Structures 55 (2023) 46–58

Contents lists available at ScienceDirect

Structures

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

A numerical study on the seismic design of buildings seated over an RSM layer

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ARTICLE INFO

Keywords:
Sand-rubber mixture
Base isolator
Earthquake-resistant buildings
Magnification factor
Acceleration

ABSTRACT

In recent years, there has been a significant effort to create innovative and affordable seismic protection systems that can be widely used in developing regions. Traditional isolators are often heavy and expensive, which restricts their application in residential buildings. To address this challenge, low-cost and low-tech approaches are being explored, such as the incorporation of rubber into the soil beneath a building's foundation. This approach aims to dampen part of the seismic energy before it reaches the superstructure. This paper investigates the use of rubber-sand mixture (RSM) as a foundation layer to improve the seismic performance of structures. The effects of varying RSM dimensions on the footing acceleration response, structural weight, and base shear forces of a prototype five-story building are analyzed by numerical simulations. Results show that increasing the depth of the RSM layer and RSM content can significantly reduce the acceleration response, particularly for low-rise buildings with natural periods less than 0.3 s. Thicker RSM layers are found to be more effective in reducing input acceleration than wider layers, although such effect declines as the depth ratio exceeds 0.25. Furthermore, incorporating RSM as a base isolator can lead to a considerable reduction in both the maximum base shear force and structural weight, with up to 30% reduction achieved with RSM 35%. This study suggests that RSM has potential as a cost-effective and efficient solution for improving the seismic performance of low-to-mid-rise structures, and the effect of the depth of RSM layer and RSM content should be carefully considered for optimal design.

1. Introduction

The safety of structures against strong earthquakes, their lifespan against environmental issues, and conservation of resources are critical concerns that require the development and upgrading of seismic-resistant systems. To address these issues, novel seismic isolation techniques have been proposed in recent decades that can significantly enhance the seismic performance of structures and minimize damage caused by earthquakes. Researchers have introduced several base isolators, including Lead Rubber Bearing (LRB), Friction Pendulum System (FPS), and Laminated Rubber Bearing (LRB), to separate the structure from earth vibration [1–6]. Several novel dampers have been proposed to enhance the sensitivity of traditional dampers to frequency deviation [7–12]. Among these methods, base isolation has been proven to be a more effective approach than seismic-resistant systems for reducing seismic loads by increasing the structure's period and damping [1,13–15].

While traditional isolation systems have been effective [16,17], their high installation and maintenance costs, as well as potentially large isolation layer drift levels, have made them less desirable and limited their use in developing countries. Researchers have conducted numerous investigations to reduce the manufacturing cost of seismic isolation systems and create more affordable designs with suitable performance [18–20]. Exploring the use of fiber reinforced elastomeric isolators, including recycled rubber, is one approach to making conventional base isolation systems more cost-effective [21–25]. However, the ideal solution would be low-cost systems that are compatible with regional conditions. For example, Trifunac et al. [26,27] found that soft soil areas can absorb some of seismic waves, reducing severe damage in the Northridge 1994 earthquake. Anastasopoulos et al. [28] also investigated using soil failure under the foundation of structures for seismic isolation purposes by quantifying the foundation's nonlinear rocking stiffness.

The Geotechnical Seismic Isolation (GSI) system, proposed by Tsang [29], has emerged as a promising technology in the last decade. This system utilizes a soft mixed soil region beneath the foundation, which

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https://doi.org/10.1016/j.istruc.2023.05.086
Received 14 March 2023; Received in revised form 21 May 2023; Accepted 22 May 2023
Available online 13 June 2023
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decreases the stiffness of the mass and dissipates the energy of earthquake waves before they reach the structure [30]. The mixed soil utilized in this system is a combination of granular soil and rubber, which functions similarly to a cushion [31]. The GSI system has gained attention as a cost-effective and reliable alternative to traditional seismic isolation systems due to its simple design and ease of installation. Furthermore, the GSI system has demonstrated a high level of effectiveness in reducing seismic damage and improving the seismic performance of buildings, and it could be implemented in the seismic design of other structures such as bridges [32,33].

Recently, many researchers have considered the use of tires in soil due to their low specific gravity, high tensile strength, flexibility, durability, and appropriate damping properties [34–45]. Previous studies have suggested that a 35% weight content of rubber is needed to increase the strength of the mixture compared to soil [46–48]. Vancatapa et al. [44] conducted several triaxial tests on soil rubber mixtures and found that a 20% rubber chips content had the best improvement in strength at the least confining pressure. Additionally, Reddy et al. [49] conducted a laboratory study showing that the optimal ratio of the rubber-sand mixture (RSM) is about 30% to 40%. Numerous studies have investigated the dynamic properties of RSM [48,50–53]. Nakhaei et al. [52] conducted large-scale consolidated undrained cyclic triaxial tests, and their results showed that the shear modulus decreases with increasing rubber content, while it increases with increasing confining pressure for all percentages of rubber. Senetakis et al. [48] performed an extensive experimental study to determine the effect of RSM content, confining pressure, and grain-size characteristics on the dynamic properties of RSM. They presented shear modulus and damping ratio curves versus shear strain to predict the dynamic behavior of RSM.

Recent studies have explored the potential of using RSM as a foundation material for creating an isolation layer with controllable properties and low stiffness [31,54–61]. These studies have found that RSM can significantly reduce both horizontal and vertical acceleration transmitted to the structure [31], and that its effectiveness is greater for buildings with lower heights and higher RSM depth [60]. Additionally, RSM has been shown to decrease seismic force and displacement for both far-field and near-field earthquakes, although high RSM content may increase the potential for structural instability [59]. However, the isolation performance of RSM is more evident when the PGA values are greater than 0.20–0.25 g, as this induces large inelastic deformation of the RSM [56]. Experimental studies using shaking-table apparatus have found that RSM can reduce the input motion subjected to the structure [57,62,63], and a centrifuge test has indicated that the use of RSM can reduce structural demand by 40–50%[58].

Previous studies have investigated the impact of RSM thickness and rubber content on the seismic response of buildings [29,31,55–57]. Bandyopadhyay et al. [57] found that increasing the depth of the RSM layer can considerably reduce acceleration amplification at the top of the footing model. The numerical results presented by Tsang et al. [29] suggest that the response of the model is mostly influenced by the thickness of the RSM layer, particularly in terms of horizontal acceleration ratio. Pitilakis et al. [55] reported that the thickness of RSM appears to have a greater impact on high-rise buildings, with deeper RSM layers resulting in a considerably higher percentage reduction of structural response compared to shallower layers, depending on the input motion. Meanwhile, Banovic et al. [64] observed that seismic layer performance and the impacts of observed layer parameters are significantly dependent on the type of excitation and PGA, with thinner layers of pebble demonstrating good responses for some excitations and the opposite for others.

Waste tire rubber is a promising material for GSI systems, as it is both cost-effective and eco-friendly, making it a viable option in low-income countries [57,62,65]. However, the impact of GSI systems on the weight of structural elements and base shear force of buildings has not been extensively studied. Therefore, this study aims to investigate the effects of different mixing percentages and dimensions of RSM regions on reducing the weight of structural elements and base shear force of a typical residential five-story building. The findings of this study could provide valuable insights for engineers and designers involved in the seismic protection of buildings.

2. Numerical modeling

2.1. Investigation of RSM dimension

In this study, the geometry is based on a simplified design proposed by Tsang [29], who suggested replacing the soil surrounding the foundation with RSM. This technique, known as the Geotechnical Seismic Isolation (GSI) system, focuses on utilizing geomaterials and their interactions with structures to mitigate seismic impacts [66,67]. The RSM layer in this system shares similarities with soil-structure interaction (SSI), as both involve the foundation's responsiveness to external forces. However, RSM specifically aims to enhance seismic performance by incorporating rubber in the soil, which reduces the building frame's overall stiffness and increases its natural period [68]. The analyses were first conducted for sand and then for the RSM region with specified depth (D_f) and width (B_f) as shown in Fig. 1. The RSM was placed under the foundation with a width of B in the model. In this study, two parameters are introduced: 1) the depth ratio (D_f/B) defined as the ratio between RSM region depth (D_f) and the loading width (B), and 2) the width ratio (B_f/B). About boundary conditions, the bottom boundary in both horizontal and vertical directions are fixed and the side boundaries are fixed in the horizontal direction, i.e., roller side boundaries.

