Protecting Low-to-medium-rise Buildings by Scrap Tyre-Soil Mixtures

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Abstract

The stockpiling of scrap tyres is a significant threat to our environment and has been a hot topic amongst the engineering community which has been looking for long term viable solutions to the recycling and reuse of rubber. This paper proposes a new method of utilizing scrap tyres for applications in infrastructure protection forming part of the solution strategy. The method involves mixing scrap tyres with soil materials and placing the mixtures around building foundations, for vibration absorption. The potential of the proposed method will be demonstrated by numerical modelling to show its effectiveness and robustness as a means of protecting low-to-medium-rise buildings in an earthquake.

Keywords: rubber, soil, scrap tyre, earthquake, seismic isolation, vibration absorption

1. INTRODUCTION

In recent years, novel infrastructure protection methods have been proposed by various researchers. Some of these involve the use of a flexible or sliding interface in direct contact with geological sediments as a vibration isolating mechanism. For example, Kim and Konagai (2001) has proposed to cover tunnel linings with a soft and thin coating for reducing deformation in an earthquake. Smooth synthetic liners have been proposed to be placed underneath the foundation of a building structure or between soil layers for dissipating seismic energy through sliding (Yegian and Kadakal, 2004; Yegian and Catan, 2004). Kirzhner et al. (2006) proposed to replace soils by softer materials surrounding a tunnel for noise and vibration absorption. Rubber-soil mixtures (RSM) have been proposed around the foundation of building structures and underground tunnels for absorbing seismic energy and exerting a function similar to that of a cushion (Tsang, 2008; Tsang et al., 2009). Hazarika et al. (2008) proposed the use of tyre chips for protecting waterfront retaining structures in an earthquake. The aforementioned seismic isolation methods could be collectively named "*Geotechnical Seismic Isolation*", in contrast to the commonly used "*Structural Seismic Isolation*" (Tsang, 2009).

This paper presents the latest works on seismic protection of low-to-medium-rise buildings by RSM. The use of scrap tyres as the rubber material can provide a promising way of consuming huge stockpiles of scrap tyres from all over the world. The potential of the method has been demonstrated by numerical modelling using various recorded earthquake ground motions.

2. USE OF RUBBER AND SCRAP TYRES

Energy dissipation is the primary mechanism attributing to the reduction of seismic ground shaking. Rubber is known for its excellent energy absorption capability, and hence its uses for vibration control and dampening such as in automotive components have been extensive. Rubber solids and soil particles are complementary in their functions. Comparing with normal soils, soil reinforced with rubber demonstrates a significant increase in shear strength (Edil and Bosscher, 1994) and more importantly a tremendous increase in energy dissipating capability. Engineering properties of rubber-reinforced soils will be discussed in details later.

2.1. THE PROBLEM OF SCRAP TYRES

In recent years, the disposal of scrap tyres has become a significant environmental problem. 800 millions of scrap tyres are disposed every year worldwide as a consequence of the huge increase in the number of vehicles on our roads. In the United States alone, about 300 million scrap tyres were generated in 2005 and the number is expected to rise by approximately 2% every year. The problem would become more severe due to the rapid economic growth of a number of developing countries, including China, India, and so forth.

Since the ban of the use of tyres for landfills in the European Union and several states in the United States, a proper way of disposing scrap tyres have become a hot topic in the engineering community. Owing to the high energy content of tyres, use of scrap tyres as fuel for energy recovery has been the main outlet of stockpiles. Despite the reduction in emissions of nitrogen oxides, uncontrolled burning of tyres can generate black smoke and sulphur dioxide which can aggravate air pollution.

2.2. CIVIL ENGINEERING APPLICATIONS OF SCRAP TYRES

From the perspective of sustainability, reusing and recycling of waste tyres is preferred to energy recovery. Due to their relatively low weight and high permeability, tyre shreds can be applied in civil engineering applications, for instances, highway embankments, landslide stabilization and backfill for retaining walls and bridge abutments. However, the scope of waste tyre utilization in civil engineering applications is relatively narrow and the amount of tyres used in these applications is limited. It is essential to seek other beneficial and practical uses to consume huge scrap tyre stockpile.

