reinforced concrete foundation. In contrast, the periodic foundation was modeled as a one-dimensional (1D) meta-material system composed of sequentially arranged concrete and rubber layers—the third model embedded piezoelectric sensors into the same layered configuration, resulting in a sensor-equipped meta-material foundation.

The concrete and rubber layers were bonded using a polyurethane-based adhesive to ensure structural integration. The primary mechanical properties of the materials used in the specimens are presented in Table 1.

Table 1. Physical properties of materials used in the experiment.

	Concrete	Rubber
Density (kg/m³)	2400	915
Young's modulus (MPa)	24392	0,15

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Poisson's ratio	0,2	0,4

Experimental Configurations

In this study, three different foundation configurations with varying structural representation capabilities were developed. Each model was tested under the same experimental conditions. The aim was to simulate different foundation systems encountered in real-world applications and compare their respective damping performances.

- **1D Meta-Material Periodic Foundation**

The first model was created by alternately arranging rubber and concrete blocks, cost-effective materials with distinct density and stiffness characteristics. This system was designed as a one-dimensional (1D) periodic foundation extending in the z-direction and intended to suppress vibration energy by forming band gaps.

The layers were bonded using a polyurethane-based adhesive and integrated into the experimental setup. Figure 4 illustrates the overall appearance of this model in the testing environment.



Fig 4. The 1D meta-material periodic foundation layout consists of alternating rubber and concrete layers in the experimental setup. The figure also shows the positioning of the servo motor, control unit, and the connection system of the accelerometer to the computer.

- **Conventional Foundation**

The second model serves as the reference system and represents conventional reinforced concrete foundations commonly used in the construction industry. This model does not include any damping or isolation mechanisms and instead simulates the direct transmission of seismic forces to structural components. Figure 5 illustrates this model's configuration, which is composed of reinforced concrete plates and integrated into the experimental setup.

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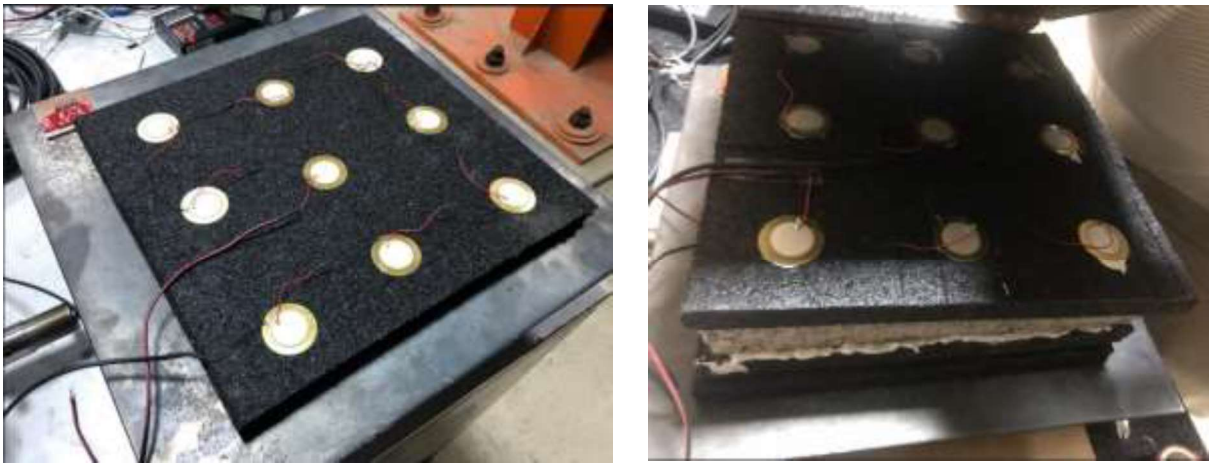


Fig 5. The layout of the test specimen is composed of reinforced concrete plates, which are used as the conventional system. The figure also shows the connection setup involving the servo motor, control unit, and accelerometer-to-computer interface.

- **Piezo 1D Foundation**

The third model is formed by embedding piezoelectric sensors into the 1D meta-material periodic foundation. This configuration aims to evaluate the contribution of piezoelectric elements to the damping performance, particularly in vibration-induced electrical energy generation.