The numerical model dimensions correspond to the actual dimensions of a physical model conducted by Bandyopadhyay et al. [57]. In this laboratory study, the effectiveness of using RSM in the reduction of acceleration transmitted to a scaled-down square footing foundation was investigated. The physical model of the foundation was created using a scale factor of 10, where a length of 2 m was scaled down to 0.2 m, whereas the dimensions of the physical model were maintained without further scaling in the numerical model. The study used heterogeneous shredded rubber tire with a maximum thread length of 10 mm and a diameter of about 1 mm. A test box filled with 65% density of sand was used, and the foundation model was a Plexiglas block placed on the soil surface. The set was subjected to harmonic movements twice with and without RSM. Taking the scale factor into account, the loading area is positioned over a 2-meter-deep layer of sand with a pressure of 40 kPa applied as the weight of the building over B = 2 m. The RSM region is modeled with different percentages of rubber 20, 30, and 50% at various depth and width ratios beneath the foundation model according to Table 1. The input wave is applied in a harmonic manner with an acceleration of 0.5 g and a frequency of 3.5 Hz from the model base.

The Mohr-Coulomb constitutive model is adopted to simulate the linear elastic perfectly-plastic behavior of the soil and RSM. The physical and mechanical properties for sand and RSM with 20%, 30%, and 50% are given in Table 2 based on experimental data obtained in the reference [57]. A constant Poisson's ratio of 0.3 is considered as it has been shown that the Poisson's ratio has little effect on RSM performance and energy dissipation characteristics [29].

The normalized shear modulus and damping ratio versus shear strain amplitude curves for the material properties of the sand and RSM are assigned based on the particle size distribution in the reference work

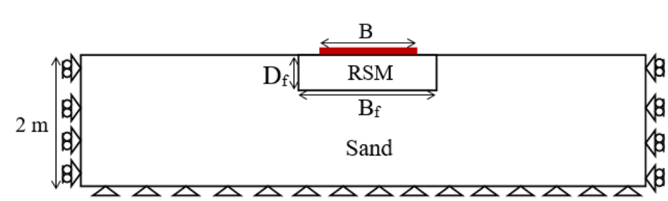

Fig. 1. Parameters used in the study for rubber-sand-mixture (RSM) region.

Table 1
Depth and width ratios of the RSM layer for a footing with B = 2 *m*.

RSM layer characteristics	Value
Depth ratio	0.1, 0.25, 0.3, 0.4, 0.5, 0.75
Width ratio	1, 1.25, 1.5, 1.75

Table 2
Physical and mechanical properties of sand and RSM [57].

Material	ρ [kN/m^3]	υ	φ' [deg]	c' [kPa]
Sand	16.7	0.3	36	0
RSM 20%	14.5	0.3	34	0
RSM 30%	12.0	0.3	32	20
RSM50%	10.0	0.3	30	30

[57]. The curves for 20% and 30% RSM are interpolated using the curves presented by Sentakis et al. [48]. For 50% RSM, the curves presented by Li et al. [53] with similar grain size distribution are chosen. The material damping characteristics are modeled using the Hardin/Drnevich hysteretic damping formulation [69] and the parameters are derived by matching the curves of the formulation with those of experimental results in the references mentioned above. The calibration of the normalized shear modulus versus shear strain amplitude curves for 20%, 30%, 35% (only used in the model with a building explained in Sec. 2.2) and 50% RSM used to model the material damping is presented in Fig. 2.

2.2. *Effect of RSM on the structural weight and base shear forces of a five-story building*

The impact of RSM incorporation on the maximum base shear force and weight of sections of a five-story building is examined in this section. Two building models were used in the study: one with a very dense sand base, and another with 20% and 35% RSM incorporated into the base. The typical five-story building and column plan used in the models is shown in Fig. 3 with dimensions of 10 m in the x-direction, 15 m in the y-direction, and bays of equal width in both directions. Assuming an ordinary braced frame structural system, each story of the building model was designed with a standard height of 3.35 m.

The buildings in this study were loaded, analyzed, and designed in accordance with Iran's national code (No. 2800) [70]. Gravity-based loading of the frames was calculated following Iran's National Building Regulations, Chapter 6 [71]. It is assumed that the building is of residential type, and the weight of all stories is considered to be equal. The dead and live loads of each story are estimated to be 500 and 200 kg/m^2, respectively. The roof load is 580 kg/m^2 for the dead load and

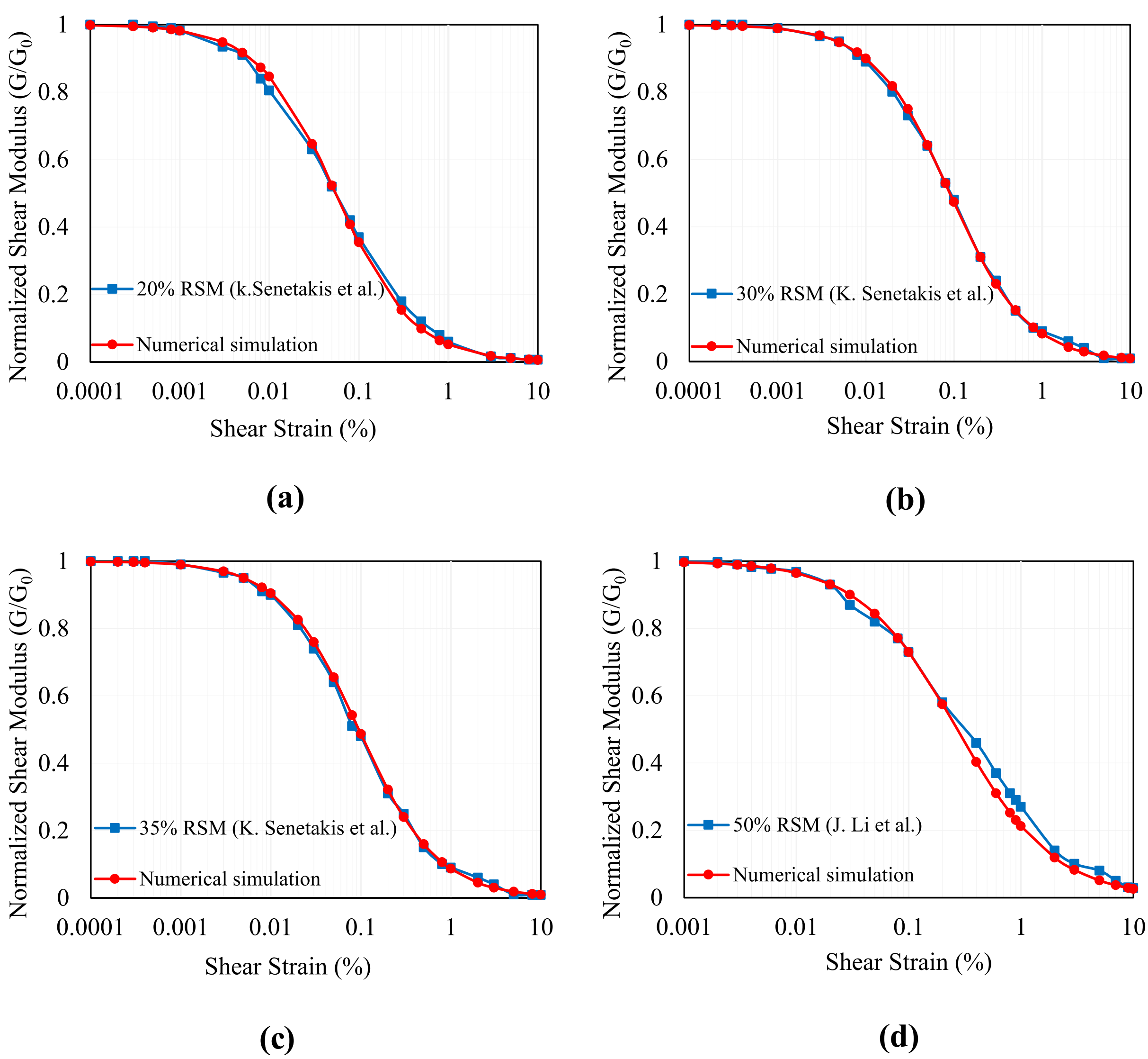

Fig. 2. Calibration of the normalized shear modulus (G/G0) versus shear strain amplitude for: a) 20% RSM, and b) 30% c) 35% and d) 50% RSM.