2.3. USING SCARP TYRES FOR ENERGY DISSIPATION

The damping property of rubber within waste tyres is yet to be exploited in common civil engineering applications. In fact, the excellent energy absorption capability of rubber is useful in mitigating earthquake hazards around the world. In the past three decades, rubber has been used in seismic isolation systems for the purpose of decoupling the horizontal motions of the ground from that of a structure and thus reducing earthquake damage to the structure. Utilizing rubber tyres in earthquake hazard mitigation can be a viable approach of resolving the chronic problems associated with waste tyre disposal and costly provisions for earthquake protection of the infrastructure.

3. MATERIAL PROPERTIES OF RSM

Extensive research has been conducted to investigate fundamental engineering properties of RSM, such as shear strength, modulus of elasticity and Poisson's ratio (e.g. Edil and Bosscher, 1994). The values of density of sand and RSM with 75% rubber by volume (abbreviated as RSM75) selected for finite element modelling are 17.4 and 9.5 kN/m^3 respectively. The Poisson's ratio (ν) is equal to 0.3.

Dynamic properties of soils are well known for their significant dependence on soil shear strains. The finite element program, specifically developed for this study, employs the commonly adopted equivalent linear method for modelling soil dynamic properties, 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 have been investigated by Feng and Sutter (2000). The maximum values of shear modulus of soil (G_{max}) adopted for sand and RSM75 are 222 and 7.5 MPa, respectively, at a confining pressure of 345 kPa. The strain dependent G/G_{max} ratio and damping ratio adopted in this study have been plotted in Figure 1.

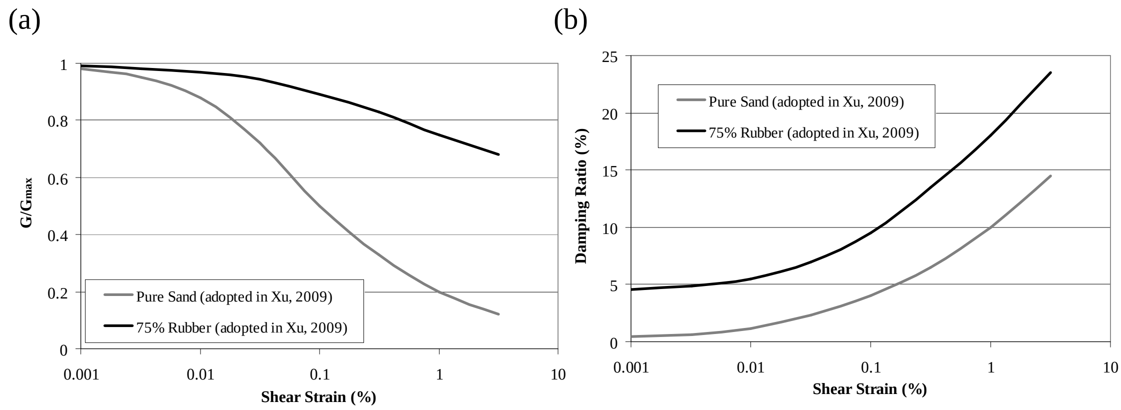

Figure 1: (a) Shear modulus degradation curves and (b) damping curves of RSM75 (Xu, 2009).

4. FINITE ELEMENT MODELLING

The new finite element analysis program developed by Xu (2009) was employed in this investigation. It is a time-domain, two-dimensional finite element program that can model the dynamic response behaviour of a soil-foundation-structure system (refer Figure 2). The superstructure is modelled by an assembly of two-dimensional frame element surrounding the nodal points. Four-node quadrilateral plain-strain elements were used to model interactions between the foundation (either footing or pile) and subsoil materials. For nodes located at the soil-structure interface, the two transformation degree-of-freedoms as in frame element is coupled with those in the four-node quadrilateral element. In order to simulate the non-reflective effects of the infinite soil transmitting half-space, the theory of *viscous boundaries* has been adopted at the boundary of the computational domain. Newmark method has been employed to solve the governing dynamic equations.

