Soil Dynamics and Earthquake Engineering 177 (2024) 108395

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic performance of rubber-sand mixture as a geotechnical seismic isolation system using shaking table test

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A R T I C L E I N F O

Keywords:
Rubber-sand mixture (RSM)
Seismic performance
Geotechnical seismic isolation (GSI) system
Shaking table test
Acceleration response
Seismic settlement

A B S T R A C T

This paper presents a comprehensive investigation into the seismic performance of structures utilizing Rubber-Sand Mixture (RSM) as a Geotechnical Seismic Isolation (GSI) system. Shaking table tests were conducted to evaluate the effectiveness of the RSM layer in modifying the acceleration response and settlement of structures under dynamic loading. The effectiveness of the RSM layer was found to be influenced by various factors, including the rubber content, depth ratio (the RSM layer to the footing width), and ground compaction. The study considers a wide range of RSM depth ratios (0.1–0.8), providing valuable insights into the optimal design of buildings equipped with RSM. The experimental results demonstrate a significant reduction in acceleration response for low-rise and medium-rise buildings, as well as potential benefits for tall buildings with a large depth ratio. However, increasing the RSM thickness is accompanied by larger settlement, highlighting the need for a balance between reducing acceleration and controlling settlement. There is a limit to the effectiveness of the depth ratio beyond which, the de-amplification and final seismic settlement become less sensitive to changes in RSM layer thickness. The study reveals that the RSM layer exhibits a more pronounced reduction in acceleration response in loose ground conditions compared to denser ground conditions. However, even in denser ground, the inclusion of RSM layers contributes to improved seismic performance to a lesser extent. The findings align with prior studies, emphasizing the potential of RSM layers in mitigating the seismic response of structures. By appropriately incorporating RSM layers and considering site-specific factors, engineers can enhance the resilience of structures, leading to safer and more earthquake-resistant built environments.

1. Introduction

Geotechnical Seismic Isolation (GSI) techniques have emerged as effective strategies for mitigating the destructive effects of seismic forces on structures, and they hold particular promise for their application in developing countries where cost-effective solutions are sought. Within the realm of GSI systems, Rubber-Sand Mixture (RSM) has garnered significant attention as a low-cost and efficient approach to attenuate the seismic behavior of superstructures. RSM-based GSI systems provide a reliable means to decouple the structure from the ground, reducing the transmission of forces and safeguarding the superstructure against excessive displacements and accelerations during seismic events [1–3]. By exploring the application, design principles, and performance evaluation of RSM-GSI systems, this paper aims to experimentally highlight their crucial role as seismic isolation systems in enhancing the resilience of structures in earthquake-prone regions, particularly in the context of low-cost and effective solutions for developing countries.

Research on GSI-RSM systems has garnered significant attention in the literature, with numerous studies investigating different aspects of their behavior and performance. The existing body of research can be categorized into numerical simulations, analytical modeling, and laboratory or experimental investigations. Numerical simulation studies have utilized sophisticated computational models to analyze the dynamic response and seismic behavior of structures equipped with GSI-RSM systems under various loading conditions [1,4–13]. Among them, Tsang [1] conducted the first numerical research on using rubber as a geotechnical seismic isolator. The study found that a soil-rubber mixture can reduce horizontal acceleration by 60 %–70 % and vertical acceleration by 80 %–90 % compared to ground motion acceleration. The thickness of the mixture and the width of the structure were identified as influential parameters, with increasing thickness having a greater effect than increasing width. There are a lot of other numerical simulations in the literature that have provided valuable insights into the system's behavior, including the influence of different design parameters and the

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https://doi.org/10.1016/j.soildyn.2023.108395
Received 13 September 2023; Received in revised form 30 November 2023; Accepted 1 December 2023
Available online 9 December 2023

effectiveness of the RSM material in reducing seismic forces [6–8,10,13,14]. Analytical modeling approaches have focused on developing simplified mathematical frameworks to capture the fundamental principles and key mechanisms governing the behavior of GSI-RSM systems [4,15,16]. These models have allowed for parametric studies, enabling researchers to assess the sensitivity of the system to various factors and optimize its design.

In the literature, laboratory or experimental works have played a crucial role in the research of GSI-RSM systems, particularly through the utilization of shaking table tests [8,12,17–20]. Shaking table tests and other experimental setups have enabled researchers to observe and measure the real behavior of structures and their interaction with GSI-RSM systems with a high level of accuracy and control. These experimental studies have provided valuable data on displacement reduction, energy dissipation, and the overall seismic performance of GSI-RSM systems. By subjecting scaled models or physical structures to simulated earthquake ground motions, shaking table tests allow for the evaluation of the system's response under realistic loading conditions. Xiong and Li [18] conducted experimental tests using a shake table on a mixture of soil and rubber. They examined the performance of using this mixture and demonstrated its effectiveness in reducing the structural response to earthquakes, particularly for low-rise buildings. The results revealed that, in order of significance, the building surcharge, RSM thickness, and rubber percentage have the greatest impact on reducing the dominant frequency in the structure. Due to the limited reduction in acceleration observed in the RSM with 35 % and 50 % volumetric rubber contents, a 35%-RSM was introduced as the optimal choice. Bandyopadhyay et al. [2] investigated the performance of a single RSM layer with sand as low cost base isolators by using shake table tests with the different rubber contents. The building foundation was modeled by a thick rigid block. The acceleration and displacement on top of the footing was measured. The results indicate that by adding rubber shred to sand, settlement increases while the transferred acceleration to the foundation decreases. Additionally, based on observations during the experiments, the footing rocking behavior occurs for the foundation at gravimetric percentages higher than 50 %. The optimal mixing percentage for the sand-rubber mixture is determined to be 50 %, which not only ensures the foundation's stability but also significantly reduces the transferred acceleration. Tsiavos et al. [20] conducted experiments using a uniaxial shaking table to investigate the dynamics of a rigid sliding block and to quantify the kinetic friction of different sliding interfaces with two different RSM grain size ratios at varying layer thicknesses. The experimental setup was subjected to harmonic and earthquake ground motion excitations. The main objective was to determine the optimal grain size ratio and RSM thickness that correspond to the lowest friction coefficient between the sand-rubber layer and the foundation, which is favorable for seismic isolation. Recently, Yin et al. [21] conducted a large-scale shaking table test on a 1/4 scale single-story masonry structure model, comparing its performance with and without the GSI-RSM system under various input acceleration amplitudes. The results demonstrate that the GSI-RSM system effectively reduces the seismic response of superstructures. The isolation effect is more pronounced for higher-magnitude earthquakes, while the RSM layer acts as a filter for high-frequency components, limiting their transmission to the superstructure and dissipating seismic energy through friction slip at the interaction with the structural foundation. More recently, Vratsikidis and Pitilaktis [19] conducted forced-vibration experiments on a large-scale prototype structure founded on gravel-rubber mixture layers. The study investigated different compositions with varying rubber content per mixture weight (0 %, 10 %, and 30 %) but the same mean grain size ratio as the foundation soil. The structure was subjected to harmonic forces across a range of excitation frequencies and force amplitudes. The findings revealed that a 0.5 m thick soil layer with 30 % rubber content effectively isolated the structure. The rubber fraction played a crucial role in extending the structure's natural period and introducing a dominant rocking component, resulting in a more "rigid-body" response. Additionally, the soil-rubber mixture exhibited reduced base shear and base moment, independent of the excitation frequency, highlighting its effectiveness. The increased damping and substantial energy dissipation further demonstrated the efficacy of the soil-rubber mixture foundation soil layer. In another recent work, this full-scale test was investigated numerically by using 3D advanced nonlinear FEM analyses [13]. Comparisons between experimental results and numerical simulations helped to identify any discrepancies and refine the models accordingly as well as to calibrate and validate numerical models. Regarding centrifuge modeling, one experiment exists in the literature [3] in which, nonlinear dynamic response characteristics of RSM and subsoil in a coupled soil-foundation-structure system was studied. It was found that an average of 40–50 % reduction of structural demand can be achieved. The increase in both the horizontal and rotation responses of the foundation was also evidenced. In summary, previous research predominantly emphasized rubber content, neglecting the comprehensive exploration of RSM depth relative to the footing width and soil compaction. While earlier studies did examine various RSM thickness values, the crucial aspect of assessing the effectiveness of the RSM thickness to the footing width ratio remained largely unexplored.

The present study aims to investigate the effectiveness of rubber-sand mixture (RSM) layers in improving the seismic performance of structures by focusing on the RSM depth and subbase soil compaction. This research is motivated by the limited investigation of these two parameters in the existing literature. To achieve these objectives, a series of shaking table tests were conducted to simulate seismic loading scenarios. The tests considered various parameters, including two rubber contents (by weight), a wide range of depth ratios (0.1–0.8), and two types of ground compaction conditions, to comprehensively analyze the influence of these factors on the seismic response of the structures. The data obtained from the tests were carefully analyzed and compared with prior research studies to validate the findings and contribute to the existing knowledge base. The combination of experimental testing and comparative analysis provides a comprehensive understanding of the behavior of RSM layers and their potential for enhancing the seismic resilience of structures.

2. Physical modeling and shaking table test

In this research, a series of shaking table tests were conducted using a manual 1g shaking table that was designed and constructed at the geotechnical laboratory of Ferdowsi University of Mashhad. Fig. 1 provides perspective views and detailed design of the manual shaking table. The design of the manual shaking table test is based on the proposed scheme introduced by Prasad [22]. In the literature review, there are several studies that used the similar scheme [e.g., 23, 24–26]. The fabricated table in the present study consists of two 1.5*0.6 m wooden boards connected by four steel plates. The steel plates are fixed at their end edges using angle brackets, creating two-fixed-end moment plates. The lower wooden board is fixed to the ground, while the upper board serves as the platform for the table, upon which a container is placed. The four steel plates, each measuring 260 mm in height, 600 mm in length, and 2 mm in thickness, are evenly spaced apart. By considering the lateral stiffness of these plates and the mass of the container as payload, they function as a spring and mass single-degree-of-freedom system, capable of generating harmonic motions along the length of the table. The shaking table operates at a frequency range of 4.6–4.7 Hz, with a payload mass of approximately 180–190 kg, which is almost constant throughout the tests conducted in this study. The manual shaking table is manually excited by applying a horizontal force to the upper wooden board. An accelerometer is attached to the container to record the generated table accelerations during excitation.