The piezoelectric sensors were placed regularly between the rubber layers and bonded using polyurethane-based adhesive. Electrical connectivity was ensured by soldering the sensor terminals to the data acquisition system. Figure 6 presents the visual layout of this test specimen, including sensor placement.



(a) (b)

Fig. 6. (a) Layout and wiring of piezoelectric sensors embedded within the rubber layer, (b) General appearance of the test specimen equipped with piezoelectric sensors integrated into the periodic foundation system.

Sensors and Data Acquisition System

In the experimental setup, two distinct groups of sensors were utilized to monitor the acceleration and energy responses of the test specimens during vibration. These sensors included accelerometers and piezoelectric elements.

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Accelerometers

ADXL345 model triaxial accelerometers were employed to capture the specimens' acceleration responses. These sensors, which offer ±2g sensitivity, were configured via the Arduino IDE software to record data at intervals of 80 milliseconds.

The accelerometers were positioned on the upper surfaces of the specimens, aligned with the direction of increasing acceleration toward the top layer. This placement allowed for more effective observation of the structural response under dynamic excitation.

Piezoelectric Sensors

Piezoelectric sensors, capable of generating electrical energy from mechanical vibration, were used to investigate the energy conversion capability of the system.

Piezo discs with a 35 mm diameter were embedded within the rubber layer at 10 cm intervals using polyurethane adhesive. The sensor terminals were soldered for voltage measurements and connected to the data acquisition system.

The spatial arrangement of the sensors and the associated foundation models is illustrated schematically in Figure 7.

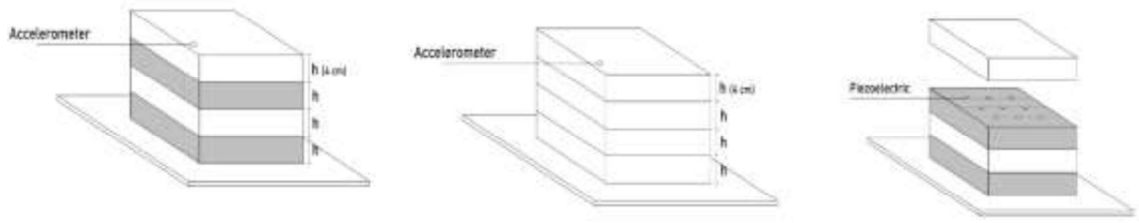


Fig 7. Schematic representation of the sensor configuration for the 1D meta-material, conventional, piezoelectric-integrated, periodic foundation. This illustration shows the positions of the accelerometers, plate thicknesses, and the schematic layout of the piezoelectric sensors.

Applied Vibration Protocols

In the experimental study, three distinct vibration protocols were applied to investigate the dynamic responses of the test specimens under seismic excitation. Using custom control codes developed in Arduino IDE software, the step count of the servo motor was adjusted to generate vibrations with varying frequency content. Each protocol was applied to the specimens for a fixed duration of 20.667 seconds.

The pulse width, step count, and evaluation parameters used in the vibration protocols are summarized in Table 2..

Table 2. Parameters of the vibration protocols applied to the test specimens.

Parameter	1D periodic foundation	Conventional foundation	Piezo periodic foundation
Pulse width	5 µs	5 µs	5 µs
Motor step count	3000 / 4000	3000 / 4000 / 5000	5000
Assessment parameter	Acceleration (g)	Acceleration (g)	Acceleration (g)

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Assessment Methodology

The acceleration data obtained from the experimental tests were analyzed using SeismoSignal software. Within the scope of these analyses, time-domain acceleration-time graphs were generated. The acceleration data were also subjected to a Fourier transformation to obtain frequency spectra, enabling the vibration frequency content evaluation.

The following criteria were adopted for comparative evaluation of system responses:

- Maximum acceleration values
- Root Mean Square (RMS) values of acceleration
- Electrical output signals from piezoelectric sensors
- Frequency spectra obtained via Fourier transforms
- Observed deformation effects under repeated vibrations

Test Results

Analysis of System Responses with a Vibration Scenario Involving 4000 Step Count

This section analyzes acceleration-time graphs, frequency-domain responses, and energy output data under a 4000-step vibration scenario. The servo motor was set to 4000 steps using the Arduino IDE, and the system operated continuously for 20.667 seconds with a constant pulse width of 5 microseconds.