4.1. BUILDING STRUCTURE

The building model adopted has a typical dimension [10-story and 40 m width] of a residential or office building, as shown in the schematic drawing of the finite element mesh in Figure 2. The soil layers surrounding the foundation (pile system as shown in Figure 2) of the building is replaced by a medium which is made up of soil mixed with a designated proportion of rubber (i.e. RSM). The medium is of thickness (t_1) in the order of 10 m. To demonstrate the feasibility of the method, a series of numerical simulations was performed. The configuration (without pile) described in Figure 2 (bolded values in Table 1) was adopted as the **Reference** model. Strong ground motions of 1994 Northridge, California earthquake have been adopted as the input ground shaking. The strong-motion data were collected from COSMOS Virtual Data Center (website: http://db.cosmos-eq.org/).

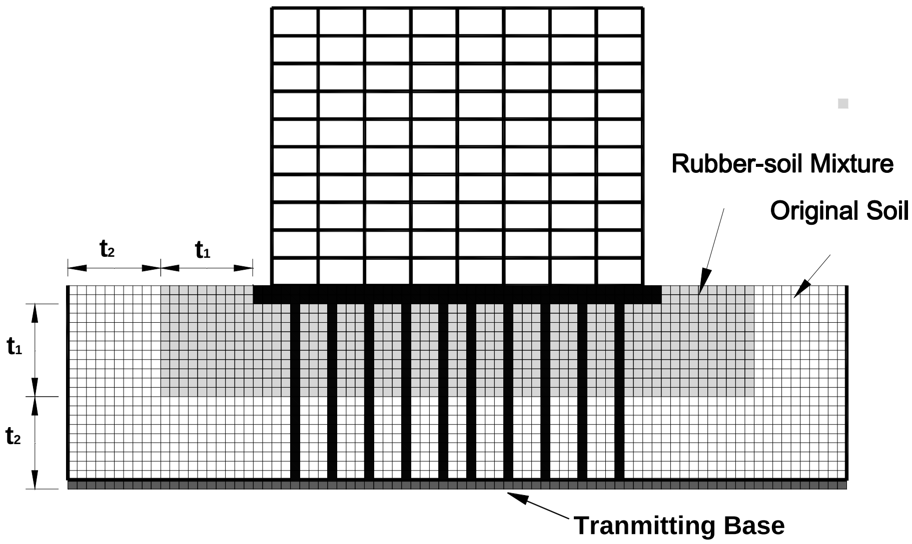

Figure 2: Schematic drawing of the finite element mesh for modelling the proposed earthquake protection scheme using rubber-soil mixtures.

Table 1: Input parameters used in the parametric study.

Input Parameter		Ref.	
Thickness of RSM t_1 (m)	5	**10**	15
Building Width (m)	20	**40**	80
Number of Stories	5	**10**	15
Length of Piles (m)	**0**	10	20
Peak Horizontal Acceleration (g)	0.72 – 1.78		
Peak Vertical Acceleration (g)	0.33 – 1.05		

Three response parameters were chosen for comparing and evaluating the effectiveness of the proposed system. As most severe damages were caused by strong ground shaking produced by near-field earthquakes that are rich in high frequency seismic wave components, horizontal acceleration response time histories were collected at the mid-point of the roof of the building (referred to as roof horizontal acceleration) and at the mid-point at the base of the footing of the pile cap (referred to as the footing horizontal acceleration). The mid-point of the roof was chosen since it typically represents the maximum horizontal acceleration response of the structure. The second location was chosen because it is commonly considered as the location where earthquake input ground motion is applied for ordinary structural analysis. Owing to the fact that soft-storey mechanism is the major cause of collapse of many buildings during an earthquake, first floor inter-storey drift was chosen as the third parameter. The peak and root-mean-square (abbreviated as RMS) values of the three parameters were computed.

