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Evaluation of Rubber/Sand Mixtures as Replacement Soils to Mitigate Earthquake Induced Ground Motions

Évaluation du mélange sable-caoutchouc comme sol de remplacement pour atténuer les mouvements sismiques

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ABSTRACT: Use of recycled rubber and rubber/sand mixtures (RSM) as lightweight material has been widely growing over the past decade. The increased damping capacity of RSM leads to considering its use as replacement soils in seismic areas to reduce the amplitude of earthquake induced ground motions. This paper presents a study on the effect of utilizing a layer of RSM within a replacement soil on the ground response during an earthquake. Site response analyses were performed using 2D finite element analyses applying an equivalent-linear constitutive model. Three earthquake ground motions of varying frequency content were applied to a deposit of sand with replacement soil having different configurations of RSM. Placing a layer of RSM within the replacement soil resulted in increasing the site natural period causing damping of spectral accelerations at low periods and amplification of spectral accelerations at high periods. Using a thin layer of RSM at deeper depths was more effective in than using thick but shallow RSM layers. The results indicate that RSM layers may be effective when the predominant period of the earthquake is lower than the site natural period, while the configuration is subject to the natural period of the intended structure.

RÉSUMÉ: Le caoutchouc recyclé et les mélanges sable-caoutchouc (MSC) en tant que matériaux légers ont eu une utilisation accrue au cours de la dernière décennie. L'augmentation de la capacité d'amortissement de MSC conduit à considérer son utilisation en tant que remplacement des sols dans les zones sismiques afin de réduire l'amplitude des secousses observées pendant les tremblement de terres. Cet article présente les résultats d'une étude sur l'influence des couches de MSC comme sol de remplacement sur la réponse du sol au cours d'un tremblement de terre. L'analyses de réponses du site ont été réalisées en utilisant la méthode d'éléments finis 2D appliquée sur un modèle constitutif du type « linéaire équivalent ». Trois régimes de tremblements de terre de fréquence variable ont été appliqués à un dépôt de sable avec terres de remplacement ayant différentes formulation de MSC. Placer une couche de MSC dans le sol de remplacement a eu pour effet d'augmenter la période naturelle du site; et ceci provoque une atténuation des accélérations spectrales à des périodes faibles et une amplification de la même accélération aux périodes fortes. L'application d'une mince couche de MSC à des profondeurs importantes a été plus efficace que d'utiliser des couches épaisses peu profondes. Les résultats indiquent que les couches MSC ne peuvent être efficaces que si la période dominante du tremblement de terre est inférieure à la période naturelle du site, et ceci en maintenant la configuration soumise à la même période naturelle de celle de la structure en question.

KEYWORDS: Recycled Material, Rubber-Sand Mixture, Replacement Soil, Earthquake Mitigation

1 INTRODUCTION

The use of recycled rubber and rubber/sand mixtures (RSM) as lightweight material in civil engineering applications has been widely growing over the past decade. Processed waste tires mixed with soils have been introduced as lightweight fills for slopes, retaining walls, and embankments. The mechanical properties of the mixture were discussed by (Edil and Bosscher, 1994; Ghazavi, 2004; Zornberg et al., 2004; and Mavroulidou et al., 2009), while dynamic properties of granulated rubber-sand mixtures were studied by (Feng et al., 2000; and Anastasiadis et al., 2012). Xu et al. (2009) performed numerical studies on protecting buildings from earthquakes hazards by RSM.

The utilization of RSM as replacement soils in seismic areas to reduce the amplitude of earthquake induced ground motions is addressed in this paper. The effect of changing the depth and thickness of the RSM layer will be investigated in this study. The results will be compared for a range of medium amplitude ground motions.

Data used in this parametric study is based on a comprehensive set of torsional resonant column tests performed for different dry and saturated specimens of sand-rubber mixture, (Senetakis et al., 2012). Based on these tests, the modulus reduction and damping curves can be generated for the sand-rubber mixture as a function of confining pressure. The parametric study is based on two-dimensional finite element analyses that can model seismic effects and site response of multilayered soil profile.

