Numerical simulation of the performance of the rubber-sand-mixture layer in reducing the acceleration of the foundation

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Abstract
This paper investigates the effect of rubber-sand-mixture (i.e., rubber–sand mixtures, abbreviated hereafter as RSM) layer on reducing the acceleration response of the foundation. Numerical modeling was performed by using finite difference in two-dimensional-plane strain method. The object of this study is to investigate the sensitivity of the foundation acceleration response to the percentage and dimensions of the RSM layer, which is placed under the foundation in different percentages and dimensions. The ground structure was considered as surcharge in the model and the wave was applied harmonically from the base of the model. As the percentage of rubber increases, the acceleration of the foundation response and the magnification factor decrease in the results. Increasing the depth ratio (ratio of depth of the RSM layer to the loading width) of the RSM layer decreases the amount of foundation acceleration response and magnification factor, this effect is more at first and gradually decreases with the addition of the depth of the RSM layer. Increasing the width of the RSM layer in the width ratio (ratio of the width of the RSM layer to the loading width) greater than 1.5 has little effect on the results.

Keywords: Sand, Rubber, Mixture, Magnification Factor, Acceleration

1. INTRODUCTION

Finding a solution to reduce the structural response caused by earthquakes is an important issue in structural engineering and geotechnics. Seismic isolation technique is extensively used as a major and effective strategy in designing earthquake resistant structures. This method leads to reducing seismic damage of numerous structures located in developed countries [1-3]. Despite the good performance of the standard isolation systems [4] applied between the building and its foundation, their high cost of installation and maintenance has limited their use in low-income (i.e., developing) countries. Thus, it would be very helpful if this systems could be replaced with an alternative low-cost system that makes use of materials that are locally available and cost-effective in these regions. The use of granulated rubber-sand-mixtures (i.e., rubber–sand mixtures, abbreviated hereafter as RSM) as a surface foundation layer for buildings is one of the recent proposals, which is expected to work similarly to seismic isolation systems. Using tire waste in seismic isolation of the buildings helps to improve the environmental problems of their disposal. In addition, this approach is cost-effective and applicable for ordinary buildings. Many studies have been performed to achieve the static and dynamic properties of rubber-sand-mixture (RSM). Nakhaei et al. [5] experimentally showed that, for all confining pressures, with an increase in rubber percentage, shear modulus decreases while for any percentage of rubber inclusion, shear modulus increased as the confining pressure increased. Senetakis et al. [6] proposed generic normalized shear modulus and damping ratio versus shearing strain amplitude curves for dry mixtures of rubber-sand (RSM) appropriate for the engineering practice. Li et al. [7] with performing a series of cyclic triaxial tests with varying rubber volume contents, rubber particle sizes, and confining pressures, proposed a new empirical model to predict the maximum shear moduli of the mixtures. The use of RSM around the foundation of the structure and its performance in seismic isolation of the building was an approach proposed by Tsang [8]. Tsang showed that using RSM can reduce the horizontal acceleration of the foundation by about 50-70%. Another numerical study by FEM method showed a decrease in the model response acceleration due to the use of RSM below and around the foundation [9]. Nanda et al. [10] performed a numerical study parametrically by FEM method and showed that the effectiveness of the system is higher for low height building and for higher depth of RSM [10]. Tsang et al. [11] performed an analytical modeling to investigate the mechanism of the RSM layer in seismic isolation system. This study showed that this mechanism is based on reducing the lateral stiffness of the RSM layer and the lower modulus of RSM, which reduces the stiffness of the mass. Pistolas et al. [12] investigated the effect of RSM layer on seismic isolation of buildings using finite element numerical modeling for two far-field and near-field earthquakes. Several laboratory studies were performed to evaluate the efficacy of using RSM in reducing the foundation acceleration response. Determining the optimal RSM grain size ratio was another result presented by Tsiavos et al. [13] in a laboratory study. Another laboratory study was performed to investigate the effectiveness of using RSM in reducing the acceleration transmitted to the foundation, by using a shake table. In this study, was performed by Bandyopadhyay et al. [14] a test box measuring 1 m × 1 m × 0.5 m (length × width × height) to 20 cm high was filled with 65% density of sand and the Plexiglas block was placed on the soil surface as a foundation model. The set was subjected to harmonic movements. In the next step, the RSM was replaced with sand up to a height of 2 cm below the Plexiglas block and was subjected to harmonic movements again. The effect of reducing the acceleration response of the foundation due to the use of RSM was observed in the results [14]. Despite numerous numerical and laboratory modelings on the performance of RSM in seismic isolation, in order to use this low-cost design, it is necessary to investigate the sensitivity of its response to the rubber percentage and dimensions of RSM region.