Figures 3(a) and (b) show the corresponding normalised roof and footing horizontal acceleration time histories of the reference scenario. Each of these time-histories has been normalised with respect to the maximum absolute acceleration of the control scenario in which pure sand was used for the construction of the foundation. Figure 3(c) shows the inter-storey drift time-history of the first floor (which has been normalised with respect to the maximum absolute drift of the control scenario). The "*percentage reduction*" (or "% *reduction*") parameter is introduced herein to represent the effectiveness of RSM in terms of its ability to reduce the acceleration and drift demand on a structure. This parameter is defined as 100% minus the response quantity (i.e. maximum acceleration or inter-storey drift) obtained from the simulated RSM model expressed as a percentage of the respective response quantity as obtained from the control model as shown in Figure 3(d). The precise values of the *percentage reduction* parameter have been enlisted in Table 2.

Parametric studies have been conducted to examine a number of important variables, namely the number of stories, width of building, length of piles, thickness of RSM, earthquake ground motions with different levels of shaking and frequency contents. Details can be found in Table 1. It is noted that only one input parameter was varied in each case, whereas all other input parameters were held constant at the default values specified for the **Reference** scenario (as shown by the bold fonts in Table 1). The purpose of this comparative analysis was to test the sensitivity of the results to variations in the values of each input parameter.

The model was subjected to three earthquake ground excitations covering different frequency contents and a range of ground shaking levels, in both the horizontal and vertical directions, as shown in Table 1. They are, respectively, 1994 Northridge, California earthquake (Mw = 6.7), 1999 Duzce, Turkey earthquake (Mw = 7.1) and 2001 El Salvador earthquake (Mw = 7.6).

On average, the horizontal accelerations of the roof can be reduced by 50-70%, horizontal acceleration of the footing by 40-60%, and inter-storey drift of the first floor by 40-60%. In regard to horizontal accelerations of the roof and the footing, it is of interests to note that the results were most sensitive to variations in the thickness of the RSM. As the thickness of the RSM increased from 5 m to 15 m, the percentage reductions in the horizontal accelerations of the roof and footings increased from 47% to 73%, and from 35% to 65% respectively. The remarkable increase in the reduction effectiveness of the RSM was likely to be resulted from the much larger amount of energy absorbed by a significantly thicker RSM layer. On the other hand, results show a higher acceleration reduction for wider buildings (40 and 80 m). Also, the presence of a piling system would decrease the reduction effectiveness by around 5%. Results obtained so far have not been sufficient to delineate other trends such as those associated with changes in the number of stories in the building and the nature of the earthquake scenarios.