2 PROPERTIES OF PARENT MATERIALS

The properties of parent materials for the RSM used in this numerical analysis are based on results of the study by Senetakis et al. (2012). In this study, dry sand of specimen code (C3D06) and rubber material of specimen code (R3) were used as parent materials for the RSM of specimen code (C3D06-R3). The sand is natural of sub-rounded to rounded particles, whereas the rubber is granulated from recycled tire shreds. The properties of the parent materials is indicated in Table 1.

Table 1. Properties of sand and granulated rubber

Material	Sand	Granulated rubber
Unit weight, □ (kN/m3)	16.50	6.50
Specific gravity, Gs	2.67	1.10
Max. particle size, D_{max} (mm)	0.85–2.00	4.75–6.35
50% passing size, D_{50} (mm)	0.56	2.8
Coefficient of uniformity, Cu	2.76	2.29
Coefficient of curvature, Cc	1.23	1.18

The RSM used in the analyses herein was assumed to contain 35% rubber content (by weight) and a dry unit weight of $12.5\ kN/m^2$. The modulus reduction and damping curves of dry RSM (C3D06-R3) for different confining pressures (σ'_m) were generated according to Senetakis et al. (2012). The modulus reduction and damping curves of dry rubber-sand mixture (C3D06-R3), sand (C3D06), and the replacement soil at confining pressures (σ'_m = 50 kPa) are shown in Figure 1. The small strain shear modulii for the sand, RSM, and replacement soil are 65.6 MPa, 10.4 MPa, and 234 MPa, respectively.

3 NUMERICAL MODEL

A number of two-dimensional finite element models were built in QUAKE/W to evaluate the site response during an earthquake. The soil was modeled using an equivalent linear constitutive model. The baseline case representing the untreated site condition constitutes a 20 m thick layer of sand above bedrock. Two additional layers were inserted into the original model to simulate replacement soil and RSM layers in the different numerical analyses, as shown in Figure (2). The width of the RSM layers was assumed 20m.

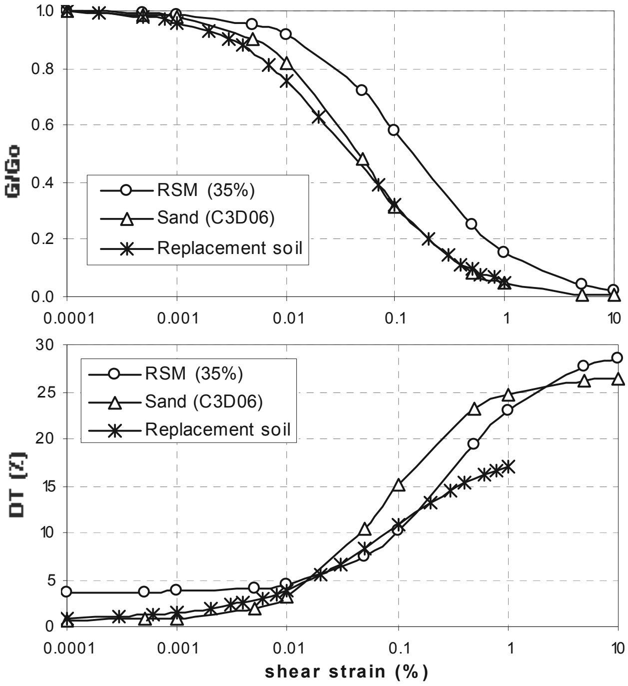

Figure 1. The modulus reduction and damping curves at (σ'm = 50 kPa)

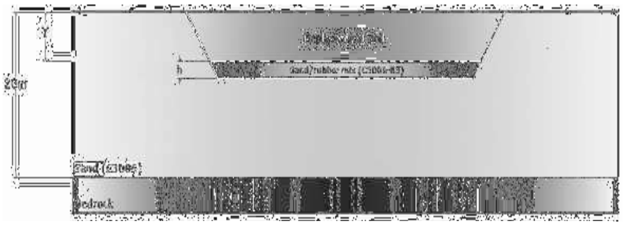

Figure 2. The FEM model used in the numerical study

The effect of changing the depth and thickness of the RSM layer and the replacement soil on top on the site response during earthquakes was investigated. An RSM layer 1 m thick was first assumed to be placed at depths of 1m, 2m, 4m, and 6m. The thickness of the RSM layer was then changed to 2m, 4m, and 6m at a depth of 2m to the top of the layer.