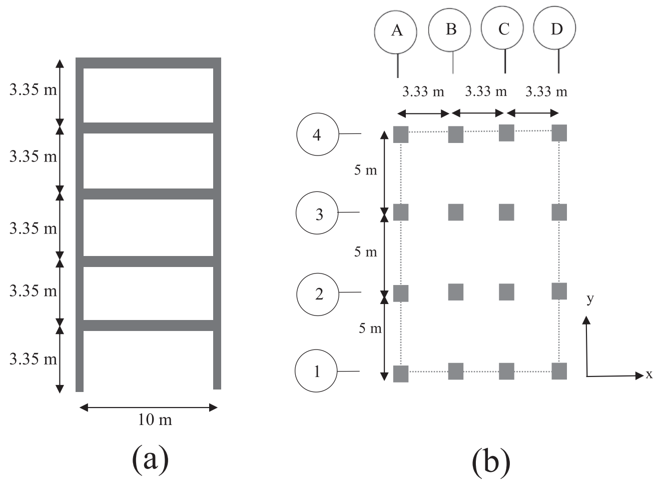

Fig. 3. Schematic view of the (a) frame and (b) column plan of the five-story building.

150 kg/m^2 for the live load. The load combination including the dead load and 20% of the live load is defined and obtained at the base level of the structures.

To perform spectral analysis and design of the five-story building resting on the very dense sand, the design spectrum of the soil Type II, as defined in national code (No. 2800) for seismic design, is chosen. This spectrum takes into account the expected ground motion for the site, which is critical for designing structures that can withstand earthquakes. As for the building resting on RSM, response spectra at the building base level should be derived. For this purpose, a two-dimensional plane-strain finite difference-based software [72] was utilized. The model in the finite difference code has a similar geometry to Fig. 1, with a footing width of B = 10 m. Initially, only sand was modeled, and then the RSM region at depth ratios of $D_f/B = 0.4$, 0.8, and a width ratio of $B_f/B = 1$ was replaced with a part of the bed soil. A surcharge equivalent to the building weight, obtained based on the structural static analysis with a width of B = 10 m was applied. Seismic loading from the model base was then applied to obtain the spectral acceleration on the footing surface.

The model's boundary dimensions were determined based on sensitivity analysis of the responses, resulting in a length of 30 m and 40 m in the horizontal and vertical directions, respectively (three and four times bigger than the building width). The mesh size was set to two-meter squares, following the recommendations of Kuhlemeyer and Lysmer [73], considering the limitation provided for dynamic analysis and assuming a shear wave velocity of 400 m/sec.

Previous research has shown that for a RSM with lower content of rubber, if the rubber content is high [49,52,57,59,74], soil behavior prevails and structural instability and high initial settlement are likely to appear. Accordingly, RSM with weight percentages of 20 and 35% are opted.

Table 3 presents the characteristics of three different earthquakes for dynamic loading application. Two horizontal records of each earthquake were used. Initially, the records were modified and scaled for 10 s, including strong ground motions with a PGA of 0.3 g. Then, the response spectrum of records at the top of the sand layer were matched with the presented spectrum of the soil Type II introduced in the national code (No. 2800) [70].

The numerical model with RSM was subjected to the same seismic loading obtained from the matched records with depth ratios of 0.4 and 0.8 with RSM of 20% and 35%. The spectral acceleration response corresponding for each model was captured pertaining to the footing surface and the mean spectral acceleration responses were obtained from six records for each weight percentage and depth ratio of the RSM region. Then, the five-story buildings were analyzed and the sections were designed based on the mean response spectra.

By controlling the maximum drift of the floors and considering the same amount for both cases (buildings over the bare sand and RSM), the effect of RSM on reducing the section weights and the maximum base shear force has been investigated. Fig. 4 shows the comparison of the building design criterion, i.e., the maximum allowable drift of the floors at different RSM content and depth ratios, for different rubber content as well as various depth ratios. As depicted, the maximum drift of all stories for both cases are the same and there is appropriate match between the design results of the buildings situated over the sand bed and 35% RSM at depth ratios of 0.4 and 0.8. This match can facilitate the comparison of section weights of the two buildings.

3. Results

To ensure the accuracy of the numerical simulations, the verification of the model is presented prior to the results. Subsequently, the impact of RSM dimensions on the seismic response of the footing is analyzed, followed by the effect of RSM on the weight sections of the five-story building.

3.1. Verification and validation

In order to evaluate the accuracy of the computational simulation, a validation was conducted by comparing the results with experimental data [75]. This validation process involved reproducing the geometry of the test box used in the experiments conducted by Bandyopadhyay et al. [57] and assigning material properties as per the reference [57] (see Table 2). To enhance the accuracy of the dynamic analysis problem-solving, a mesh with a dimension of 0.02 m were generated in order to satisfy the recommendations of Kuhlemeyer and Lysmer [73]. Hysteretic damping was employed to model the soil's intrinsic damping before yielding. Irreversible plastic strain arises due to Mohr-Coulomb yielding, causing energy dissipation, so hysteretic damping is then "switched off" for each zone while plastic flow is occurring [69]. Since two vertical sides of the physical model were covered with thick thermocol sheets to minimize wave reflection at the boundaries (see Bandyopadhyay et al. [57]), free-field boundaries were employed along the side boundaries to minimize wave reflections in the dynamic numerical simulation.

Fig. 5 shows a comparison between the foundation accelerations obtained from numerical modeling and laboratory data. A harmonic wave with an acceleration amplitude of 0.3 g and a frequency of 3.5 Hz was applied to the base of the model when the foundation was seated on only sand or 50% RSM. As seen, there is a suitable correlation between the data obtained from the experiments and the numerical model results. Unlike sand, the response of the model footing resting on 50% RSM is remarkably less than the base motion. However, experimental results indicate that as the percentage of shredded tire in sand exceeds 50%, both unit weight and effective friction angle decrease considerably. In such cases, the foundation's settlement (punching failure) and rocking

Table 3
Earthquake records used for dynamic analysis.

Event	Year	Station	Magnitude	fault type	R-jb (km)	Vs30 (m/s)	D5-95 (s)
San Fernando	1971	Castaic- Old Ridge Route	6.61	Reverse	19.33	450	16.8
Fruili- Italy	1976	Forgaria Cornino	5.91	Reverse	14.65	412	4.6
Karebas-Baladeh	2004	Baladeh-Iran	6.3	Reverse	20	380	8.2