This paper uses the finite difference method and FLAC^{2D} [15] (Fast Lagrangian Analysis of Continua in 2D) software to investigate the sensitivity of the results and the seismic response influenced by the percentage of the rubber-sand-mixture (RSM) content and its dimension (depth and width) beneath the footing area.

Figure 1 shows the parameters of the RSM region used in the study. In order to find the effectiveness of the RSM zone, two parameters are introduced: 1) the depth ratio which is defined as the ratio of RSM region depth (D_f) to the loading width (B); and 2) width ratio which is the ratio of the RSM region width (B_f) to the loading width (B). For numerical investigation, one particular case with B = 2m is considered where the loading area is situated over a sandy layer. The total depth of the sandy layer is assumed to be 2 m.

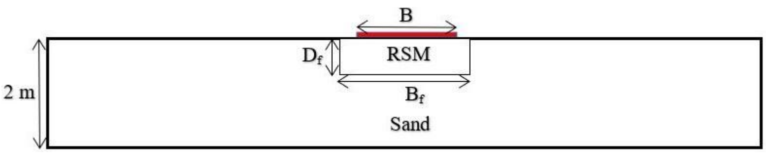

Figure 1. Parameters used in the study for RSM (rubber-sand-mixture) region dimensions

2. NUMERICAL MODELING

Numerical modeling was performed by using finite difference in two-dimensional-plane strain method using FLAC^{2D} [15] software. The soil was modeled in dry conditions with square mesh and the ground structure was considered as surcharge in the model. A pressure of 40 kPa was applied as the weight of the building in the loading width (B). The RSM layer was modeled below the loading surface with different dimensions and percentages. Figure 2 shows the meshing of the soil mass and the location of the RSM region in one of the modelings performed in this study.

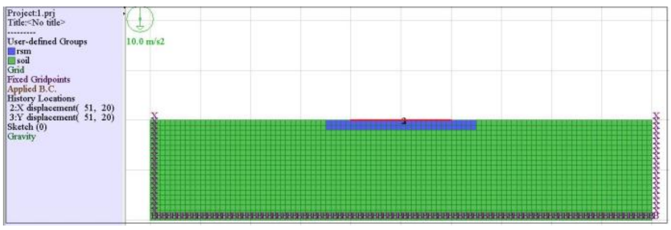

Figure 2. the meshing of the soil mass and the location of the RSM (rubber-sand-mixture)

The physical and mechanical properties assumed in the modeling for sand, 20%, 30% and 50% RSM based on [14] are given in Table 1. The Poisson ratio has little effect on RSM performance and energy dissipation characteristics [8], so a constant Poisson ratio of 0.3 was considered in this study.