It is important to specify the geotechnical site category that helps us to determine the site natural period for the baseline case which consists of 20 m of pure sand above extended base bedrock. Site period can be obtained depending on the depth and characteristics of the soil deposit (Bray and Rodriguez-Marek, 1997). Because the sand soil deposit depth is greater than 6m and less than 30m, the site is classified as "Shallow Stiff Soil" and the site natural period will be around (0.5 sec), (Bray and Rodriguez-Marek, 1997).

4 EARTHQUAKE GROUND MOTIONS

Three earthquake ground motions of comparable magnitude and different frequency content were used to investigate the ground surface layer response in case of pure sand deposit (baseline case) and in cases of the existence of the RSM layer. The earthquake ground motions data were obtained from the ground motion database of the Pacific Earthquake Engineering Research Center (PEER). The ground motion database includes a very large set of ground motions recorded in worldwide shallow crustal earthquakes in active tectonic regimes. Figure (3) shows the response spectrum of earthquake input ground motions, and Table (2) summarizes their characteristics. The predominant period of the selected input ground motions varies between lower than the site natural period (T_{site} = 0.5 sec) such as in Lytel Creek (T_p = 0.08 sec) and San Francisco (T_p = 0.26 sec), and greater than the site natural period such as in Mammoth Lake earthquake (T_p = 0.925 sec) in order to cover a range of frequency contents for intermediate earthquakes.

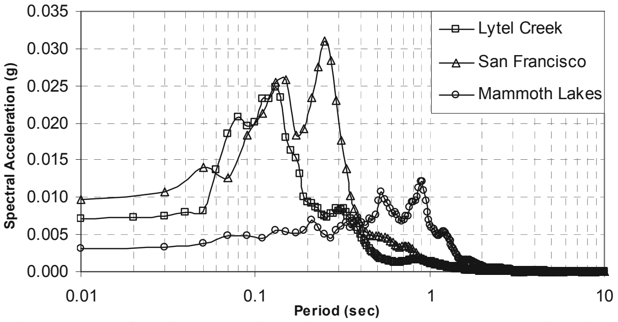

Figure 3. Earthquake ground motions response spectrum at damping ratio (5%)

Table (2): Earthquake ground motions characteristics

Event Name	Magnitude (M)	Peak Grnd. Accel. PGA (g)	Predominant Period, T_p (sec)	Station
Lytel Creek (1970)	5.33	0.070	0.130	Cedar Springs, Allen Ranch
San Francisco (1957)	5.28	0.095	0.260	Golden Gate Park
Mammoth Lake (1980)	4.73	0.031	0.925	USC Cash Baugh Ranch

5 RESULTS AND DISCUSSION

The influence of two parameters on the site response was studied, namely the depth of the rubber-sand mixture layer (Y) and the thickness of the rubber-sand mixture layer (h).

A. Depth of the rubber-sand mixture layer (Y)

The numerical simulations were performed for the baseline model (Pure sand) and for another three models in which a 1 m thick layer of RSM were placed at depths of 2m, 4m, and 6m. The three different input ground motions were applied to each model. The replacement soil on top of the RSM layer was modeled as a well compacted sand-gravel mixture layer with a unit weight of 20 kN/m^2. The modulus reduction and damping curves for the replacement soil are shown in Figure 1. The thickness of the replacement soil is the same as the depth of the RSM layer from ground surface (Y).

The response spectra at ground surface were plotted to investigate the effect of changing the depth of the RSM layer on the ground response. Figure (4) shows the results for the three earthquake ground motions. The results were divided into two groups. The first group is for earthquake ground motions that have a predominant period less than the site natural period ($T_p < T_{site}$), i.e. Lytel Creek (1970) and San Francisco (1957) earthquakes. The second group is for earthquake ground motions that have a predominant period grater than the site natural period ($T_p > T_{site}$), i.e. Mammoth Lake earthquake.

