Rubber-Soil CUSHION for Earthquake Protection

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Abstract

This paper proposes a promising seismic isolation method particularly suitable for developing countries using rubber-soil mixtures – the CUSHION. Apart from reducing the level of shaking in the horizontal direction, the distinctive advantage of the proposed method is that it also significantly reduces the shaking level in the vertical direction, to which increasing attention has been paid by the earthquake engineering community. The use of scrap tyres as the rubber material can provide an alternative way to consume the huge stockpile of scrap tyres from all over the world. Moreover, the low-cost of this proposed seismic protection scheme can greatly benefit the developing countries where resources and technology are not adequate for earthquake mitigation with well-developed, yet expensive, techniques. The proposed method has been demonstrated through a series of numerical simulations. A parametric study has been carried out to evaluate the effectiveness of this new method.

Keywords: seismic isolation; rubber; soil; developing countries; scrap tyre; damping

1. INTRODUCTION

A seismic isolation system is defined as a flexible or sliding interface positioned between a structure and its foundation, for the purpose of decoupling the horizontal motions of the ground from the horizontal motions of the structure, thereby reducing earthquake damage to the structure and its contents. There is an increasing interest in applying seismic isolation technology to housing, schools and hospitals particularly in high-seismicity developing countries. This paper presents a novel seismic isolation method using rubber-soil mixtures (RSM), which can provide cushioning effect for earthquake protection.

The method has been demonstrated through a series of numerical simulations. Similar to other well-known seismic isolation systems, it can greatly reduce the level of horizontal shaking. In addition, it can significantly reduce the level of vertical shaking, to which an increasing attention has been paid in the earthquake engineering community. A parametric study has also been carried out to test the robustness of the proposed system.

The use of scrap tyres as the rubber material can provide an alternative way to consume the huge stockpile of scrap tyres all over the world. Moreover, the lower cost of this proposed seismic protection scheme can greatly benefit those developing countries where resources and technology are not adequate for the mitigation of earthquake risks.

It is possible that some hidden problems may exist in the early stages of development of such new method. In the discussion section, five important issues regarding the concept and feasibility of the proposed method have been identified and briefly discussed.

2. PROPOSED SCHEME

The proposed seismic isolation method is demonstrated by a schematic drawing in Figure 1. The notional building structure has a typical dimension (10-storey and 40 m width (w)) of a residential, hospital or office building. Surrounding the footing (of low-rise building) or the pile cap (of high-rise building; piles not shown in Figure 1), a layer of soil was replaced by soil mixed with a designated proportion of rubber (rubber-soil mixture, RSM) of thickness (t) in the order of 10 m.

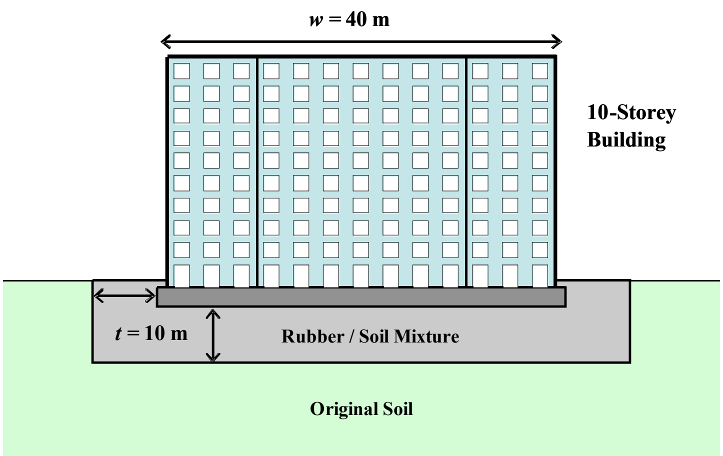

Figure 1. Schematic drawing of the proposed seismic isolation method using a layer of rubber-soil mixture (RSM) – the CUSHION.