The physical model in this study consists of a rigid footing placed on a rubber-sand mixture (RSM) layer over a sandy ground, as illustrated in Fig. 2. The container used for holding the physical model has a length of

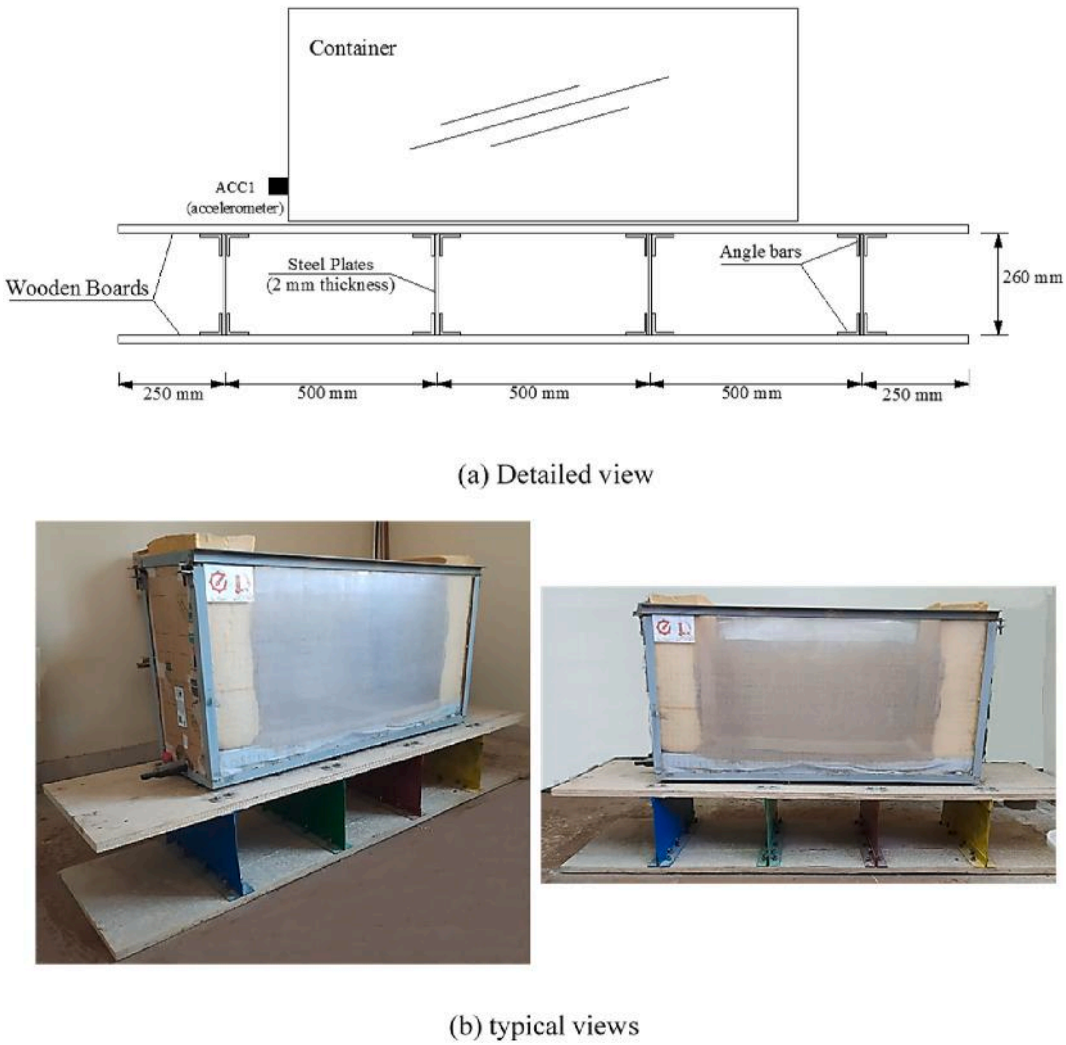

Fig. 1. Schematics of the designed manual shaking table.

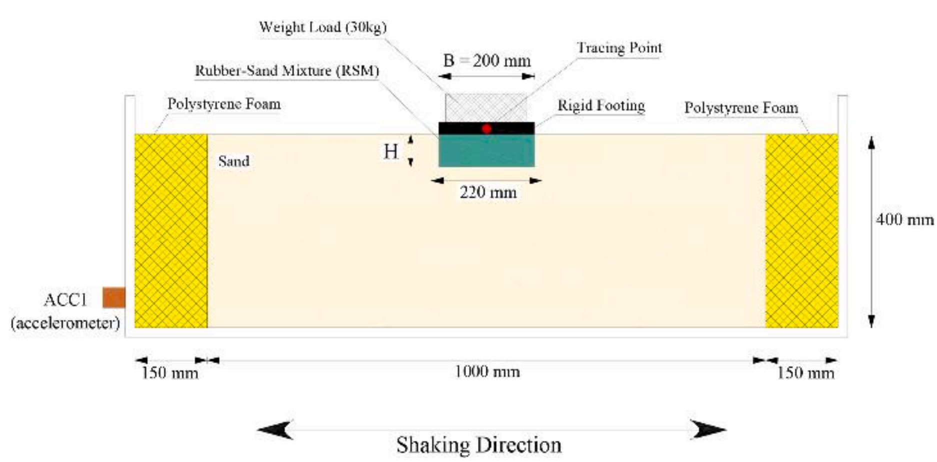

Fig. 2. Characteristics of the physical model test in the container.

1.2 m and a width of 350 mm, filled with sand up to a height of 400 mm. In the center of the container and over the surface, a 200 mm-wide rigid block is put representing the footing or an equivalent structure. The soil just beneath the footing is replaced with RSM with a specific rubber content when conducting the tests. The width of the RSM layer (B) matches that of the footing, while the depth of the RSM layer (H) varies as per the testing program, considering depth ratios (H/B) of 0.1, 0.2, 0.4, and 0.8. To simulate a free field condition and prevent wave reflections from the container's rigid boundaries during dynamic loading, two 150 mm-thick polystyrene foam sheets are attached to the lateral walls of the container. These foam sheets act as absorbing layers, representing viscous boundaries [27]. Since the input motion is only in the horizontal direction, no foam was installed at the bottom of the model. An accelerometer (ACC1) is mounted on the container to measure the applied input wave accelerations. Additionally, a red point on the rigid footing indicates the location where Particle Image Velocimetry (PIV) is employed to capture the variation of accelerations during the tests, as further explained in the subsequent section.

In 1g shaking table tests, the physical model's dimensions are reduced compared to the real-world prototype to facilitate experimentation in a laboratory setting. To ensure meaningful and representative results, it is necessary to adhere to a similarity law that establishes dimensional similitude between the model and the prototype. For this study, the 1g shaking table tests were designed based on the similarity law proposed by Iai [28]. According to this law, the dimensions of the physical model, including length, width, and height, are scaled down from the prototype structure using a specific scale factor (λ). In this research, a scale factor of $\lambda = 10$ is applied, resulting in a 2 m width for the footing, a uniform stress of 7.5 kPa under the footing, and a harmonic wave frequency of 1.5 Hz. The chosen scale factor ensures that the physical model accurately represents the real-world prototype, allowing for reliable comparisons. Table 1 presents a summary of the similarity law parameters used in this study. All the tests are conducted over a time span of T = 10s, equivalent to a harmonic time of 31s in the real-world scale. By employing this similarity law and appropriate scaling, the shaking table tests produce results that are directly applicable to the behavior and performance of the full-scale prototype structure in real seismic conditions.

3. Materials and methods

For the granular materials used in this study, Firuzkuh-161 silica sand and rubber powder made from waste tires were employed. The gradation curves of these materials are shown in Fig. 3, and the corresponding grain sizes are listed in Table 2. The grain size of the rubber powder was chosen to match that of the sand to maintain scale similarity in the soil-rubber mixture. The sand has a coefficient of uniformity (C_U) of 2.1, while the rubber powder has a C_U of 3.1. The coefficient of curvature (C_C) for the sand is 0.84, whereas for the rubber powder it is 1.6. According to the unified soil classification system (ASTM D2487 [29]), both materials are categorized as poorly graded.

In this study, two different mixtures of rubber (R) and soil (S), i.e., RSM were utilized. The RSM with R = 20 % and S = 80 % (in terms of unit weight) is denoted as RSM 20 % and that with R = 35 % and S = 65 % is denoted as RSM 35 %. The selection of these specific rubber content ratios was based on previous research [30–34], which suggested that an optimal range of 20 %–40 % would yield desirable mechanical behavior, providing adequate strength and deformability under static and dynamic loading conditions.

To determine the physical properties of the RSMs and the sand, laboratory tests were conducted following the standards ASTM D4254 [35] and ASTM D4253 [36]. Table 3 presents the results of these tests, including the minimum and maximum dry unit weight values obtained for the RSMs and sand. These dry unit weight values serve as indicators for the desired relative density (Dr) of the materials. In this study, two distinct relative density values were considered: Dr = 55 % and Dr = 85 %. These values represent loose and dense states, respectively, for both the sand and the RSMs. By incorporating these two relative density values, the influence of site seismic class and density can be investigated

Table 1
The similarity law used in the 1g shaking table tests according to Iai [28].

Quantity	Model	Prototype
Length and width	L	$\lambda \times L$
Stress and stiffness	S	$\lambda \times S$
Frequency	f	$\lambda^{-0.5} \times f$
Time	T	$\lambda^{0.5} \times t$

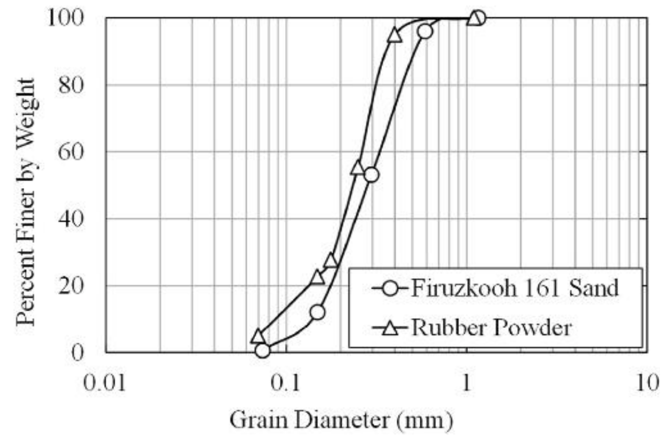

Fig. 3. Grain size distribution of the soil and the rubber powder.

Table 2
Characteristics of Firouzkuh-161 sand and rubber powder.

Characteristics	Sand	Rubber
G_s	2.65	1.14
D_{10} (mm)	0.16	0.08
D_{30} (mm)	0.21	0.18
D_{50} (mm)	0.20	0.22
D_{60} (mm)	0.33	0.25
C_U	2.1	3.1
C_C	0.84	1.6

Table 3
Maximum and minimum dry densities of the granular materials.

Granular materials	Maximum dry unit weight (kg/m^3)	Minimum dry unit weight (kg/m^3)
Sand	1430	1680
RSM20 %	112	134
RSM35 %	760	910

in relation to the effectiveness of RSMs on the seismic behavior of the footing. This approach allows for a comprehensive examination of how varying relative densities of the sand and RSMs affect the overall seismic response of the system.