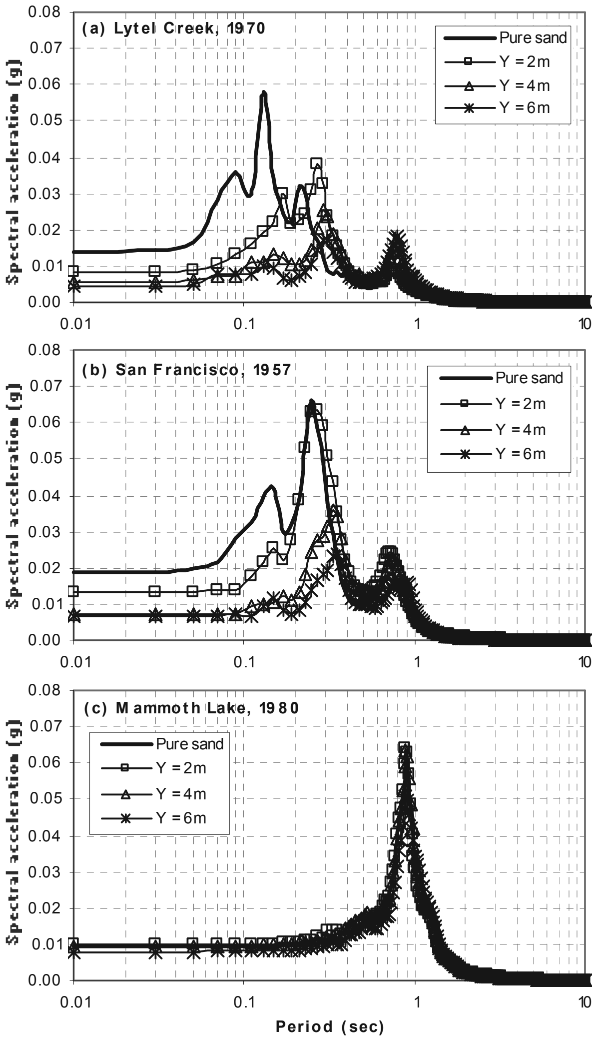

Figure 4. Response spectra of surface layer for variable RSM depth having thickness (h =1 m)

Group (1) - ($T_p < T_{site}$)

This group contains two earthquake ground motions, Lytel creek and San Francisco. The response of this group due to increasing the depth of the RSM layer is summarized below.

Because the predominant period of the ground motion is less than the site natural period, amplification may occur at the fundamental or at secondary order periods of the site. The amplification factor between the spectral acceleration (Sa) at bedrock layer and at the surface layer has a maximum value at the fundamental period of the site. This value is reduced strongly in the successive secondary order periods.

Placing a layer of RSM resulted in increasing the site natural period causing shifting in the fundamental and secondary site periods to higher periods. Shifting of the site periods leads to maximum amplification at higher – more damped periods. This resulted in damping of spectral accelerations at lower periods and amplification of spectral accelerations at higher periods when using RSM compared to the baseline case (pure sand).

Increasing the depth of the rubber-sand mixture layer resulted in increasing the shifting towards the higher periods that leads to a higher order matching between site periods and ground motion predominant period (T_p). Thus, increasing the depth of the rubber-sand mixture layer resulted in highly damped response spectra of the surface layer at lower periods and amplification at higher periods (Figure 5). Increasing the RSM depth to 4m resulted in reduction in the maximum spectral acceleration reaching up to 56% to 45% in case of Lytel Creek and San Francisco earthquakes, respectively. Placing the RSM layer at 6m depth resulted in reduction in the maximum spectral acceleration ranging from 71% to 64% for the case of Lytel Creek and San Francisco earthquakes, respectively, compared to the baseline case (Pure sand).