Table 1- Physical and mechanical properties of sand and RSM (rubber-sand-mixture)

Material	ρ [kN/m^3]	υ	φ' [deg]	c' [kPa]
Sand	16.7	0.3	36	0
20% RSM	14.5	0.3	34	0
30% RSM	12.0	0.3	32	20
50% RSM	10.0	0.3	30	30

To model the materials and assign their damping, with considering the particle size distribution of 1–2 mm and mean confining pressure of 100 kPa (which corresponds to the confining pressure in the middle of the RSM layer), the normalized shear modulus and damping ratio versus shear strain amplitude curves were choosen. These curves for 20% and 30% RSM were obtained using the curves provided by Sentakis et al. [6] and by interpolation method. To model the 50% RSM, the curves presented by Li et al. [7] with similar grain size and confining pressure were used. The Hardin/Drnevich hysteretic damping formulation was used to consider the damping of the materials. Calibration was performed to ensure the suitability of the damping coefficient selected for the material. Calibration of the tangent-modulus function involves both a comparison of the function results to the target shear-modulus reduction curve, and a comparison to the target damping-ratio curve [16]. For sand, and mixtures of 20%, 30% and 50% RSM, this matching was performed and accordingly, damping coefficients were considered in the numerical modeling. Figures 3 and 4 show the the normalized shear modulus and damping ratio versus shear strain amplitude curves for the confining pressure of 100 kPa, used to model the dynamic damping of materials.

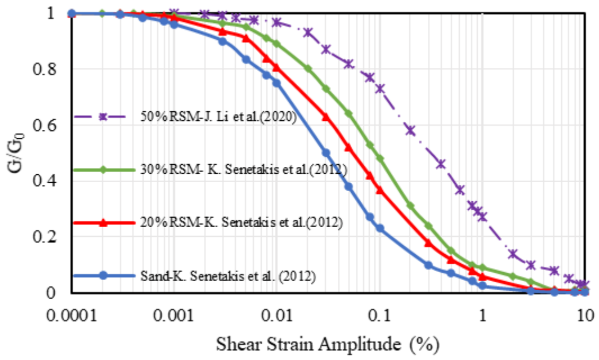

Figure 3. Normalized shear modulus, G/G₀, versus shear strain amplitude for the confining pressure of 100 kPa and the variation of rubber percentages.

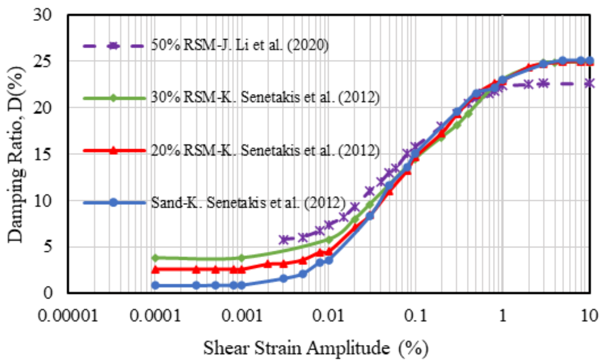

Figure 4. Damping ratio versus shear strain amplitude for the confining pressure of 100 kPa and the variation of rubber percentages.

To investigate the effect of the percentage of rubber in RSM on reducing the acceleration of the foundation, first modeling was performed for sand only with the frequancy of 3.5 Hz and acceleration values of 0.15 g, 0.2 g, 0.3 g, 0.5g and 0.8 g. The input wave was applied harmonically from the base of the model. Subsequent modeling was performed for the RSM with percentages of 20, 30 and 50 at a depth ratio of 0.1 and a width ratio of 1.25 with these accelerations. Peak accelerations were obtained at the point marked on the foundation in these cases.

The effect of RSM region dimensions was investigated in subsequent modeling. For accelerate 0.5 g, the RSM region was modeled with different percentages and different depth ratios and width ratios below the model of foundation. According to the acceleration values obtained on top of footing, the magnification factor values were obtained. By transferring the acceleration data related to the middle and on the foundation to the SeismoSignal [17] software, the acceleration response spectra were obtained and compared for different percentages of RSM and its different dimensional ratios. Tables 2 and 3 show the dimensional ratios of the RSM layer used in numerical modeling. Table 2 shows the depth values and depth ratios used to model the RSM layer. Also, the values of different widths and width ratios of the RSM layer are given in Table 3. The loading width (B) was considered to be equal to 2 meters.