2.1 Use of Rubber and Scrap Tyres

Energy dissipation is the primary mechanism accounting for the reduction of shaking level in the proposed isolation method. Rubber has excellent energy absorption capability, rendering its extensive uses for vibration control and dampening such as in automotive components. Moreover, soil reinforced with rubber demonstrates a substantial increase in shear strength compared to normal soils (Edil and Bosscher, 1994; Foose *et al.*, 1996; Masad *et al.*, 1996). It is generally believed that recycled rubber will play an important role in base isolation in the near future, and scrap tyre is potentially a suitable source of material for the proposed method. The durability of tyres is also guaranteed, for instance, they are termite proof, fireproof and do not outgas once they are buried.

Scrap tyre stockpile has been a significant disposal problem. Citing the United States as an example, since the banning of the disposal of used tyres in sanitary landfills, the stockpile has grown up rapidly at a rate of around 300 million tyres per year. It has been a challenge for the engineering community to find new beneficial ways to recycle and reuse this huge stockpile. Hence, the proposed seismic protection method presented in this paper provides a promising way to reduce the huge stockpile, especially that each project could use up a large volume of tyres. Taking the **Reference** scenario in Figure 1 as an example, around two million tyres can be consumed. This amount is well beyond the consumption in typical earthwork projects.

3. FINITE ELEMENT MODELING

The computer program *QUAD4M* (Hudson *et al.*, 1994) has been employed to model the dynamic response of soil structures in this study. It is a dynamic, time-domain, equivalent linear two-dimensional finite element program, which can provide reasonable approximation to the site response simulations with a minimal input file.

3.1 Engineering Properties of RSM

Fundamental engineering properties of RSM, such as compaction characteristics, compressibility, permeability, shear strength, modulus of elasticity and Poisson's ratio, have been extensively investigated (e.g. Edil and Bosscher, 1994). The values of density were selected as 17.4 and 9.5 kN/m^3, respectively, for sand and RSM with 75% rubber by volume (abbreviated as RSM75). A single value of 0.3 for Poisson's ratio was adopted.

It is well known that dynamic properties of soils are significantly dependent on the soil shear strains. *QUAD4M* employs equivalent linear method, in which the nonlinear characteristics of soils can be captured by two strain-compatible material parameters, namely, secant shear modulus G and damping ratio ξ. The dynamic properties of RSM were obtained from Feng and Sutter (2000). The maximum shear modulus of soil ($G_{\max}$) adopted in this study are 222 and 7.5 MPa for sand and RSM75, respectively. As there is inevitably large uncertainty in estimating the dynamic properties of soil materials, certain amount of tolerances ($\pm$ around 10%) has been allowed for shear modulus degradation and damping in the parametric study.

3.2 Numerical Simulations

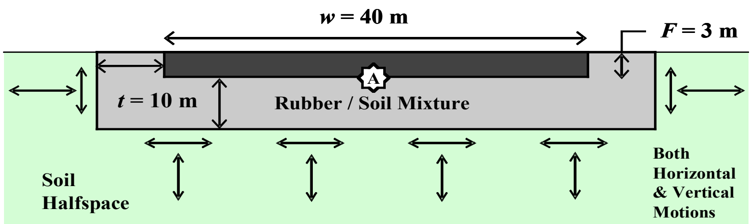

Figure 2. Simplified model for the **Reference** scenario in finite element modeling using *QUAD4M*.

The feasibility of the proposed method has been demonstrated through a series of numerical simulations. The configuration described in the previous section (refer Figure 1) would be adopted as the **Reference** model. In addition, parametric studies have been carried out for a number of important variables, including building height (number of storeys) and width, depth of underground structure (annotated as ***F*** in Figure 2), thickness of RSM, potential discrepancies in dynamic properties of RSM, shaking level and frequency content of the applied ground motions. Detailed information can be found in Table 1. It is noted that only one input parameter was varied in each case, whilst all other input parameters were held constant at the default values specified for the **Reference** scenario (bolded in Table 1). The purpose of this comparative analysis was to test the relative sensitivity of the results to each input parameter.