The physical model used in this study consists of several key components, including the sandy ground serving as the footing bed and the RSM layer acting as a cushion beneath the footing. The construction process of the physical model is illustrated in Fig. 4. To create the sandy ground, the container was filled with sand to a height of 400 mm. The sand was poured in layers of 40 mm thickness and compacted using a manual 5 kg-tamper, as shown in Fig. 4a. The desired density of the sand was achieved by adjusting the number of tamper strokes, with approximately 14–24 strokes for a relative density of 55 % and 38–42 strokes for a relative density of 85 %. The falling height of the tamper was kept constant equal to 100 mm. The compaction degree was carefully monitored using small samplers at various depths. The construction of the RSM layer followed a similar process. As depicted in Fig. 4b, a paperboard mold was utilized to define the boundaries of the RSM layer beneath the footing. The RSM was poured into the mold and compacted using a lighter tamper. The footing body was constructed using a wooden block, which was then placed over the RSM layer. A cast iron 35-kg weight was added to provide surcharge. Prior to commencing the dynamic test, it was ensured that the footing and weight were leveled horizontally. Fig. 4c illustrates a typical view of a prepared physical model for the shaking table test. As mentioned earlier, the side walls of the container were covered with polystyrene layers to absorb any

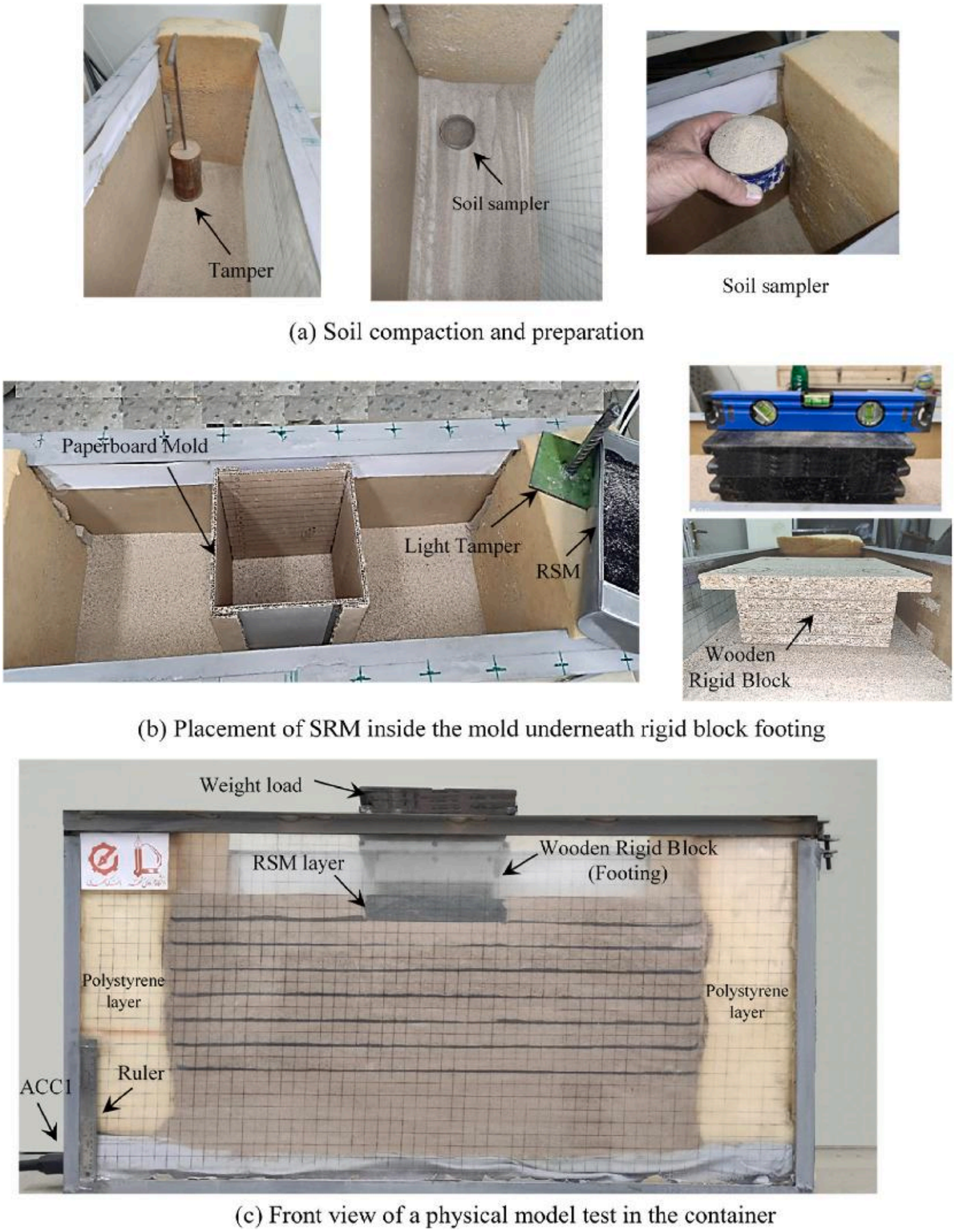

Fig. 4. Different stages of preparation of a physical model test.

impacts from the soil.

In this study, a Particle Image Velocimetry (PIV) technique was employed to measure the displacement and acceleration of the footing during the shaking table tests. There are similar experiments in the literature [e.g., 37, 38]. A high-resolution 48-megapixel camera with a capture speed of 90 frames per second was positioned to record the movement of the physical model throughout the experiments. The captured images per frames were then subjected to image processing algorithms to track the position of a benchmark point on the footing over time. A kinematic particle model track, representing a mathematical model of a point mass, was implemented. This model defines position functions over time for each selected point mass. Analyzing the displacement of the reference point between consecutive frames at specific incremental times allowed us to derive the corresponding displacement in the global Cartesian coordinate system. By applying the numerical finite difference method to differentiate the displacement data with respect to time, the velocity and acceleration values of the footing was calculated. No specific numerical filter was employed. This approach allowed for a non-intrusive and accurate measurement of the dynamic response of the footing during the tests, providing valuable insights into its behavior under cyclic loading condition.

Prior to conducting the experiments, a calibration process was conducted to validate the accuracy and reliability of the PIV technique used to measure the displacement and acceleration of the footing. The calibration involved tracking and recording the motion of a specific point on the platform (upper wooden board) of the shaking table using the high-resolution camera. Simultaneously, the acceleration of the shaking table was measured using an accelerometer attached to the container, which was securely fixed to the table. The results of the measurements from both methods, i.e., PIV and direct measurements from the accelerometer, are depicted in Fig. 5, illustrating the time history of the acceleration (Fig. 5a) and the corresponding Fourier amplitude (Fig. 5b). The input wave applied was a sinusoidal wave with a magnitude of 0.2g. The comparison of the results demonstrates a good match between the two methods. The peak point in the Fourier amplitude from the PIV and the direct measurement represents the dominant frequency of 4.36 and 4.34 Hz, respectively, which are so close to each other. By comparing the acceleration data obtained from both methods, the calibration process aimed to ensure consistency and alignment between the camera-based measurements and the accelerometer readings. This calibration step was essential to establish the accuracy of the image processing technique and ensure reliable results during the subsequent tests. Based on the measured Fourier amplitudes, it is noted that the physical model was not excited by a pure harmonic, i.e., single-frequency loading but the loading frequency contains a small bandwidth which can be ignored.

4. Results

In this section, the results of the shaking table tests are presented and analyzed. A series of 18 shaking table tests were conducted to study the dynamic behavior of a footing supported by an RSM layer. The effect of the RSM layer on the amplification or de-amplification of footing acceleration, as well as the response of the footing to the structural period, was investigated. Emphasis was placed on the crucial role played by the depth ratio and the compactness of the ground in determining the output results. Furthermore, the settlement of the footing, which is influenced by the rubber content and depth ratio of the RSM layer, was also investigated. It is noted that all the tests were carried out using an input harmonic wave with an acceleration magnitude of 0.2g with an average frequency of 4.65 Hz for a time duration of 10 s.

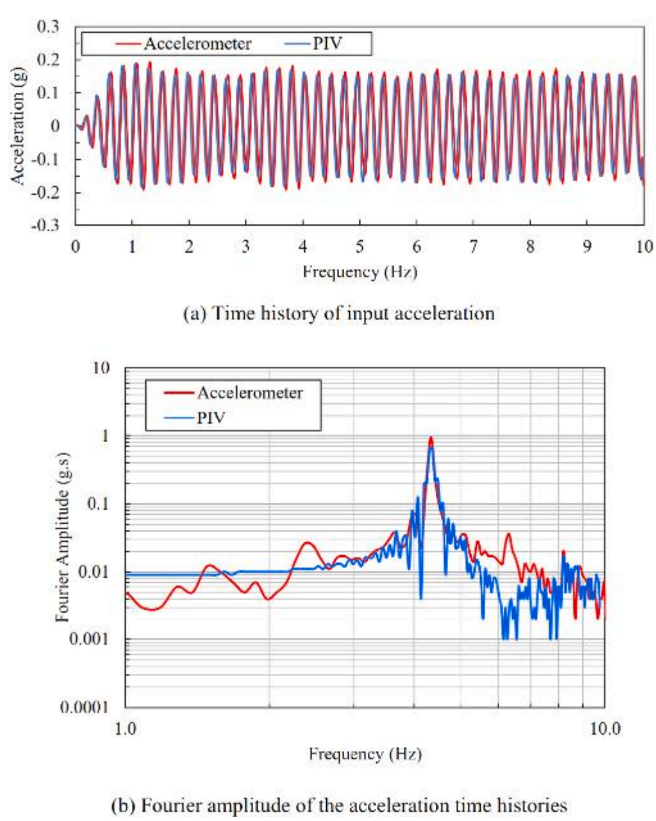

Fig. 5. Comparison of the a harmonic 0.2g-acceleration characteristics generated by the manual shaking table measured by an accelerator (ACC1) and PIV technique (for a duration of 10 s).

4.1. Effect of RSM layer on the footing acceleration

The acceleration of a structure situated on the ground may exhibit variations compared to the input wave source. Fig. 6 typically illustrates the acceleration time histories of the shaking table at the base and the footing positioned over RSM20 % and RSM35 % with a loose ground condition (Dr = 55 %) and a depth ratio (H/B) of 0.2. Upon comparison, it is observed that the footing acceleration is slightly amplified in the absence of RSM (Fig. 6a). However, the dynamic response of the footing shows variation depending on the rubber content. In the case of RSM20 %, the graph displays a harmonic pattern with a time phase, yet no reduction in acceleration is perceived. Conversely, for RSM35 %, the magnitude of the footing acceleration decreases.

In order to investigate the combined influence of RSM layer characteristics, including rubber content and depth ratio, along with ground compaction on the seismic behavior of the footing, the ratio of observed peak acceleration of the footing to that of the base was determined for all tests. These values were compiled and are presented in Fig. 7. The analysis reveals that this ratio is significantly affected by the rubber content, depth ratio, and ground compaction. As depicted in Fig. 7a, neither of the RSM layers demonstrates notable effectiveness in reducing the footing acceleration for shallow cases with H/B smaller than 0.2. However, a pronounced reduction is observed for H/B = 0.4, while increasing H/B does not yield significant effects. Moreover, the degree of de-amplification is more pronounced for RSM35 % in both loose and dense ground conditions. Fig. 7b highlights the notable effectiveness of the RSM layer in reducing acceleration for the loose ground, with the acceleration ratio being significantly attenuated for RSM35 %.

4.2. Effect of RSM depth ratio on spectral acceleration

Spectral acceleration is a fundamental parameter employed in seismic engineering to quantify the level of ground shaking at various frequencies during an earthquake. It characterizes the maximum acceleration response of a single-degree-of-freedom structure subjected to a specific ground motion at a given structural period. In this study, the acceleration time histories of the footing, representing the structure, were recorded to derive the corresponding spectral acceleration curves. The results, as shown in Fig. 8, depict the spectral accelerations for different scenarios, including loose and dense ground conditions with RSM20 % and RSM35 % and depth ratios of 0.1, 0.2, 0.4, and 0.8. In the case of loose ground (Fig. 8a), a big spectral acceleration is observed when no RSM layer is present, whereas it decreases when a thin RSM layer with a depth ratio of 0.1 is employed. Conversely, for dense ground conditions, the thin RSM layer (H/B = 0.1) proves ineffective, and the use of thicker RSM layers aids in reducing the peak spectral acceleration. Notably, the peak spectral acceleration tends to occur at a lower period as the depth ratio of the RSM layer increases, with this variation being particularly sensitive in loose ground conditions. In the spectral acceleration graphs, particularly notable for depth ratios exceeding 0.1, an additional peak emerges after the primary peak. To the Authors, this secondary peak would be arisen from the intricate interaction between the structure, i.e., the weight load and the underlying RSM layer. The heightened rocking-tilting deformation induced by the weight load, coupled with the damping effects of the RSM layer, is posited to significantly influence the system's dynamic response. This phenomenon can justify a distinctive double-horned shape in the spectral acceleration, emphasizing the complexity of the structure-RSM interaction under seismic loading conditions.