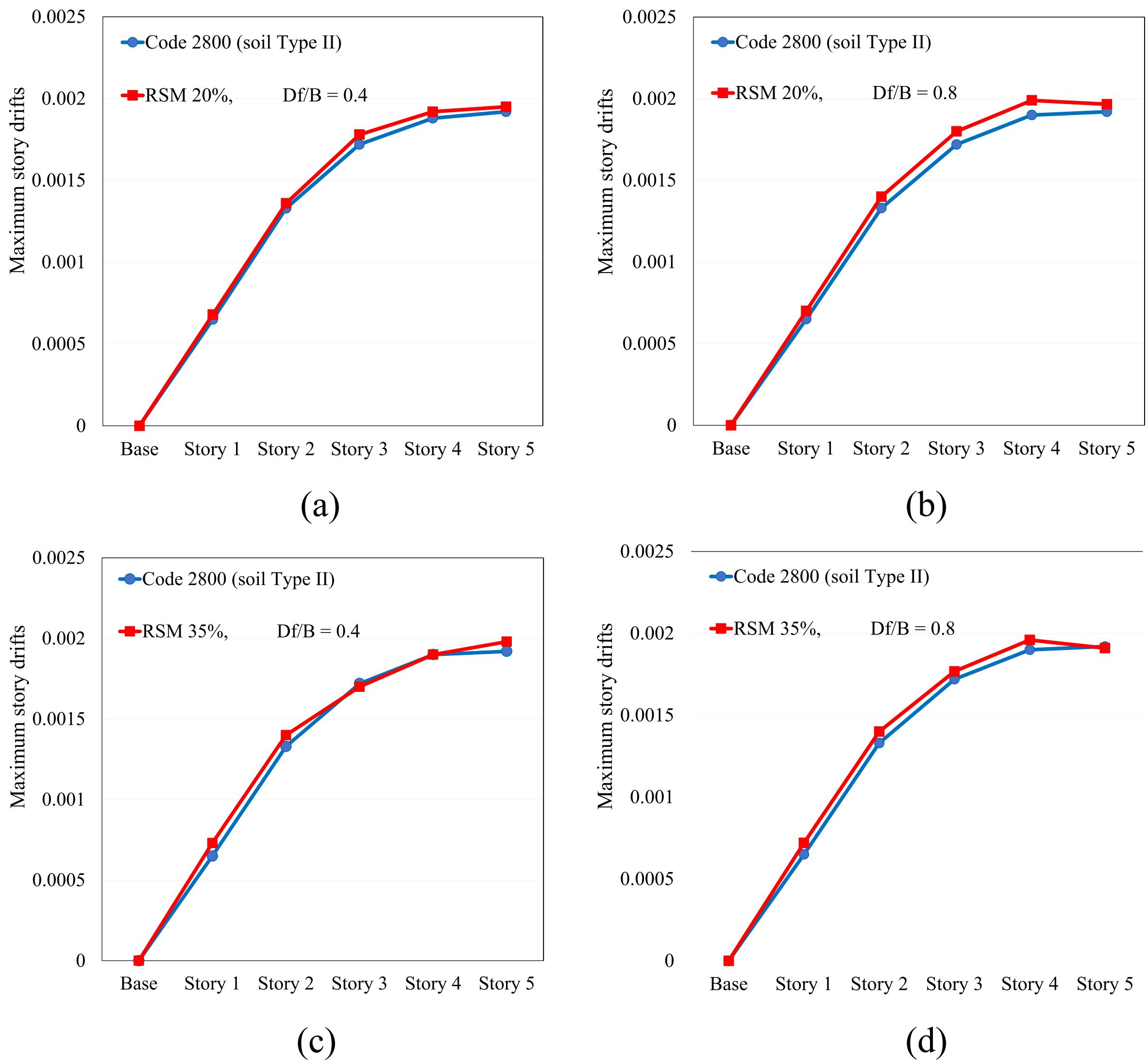

Fig. 4. Maximum allowable drift comparison for five-story buildings with and without RSM layer (a) RSM 20%, Df/B = 0.4 (b) RSM 20%, Df/B = 0.8, (c) RSM 35%, Df/B = 0.4 and (d) RSM 35%, Df/B = 0.8.

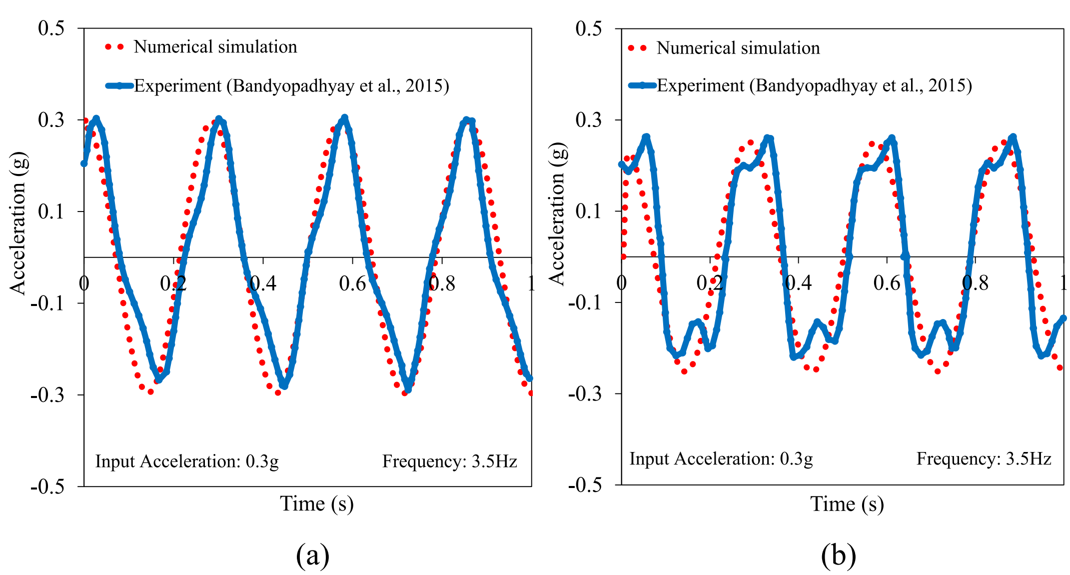

Fig. 5. Footing acceleration response from experimental and numerical simulation in models on (a) sand and (b) RSM 50%.

motion during loading become critical issues [57]. Other studies have also reported high initial settlement and potential for failure with higher RSM content. Kim and Santamarina [58] concluded that as RSM content increases, shear strength decreases, while initial settlement increases due to the high compressive capacity of RSM, and the rubber controls both the static and dynamic response of RSM.

Fig. 6 depicts the horizontal displacements of the foundation when seated on 50% RSM and subjected to a harmonic wave with an acceleration amplitude of 0.3 g and a frequency of 3.5 Hz. The results are compared with those of experiments conducted by Bandyopadhyay et al. [57]. The maximum displacement obtained from the numerical analysis is 1.15 mm while the laboratory test yielded a displacement of 1.58 mm. The discrepancy can be attributed to plastic relative displacements of the particles and the slipping of the foundation model, which were not accounted for in the numerical analysis. It should be noted that the initial displacement was set to zero, whereas in the laboratory results, the initial displacement was around 1 mm.

Fig. 7 shows the footing acceleration response spectra obtained from shake table experiments with an acceleration of 0.4 g and a frequency of 3.5 Hz for models resting on three RSM contents. Fig. 7a corresponds to 20% RSM where the spectra obtained at low periods are slightly different, but are appropriately matched at high periods. Fig. 7b and 7c show the response spectra obtained from laboratory and numerical modeling results corresponding to 30% and 50% RSM, respectively. As seen, the predominant period in the obtained laboratory data is slightly longer than the results of numerical modeling. It should be noted that the large initial peaks in the response spectrum obtained from laboratory results are due to system vibrations at low frequencies and should be ignored [15,57].

3.2. Effects of RSM dimensions on the footing response

In this section, the importance of considering the dimension of the RSM region in seismic protection design is highlighted. Results demonstrate that increasing the depth of the RSM layer and the RSM content significantly reduces acceleration response of the footing, making RSM a highly effective technique for seismic protection, particularly for low-rise buildings. The results of this section would be essential for designers and engineers working on seismic protection of buildings.

Fig. 8 shows the acceleration-time curves of a footing model subjected to a base motion amplitude of 0.5 g, while varying the RSM depth ratio from 0.1 to 0.75 with a constant $B_f/B = 1.5$. The graph illustrates the acceleration response of the footing versus time on the horizontal axis in terms of second and acceleration in g unit on the vertical axis. The models used in this analysis considered the RSM content of 50%. The results show that increasing the depth of the RSM layer leads to a

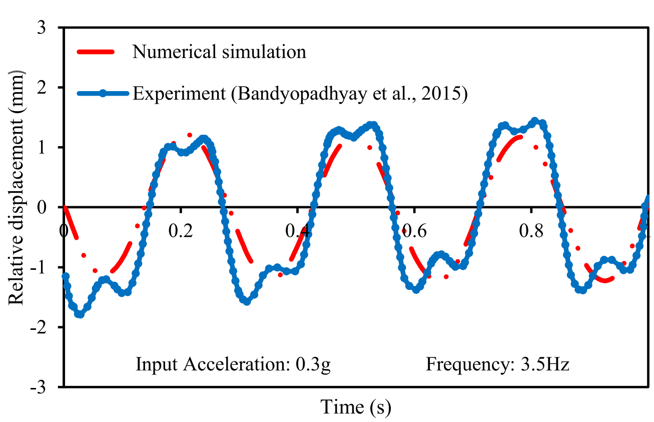

Fig. 6. Footing horizontal displacement from experimental and numerical simulation in the model resting on 50% RSM.

reduction in acceleration response, with a decrease from 0.48 g to 0.35 g observed at D_f/B ranging from 0.1 to 0.75, corresponding to a moderate reduction of approximately 27%. This finding aligns with previous studies, as Bandyopadhyay et al. [57] found that deeper RSM layers reduce the amplification in acceleration response, while Tsang et al. [29] suggested that the increase in thickness of the RSM layer primarily affects the response of the model.

Acceleration response spectra were analyzed for various combinations of RSM percentages and dimensional ratios. The results are shown in Fig. 9, which displays the acceleration response spectra for 20%, 30%, and 50% RSM at different depth ratios ($D_f/B = 0.1$, 0.25, 0.3, 0.4, 0.5, and 0.75). The constant parameters used were a base acceleration of 0.5 g, a frequency of 3.5 Hz, and $B_f/B = 1.5$. The analysis revealed that the acceleration response spectra decrease as the RSM depth ratio increases. However, the rate of reduction in acceleration response significantly decreases as the depth ratio exceeds 0.25. This can be attributed to the increasing stiffness of the GSI system, which results in a smaller reduction in acceleration response for a given increase in depth ratio. The distance of the response spectra from the input motion is greater for higher RSM percentages and lower depth ratios. In other words, the effect of reducing input acceleration associated with the RSM depth ratio gradually diminishes with increasing depth. The response spectra indicate that the acceleration response values obtained for long periods are relatively the same. Therefore, the depth of the RSM layer has a negligible impact on reducing acceleration response for high-rise structures with relatively large natural periods. However, this technique is more effective for low-rise buildings with natural periods less than approximately 0.3 s.