Table 2- Depth values and depth ratios of the RSM layer

Loading width B (m)	Depth of RSM layer D_f (m)	D_f/B
2	0.2	0.1
	0.5	0.25
	0.6	0.3
	0.8	0.4
	1	0.5
	1.5	0.75

Table 3- Width values and width ratios of the RSM layer

Loading width B (m)	Width of the RSM layer B_f (m)	B_f/B
2	2	1
	2.5	1.25
	3	1.5
	3.5	1.75

3. Results and Discussion

The effect of the rubber-sand-mixture (RSM) on reducing peak acceleration at the top of the layer is shown in Table 3 and Figure 5. Figure 5 shows a comparison of the acceleration on top of footing resting on sand and 50% RSM for a base motion of amplitude 0.5 g, the D_f/B of 0.1 and for the B_f/B of 1.25. While at acceleration of 0.5 g sand transmits the same input acceleration to the top of the layer, 50% RSM can significantly reduce the input acceleration.

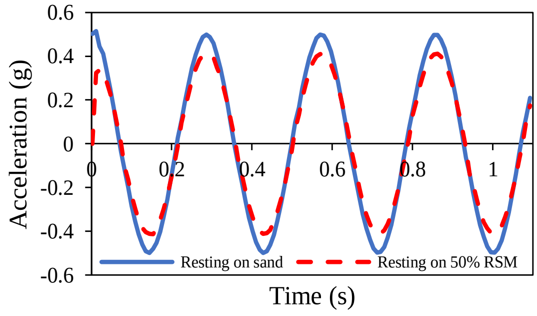

Figure 5. Response of the footing resting on sand and 50% RSM for a base motion of amplitude 0.5 g, D_f/B = 0.1, B_f/B = 1.25 and frequency 3.5 Hz

Table 4 shows the results obtained from the dynamic analysis for the sand model and the model with the RSM layer at 20, 30 and 50 percent and for the constant D_f/B value of 0.1 and the B_f/B of 1.25. For the input frequency of 3.5 Hz, the results showed that the sand at low accelerations transmits exactly the same input motion to the soil surface, and only at higher amplitudes of the base motion can reduce the input acceleration. According to the peak accelerations obtained from the middle and top of footing, it is observed that the effect of RSM in reducing the magnification factor increases at higher accelerations.

Table 4- Peak acceleration and Magnification factor at the top of the footing at a constant frequency of 3.5 Hz, D_f/B = 0.1, B_f/B = 1.25 and different amplitude of base motion

Material below the loading surface	Input acceleration (g)	Frequency (Hz)	Peak acceleration on top of footing (g)	Magnification Factor (peak acceleration)
Sand	0.15	3.5	0.15	1.0
	0.2		0.2	1.0
	0.3		0.3	1.0
	0.5		0.5	1.0
	0.8		0.77	0.96
20% RSM	0.15	3.5	0.15	1.0
	0.2		0.19	0.96
	0.3		0.28	0.95
	0.5		0.46	0.93
	0.8		0.74	0.92
30% RSM	0.15	3.5	0.15	1.0
	0.2		0.18	0.92
	0.3		0.27	0.91
	0.5		0.45	0.90
	0.8		0.72	0.9
50% RSM	0.15	3.5	0.15	1.0
	0.2		0.17	0.89
	0.3		0.26	0.88
	0.5		0.43	0.87
	0.8		0.67	0.83

A comparison of the acceleration response spectrum of the foundation, for different percentages of RSM is given in Figure 6. As the percentage of rubber in the mixture increases, the damping behavior of the layer increases and the maximum acceleration response decreases.