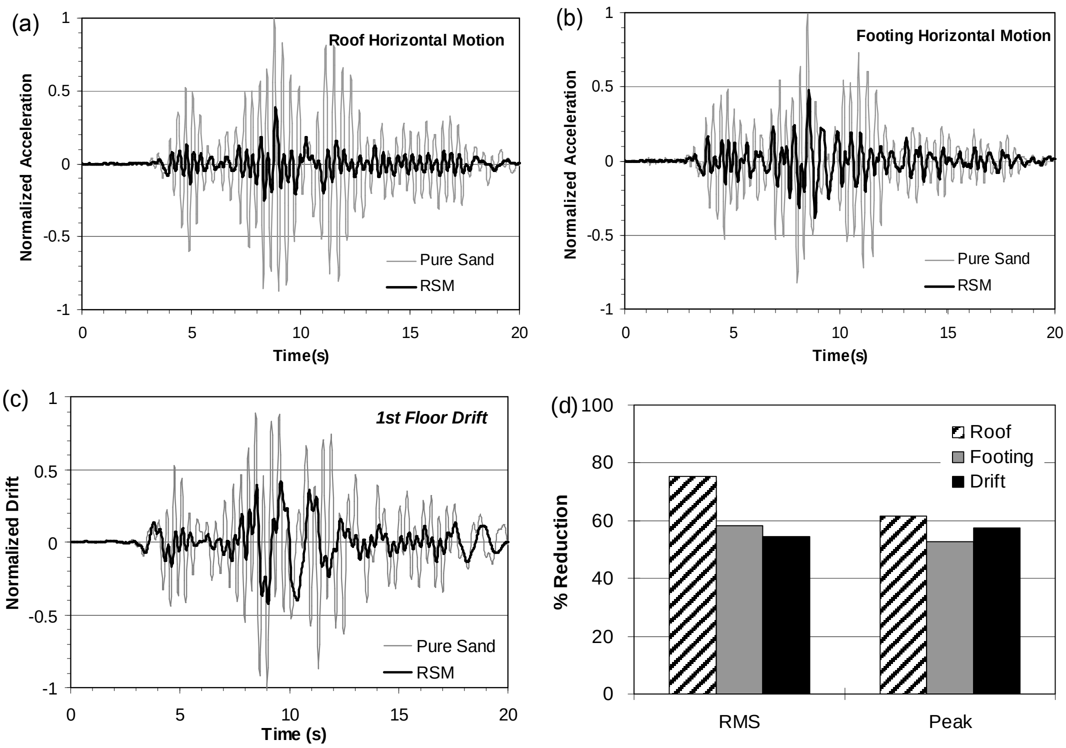

Figure 3: Normalised time histories of (a) roof and (b) footing horizontal acceleration, and (c) first-floor inter-storey drift for the reference scenario. (d) Acceleration and drift percentage reduction values.

Table 2: Percentage (%) reduction obtained in the parametric study.

Input parameters		Roof horizontal acceleration (% reduction)		Footing horizontal acceleration (% reduction)		First floor drift (% reduction)	
		RMS	Peak	RMS	Peak	RMS	Peak
Thickness of RSM (m)	5	61	47	36	35	49	49
	10	75	62	58	53	54	58
	15	80	73	71	65	49	52
Building Width (m)	20	56	50	37	21	26	40
	40	75	62	58	53	54	58
	80	70	56	63	50	46	50
Number of Storeys	5	67	62	69	64	59	41
	10	75	62	58	53	54	58
	15	64	63	67	62	42	25
Length of Piles (m)	0	75	62	58	53	54	58
	10	64	56	36	35	50	54
	20	63	58	43	39	47	51
Earthquake Scenarios	Northridge	75	62	58	53	54	58
	El Salvador	71	55	55	59	55	56
	Turkey	71	70	65	66	56	71

Notes: Only one input parameter was varied in each case, while all other input parameters were held constant at the default values specified for the ***Reference*** *scenario.*

As for the result of the first floor inter-storey drift, results show significantly higher drift reductions for buildings wider than 20 m. Also the proposed method tends to be more effective with lower rise buildings. Other trends will emerge when more results from both simulations and experimentations become available. With results obtained so far, it is already evident that the utilization of RSM can effectively reduce the acceleration and drift demands in the building at all levels and this applies to the worst-case scenarios considered in the parametric study.

5. CONCLUSIONS

This paper presented a potential earthquake protection method by placing rubber-soil mixtures (RSM) around foundations (footing or pile) of low-to-medium-rise buildings for absorbing vibration energy and exerting a function similar to that of a cushion. The validity of the proposed method has been shown by a number of numerical simulations using various recorded ground motions. On average, 40-60% reduction in horizontal accelerations at roof and foundation as well as first floor inter-storey drift can be achieved.

The use of scrap tyres as the rubber material can provide an alternative way of consuming huge stockpiles of scrap tyres from all over the world. Moreover, the possibly low-cost of this proposed earthquake protection scheme can greatly benefit developing countries where resources and technology are not adequate for earthquake mitigation with well-developed, yet expensive, techniques.

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