The magnification factor of footing acceleration with respect to input acceleration can be determined from the acceleration values obtained at the top of the footing. This factor is defined as the ratio of peak acceleration on top of the footing to peak input acceleration. Fig. 10 illustrates the changes in the acceleration magnification factor with respect to the RSM layer's depth and width ratio. Comparing the diagrams in Fig. 10a and b, it is evident that the depth of the RSM layer has a more significant impact on reducing input acceleration than the layer's width (B_f). As shown in Fig. 10a, the magnification factor nonlinearly decreases with increasing depth ratio, indicating that thicker RSM layers are more effective in reducing input acceleration. Moreover, the distances between the graphs indicate that the rubber percentage has a significant influence on reducing the magnification factor. Increasing the RSM percentage enhances the layer's damping behavior and leads to a decrease in the maximum acceleration response. This effect has been observed in previous research [56,57,60], which is in line with the results of this study. Shake table tests conducted by Bandyopadhyay et al. [57] demonstrated that the response at the top of the model footing decreases with increasing rubber content. Brunet et al. [56] used a nonlinear model to show that increasing the RSM percentage results in higher layer damping and a lower peak acceleration response.

3.3. Effect of RSM on structural weight and base shear forces of the five-story building

This section examines the use of RSM as a base isolator (GSI system) in designing a five-story building. The results show that incorporating RSM can lead to a significant reduction in both the maximum base shear force and structural weight of the building.

The effectiveness of using RSM as a base isolator in earthquake-resistant buildings has been evaluated by comparing mean response spectra obtained from dynamic analyses using six acceleration records to the design spectrum presented in the national code 2800. The results indicate that increasing D_f/B can gradually reduce the maximum spectral response transmitted to the surface. Fig. 11a and b illustrate the maximum response spectra obtained from the model with 20% RSM content and depth ratios of 0.4 and 0.8, respectively, while Fig. 11c and d display the corresponding response spectra for RSM content of 35%

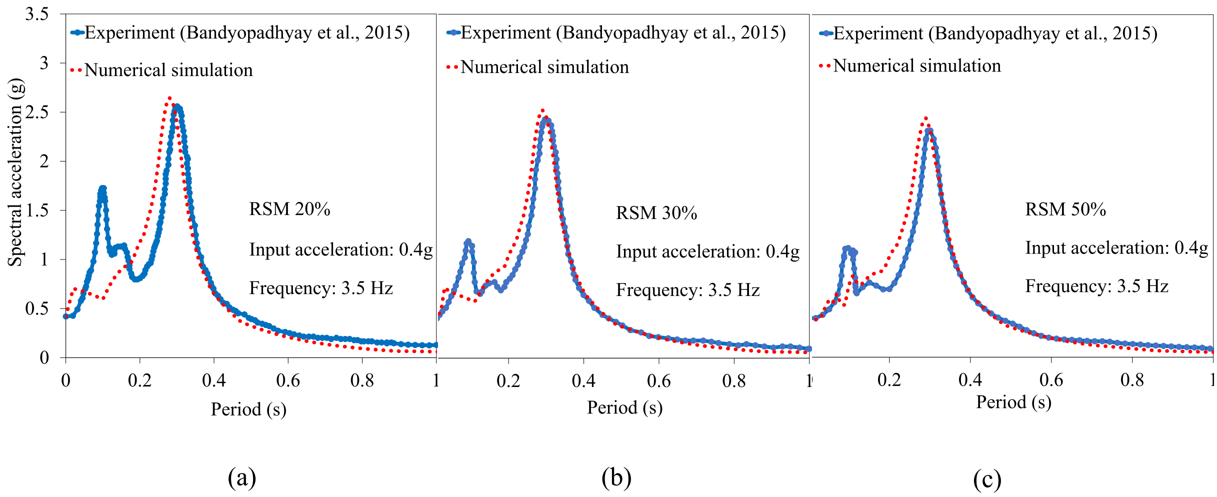

Fig. 7. Footing acceleration response spectra: experimental vs. numerical simulation (a) RSM 20%, (b) RSM 30% and (c) RSM 50%.

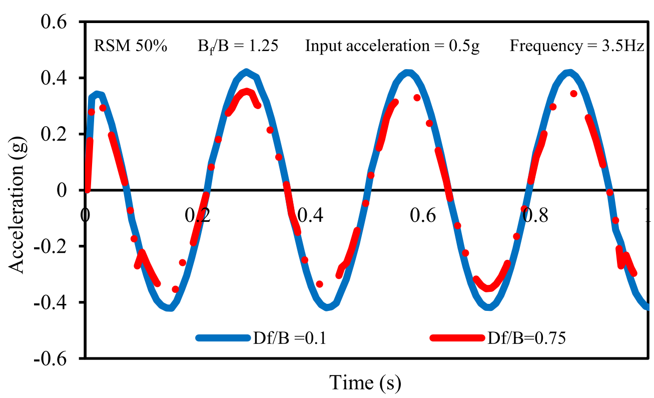

Fig. 8. Comparison of acceleration of footing on RSM 50% when depth ratios vary between 0.1 and 0.75.

and depth ratios of 0.4 and 0.8, respectively. Increasing the RSM content from 20% to 35% resulted in a more effective approach, reducing the response spectra by approximately 20% compared to doubling the D_f/B from 0.4 to 0.8. Additionally, the mean response spectra shifted slightly to the right side when compared to the design spectrum, indicating that the GSI system was well-damped in all cases. These findings demonstrate the potential of using RSM as a base isolator to provide a safe and stable solution for sustainable construction.

Fig. 12 presents the transmissibility ratio as a function of frequency, considering varying RSM percentages and depth ratios. The transmissibility ratio is defined as the ratio of the acceleration response spectrum in the RSM layer to the input acceleration spectrum. Fig. 12a and b showcase the transmissibility ratio for a model with 20% RSM content and depth ratios of 0.4 and 0.8, while Fig. 12c and d depict the transmissibility ratio for 35% RSM content and depth ratios of 0.4 and 0.8, respectively. The results demonstrate that the transmissibility ratio decreases with increasing frequency across all RSM percentages and depth ratios. Furthermore, an increase in RSM percentage and depth ratio leads to a reduction in the transmissibility ratio, implying an enhanced foundation performance through diminished transmitted vibration to the structure. The RSM layer's optimal performance in attenuating input motion is observed at high frequencies (low periods), which is consistent with the results of previous studies [31,61,76–79], with maximum transmissibility occurring at a frequency of 2.85 Hz for RSM 20% and frequency of 2.5 Hz for RSM 35%, indicating the potential for resonance phenomena in structures with this natural frequency. However, the resonance is unlikely at the studied five-story building's frequency of 1.52 Hz.

Incorporating an RSM layer can provide a feasible approach to building design, as demonstrated by a comparison of the structural

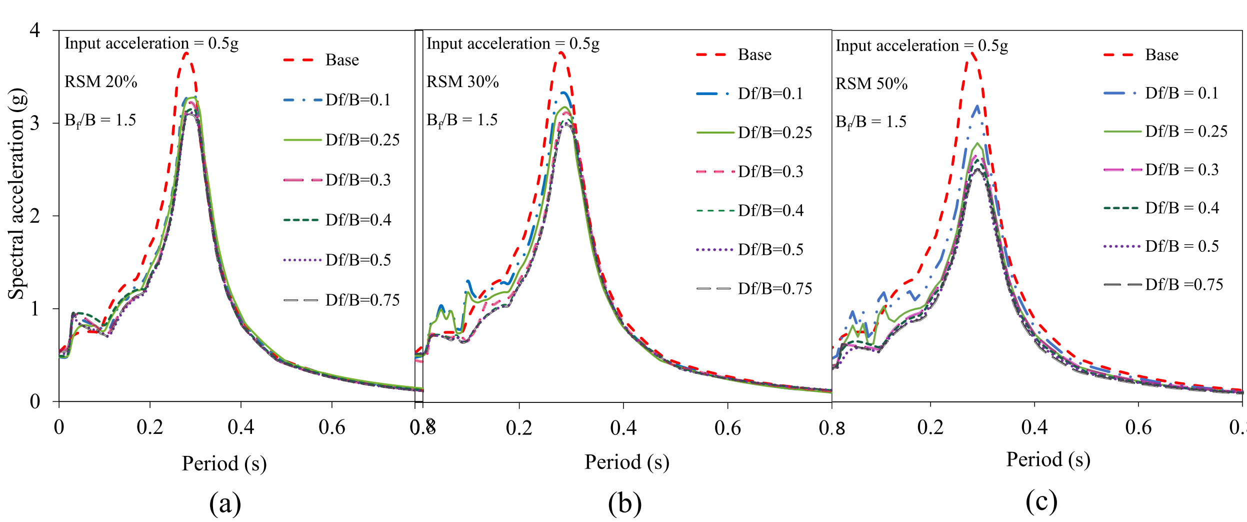

Fig. 9. Base motion and footing response, resting on (a) 20% RSM (b) 30% RSM and (c) 50% RSM at various depth ratios.