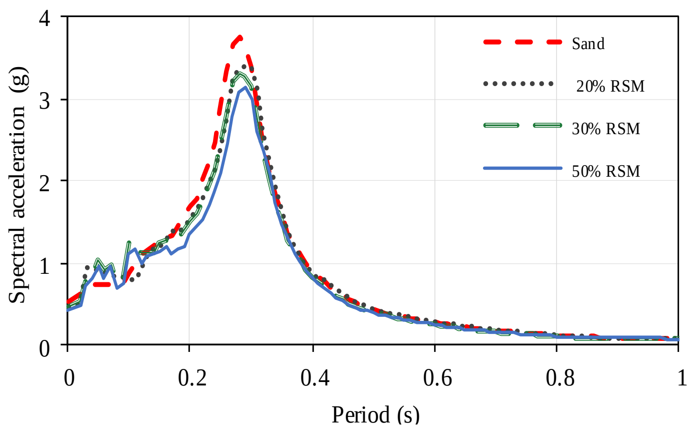

Figure 6. Responses of the footing resting on sand and on 20%, 30% and 50% RSM for a base motion of amplitude 0.5 g, D_f/B = 0.1, B_f/B = 1.25 and frequency 3.5 Hz

The diagram of the acceleration magnification factor changes related to the middle and top point of the foundation versus the depth ratio of the mixture for different percentages of RSM is shown in Figure 7. By comparing the beginning and end of the diagram, it is clear that the depth of the RSM layer has a significant effect on reducing the input acceleration. According to the trend of changes in the slope of the curve at different depth ratios, it is observed that the slope of the curve is initially high and gradually decreases, in other words, the effect of RSM layer depth gradually decreases with increasing layer depth.

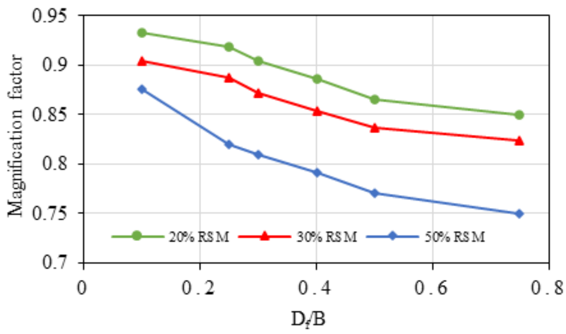

Figure 7. Magnification factor versus RSM depth ratio for a base motion of amplitude 0.5 g, $B_f/B = 1.5$ and frequency of 3.5 Hz

Figure 8 shows a graph of changes in the acceleration magnification factor at the midpoint and at the top of the layer, versus the width ratio of the RSM layer, for different percentages of RSM. Comparing the diagram with Figure 7 shows that the width of the RSM layer has less effect than its depth because the beginning and end of this diagram have less difference than the diagram in Figure 7. Considering the slope at the beginning of this graph, it seems that the effect of RSM layer width in reducing the input acceleration is greater for higher percentages of RSM. Also, the distances between these graphs show that the effect of rubber percentage on the reduction of magnification factor is significant.

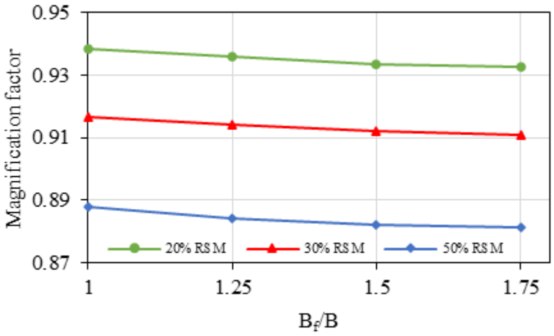

Figure 8. Magnification factor versus RSM width ratio for a base motion of amplitude 0.5 g, $D_f/B = 0.1$ and frequency of 3.5 Hz

Figures 9 shows the acceleration response spectra for 20%, 30% and 50% RSM, respectively, at different depth ratios of the RSM layer. These graphs show that the acceleration response spectrum decreases with increasing RSM layer depth ratio. In all three diagrams, the distances of the response spectra are large at first and then decrease. This distance is greater for higher percentages of RSM. In other words, the results show that the effect of decreasing the input acceleration related to the depth ratio of the RSM layer, gradually decreases with increasing its depth.