To comprehensively investigate the effectiveness of the rubber-soil mixture (RSM) layer on the seismic behavior of structures, the spectral ratio parameter is employed in this study. The spectral ratio compares the response spectra of different ground motions or structural systems.

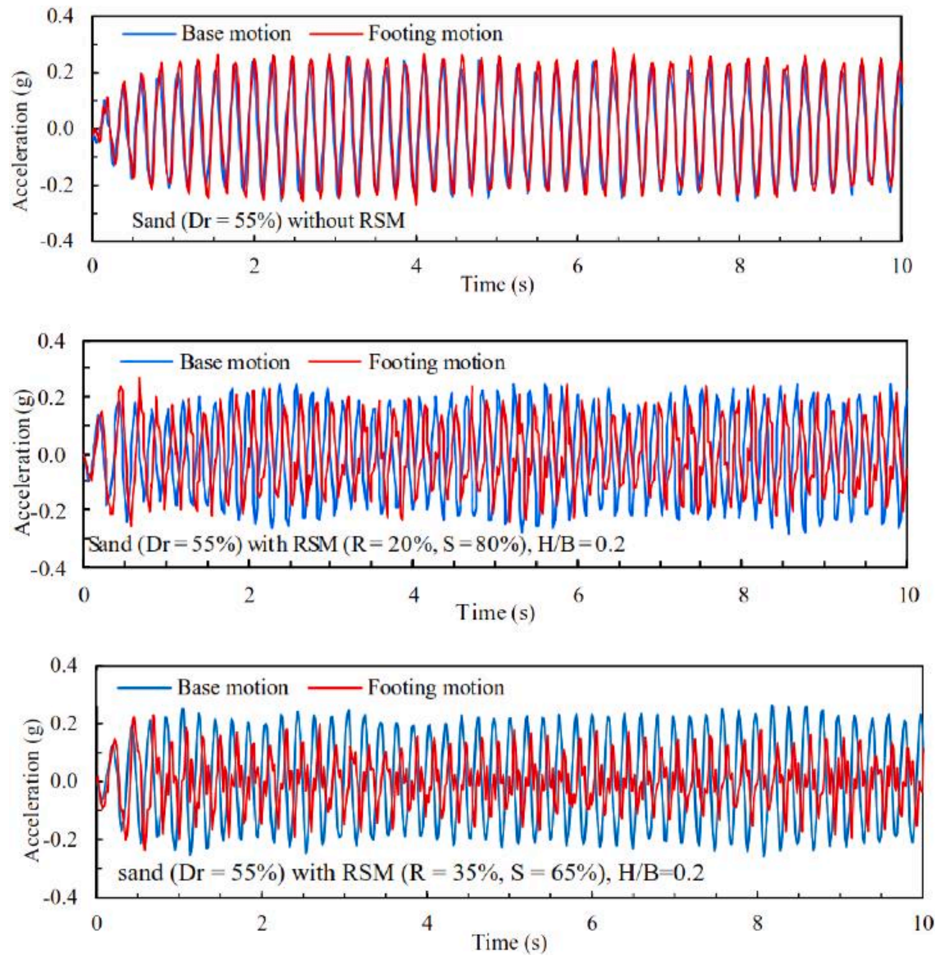

Fig. 6. Comparison of times histories of the base (shaking table) and the footing for different RSM (rubber content of zero, 20 %, and 35 %), H/B = 0.2 situated over the low-density sandy bed (Dr = 55 %).

In this research, it specifically represents the ratio of the spectral acceleration of the footing to that of the input wave motion at the same period. By analyzing the spectral ratio, insights into the relative amplification or de-amplification of the structural response at different frequencies can be obtained. Fig. 9 illustrates the variation of the spectral ratio with different structural periods, considering loose and dense ground conditions, various RSM depth ratios, and rubber contents. Values greater than one indicate an intensifying site effect, while values lower than one indicate reduced acceleration experienced by the structure. In all the graphs, the amplification effect of the bare soil on the structure is evident, with a spectral ratio of approximately 1.1 across all structural periods. However, the presence of the RSM layer has diverse effects on the structure. It is observed that for cases with structural periods smaller than 0.2, the RSM layer consistently reduces the spectral ratio. However, no clear trend is evident for larger structural periods, and the depth ratio of the RSM layer becomes another influencing factor. Notably, a thick RSM layer with a depth ratio of H/B = 0.8 proves effective for structures with a wide range of structural periods, irrespective of loose or dense ground conditions, when RSM35 % is utilized. However, the same cannot be concluded if RSM20 % is used.

To scrutinize the impact of the Rubber-Sand Mixture (RSM) depth ratio (H/B) on the seismic response of the structure, spectral ratios in accordance with Fig. 9, were graphed against the RSM depth ratio for specific structural periods (0.1, 0.2, 0.4, and 0.8s). Fig. 10 depicts the outcomes for both loose and dense ground conditions, considering two distinct RSM compositions. Regardless of soil compaction, it is clear that, for structures with shorter periods (0.1s and 0.2s), the spectral ratio consistently decreases as the RSM layer's depth ratio increases. However, for structures with periods of 0.4s and 0.8s, the trend varies. In the latter cases, an increase in RSM thickness to D/H = 0.1 and 0.2 for loose and dense grounds, respectively, results in an initial rise in the spectral ratio, followed by a minor effect of the RSM depth ratio in reducing the acceleration response; the effectiveness is higher for RSM content of 35 % and the spectral ratio remains almost constant for RSM content of 20 %.

Fig. 11 illustrates the variation of the spectral ratio as a function of the RSM depth ratio for three distinct structural periods of 0.1s, 0.2s, and 0.4s and categorizing the soil compaction. The comparison is performed considering different rubber content classifications (RSM20 % and RSM35 %). Examining the results provides insights into the effectiveness of RSM application. It is observed that the use of RSM yields more significant benefits when the rubber content is 20 % but limited to smaller structural periods of 0.1s and 0.2s. Additionally, the rubber content becomes less critical for depth ratios exceeding 0.4. Furthermore, it is figured out that the RSM20 % layer is more effective for the structures with periods of 0.1 and 0.2s, which is more highlighted if the ground is loose. For other cases, a similar trend is observed regardless the soil compactness. As previously discussed, the ineffectiveness of RSM is evident for a moderate structural period of 0.4s. These findings suggest that the performance of RSM is influenced by the combination of rubber content, RSM depth ratio, ground compaction, and structural period, emphasizing the importance of selecting suitable parameters to achieve desired outcomes. Further investigation and analysis are warranted to gain a comprehensive understanding of the complex behavior exhibited by the spectral ratio in relation to these factors.

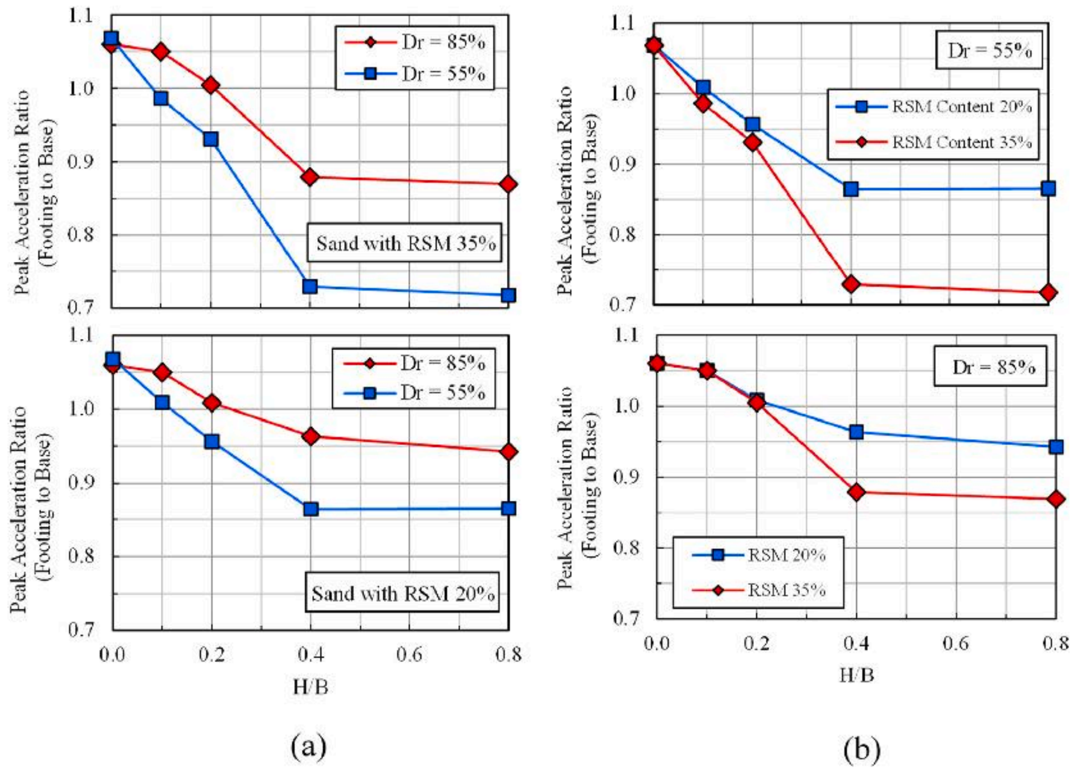

Fig. 7. PGA ratio of the foundation to the base for different depth ratios (H/B) and RSMs by investigating the effect of (a) RSM content (b) sandy ground density.

4.3. Effect of RSM on the footing settlement

The compressibility of rubber powder in comparison to sand places limitations on the application of rubber-sand mixtures (RSM) and higher rubber content leads to excessive settlement of the footing, which is undesirable. This concern extends to dynamic loading scenarios in addition to static loading. During the loading excitation, the rocking-tilting behavior of the weight load was observed in all the tests which was intensified by increasing the depth ratio. It was not possible to trace the rocking deformation but the settlement of the central point was measured during the loading. Fig. 12 provides insight into the time histories of the footing settlement during the input wave for both loose and dense ground conditions, considering different RSM characteristics including depth ratio (H/B) and rubber content. The results demonstrate that the presence of an RSM layer increases the magnitude of footing settlement compared to that observed when only the soil is present, regardless of ground density. Moreover, the magnitude of footing settlement further increases with an increase in RSM thickness. For the loose ground condition (Fig. 12a), the settlement rate of the footing on bare sand is initially significant, rapidly reaching its ultimate value and remaining constant. When RSM layers with small depth ratios of 0.1 and 0.2 are present, settlement occurs gradually until approximately 2 s (out of 10 s), after which the settlement rate accelerates. Notably, this trend was not observed in the case of H/B = 0.2 and RSM20 %. Settlements in all cases still remain comparable to those in the bare soil for the first 5 s. To explain this intricate behavior in loose sandy ground, it is important to consider the compressibility of both loose sand and RSM. The rearrangement of soil grains in loose conditions and the composition change in RSM with small thickness during compaction appear to be major factors influencing distinct settlement patterns. In contrast, for thicker RSM layers, i.e., depth ratios of 0.4 and 0.8, the settlement pattern resembles that of bare soil, with a large settlement rate from the onset of dynamic loading and reaching a constant value around the midpoint of the motion duration. In the case of dense ground conditions (Fig. 12b), the footing settlement rate is high right from the beginning. Further analysis and investigation are necessary to understand the underlying mechanisms driving these settlement trends and to develop mitigation strategies to control and manage footing settlement in RSM-supported structures under dynamic loading conditions.