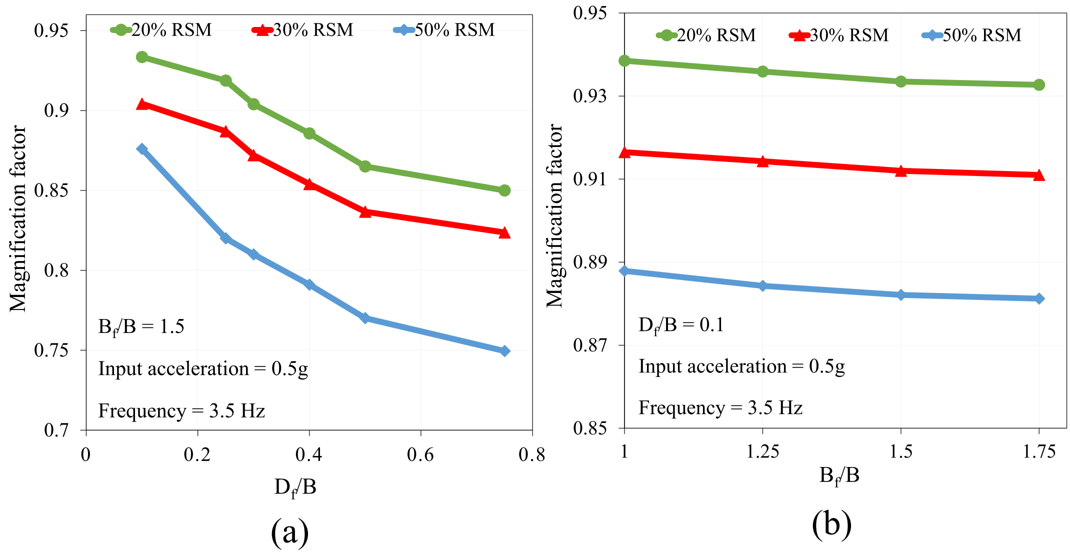

Fig. 10. Magnification factor for different (a) depth ratio, (b) width ratio and RSM content.

weight of key building elements (columns, beams, and braces) in a five-story building designed using the design spectrum (code 2800) and the mean spectrum (illustrated in Fig. 11). Fig. 13 provides an analysis of the structural weight (in kg/m^2) for various ground conditions (soil type II, RSM content of 20% and 35%, with D_f/B of 0.4 and 0.8). The results show that increasing the D_f/B from 0.4 to 0.8 leads to a reduction in structural weight of approximately 5%. However, the use of higher RSM content resulted in greater weight reductions, particularly for braces, which experience lateral loads during earthquakes. Using 20% RSM content resulted in a 15% and 20% reduction in weight sections for D_f/B of 0.4 and 0.8, respectively. Similarly, using 35% RSM content with D_f/B of 0.4 and 0.8 resulted in a significant reduction in weight sections by 25% and 30%, respectively. This suggests that a higher RSM content is more effective than a lower RSM content with a double depth ratio. Braces witnessed the most significant reduction in weight sections as they absorb lateral loads during earthquakes. This is due to the shock-absorbing properties of GSI, which help dissipate energy and reduce the loads on the braces. As a result, smaller cross-sectional areas are needed, enabling a more flexible and lighter superstructure. Therefore, utilizing RSM with an optimal rubber content and depth ratio can lead to a more efficient and sustainable building design.

With the reduction of response spectrum, the base shear force is expected to change as well due to the modified dynamic behavior of the building. Fig. 14 presents the results of evaluating the story base shear forces of a five-story building, measured in kN, to investigate the impact of incorporating RSM with different content percentages and D_f/B ratios on the base shear forces. The findings show that the use of RSM in the bed soil leads to a significant reduction in the base shear forces of all stories, with the maximum reduction occurring in Story 1. The effect of increasing RSM content from 20% to 35% on reducing base shear force is much greater than that of increasing D_f/B. This is due to the higher energy dissipation that occurs in the RSM layer with higher RSM content, resulting in lower seismic forces being transmitted to the superstructure. Specifically, incorporating RSM at a content of 20% results in a 13% and 19% reduction in the maximum base shear force when the depth ratio is 0.4 and 0.8, respectively. Using 35% RSM with depth ratios of 0.4 and 0.8 leads to a significant reduction of the base shear force by 24% and 31%, respectively. These results indicate that the use of RSM as a base isolator can effectively reduce seismic forces acting on building structures and improve their seismic performance, thereby reducing the need for costly and complex seismic-resistant systems.

4. Discussion

This study investigates the influence of RSM region depth and width on the seismic response of buildings. Results from several numerical analyses show that increasing the RSM content and depth ratio has a significant impact on mitigating the peak horizontal acceleration of the foundation. On the other hand, the width of the RSM layer was found to have an insignificant effect on seismic performance, suggesting that the seismic response is primarily influenced by the RSM content and depth of the layer. Furthermore, the study demonstrates that incorporating an RSM layer beneath the building foundation can significantly reduce both the structural weight and the maximum base shear force of the building, paving the way for designing effective and economically viable buildings. This section provides a discussion of the findings of the study and compares the overall results with those of other related studies in the literature.

The study's findings suggest that increasing the depth ratio of the RSM region can lead to a more pronounced reduction in footing acceleration response. This result is consistent with previous research that has shown a noticeable decrease in the peak horizontal acceleration of the footing with an increase in RSM region depth [29,31,60,61,80]. Unlike previous studies that only focused on the depth of the RSM layer, this study examines the impact of the ratio of RSM region depth to footing width, thereby offering valuable insights into the optimal design of buildings equipped with RSM. By investigating the only depth parameters, Tsiavos et al. [62] found that increasing the depth of the RSM layer can affect the acceleration response of the building differently depending on the frequency range, with higher depths resulting in dynamic amplification in the frequency range of 5–6 Hz. This highlights the importance of considering the frequency-dependent behavior of the GSI system when selecting appropriate RSM region depths. Pitilakis et al. [55] conducted a numerical investigation on reinforced concrete buildings of varying heights and found that the depth of the RSM region primarily affects the response parameters of high-rise buildings. They noted that as the RSM region 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. Regarding to the effect of depth ratio on the footing response, Dhanya et al. [61] investigated the effect of RSM depth ratio on the degree of isolation provided by the GSI system. They found that the degree of isolation increased with increasing RSM region depth, indicating that deeper RSM region are more effective at absorbing