The maximum acceleration and RMS values recorded by the accelerometers positioned on the upper layers of the specimens were evaluated comparatively. The results are presented in Figure 8 and Table 3

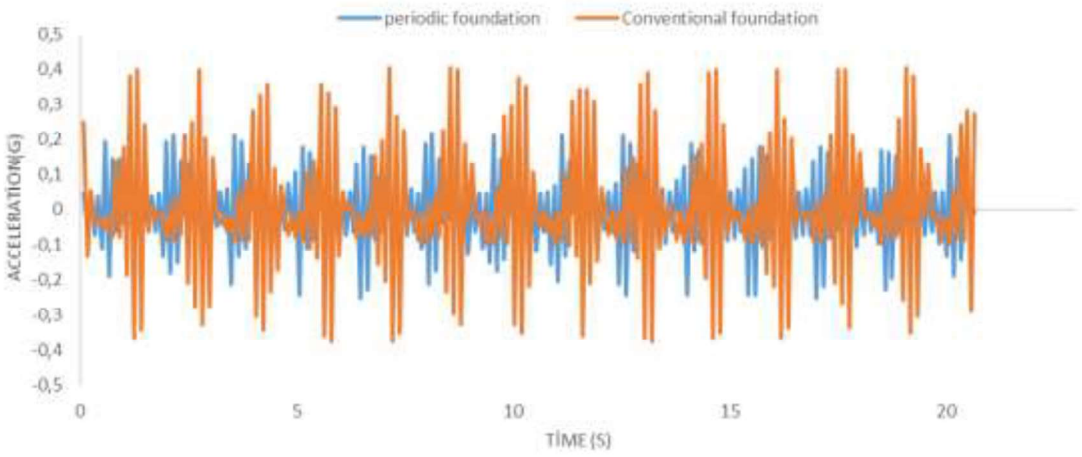


Fig 8. Comparison of acceleration-time responses of periodic foundation and conventional foundation specimens under 4000-step vibration input

Table 3. Comparative analysis of maximum acceleration and RMS acceleration values under vibration for different foundation systems

System	Maximum Acceleration (g)	RMS Acceleration (g)
Periodic foundation	0,25069	0,11227
Conventional foundation	0,40576	0,19682

As a result of this scenario, it was observed that the maximum acceleration value recorded for the periodic foundation system containing seismic meta-materials was reduced by approximately 38.21%

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compared to the conventional foundation. The RMS acceleration value showed a 43% reduction, indicating that the periodic foundation system attenuated the transmitted vibration energy more effectively.

- **Frequency Spectrum Analysis and Energy Flow Evaluation**

The frequency content of the applied vibration protocol was analyzed through the Fourier transformation, and the corresponding spectral distributions are presented in Figure 9.

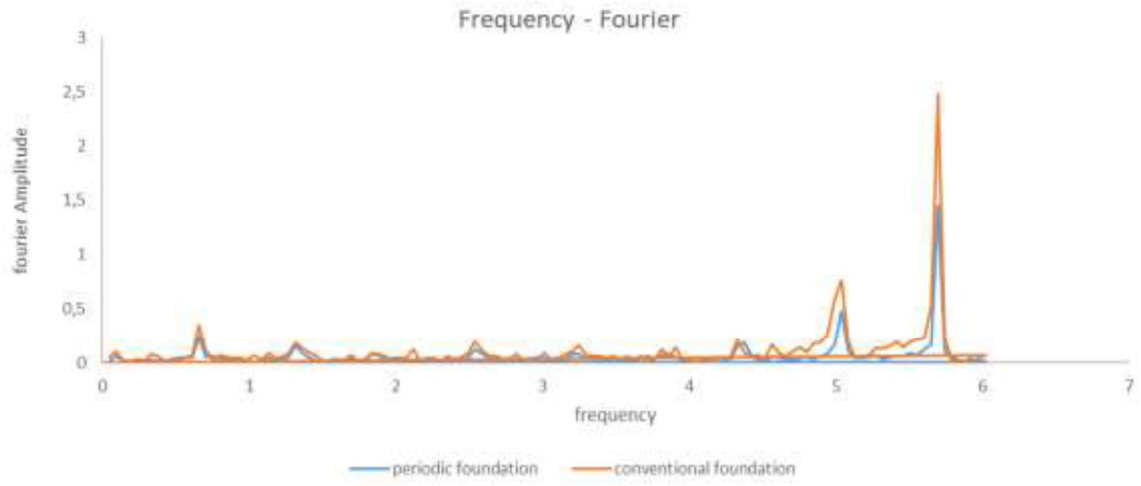


Fig 9. Comparison of frequency–Fourier amplitude responses obtained from Fourier transformations of periodic and conventional foundation systems.