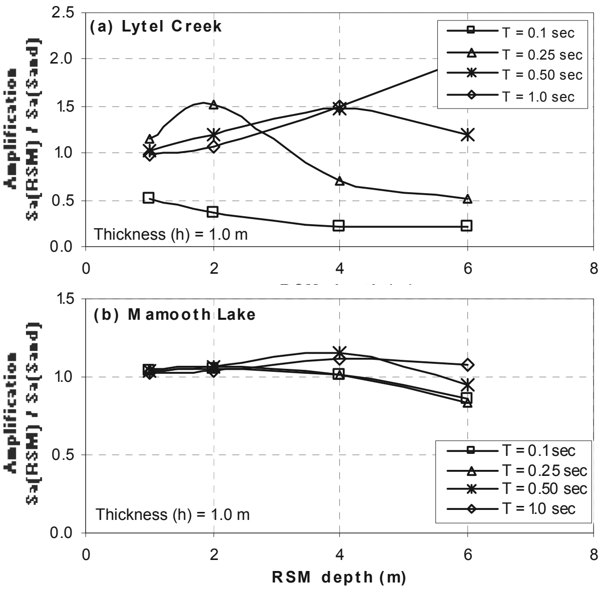

Figure 5. Effect of RSM depth on spectral acceleration

Group (2) - (Tp > Tsite)

This group contains only one earthquake ground motion, which is Mammoth Lake (1980). Because the predominant period of the ground motion is greater than the site natural period, significant amplification does not occur neither at the fundamental site period nor at secondary order periods. Increasing the depth of the RSM layer resulted in insignificant effect on the surface layer response spectrum. Placing the RSM layer at depths 2m and 4m resulted in approximately the same surface layer response spectrum of the baseline case (Pure sand). Placing the RSM layer at 6m depth resulted in a small reduction in the maximum spectral acceleration equals to 16 % compared to the baseline case (Pure sand), and this percentage may be slightly increased if RSM layer is put in deeper level.

B. Thickness of the rubber-sand mixture layer (h).

In this section, the numerical simulations were performed for the baseline model (pure sand) and for another three different models including RSM layers of varying thickness. Different values for the thickness of the RSM layer (h) were chosen to be 2m, 4m and 6m in the models, while the depth of the top of the RSM layer was constant at (Y=2 m) below ground surface in all simulations. The three different input ground motions were applied to each model. In case of Mammoth Lake earthquake, an additional simulation was performed with an RSM layer thickness of 9m.

The result of simulations was plotted in terms of the response spectrum of the ground surface layer to investigate its response to the change in the thickness of the RSM layer. Figure (6) shows the simulation results for the three different earthquake ground motions. Similar to the previous section, the results can be divided into two groups as follow:

Group (1) - ($T_p < T_{site}$)

Increasing the thickness of the RSM layer caused decreasing of low period spectral acceleration and also caused considerable increasing in the high period spectral acceleration comparing by the base line case (balancing). This is evident from the amplification factors plotted in Figure (7) against different RSM thicknesses for different periods. Comparing to the baseline case (pure sand), at thickness of RSM layer equals to 6m a reduction in the maximum spectral acceleration in cases of Lytel Creek and San Francisco earthquakes ranged from 47% to 36%, respectively.

Group (2) - ($T_p > T_{site}$)

Increasing the thickness of the RSM layer from 1m to 4m caused increasing in the maximum spectral acceleration compared to the base line case. Increasing the thickness of the RSM layer from 4m to 6m resulted in a reduction in the maximum spectral acceleration decreased but still higher than the maximum spectral acceleration in the base line case. Increasing the RSM thickness to 9m resulted in reduction in the maximum spectral acceleration equals to 38% compared to the baseline case. Increasing the thickness of the RSM layer from 1m to 4m caused increasing in the spectral acceleration at low and high periods compared to the base line case (Figure 7). However, further increase in the thickness up to 9m resulted in a reduction in the amplification factor below the baseline case.