Table 1. Input parameters used in the parametric study.

Input Parameter		**Reference**		
Thickness of RSM (m)	5	**10**	20	
Dynamic Properties of RSM	– 10%	**Median**	+ 10%	
Building Width (m)	20	**40**	80	
Number of Storey (Equivalent Density of Elements; kN/m^2)	5 (40)	**10** **(60)**	15 (80)	
Depth of Underground Structure ***F*** (m) (Equivalent Density of Elements; kN/m^2)		**3** **(60)**	7 (30)	10 (23)
Peak Horizontal Acceleration (g)		0.45 – 3.56		
Peak Vertical Acceleration (g)		0.33 – 2.10		

To compare the effectiveness of different systems, peak and root-mean-square ground accelerations, both horizontal and vertical, have been chosen. The location chosen for collecting acceleration time histories is the mid-point of the bottom of the footing or pile cap, as annotated by the letter “A” in Figure 2. It can be considered as the point where earthquake motion is applied for structural analysis. For the sake of simplicity, the weight of the whole building structure was condensed to the footing, resulted in different “equivalent” densities of elements for different scenarios listed in Table 1. The model is subjected to four earthquake ground excitations, which cover different frequency contents and a wide range of ground shaking levels, both horizontal and vertical, as shown in Table 1.

Figures 3(a)–(b) show the *Fourier* amplitude spectra (*FAS*) of the horizontal and vertical ground accelerations, respectively. In each figure, the *FAS* of the scenarios of placing RSM and pure sand have been plotted. Figures 3(c)–(d) show the corresponding normalised horizontal and vertical ground acceleration time histories of the two scenarios. Each time history was normalised by the respective maximum absolute ground acceleration of the scenario with pure sand, so that the reduction ratio can be conveniently observed for direct comparison.

The model is subjected to four earthquake ground excitations. Three of them are strong-motion data collected from COSMOS Virtual Data Center (website: http://db.cosmos-eq.org/). The fourth set was obtained by multiplying the motion, with the greatest horizontal shaking level amongst the three, by a factor of two, in order to give a stronger shaking level.

Figures 4(a)–(f) show the effectiveness of acceleration reduction by the proposed method. The “Acceleration Ratio (%)” is the ratio of the ground acceleration obtained from the model with RSM to that obtained from the model with sand. In that sense, a smaller acceleration ratio means higher effectiveness in reducing ground acceleration. Generally, it is evident in all cases that the proposed method can effectively reduce ground accelerations, both horizontal and vertical. On average, the acceleration ratio is in the order of 30–40% for horizontal motion and 10–20% for vertical motion. It is noteworthy that the vertical acceleration could not be reduced by all conventional seismic isolation schemes. This is a unique advantage of the proposed method using RSM. More results can be found in Tsang (in press).