To investigate the influence of RSM layer thickness on footing settlement, Fig. 13 presents the variation of residual settlement at the end of the loading time as a function of depth ratio. Irrespective of rubber content and ground compaction, a general trend emerges where the footing settlement increases with increasing depth ratio up to H/B = 0.4, beyond which thicker layers (H/B = 0.8) do not exhibit any significant effect. According to Fig. 13a, as expected, the final settlement of the footing is smaller for the dense ground compared to the loose ground. However, as the depth ratio increases, the influence of ground compaction on the final settlement diminishes, resulting in similar settlements for both loose and dense ground conditions at depth ratios of 0.4 and 0.8. The impact of ground compaction on the final settlement is more pronounced for RSM35 % compared to RSM20 %. Fig. 13b illustrates that the final settlement with RSM35 % is larger than with RSM20 %, especially in loose ground conditions. The effectiveness of the RSM layer is more evident in loose ground, where the maximum reduction in settlement is 2 mm, whereas the footing experiences larger settlement (approximately 4 mm) in dense ground, particularly for thicker RSM layers. These findings emphasize the importance of considering RSM layer thickness, ground conditions, and rubber content when assessing and mitigating settlement concerns in structures supported by RSM layers. Further investigations are needed to understand the underlying mechanisms and optimize the design parameters for minimizing settlement effects in practical applications.

5. Discussion

This study is dedicated to examining the effectiveness of a rubber-sand mixture (RSM) layer in influencing the seismic behavior of structures through a series of rigorous shaking table tests. The experimental setup focused on investigating the seismic response of a rigid block

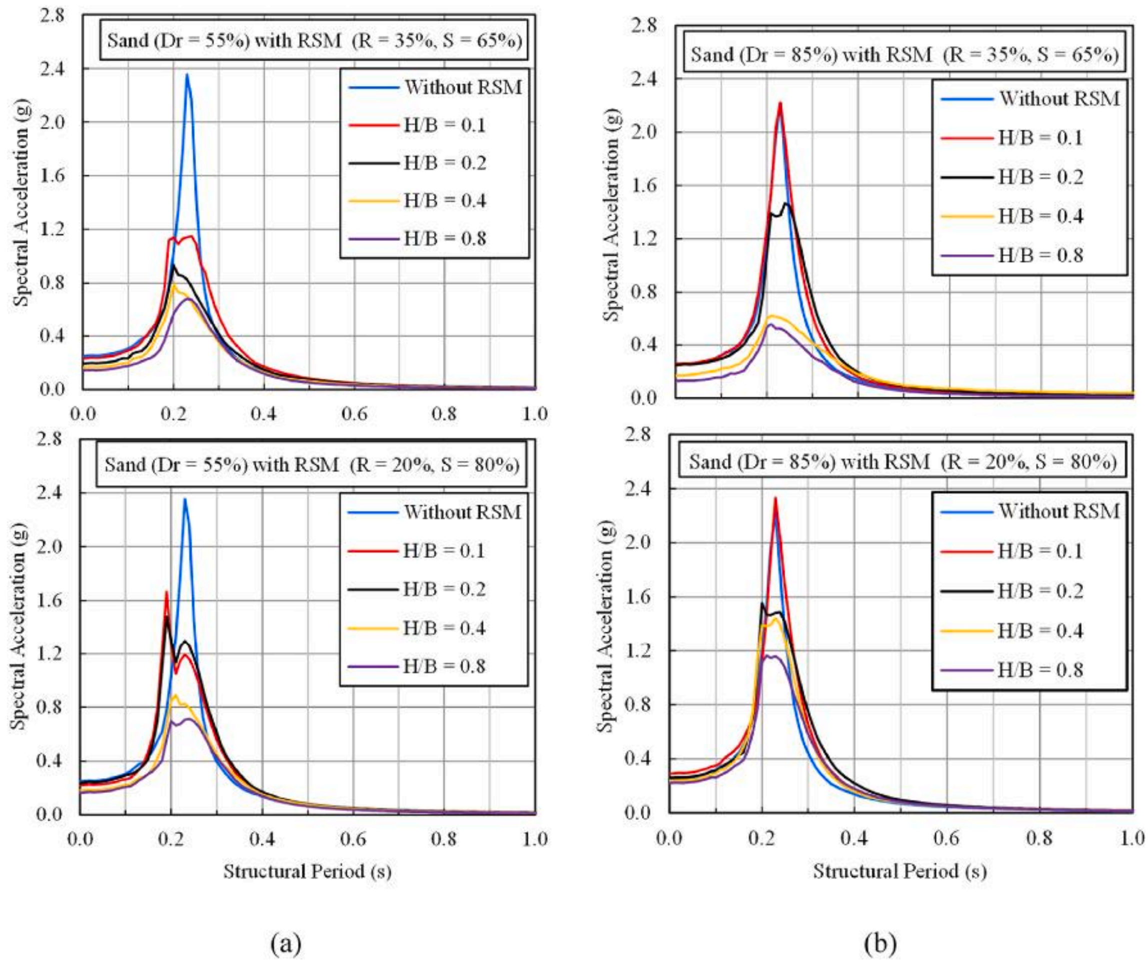

Fig. 8. Presentation of spectral acceleration of the footing resting over an RSM cushion with different thicknesses situated in: (a) loose sandy ground; (b) dense sandy ground.

placed on the test surface. The results obtained from this investigation provide valuable insights from two perspectives. Firstly, the rigid block can be seen as a representative footing of a larger structure, allowing to analyze the transmitted acceleration and displacements experienced by the block. Secondly, the scenario, where a single-degree-of-freedom structure is placed on this rigid footing, enables to explore the motion experienced by the structure using the concept of spectral acceleration. By examining the seismic response of the rigid block and the associated spectral acceleration, this study sheds light on the effectiveness of the RSM layer in mitigating the effects of seismic loading on structures.

The primary objective of this study was to assess the effectiveness of the rubber-sand mixture (RSM) layer in mitigating the acceleration response of a single footing. The obtained results provide compelling evidence of the significant impact of the RSM layer in reducing the acceleration experienced by the footing. A comprehensive comparison of the acceleration time histories between the footing with and without the RSM layer clearly demonstrates the attenuation effect achieved by the presence of the RSM layer. Notably, this attenuation effect is more pronounced in cases where higher rubber contents and thicker RSM layers are utilized. These findings align with previous research studies encompassing various experimental techniques such as shaking table tests [2,18,20,21], centrifuge tests [3,39], large-scale field testing [19], and numerical investigations [9,13]. The consistency of these findings across different research approaches supports the robustness and reliability of the observed trends in the reduction of acceleration response due to the incorporation of the RSM layer.

This study stands out from previous works in a significant way by considering a wide range of rubber-sand mixture (RSM) depth ratios (H/B = 0.1–0.8), while the depth ratio was either not considered or limited in earlier studies. Furthermore, unlike most previous investigations that focused solely on the depth of the RSM layer itself, this study explores the impact of the ratio between the thickness of the RSM layer and the footing width. This novel approach provides valuable insights into optimizing the design of buildings incorporating RSM layers. Investigating the effects of depth parameters, Tsiavos et al. [20] found that increasing the depth of the RSM layer can yield different effects on the acceleration response of the building, depending on the frequency range. By introducing a simple analytical model along with a number of ground motion records, Wu et al. [15] concluded that the isolation effect increases with increasing RSM layer thickness from 200 mm to 300 mm, however, they mentioned that thicker RSM layer (500 mm) resulted in worse seismic performance. Dhanya et al. [11], on the other hand, examined numerically the influence of the RSM depth ratio in conjunction with the use of geogrid layers on the degree of isolation provided by the GSI system. They discovered that the degree of isolation increases as the RSM layer depth increases, indicating that deeper RSM layers are more effective at absorbing energy and reducing seismic forces. Consistent with previous studies, including those cited [1,2,6,14,19,34], in the present study, a noticeable decrease in the peak horizontal acceleration of the footing was observed with an increase in RSM layer depth. However, the present study revealed a crucial finding that beyond a certain depth ratio (H/B = 0.4), there is no further reduction in the footing acceleration. This finding highlights the limitation of the RSM layer thickness in its role of dissipating energy. In summary, the

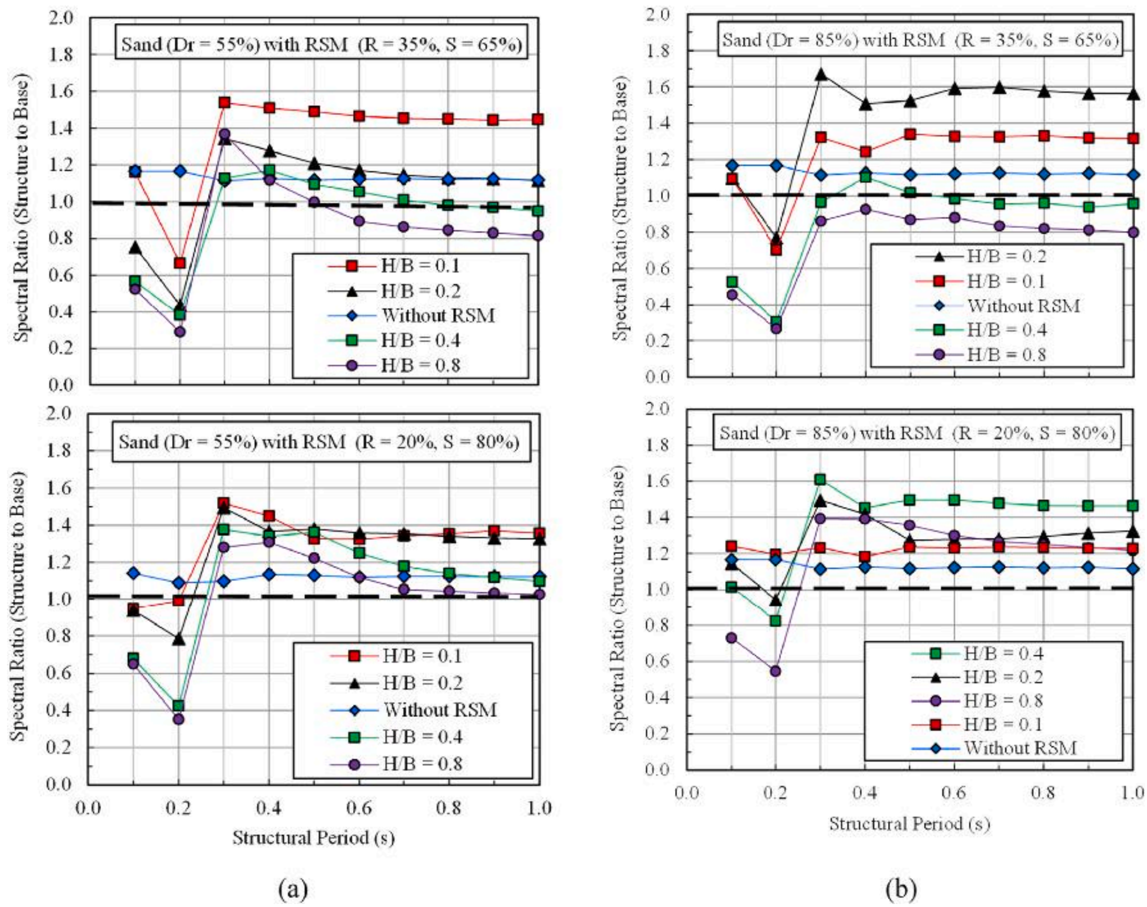

Fig. 9. Presentation of spectral ratio of footing to base for different depth ratios (H/B) and RSMs of 20 % and 35 % situated over: (a) loose sandy ground, (b) dense sandy ground.

findings emphasize the importance of selecting an optimal depth ratio to achieve the desired reduction in footing acceleration, shedding light on the limitations of RSM layer thickness in energy dissipation.