As a result of the analysis, it was determined that the dominant frequency range lies between 5 and 6 Hz. The amplitude values within this frequency range were approximately 42% higher in the conventional foundation compared to the periodic foundation. This indicates that incorporating seismic metamaterials, the periodic foundation provides improved frequency domain damping performance.

Energy flow was further evaluated using the SeismoSignal software interface. The energy-based trends derived from the acceleration data are presented in Figure 10.

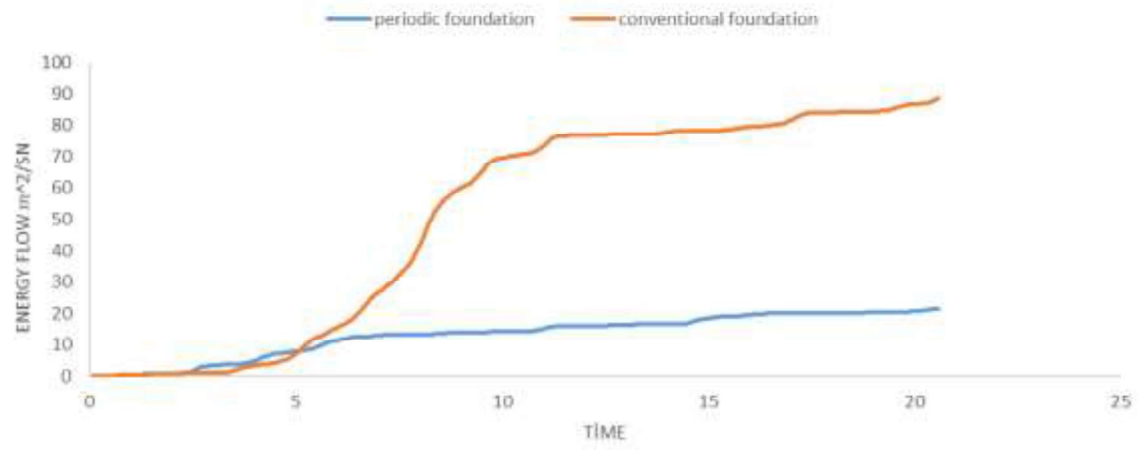


Fig 10. Time-dependent comparison of energy flow percentages for periodic and conventional foundation systems under vibration excitation.

As illustrated in the graph, the energy flow curve of the conventional foundation rises more rapidly over time. In contrast, the periodic foundation exhibits a slower and more gradual energy increase. These results confirm that the periodic foundation system attenuates seismic energy transfer more effectively.

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Analysis of System Responses with a Vibration Scenario Involving 3000 Step Count

In the second scenario, the step count of the servo motor was set to 3000, while all other parameters remained consistent with the previous 4000-step test configuration. The vibration signal was applied to the systems for 20.667 seconds with a constant pulse width of 5 microseconds.

As shown in Figure 11, the maximum acceleration value observed in the periodic foundation system was approximately 45% lower than that of the conventional foundation. Similarly, when the root mean square (RMS) values were compared, the periodic foundation exhibited a 57% reduction compared to the traditional system. These findings confirm the superior energy mitigation performance of the periodic foundation. The corresponding numerical results are summarized in Table 4.