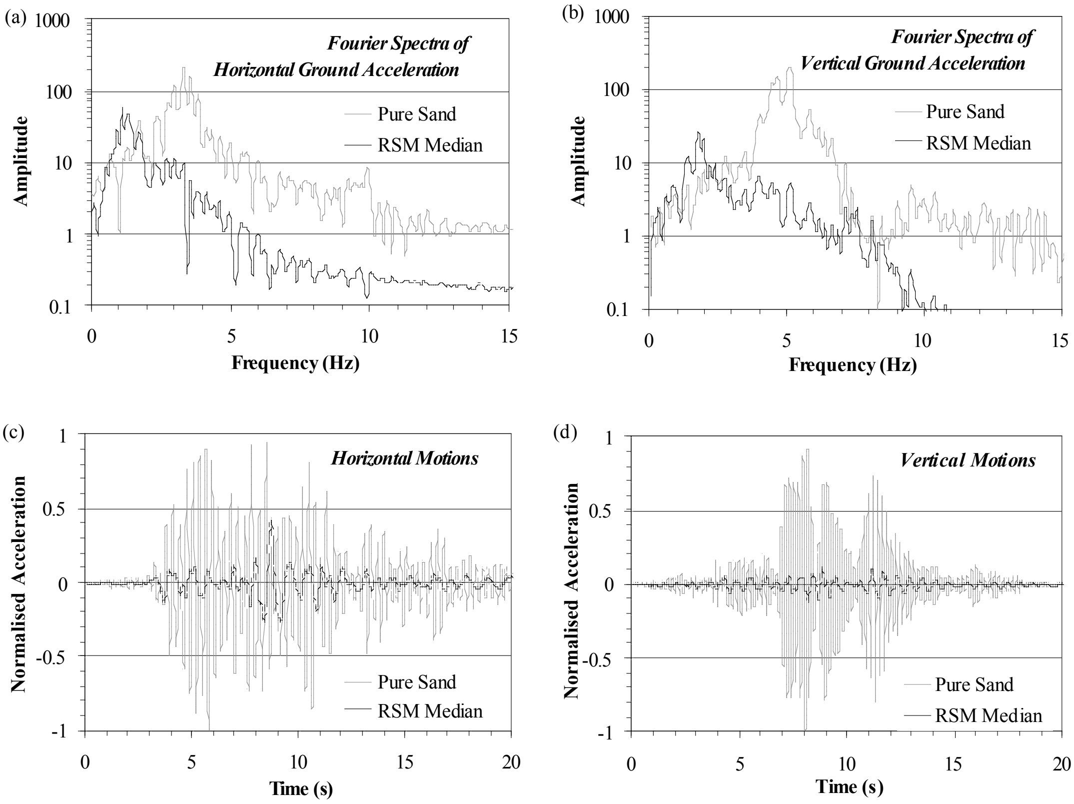

Figure 3. The *Fourier* amplitude spectra (*FAS*) of the (a) horizontal and (b) vertical ground accelerations; and the corresponding normalised (c) horizontal and (d) vertical ground acceleration time histories for the **Reference** scenario.

4. DISCUSSION

For a newly proposed technology, it is possible that some hidden problems may exist and it is essential to carefully evaluate, investigate and criticise the proposed method. Five important issues regarding the concept and feasibility of the proposed method are given in the following subsections.

4.1 Nonlinear Site Response

It is well-recognised that soils yield at moderate to high levels of strains and give rise to nonlinear response. There was a consensus that damage was mostly caused by soft, near-surface ground conditions, as stated in Hauksson and Gross (1991). Hence, it might be reasonable to postulate that RSM may not be beneficial in reducing shaking levels under nonlinear soil conditions. However, Trifunac and Todorovska (1998) showed that buildings on softer soils were damaged to a lesser degree, because the energy absorption of incident seismic waves by nonlinear soil response would lead to a reduction of the destructive power of the strong motion. Hence, soft soils can potentially act as a natural mechanism for passive isolation, especially for near-field earthquakes that are rich in high-frequency wave components. Evidences have already been shown in the simulations presented in the form of

FAS in Figures 3(a)–(b), from which significant reduction in amplitudes could be observed in high-frequency range. It is therefore believed that seismic isolation using RSM should be a feasible method, considering the excellent energy absorption capability of rubber.