By investigating the spectral ratio, which compares the spectral acceleration of the transmitted footing motion to that of the input wave motion at the same period, this study reveals that a de-amplification effect is generally observed for low-rise buildings with smaller structural periods. This finding is consistent with prior research, indicating that incorporating an RSM layer is more effective in low-rise and mid-rise buildings, compared to high-rise or flexible structures. Most previous works in this area are based on numerical simulations. For example, Dhanya et al. [11] similarly found that the use of RSM led to a significant reduction in peak spectral acceleration and a shifting of the fundamental period of the structure. Notably, in low-frequency earthquakes, the maximum change in acceleration amplitude due to the use of RSM occurred in the period range of 0.3–1 s, indicating further reductions in acceleration amplitude in low-rise buildings. Tsang et al. [5] proposed the use of the GSI system for low-to-medium-rise buildings and reported that the increase in the fundamental period of the building due to the use of RSM resulted in a more perceptible reduction in the acceleration transmitted to the building. Additionally, Pitilakis et al. [6] conducted a numerical investigation on reinforced concrete buildings of varying heights and found that the depth of the RSM layer primarily affects the acceleration response parameters of high-rise buildings. They noted that as the RSM layer depth increases, the percentage reduction in the response of high-rise buildings decreases. This suggests that while the use of RSM as a base isolator can be effective for reducing seismic forces in buildings of all heights, it may be especially beneficial for mid-rise and low-rise buildings. More recently, dynamic numerical analysis performed by Gorbanzadeh and Hosseininia [9] revealed that even with a high percentage and depth of the RSM layer, the acceleration response spectra converged at high periodicity. Consequently, the use of RSM in buildings with high periodicity (tall buildings) has no significant effect on reducing the structural response to dynamic loading. However, based on the results of the present study, it was observed that the de-amplification effect can also occur for high-rise buildings seated over either of loose or dense ground, but only when a sufficient rubber content is applied to the RSM layer with a large depth ratio. This indicates that the use of RSM, under specific conditions, might also be beneficial for tall buildings in attenuating the seismic response. In summary, the findings of this study align with previous research, showcasing the effectiveness of RSM layers in reducing the acceleration response in low-and mid-rise buildings and even high-rise buildings.

In seismic design, it is crucial to consider not only the reduction in structural acceleration but also the deformational behavior of structures during earthquake loading. As mentioned in Section 4, the experimental tests conducted in this study have revealed that when a footing is placed over an underlying rubber-sand mixture (RSM) layer, it exhibits more rocking and tilting behavior compared to when it is seated directly on the pure soil. This observation underscores the importance of examining structural deformation in addition to assessing acceleration response. It's worth noting that similar findings were reported by Tsiavos et al. [20] in their large-scale experimental tests, where low-rise buildings isolated with an RSM layer exhibited significant detrimental rocking behavior. This rocking behavior can have serious implications, especially for low-rise masonry buildings, and highlights the need for a comprehensive understanding of both structural acceleration and deformation characteristics when implementing RSM layers as seismic

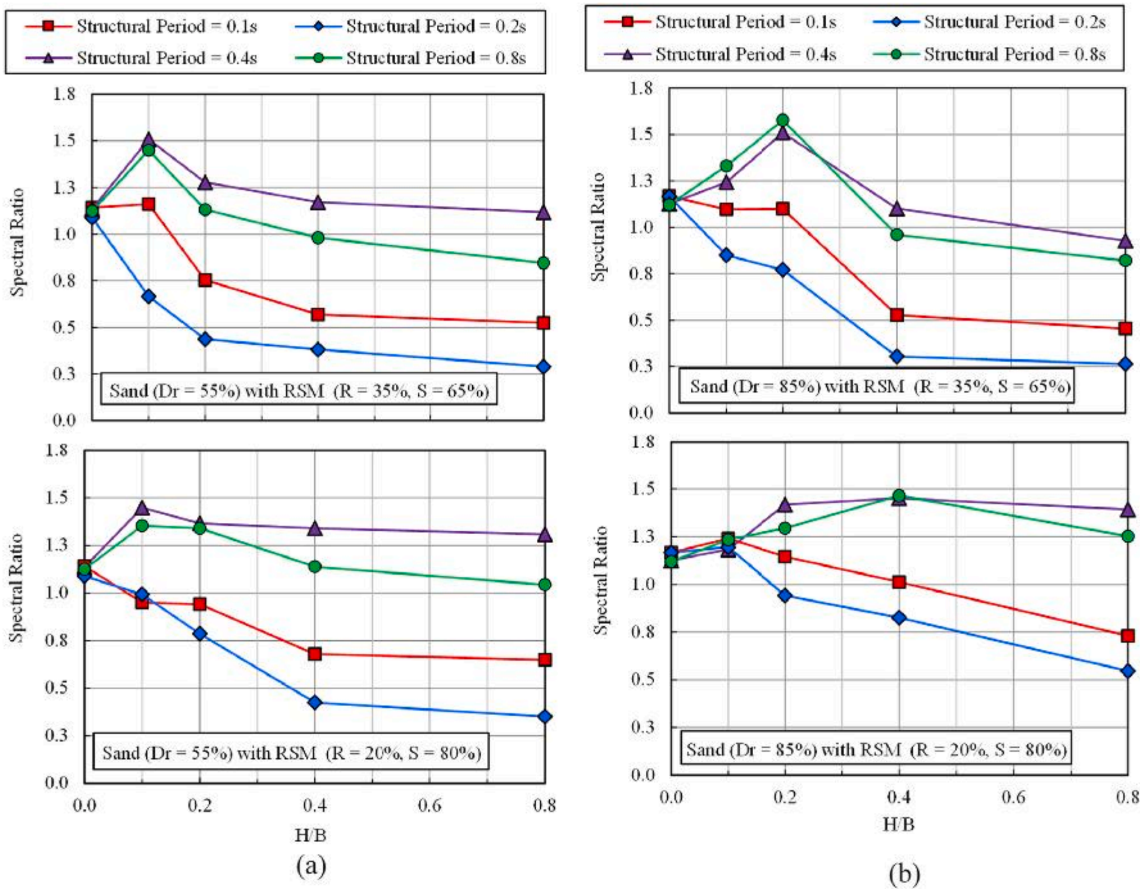

Fig. 10. Effect of structural period on the spectral ratio for different depth ratios and RSMs situated over: (a) loose sandy ground; (b) dense sandy ground.

isolation systems.

In terms of ground compaction, the findings of this study revealed that the attenuation of footing acceleration was significantly affected by the compactness nature of the underlying ground. Specifically, it was observed that the decrease in acceleration attenuation was more prominent when the footing was situated over loose ground compared to dense ground condition. This implies that the presence of the RSM layer had a greater influence on reducing acceleration response in loose soil condition. Furthermore, when examining the spectral ratio of the structures, it was found that for depth ratios greater than 0.1, the effectiveness of the RSM layer was more pronounced for structures with shorter structural periods ranging from 0.1 to 0.3 s, particularly when seated over loose ground and RSM content of 20 % rather than 35 %. Interestingly, these observations in the shaking table tests contradict the findings of Wu et al. [15] in their theoretical study. They utilized a simplified analytical model based on a one-degree-of-freedom system and conducted various examples to investigate the isolation effect of the RSM layer. Only one gravimetric RSM content (=30 %) was adopted with different RSM thicknesses under a rigid footing. Since the footing was modeled as a concentrated mass without any dimension, it was not possible to define the RSM depth ratio. Based on their study, it was concluded that the RSM layer may exhibit better isolation properties in sites with higher soil compaction and stiffness. In addition, smaller RSM thickness of 0.2–0.3 m is more effective but thicker RSM layer (0.5 m) makes the seismic performance worse and the effect of ground compactness diminishes. To address this discrepancy and provide more accurate insights, future research could consider conducting additional experimental tests or employing advanced numerical modeling techniques that consider a wider range of ground conditions and incorporate more sophisticated soil-structure interaction analyses. By doing so, a more robust understanding of the effectiveness of RSM layers in different ground conditions can be obtained, which would contribute to the development of more reliable design guidelines and strategies for seismic mitigation.

Due to the high compressibility of rubber particles, the settlement of buildings utilizing RSM layers as ground improvement systems (GSIs) becomes an important consideration for engineers ([e.g., 12, 31, 40]). It is widely recognized that the inclusion of RSM layers generally leads to increased settlement compared to cases where the footing is solely supported by the underlying soil. Previous research studies have highlighted this intensification effect on settlement and proposed remediation methods, such as using geotextile/geogrids [11,41,42] or piled foundations [14]. In the present study, different settlement trends were observed during seismic loading, influenced by rubber content and especially the depth ratio. In general, the settlement rate increased with the depth ratio. However, it is important to note that there is a limit to the effectiveness of the depth ratio in influencing settlement. Beyond a certain depth ratio, the final seismic settlement of the footing becomes less sensitive to changes in the thickness of the RSM layer. This suggests that there may be a point at which further increasing the thickness of the RSM layer does not lead to significant changes in settlement.