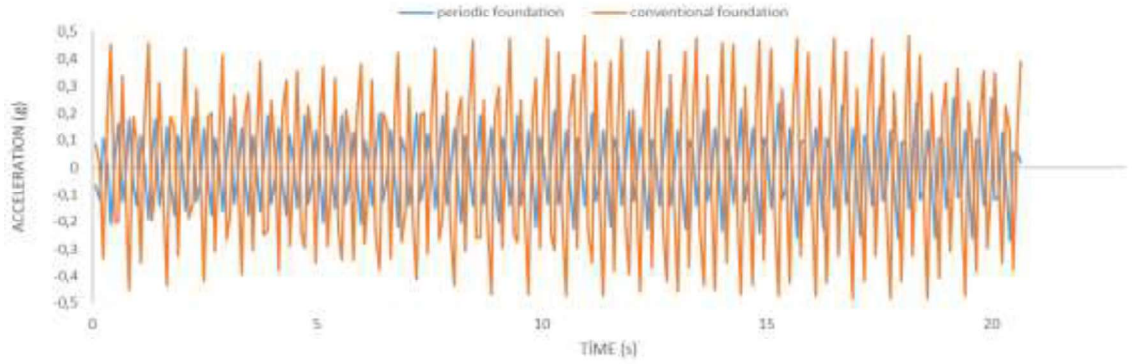


Fig 11. Comparison of acceleration-time responses of periodic and conventional foundation specimens under 3000-step vibration excitation

Table 4. Maximum and RMS acceleration values of periodic and conventional foundations tested under the 3000-step scenario.

System	Maximum Acceleration (g)	RMS Acceleration (g)
Periodic foundation	0,26707	0,13044
Conventional foundation	0,4836	0,30265

Upon reviewing Figure 11, it is evident that the periodic foundation system produces acceleration responses with lower amplitudes than the conventional foundation. This observation suggests that integrating seismic metamaterials effectively attenuates seismic energy, thereby reducing the magnitude of vibrations transmitted to the structure's base. Furthermore, the consistent amplitude trend in the acceleration-time graph indicates that the periodic foundation exhibits a more stable and balanced dynamic performance.

The numerical results in Table 4 support these observations. In particular, the RMS value, which reflects the average dynamic load acting on the structure during vibration, is a critical indicator of structural stress and the potential for cumulative seismic damage. The periodic foundation presents a more advantageous and resilient solution from an engineering perspective.

In addition, the frequency content of the applied vibration protocol was analyzed via the Fourier transformation, with the corresponding spectra presented in Figure 12. According to the results, the dominant frequency components are concentrated in the 3–4 Hz range, aligning with the natural frequency characteristics of the experimental setup. However, within this same frequency range, the

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amplitude of the periodic foundation spectrum was approximately 63% lower than that of the conventional foundation, demonstrating superior damping performance.

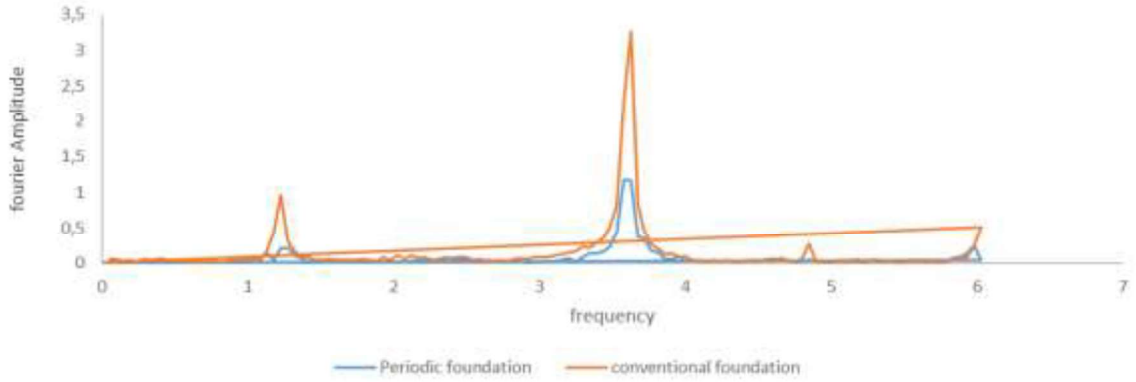


Fig 12. Comparison of frequency spectra for periodic and conventional foundations under the 3000-step scenario, obtained via the Fourier transformation.

These findings suggest that the periodic foundation's peak accelerations and the entire range of frequency components are more effectively attenuated. This is particularly advantageous for structural systems sensitive to resonance effects, where integrating metamaterial-based features offer notable performance enhancements due to their frequency-selective damping characteristics.

Piezoelectric Activity and Voltage Observations

The version of the meta-material periodic foundation supported with piezoelectric sensors was examined to evaluate the potential of piezoelectric materials for stress-to-voltage energy conversion under dynamic loading. Piezoelectric materials possess the intrinsic ability to generate electrical potential in response to applied mechanical forces. This capability facilitates energy harvesting and enables their application as smart isolators or sensor-integrated dampers in structural systems.