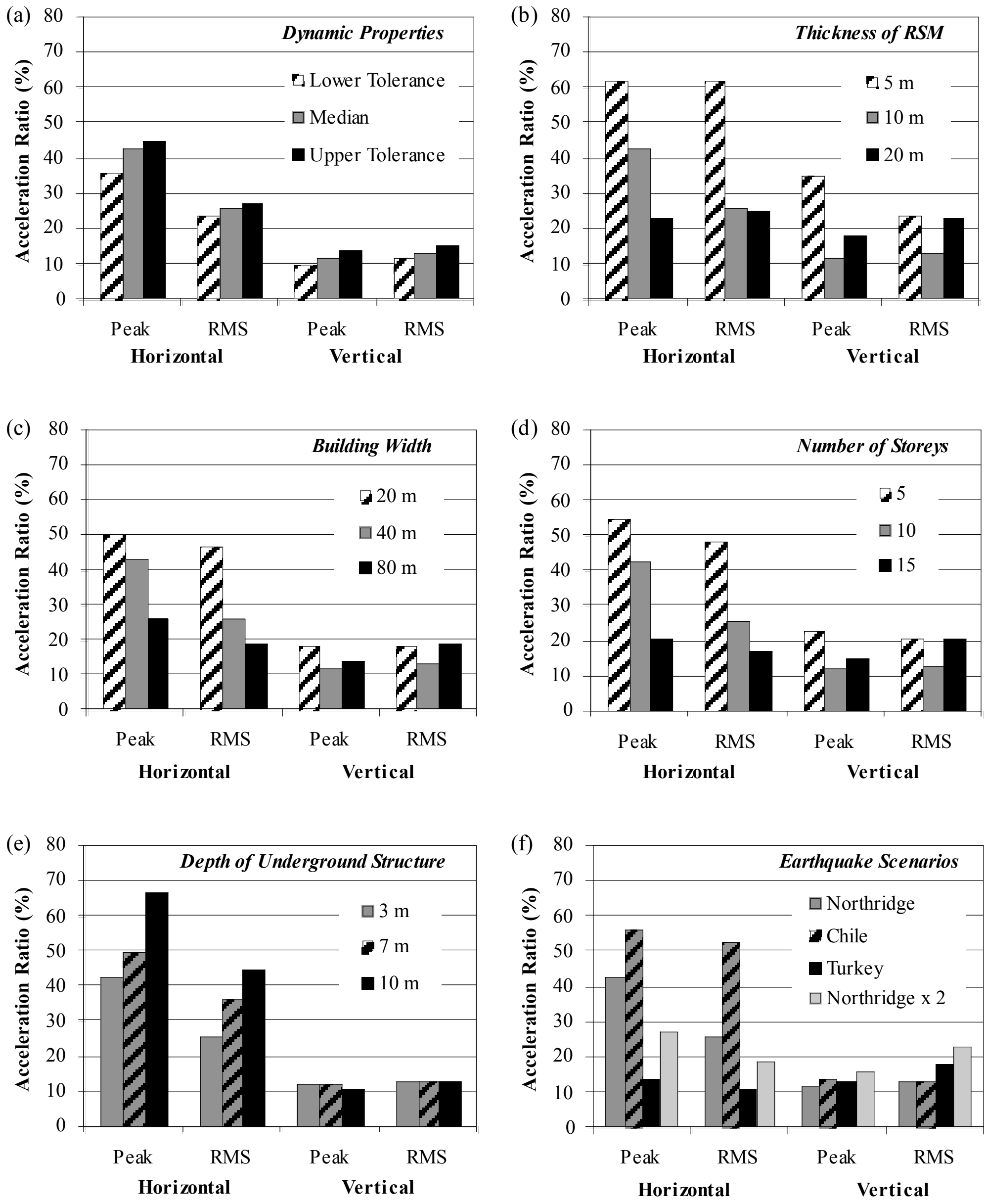

Figure 4. Comparison of the acceleration ratio, with respect to different (a) dynamic properties of RSM; (b) thicknesses of RSM; (c) building widths; (d) building heights (number of storey); (e) number of basement level (depths of underground structure); and (f) earthquake scenarios.

4.2 Soil Resonance Effects

Earthquakes produce seismic waves with a wide spectrum of frequencies. If a certain seismic wave component with high energy matches the natural frequency of the surface geological deposits, the interaction could potentially amplify the level of shaking, commonly referred as soil resonance. As the proposed method requires replacement of certain thickness of surface geological deposits by RSM, which would significantly modify the stiffness (and in turn the natural frequency) of the materials beneath the structure, the potential harmful effects should not be neglected. Although this problem could not be observed in the finite element modelling in the previous section, further investigation has to be carried out.