Additionally, the effect of ground compaction on seismic settlement was investigated. It was observed that for thick RSM layers, the final seismic settlement was similar for both dense and loose ground conditions. These findings qualitatively align with previous studies, although very few studies have focused on the magnitude of settlement in the case of RSM, whether under static or seismic conditions. Tsang et al. [43] conducted a numerical investigation on the serviceability performance of a building seated over an RSM layer and concluded that the elastic settlement significantly increased when 30 % rubber content was added to the soil, although it still satisfied the criteria specified by design codes. However, they did not study the seismic settlement of the

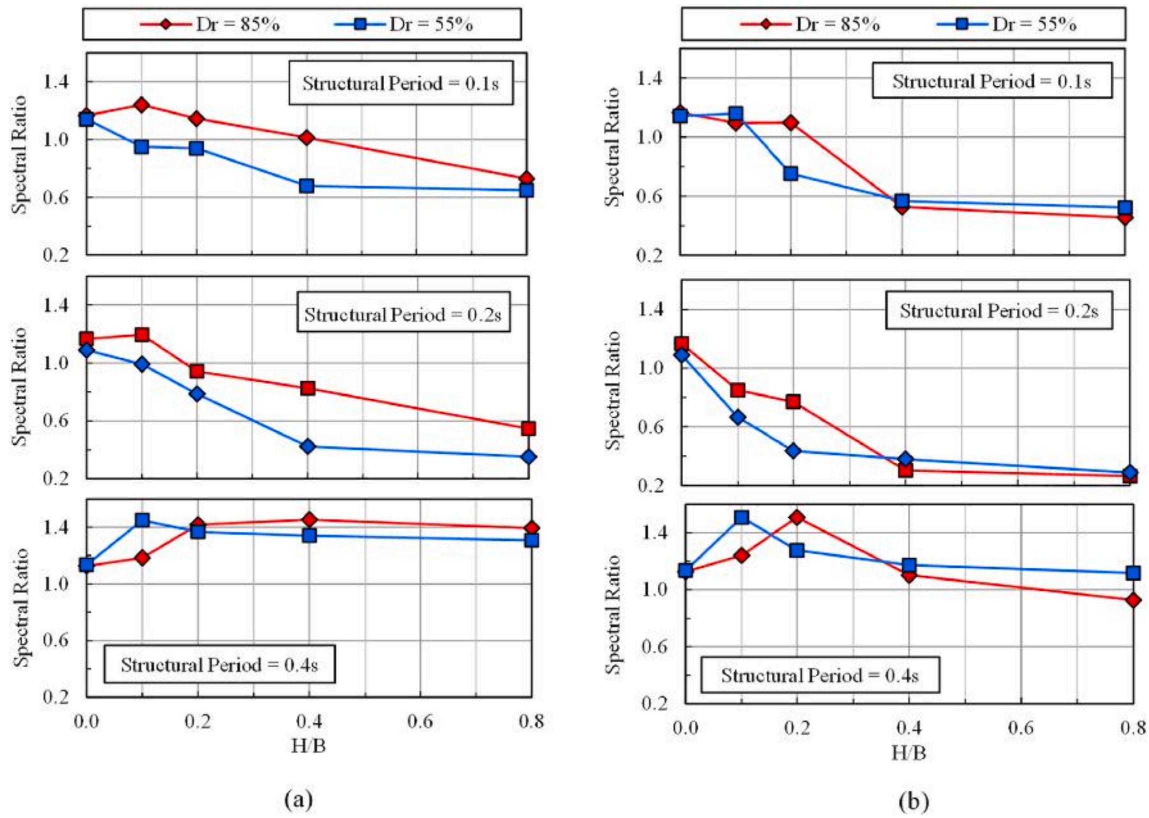

Fig. 11. Effect of ground density on the spectral ratio of the footing with respect to the base with a cushion of: (a) RSM20 %; (b) RSM35 %.

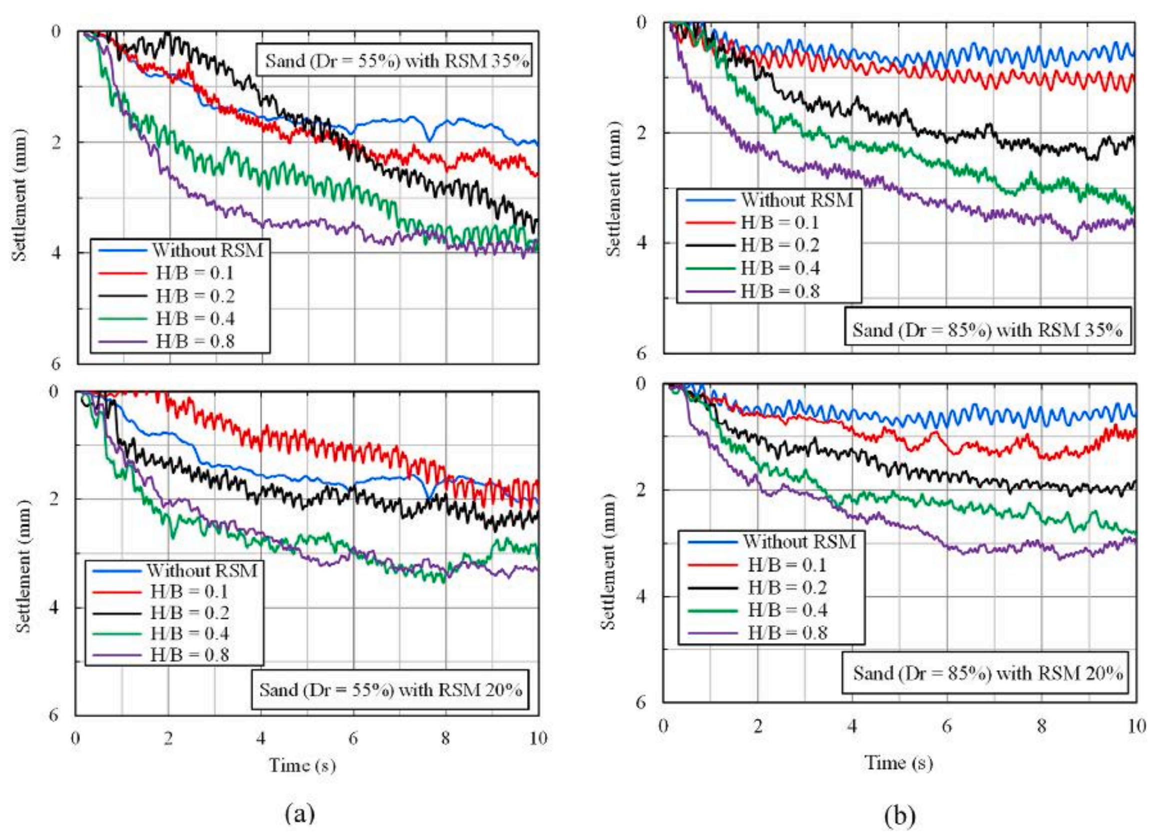

Fig. 12. Variation of the footing settlement versus time for different depth ratios of RSM cushion situated over: (a) loose sandy ground; (b) dense sandy ground.

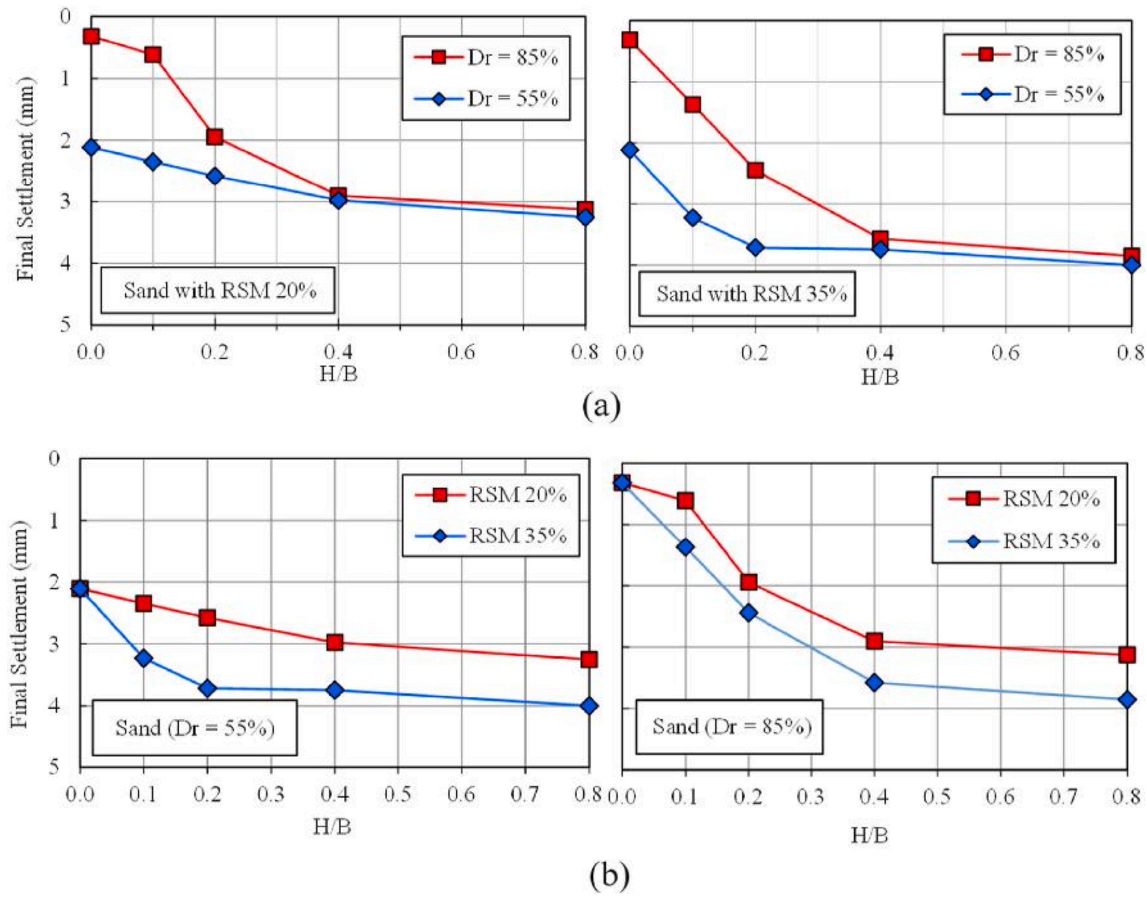

Fig. 13. Effect of (a) ground density, and (b) RSM content on the footing settlement with different depth ratios.

building. Abate et al. [13] performed a full-scale prototype structure study resting on SRM and examined the effective parameters of the seismic behavior through numerical simulations. They reported only the amount of static settlement, comparing it to design codes. In centrifuge testing, Tsang et al. [3] concluded that RSM exhibited more elastic behavior with reversible deformation under earthquake shaking, leading to a reduction in the rocking motion of buildings. Dhanya et al. [11] conducted numerical studies on the seismic performance of a two-storied building supported by a raft footing resting on an RSM layer, along with geogrid layers as a GSI system. Based on the simulation results, the seismic settlement with RSM was found to be intensified compared to bare soil conditions. Overall, these findings contribute to the understanding of settlement characteristics associated with RSM layers, shedding light on the dynamic behavior of structures and providing insights for design and mitigation strategies in seismic applications.

In summary, the presence of the RSM layer below a superstructure can potentially cause excessive settlement, which may have detrimental effects on the structural integrity. Therefore, careful consideration must be given to the rubber content of the RSM layer. It is crucial to find a balance between reducing acceleration through the RSM layer and preventing excessive settlement that could compromise the overall stability of the structure. Future research could further explore the optimal rubber content and depth ratio of the RSM layer to minimize settlement while still harnessing its benefits in reducing acceleration.

6. Concluding remarks

In this study, the effectiveness of rubber-sand mixture (RSM) layers in improving the seismic performance of structures has been investigated through shaking table tests. This paper significantly advances our understanding of the seismic performance of structures when equipped with rubber-sand mixture (RSM) layers. By comprehensively investigating the influence of RSM depth ratios, ground compaction, and structural periods, it provides crucial insights into the optimal design parameters for enhancing seismic resilience. The study's innovative approach of considering a wide range of RSM depth ratios fills a notable gap in the existing literature, offering valuable guidance for engineers and researchers. The observations, particularly regarding the interaction between RSM layers and ground conditions, challenge some theoretical expectations, underlining the need for practical experimentation. The findings provide valuable insights into the behavior and performance of RSM layers under dynamic loading conditions. The conclusions drawn from this study are as follows.