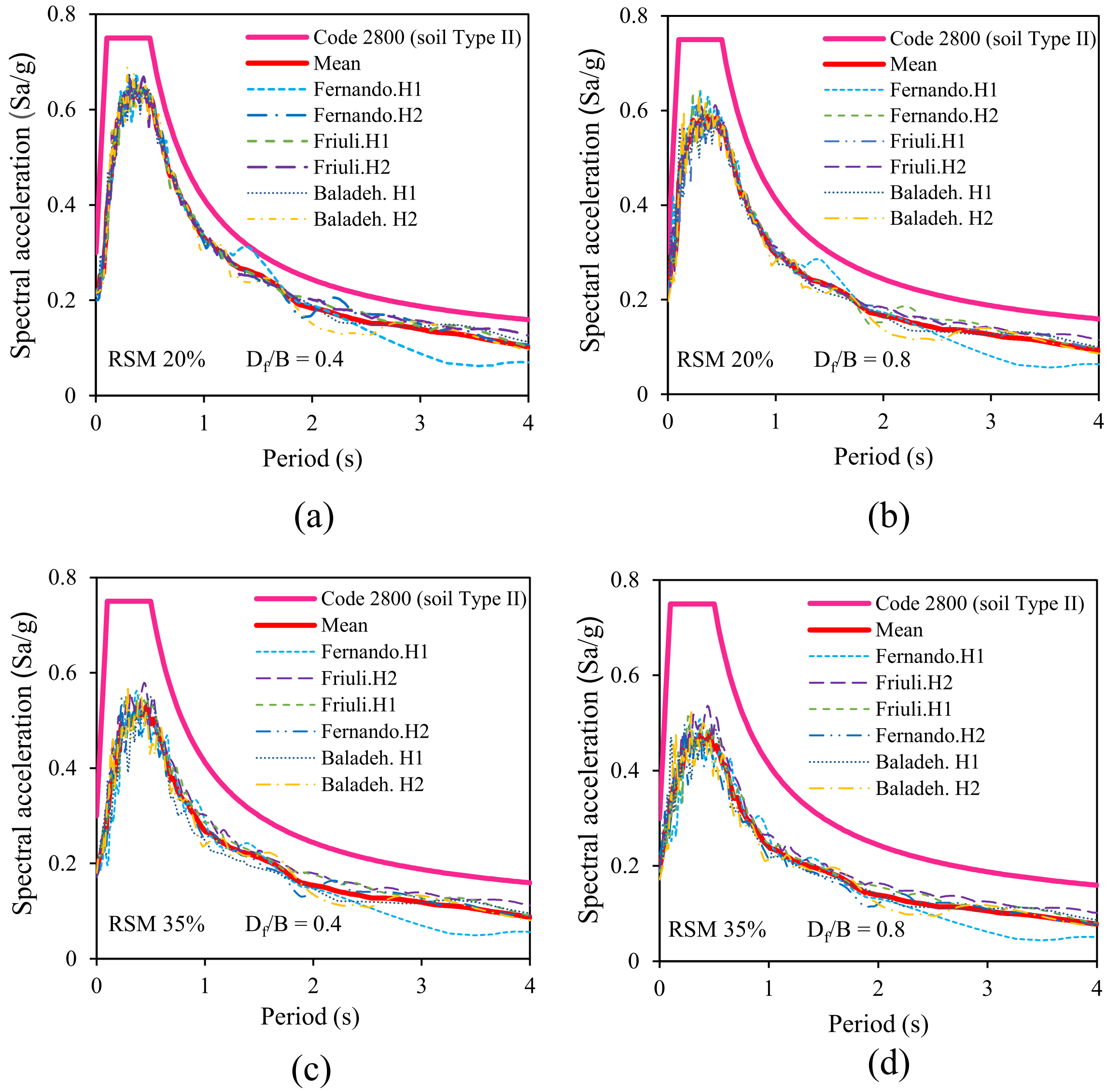

Fig. 11. Mean response spectra vs. design spectrum for varying RSM content and depth ratios (a) RSM 20%, Df/B = 0.4 (b) RSM 20%, Df/B = 0.8 (c) RSM 35%, Df/B = 0.4 (d) RSM 35%, Df/B = 0.8.

energy and reducing seismic forces. Additionally, they found that increasing D_f/B beyond 0.1 resulted in only marginal reductions in peak spectral acceleration values. However, the present study observed a more significant effect of increasing D_f/B beyond 0.1, with the maximum horizontal spectral acceleration response first decreasing and then converging at D_f/B greater than 0.25, particularly for higher percentages of rubber. This may be explained by the additional stiffness introduced to the system by the geogrid, as noted by Dhanya et al. [61], which can affect the energy dissipation process [81]. These findings highlight the importance of considering the depth of the RSM region, the frequency-dependent behavior of the GSI system, and the interaction between RSM and geogrid in designing effective GSI systems for different building heights and seismic hazard levels.

The findings of the present study also show that the width of the RSM region has a negligible effect on the acceleration response of the footing, which has not been previously reported in the literature. Previous studies have generally considered the RSM width as a constant parameter [55,57,60–62,82], but the present results indicate that this parameter may be varied without compromising the efficacy of the GSI system. Tsang [31] investigated the impact of building width on the seismic response of structures supported by RSM and found that wider buildings experience less acceleration. Similarly, Banovic et al. [83] studied the impact of foundation size on the efficiency of GSI systems containing a layer of stone pebble, and their results indicated that wider foundations can lead to higher earthquake forces and lower bearing capacity [84]. Further research is needed to determine the effect of RSM region width on the seismic performance of buildings, taking into account factors such as variation in frequencies and number of stories. Nevertheless, the present results provide useful guidance for practical design, suggesting that RSM region width can be considered a constant parameter without compromising the effectiveness of the GSI system.

The results of this study are consistent with previous research indicating that the use of RSM can significantly reduce the maximum base shear force of buildings by up to 30% [55,59,61]. For instance, Dhanya et al. [61] studied the impact of RSM region on inter-story drift and base shear force in a low-rise (two-story) building and concluded that the RSM region substantially reduced the base shear force, and the addition of a geogrid reinforcement layer resulted in further reduction. Pistolas et al. [59] also investigated the effect of RSM on base shear force reduction and found that increasing the RSM content resulted in a greater reduction for all input motions. Pitilakis et al. [55] used numerical modeling to investigate the impact of RSM on the seismic

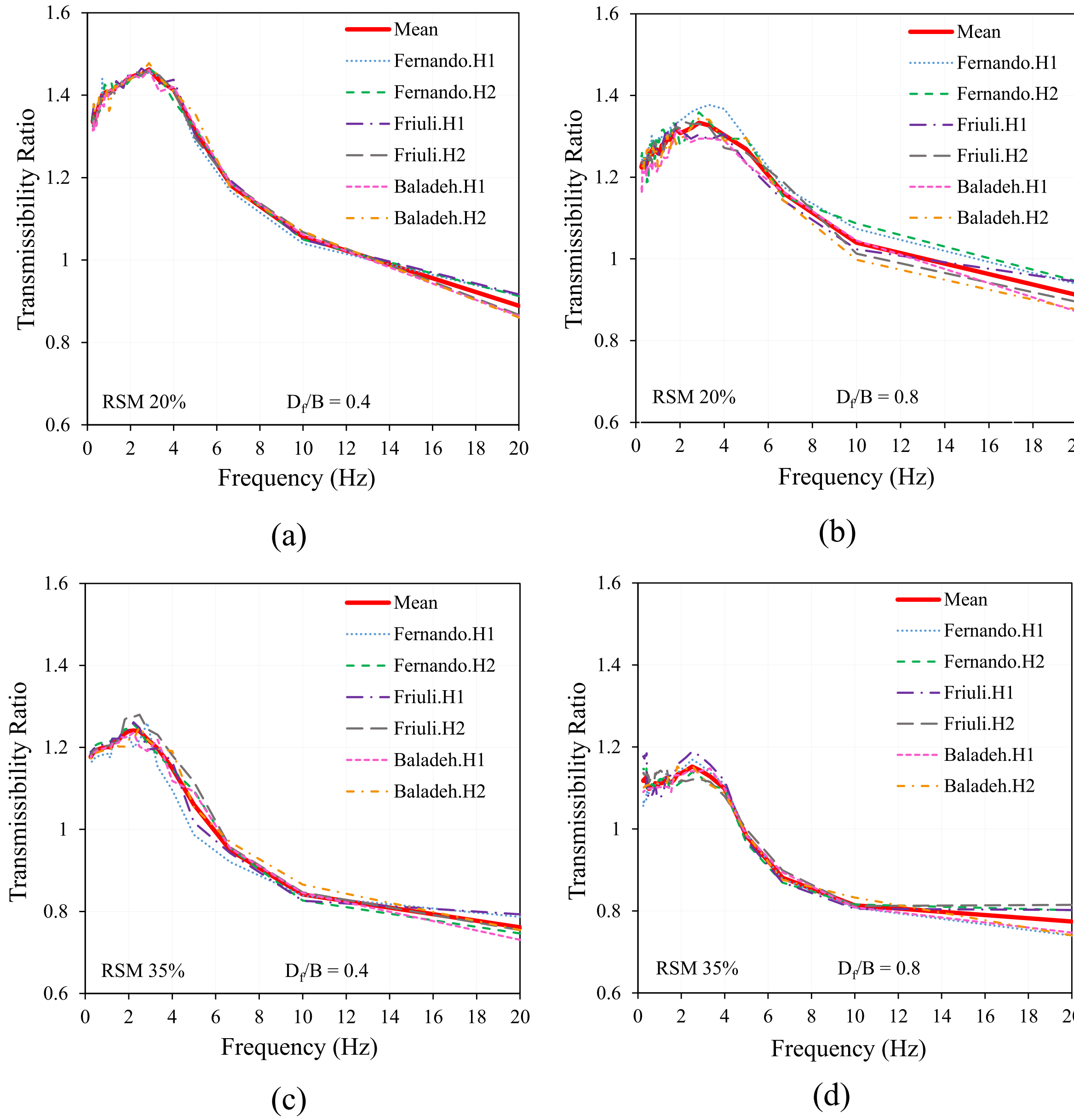

Fig. 12. Transmissibility ratio at different frequencies for varying RSM content and depth ratios (a) RSM 20%, Df/B = 0.4 (b) RSM 20%, Df/B = 0.8 (c) RSM 35%, Df/B = 0.4 (d) RSM 35%, Df/B = 0.8.

performance of reinforced concrete buildings and reported that RSM had a particularly noticeable effect on reducing the base shear force of mid-rise and high-rise buildings. However, for low-rise buildings, the maximum base shear force only decreased for the Ricker pulse with a period of 0.3 s, and for other cases, it remained constant or even increased due to the use of RSM. While the present study investigated buildings with equal maximum inter-story drift and compared the base shear forces and weight of sections with and without RSM, the findings are consistent with previous research, providing further evidence that incorporating RSM can be an effective means of reducing base shear force in building design.