On the other hand, if the natural frequency of the site can be adjusted, with specific design of the configuration and properties of the RSM layer, to a frequency that does not coincide with that of the incident seismic waves, the level of shaking can then be further reduced, in addition to energy dissipation by RSM, which is basically the underlying philosophy of the traditional base isolation system.

4.3 Liquefaction

The two most important factors attributing to the occurrence of liquefaction are (1) the cohesiveness and density of the soil deposit and (2) the level of shaking. As the proposed method requires partial replacement of the soil materials by RSM, it is concerned whether it would enhance the potential of liquefaction during earthquakes.

Various studies of the engineering properties of RSM demonstrate a substantial increase in the cohesion intercept (commonly referred as the c–value) (Masad *et al.*, 1996). Moreover, rubbers generally have higher frictional angles (commonly referred as the ϕ–value) compared to normal soils (Edil and Bosscher, 1994), and shown to be increasing with the percentage of shred content (Foose *et al.*, 1996). It is mentioned in the previous section that the density of RSM is reduced from 17.4 kN/m^3 (of pure sand) to 9.5 kN/m^3, which would result in a decrease in the shear strength and potentially increase the possibility of liquefaction. However, it is shown that an addition of more than 10% tyre chips into loose sand results in shear strength greater than that of the dense sand (Edil and Bosscher, 1994). Edil and Bosscher (1994) showed clearly that randomly mixing tyre chips can reinforce sand to shear strength greater than the strength of pure sand at its densest state. Furthermore, densification works can be done to reduce the void ratio and hence increase the density.

Regarding the ground shaking intensity, it is evident from the previous section that the damping effects of RSM could significantly reduce both the peak and root-mean-square ground accelerations. Thus, the probability of liquefaction occurrence should be reduced.

4.4 Ground Settlement

It is well known that tyre shred (as well as RSM) is highly compressible. However, it is shown that the compressibility decreases substantially once the tyre shreds have experienced one load application (Edil and Bosscher, 1994). For example, it is found that embankment sections composed of tyre shreds that were overlain with a soil cap (in the order of 1 m thick) can significantly reduce the compressibility and deflections. Thus, preloading can be used to eliminate plastic compression once the fill has been constructed. Moreover, it is reported that soil-tyre shred mixtures can be compacted using common compaction procedures.

4.5 Environmental Effects

The long-term environmental issues, such as ground water contamination and impact on local ecology, have been the subjects in intense debate. It was shown by laboratory tests and augmented by field studies (Liu *et al.*, 2000) that both the concentrations of metallic components and the organics were well below the standards specified in two protocols in the

United States, namely, Toxicity Characteristics Leaching Procedure Regulatory Limits and Extraction Procedure Toxicity, proven that recycled scrap tyre is not a hazardous recycled material.

There is a common concern regarding the increase in iron and manganese levels. However, iron level is only specified in the aesthetic drinking water standard (taste), rather than of health concern. Also, manganese is naturally present in ground water in many areas. Hence, it was concluded that there is little or no likelihood of significant leaching of tyre chips for substances that are of specific public health concern.

5. CONCLUSIONS AND CLOSING REMARKS

This paper presented a new seismic isolation method using RSM, which is particularly suitable for developing countries. There are a number of distinctive advantages, including the ability of reducing both horizontal and vertical ground motions and the substantial consumption of the huge stockpile of scrap tyres all over the world. A series of numerical simulations and parametric study have been carried out to demonstrate the effectiveness and the robustness of the proposed method. On average, it can reduce the horizontal and vertical ground accelerations by 60–70% and 80–90%, respectively.

Five important issues regarding the concept and feasibility of the proposed method have been identified, namely, (1) nonlinear site response, (2) soil resonance effects, (3) liquefaction, (4) ground settlement, and (5) environmental effects. In addition, the proposed method can be generalised as a *distributed seismic isolation system*, which involves isolating the entire contact surface of the foundation structure. This attribute distinguishes clearly from the conventional systems based on isolation of certain discrete supporting points. Further research can be directed to the development of the *distributed seismic isolation system*.

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