6 CONCLUSIONS

The following main points may be concluded based on the analyses presented herein:

- The effect of using RSM layer is dependant on the site natural period and the frequency content of the ground motion, while the effective configuration of the RSM layer is subject to the natural period of the intended structure.
- Placing a layer of RSM resulted in increasing the site natural period causing damping of spectral accelerations at low periods and amplification of spectral accelerations at higher periods compared to the baseline case.
- The deeper the RSM layer, the larger the shift in site natural period resulting in more effective damping and lower response spectrum at ground surface for a wider range of periods. Thus, the higher the natural period of the structure, the deeper the sand/rubber layer needed to achieve damping.
- For the same excavation depth, using a thin layer of RSM at the bottom of the excavation is more effective in damping the spectral accelerations at ground surface than using a thick layer of RSM.
- Settlements and creep in RSM layer should be studied in case of large thickness.
- Further investigation is needed to confirm the observation through physical and numerical modeling for earthquakes of different magnitude, amplitude, and frequency content.
- Soil structure interaction needs to be further investigated to examine the effect of the overlaying structure on the response.

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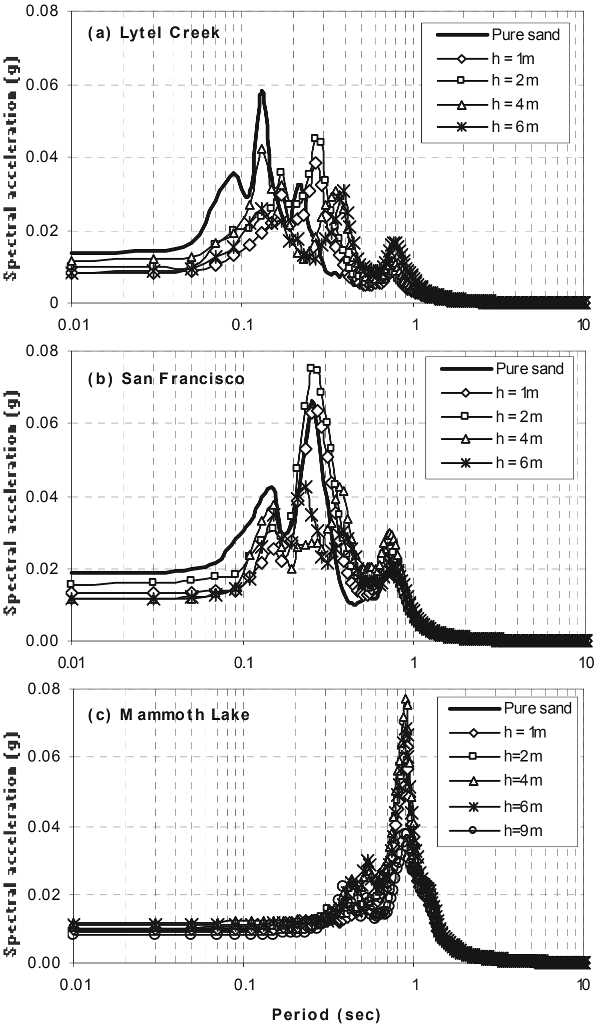

Figure 6. Response spectra of surface layer for variable RSM thickness having depth (Y = 1m) to top of RSM layer

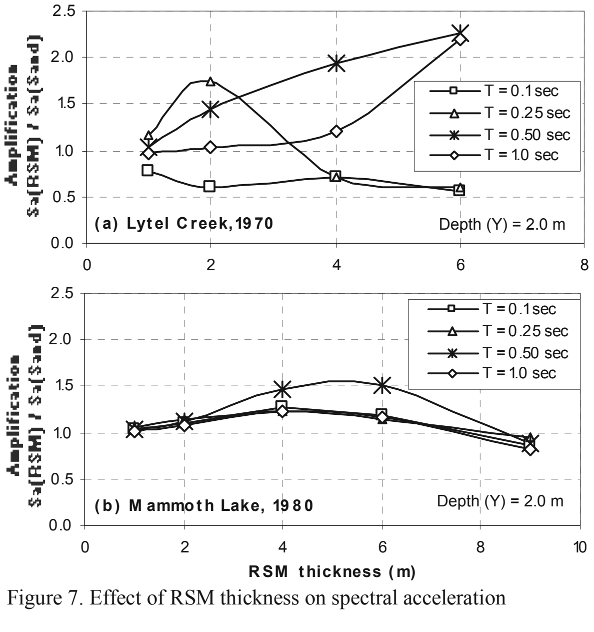

Figure 7. Effect of RSM thickness on spectral acceleration