1. The inclusion of RSM layers in the design of structures significantly reduces the acceleration response, indicating improved seismic resilience. The damping and energy dissipation properties of RSM layers contribute to the attenuation of transmitted seismic forces. This finding underscores the potential of RSM layers as effective mitigation measures.
2. The effectiveness of the RSM layer is influenced by various factors, including the rubber content, depth ratio, and ground compaction. Optimal design parameters and thickness of RSM layers should be carefully selected based on site-specific conditions and engineering requirements. The results emphasize the need for a comprehensive understanding of these factors to ensure the successful implementation of RSM layers.
3. Comparisons with prior studies reveal that the findings of this study align with the existing literature, reaffirming the potential of RSM layers in mitigating the seismic response of structures. The contradictory finding with the previous theoretical study by Wu et al. [15]

regarding the effect of soil compaction emphasizes the necessity for refined and site-specific considerations.
4. The influence of ground conditions, such as compaction and density, on the behavior of RSM layers has been demonstrated. RSM layers show a more pronounced reduction in the acceleration response in loose ground conditions compared to denser ground conditions. Nevertheless, even in denser ground conditions, the inclusion of RSM layers contributes to improved seismic performance, albeit to a lesser extent.
5. The engineering implications of this study are significant. Incorporating RSM layers in the design and construction process can enhance the seismic resilience of structures. Site-specific considerations, such as soil properties, compaction levels, and amplification effects, should be carefully evaluated to determine the appropriate design parameters and thickness of RSM layers. This study provides valuable guidance for engineers in implementing RSM layers effectively.
6. The findings of this study highlight the influence of RSM layers on the settlement of structures. The results demonstrate that the inclusion of RSM layers generally leads to increased settlement compared to cases where the footing is solely supported by the underlying soil. The settlement is influenced by factors such as rubber content and depth ratio of the RSM layer. Careful consideration must be given to the design of RSM layers to prevent excessive settlement while still harnessing their beneficial effects in reducing acceleration.

It is important to acknowledge the limitations of this study, which include the small-scale effect of physical modeling in shaking table tests, surface footings, and the use of a single input acceleration excitation and frequency. These limitations should be taken into consideration when interpreting the results and generalizing them to real-world applications. Moreover, while this study delves into various aspects of RSM layers, it is essential to note that the optimal rubber content and proper depth ratio of the RSM layer, as critical factors in determining its effectiveness, have not been extensively explored within this research.

Future research and development efforts should focus on expanding our understanding of the behavior and performance of RSM layers and structures. Investigations into different soil types, variations in compaction levels, optimal rubber content and depth ratio, footings with embedded depth, and advanced numerical modeling techniques can further enhance our knowledge and aid in the development of design guidelines and recommendations. Additionally, studies on the long-term performance and durability of RSM layers under various environmental conditions will be decisive for their widespread adoption in seismic engineering practice.

CRediT authorship contribution statement

Elyas Golestani Ranjbar: Data curation, Investigation, Validation, Visualization, Writing – original draft. **Ehsan Seyedi Hosseininia:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Tsang HH. Seismic isolation by rubber–soil mixtures for developing countries. Earthq Eng Struct Dynam 2008;37:283–303.
[2] Bandyopadhyay S, Sengupta A, Reddy GR. Performance of sand and shredded rubber tire mixture as a natural base isolator for earthquake protection. Earthq Eng Eng Vib 2015;14:683–93.
[3] Tsang H-H, Tran D-P, Hung W-Y, Pitilakis K, Gad EF. Performance of geotechnical seismic isolation system using rubber-soil mixtures in centrifuge testing. Earthq Eng Struct Dynam 2021;50:1271–89.
[4] Tsang H-H, Pitilakis K. Mechanism of geotechnical seismic isolation system: analytical modeling. Soil Dynam Earthq Eng 2019;122:171–84.
[5] Tsang H-H, Lo SH, Xu X, Neaz Sheikh M. Seismic isolation for low-to-medium-rise buildings using granulated rubber–soil mixtures: numerical study. Earthq Eng Struct Dynam 2012;41:2009–24.
[6] Pitilakis K, Karapetrou S, Tsagdi K. Numerical investigation of the seismic response of RC buildings on soil replaced with rubber–sand mixtures. Soil Dynam Earthq Eng 2015;79:237–52.
[7] Pistolas GA, Pitilakis K, Anastasiadis A. A numerical investigation on the seismic isolation potential of rubber/soil mixtures. Earthq Eng Eng Vib 2020;19:683–704.
[8] Lee C, Shin H, Lee JS. Behavior of sand–rubber particle mixtures: experimental observations and numerical simulations. Int J Numer Anal Methods GeoMech 2014;38:1651–63.
[9] Ghorbanzadeh S, Seyedi Hosseininia E. A numerical study on the seismic design of buildings seated over an RSM layer. Structures 2023;55:46–58.
[10] Forcellini D. Assessment of geotechnical seismic isolation (GSI) as a mitigation technique for seismic hazard events. Geosciences 2020;10(6). 222 (14pages), https://doi.org/10.3390/geosciences10060222.
[11] Dhanya JS, Boominathan A, Banerjee S. Response of low-rise building with geotechnical seismic isolation system. Soil Dynam Earthq Eng 2020;136:106187.
[12] Asadi M, Thoeni K, Mahboubi A. An experimental and numerical study on the compressive behavior of sand-rubber particle mixtures. Comput Geotech 2018;104: 185–95.
[13] Abate G, Fiamingo A, Massimino MR, Pitilakis D. FEM investigation of full-scale tests on DSSI, including gravel-rubber mixtures as geotechnical seismic isolation. Soil Dynam Earthq Eng 2023;172:108033.
[14] Tsang HH, Lo S, Xu X, Neaz Sheikh M. Seismic isolation for low-to-medium-rise buildings using granulated rubber–soil mixtures: numerical study. Earthq Eng Struct Dynam 2012;41:2009–24.
[15] Wu M, Tian W, He J, Liu F, Yang J. Seismic isolation effect of rubber-sand mixture cushion under different site classes based on a simplified analysis model. Soil Dynam Earthq Eng 2023;166:107738.
[16] Tsang H-H. Analytical design models for geotechnical seismic isolation systems. Bull Earthq Eng 2023;21:3881–904.
[17] Xiong W, Tsang HH, Lo S, Shang SP, Wang HD, Zhou FY. Geotechnical seismic isolation system-Experimental study. In: Advanced materials research. Trans Tech Publ; 2011. p. 4449–53.
[18] Xiong W, Li Y. Seismic isolation using granulated tire–soil mixtures for less-developed regions: experimental validation. Earthq Eng Struct Dynam 2013;42: 2187–93.
[19] Vratsikidis A, Pitilakis D. Field testing of gravel-rubber mixtures as geotechnical seismic isolation. Bull Earthq Eng 2023;21:3905–22.
[20] Tsiavos A, Alexander NA, Diambra A, Ibraim E, Vardanega PJ, Gonzalez-Buelga A, Sextos A. A sand-rubber deformable granular layer as a low-cost seismic isolation strategy in developing countries: experimental investigation. Soil Dynam Earthq Eng 2019;125:105731.
[21] Yin Z, Sun H, Jing L, Dong R. Geotechnical seismic isolation system based on rubber-sand mixtures for rural residence buildings. Shaking Table Test; 2022. Materials.
[22] Prasad SK, Towhata I, Chandradhara GP, Nanjundaswamy P. Shaking table tests in earthquake geotechnical engineering. Curr Sci 2004;87:1398–404.
[23] Kheradi H, Morikawa Y, Ye G, Zhang F. Liquefaction-induced buckling failure of group-pile foundation and countermeasure by partial ground improvement. Int J GeoMech 2019;19:04019020.
[24] Rasekh F, Omidi A, Saeedi Azizkandi A, Shahnazari H. Effect of air injection on pile and pile group behavior in liquefiable soil. Bull Eng Geol Environ 2020;79: 4501–14.
[25] Baziar MH, Sanaie M, Amirabadi OE, Khoshniazpirkoohi A, Azizkandi AS. Mitigation of hunchbacked gravity quay wall displacement due to dynamic loading using shaking table tests. Ocean Eng 2020;216:108056.
[26] He J, Chu J, Ivanov V. Mitigation of liquefaction of saturated sand using biogas. Geotechnique 2013;63:267–75.
[27] Azizkandi AS, Baziar MH, Yeznabad AF. 3D dynamic finite element analyses and 1 g shaking table tests on seismic performance of connected and nonconnected piled raft foundations. KSCE J Civ Eng 2018;22:1750–62.
[28] Iai S. Similitude for shaking table tests on soil-structure-fluid model in 1g gravitational field. Soils Found 1989;29:105–18.
[29] A. D2487-11. Standard practice for classification of soils for engineering purposes (unified soil classification system). 2011.
[30] Senetakis K, Anastasiadis A, Pitilakis K. Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. Soil Dynam Earthq Eng 2012;33:38–53.
[31] Edil TB, Bosscher PJ. Engineering properties of tire chips and soil mixtures. Geotech Test J 1994;17:453–64.
[32] Rezapour A, Seyedi Hosseininia E. A study on the effect of shredded tire size on the mechanical behavior of sand and shredded tire mixtures using direct shear test. J Civ Eng 2017;29:17–29.
[33] Reddy SB, Krishna AM, Reddy KR. Sustainable utilization of scrap tire derived geomaterials for geotechnical applications. Indian Geotech J 2018;48:251–66.

[34] Brunet S, de la Llera JC, Kausel E. Non-linear modeling of seismic isolation systems made of recycled tire-rubber. Soil Dynam Earthq Eng 2016;85:134–45.
[35] A. D4254-14. Standard test methods for minimum index density and unit weight of soils and calculation of relative density. 2014.
[36] A. D4253-14. Standard test methods for maximum index density and unit weight of soils using a vibratory table. 2014.
[37] Maghsoudi MS, Chenari RJ, Farrokhi F. A multilateral analysis of slope failure due to liquefaction-induced lateral deformation using shaking table tests. SN Appl Sci 2020;2:1–11.
[38] White D, Take W, Bolton M. Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. Geotechnique 2003;53:619–31.
[39] Gajan S, Kutter BL. Effects of moment-to-shear ratio on combined cyclic load-displacement behavior of shallow foundations from centrifuge experiments. J Geotech Geoenviron Eng 2009;135:1044–55.
[40] Bosscher PJ, Edil TB, Kuraoka S. Design of highway embankments using tire chips. J Geotech Geoenviron Eng 1997;123:295–304.
[41] Dhanya JS, Boominathan A, Banerjee S. Investigation of geotechnical seismic isolation bed in horizontal vibration mitigation. J Geotech Geoenviron Eng 2022;148:04022108.
[42] Anbazhagan P, Manohar D. Energy absorption capacity and shear strength characteristics of waste tire crumbs and sand mixtures. Int J Geotech Earthq Eng 2015;6:28–49.
[43] Tsang H-H, Tran D-P, Gad EF. Serviceability performance of buildings founded on rubber–soil mixtures for geotechnical seismic isolation. Aust J Struct Eng 2023:1–14.