The findings of this study support previous research indicating that incorporating an RSM layer is more effective in low-rise and mid-rise buildings, as opposed to high-rise or flexible structures. The dynamic analysis 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 has no significant effect on reducing the structural response to dynamic loading. Dhanya et al. [61] 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. 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 a further reduction in acceleration amplitude in low-rise buildings. Tsang et al. [31] 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. These findings are consistent with the previous studies and highlight the importance of considering the fundamental period and periodicity of a building when determining the effectiveness of RSM in reducing structural response to dynamic loading.

5. Conclusions

Geotechnical seismic isolation (GSI) system is a promising new technique for protecting structures from earthquake ground shaking by

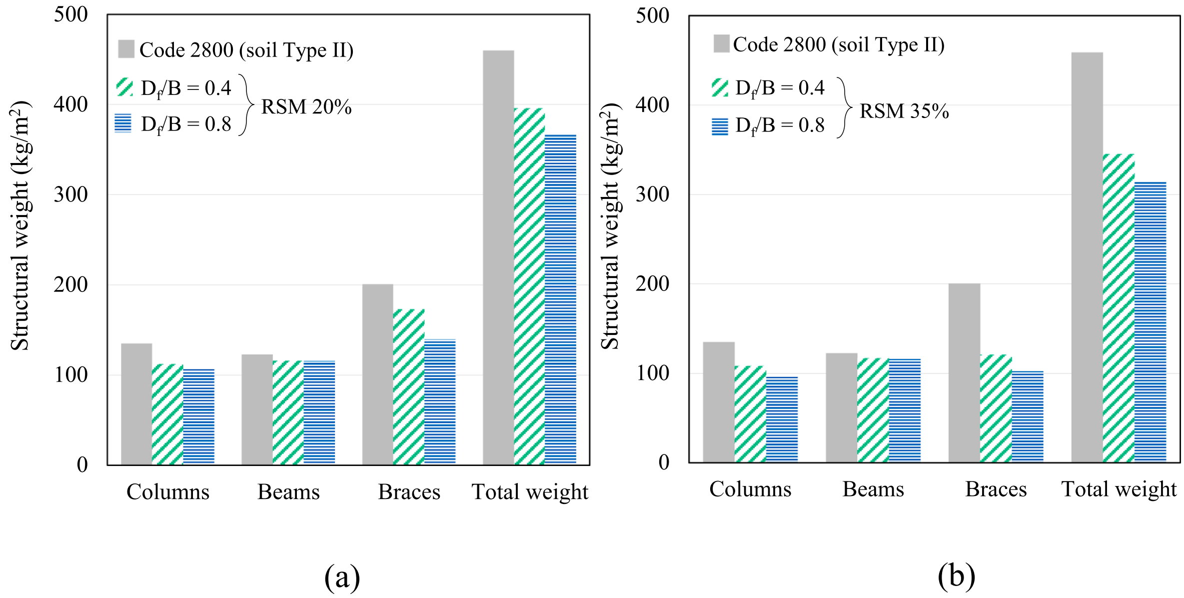

Fig. 13. Impact of RSM content and depth ratio on structural weight of the five-story building for (a) RSM 20% and (b) RSM 35%.

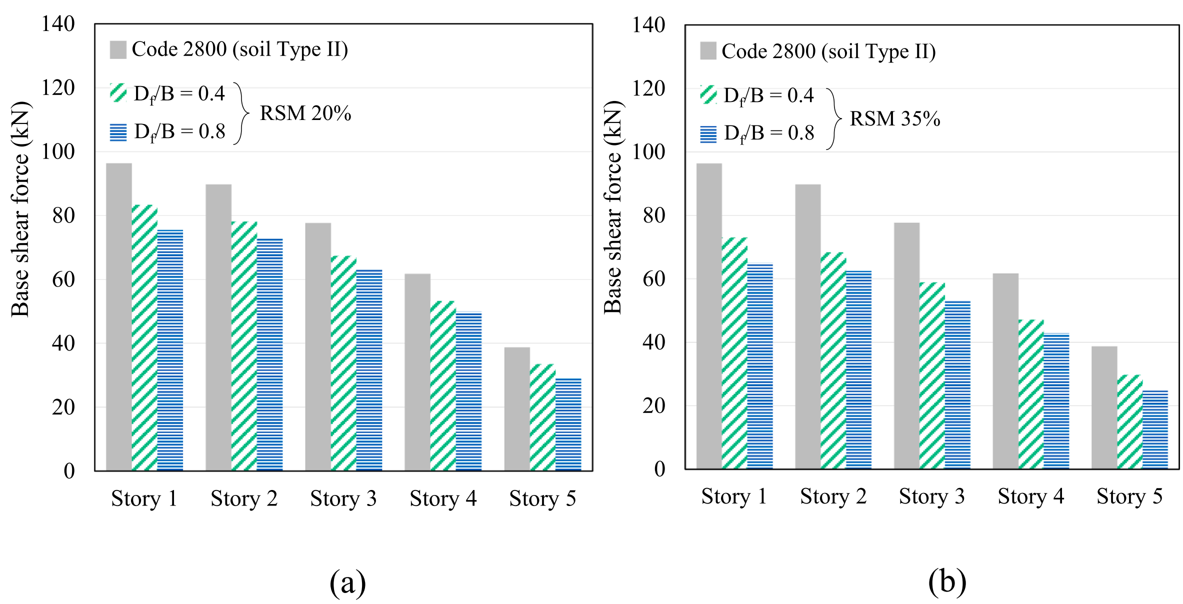

Fig. 14. Impact of RSM content and depth ratio on story base shear forces in a five-story building for (a) RSM 20% and (b) RSM 35%.

replacing a part of the bed soil with rubber-sand mixture (RSM). To evaluate the technical viability of this technique, this study investigated the effects of RSM dimensions on the rate of footing acceleration response reduction and the effect of RSM layer on the structural weight and base shear forces of a prototype five-story building using numerical simulation with a finite difference code. The accuracy of the numerical modeling was verified by comparing the output data to that of shake table experiments from a previous study. By replacing a part of the bed soil with RSM and comparing the footing acceleration response spectra to those of sand, the impact of RSM depth and width ratios were assessed. Finally, two similar building models were designed using a national earthquake design code [45], with the one seated over a dense sand base and the other over 20% and 35% RSM, using the spectral dynamic method. The findings of this study highlight the potential benefits of using RSM as a cost-effective and efficient solution for improving the seismic performance of buildings. The following conclusion can be drawn:

- Increasing the depth of the RSM layer and RSM content reduces the acceleration response of the footing, making RSM a highly effective technique for seismic protection, particularly for low-rise buildings.
- The acceleration response spectra decrease as the RSM depth ratio increases, however, the rate of reduction significantly decreases as the depth ratio exceeds 0.25. This technique is more effective for low-rise buildings with natural periods less than approximately 0.3 s.
- Thicker RSM layers are more effective in reducing input acceleration than the layer's width (B_f), and increasing the RSM percentage enhances the layer's damping behavior and leads to a decrease in the maximum acceleration response.
- Incorporating RSM in designing a five-story building can lead to a significant reduction in both the maximum base shear force and structural weight of the building.
- Increasing D_f/B can gradually reduce the maximum spectral response transmitted to the surface. Increasing the RSM content from 20% to 35% is more effective than doubling the D_f/B from 0.4 to 0.8.

The study presents an innovative and eco-friendly approach to sustainable construction that ameliorates safety and stability. However, the study's findings are limited to a single five-story building with a specific natural frequency (1.52 Hz), and other important factors such as soil type, location, seismic activity, and fundamental period of the bare structure were not considered. To ensure that the proposed approach can be generalized and applied to real buildings with different properties, such as fundamental period and seismic hazard, it is necessary to analyze different buildings with various frequencies under different earthquake loadings. Additionally, the site's response to earthquake records is reliant on several factors, including the frequency range of the earthquake and the natural oscillating frequency of the site, which may result in resonance phenomenon for different buildings. Therefore, further research is required to investigate the frequency-dependent behavior of RSM and its performance under different conditions and frequencies of earthquakes.

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.

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