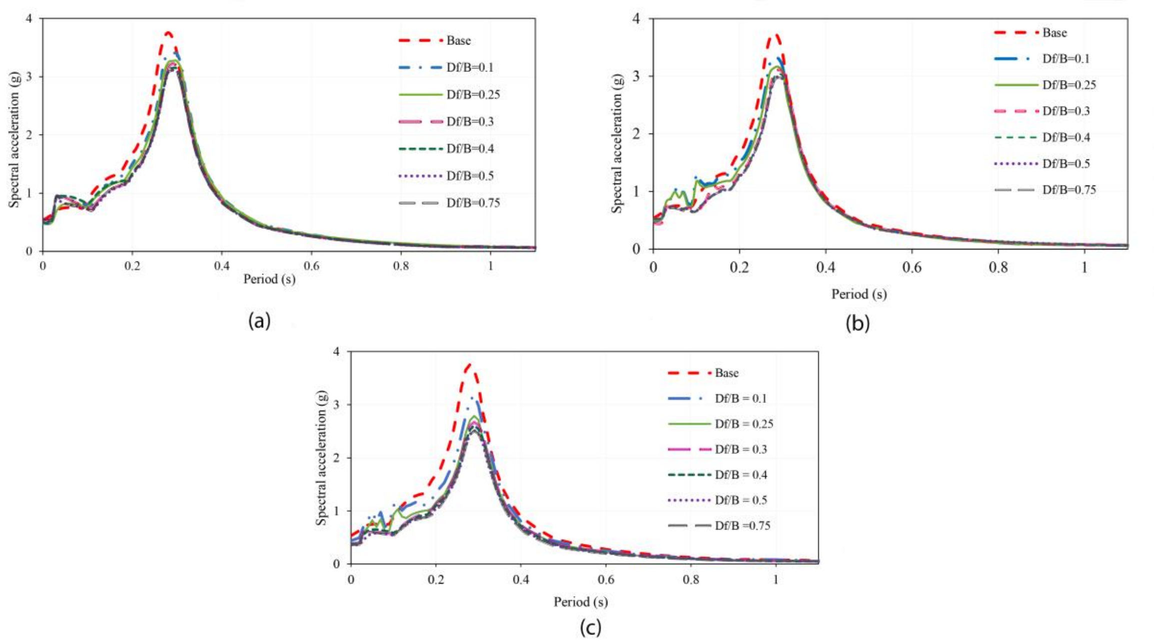

Figure 9. Responses of the base motion and footing resting on a) 20% b) 30% and c) 50% RSM (rubber-sand-mixture) for a base motion of amplitude 0.5 g, B_f/B = 1.5 and frequency 3.5 Hz for various D_f/B

4. CONCLUSIONS

In this paper, the effectiveness of using rubber-sand mixture (RSM) in reducing the acceleration response of the foundation and the sensitivity of the results to the percentage and dimensions of the RSM layer has been investigated through numerical simulation. By utilizing the outputs of FLAC^{2D} [15] software for 20%, 30% and 50% RSM in different dimensions, the following results can be obtained.

- the rubber-sand mixture (RSM) could effectively reduce the input acceleration and this result increases with increasing the rubber percentage.
- Increasing the depth ratio of the RSM layer reduces peak acceleration and acceleration magnification factor. This effect is initially large and gradually decreases with increasing the depth of the RSM layer.
- The width ratio of the RSM layer has less effect than the depth ratio of this layer in reducing the input acceleration.
- The effect of RSM on reducing the acceleration response of the foundation is greater at higher amplitudes of the base motion.

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