In the experimental setup, the system was operated for 20.667 seconds using a fixed vibration signal with a pulse width of 5 μs, defined via Arduino IDE software. The motor step count was set to 5000. The performance of the piezoelectric-integrated periodic foundation was compared with that of conventional foundation systems, and the recorded data were analyzed accordingly.

Figure 13 presents the voltage output obtained from the piezoelectric sensors during vibration. While the static (non-vibrating) condition yielded an output of approximately 0.15 V, this value increased to 1.64 V during vibration. This corresponds to an approximate 10-fold increase, highlighting the system's capacity for mechanical-to-electrical energy conversion. These results demonstrate that even at a small experimental scale, the integration of piezoelectric elements enables feasible energy harvesting. When scaled to real-world structures, this approach could contribute to partially converting seismic energy into usable electrical energy.

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Fig 13. Voltage values obtained from the piezoelectric sensors in static and dynamic (vibrating) conditions. The left indicator shows 378 millivolts recorded in the stationary state, while the right indicator shows 1.5 volts generated during vibration.

Upon analyzing the acceleration responses presented in Figure 14, it was observed that the maximum acceleration value recorded for the piezoelectric-supported periodic foundation was approximately 11% lower than that of the conventional foundation system. However, no significant difference was found in the RMS acceleration values between the two systems. These results are summarized in Table 5.

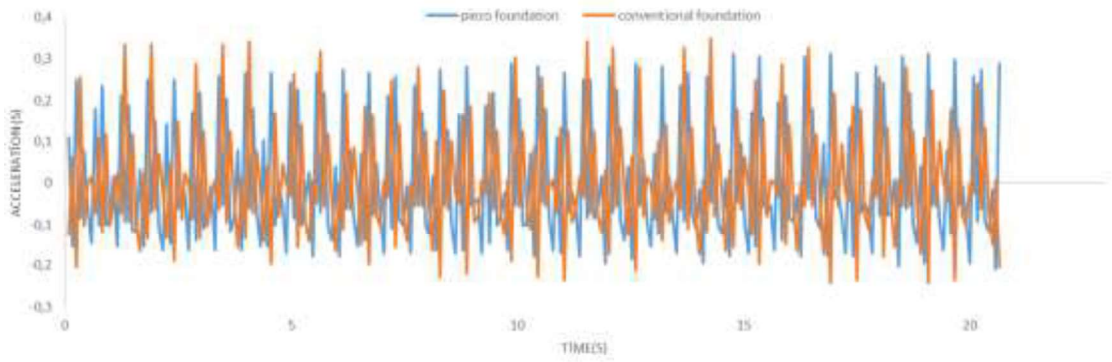


Fig 14. Comparison of acceleration-time responses between the piezoelectric-supported periodic foundation and the conventional foundation under the 5000-step vibration scenario.

Table 5. Maximum and RMS acceleration values recorded for the piezoelectric-supported periodic foundation and the conventional foundation under the 5000-step test condition.

System	Maximum Acceleration (g)	RMS Acceleration (g)
Piezo Periodic foundation	0,31278	0,15644
Conventional foundation	0,34991	0,14197

Although the piezoelectric-supported system demonstrated only a modest improvement in acceleration damping compared to the conventional foundation, the results indicate that it holds additional advantages, such as the potential for energy harvesting and real-time structural monitoring.

The system's frequency response was examined using Fourier spectra, as illustrated in Figure 15. The piezoelectric-integrated foundation displayed a mild resonance tendency around 2 Hz; however, the amplitude at this frequency remained relatively low. A secondary resonance peak was observed near 4.5

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Hz, though its amplitude was similarly limited. These results suggest that the piezo-supported system offers effective resonance mitigation and damping performance in the low-frequency range.

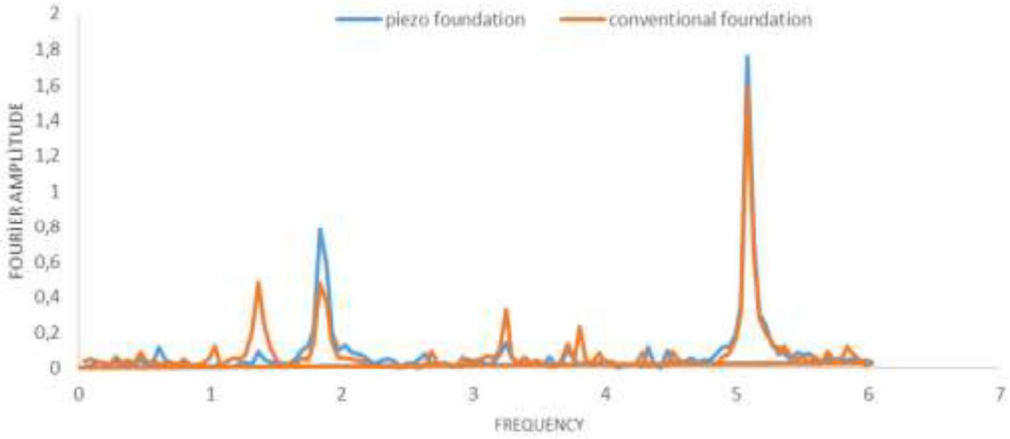


Fig 15. Comparison of Fourier amplitude spectra in the frequency domain for the piezoelectric-supported and conventional foundation systems under the 5000-step vibration scenario.

Based on the data summarized in Table 6, although the piezoelectric-supported system demonstrates a relatively limited reduction in acceleration, it introduces additional functionality to seismic metamaterial foundations, specifically in terms of energy harvesting potential, frequency selectivity, and sensing capability. Furthermore, it is anticipated that system performance can be enhanced by increasing the number and spatial configuration of piezoelectric sensors.

In this regard, the present study is one of the preliminary experimental efforts contributing to developing multifunctional damping systems in earthquake engineering.

DISCUSSION AND CONCLUSION

This experimental study evaluated the dynamic performance of three different foundation systems: a conventional reinforced concrete foundation, a one-dimensional (1D) meta-material periodic foundation, and a periodic foundation integrated with piezoelectric sensors. The analysis conducted using acceleration-time data, frequency-domain transformations, and piezoelectric voltage measurements under applied horizontal seismic excitations, provided both quantitative and qualitative insights into the seismic response characteristics of each foundation system.

Discussion

Based on the experimental findings:

- Conventional Foundation: The conventional reinforced concrete foundation exhibited high-amplitude acceleration responses under seismic excitation. Frequency spectrum analyses revealed that this system is prone to resonance effects, with a substantial portion of the vibrational energy transmitted to the structural components. These observations suggest that conventional foundations possess limited energy dissipation capacity and are less effective in attenuating seismic waves.
- 1D Meta-Material Periodic Foundation: The periodic foundation system, characterized by alternating concrete and rubber layers, effectively attenuated seismic waves by forming band-gap effects, particularly within specific frequency ranges. Compared to the conventional system, both maximum and RMS acceleration values were significantly lower, and the system's ability to selectively filter seismic vibrations was experimentally verified. The presence of distributed, low-amplitude energy in the Fourier spectrum further confirmed the frequency-selective damping capacity of the meta-material configuration.

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- Piezoelectric-Supported Periodic Foundation: Besides its damping functionality, the piezoelectric-integrated foundation enabled energy harvesting from vibrational inputs. The recorded voltage output of approximately 1.64 V under dynamic conditions illustrates the feasibility of converting a portion of the seismic energy into electrical energy within small-scale systems. Considering both the system's low-frequency damping performance and its energy conversion potential, it can be inferred that such hybrid foundations hold promise for developing next-generation multifunctional seismic isolation solutions.

Conclusion

In conclusion;

- Periodic foundation systems, when compared to conventional reinforced concrete foundations, effectively reduce transmitted vibration energy and lower the amplitude of accelerations experienced by structural components.
- The integration of piezoelectric elements enhances the structural control capabilities of these systems. It enables advanced functionalities such as real-time sensing and energy harvesting by generating electrical output under dynamic loading.
- In this regard, periodic and piezoelectric-supported foundations represent multifunctional, sustainable, and innovative solutions that extend beyond traditional earthquake isolation strategies.

The small-scale experimental findings presented in this study offer a foundational understanding for future large-scale implementations and demonstrate that metamaterial-supported foundation systems hold significant potential to contribute to structural resilience, energy efficiency, and sustainable seismic design.

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