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ABSTRACT

The stockpiling of scrap tires 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 tires. This paper proposes a new method of utilizing scrap tires for applications in infrastructure protection forming part of the solution strategy. The method involves mixing scrap tire particles with soil materials and placing the mixtures around civil engineering systems, for vibration absorption. The inexpensive nature of the proposed method can be of great benefits to developing countries where there are affordability issues with employing expensive resources and state-of-the-art technology for infrastructure protection.

The interaction of compacted soil with interlocking rubber components exploits the well known reinforced earth principles. This study employs conventional soil-structure interaction analysis techniques for quantifying the effectiveness of rubber-soil mixtures in terms of its ability to dissipate energy and control vibrations. While deriving closed-form analytical expressions for such heterogeneous conditions remains to be a difficult task, the potential of the proposed method has been demonstrated by numerical modeling to show its effectiveness and robustness as a means of protecting low-to-medium-rise buildings in an earthquake.

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 tire 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 tires as the rubber material can provide a promising way of consuming huge stockpiles of scrap tires from all over the world. The possibly low-cost of these infrastructure protection methods can greatly benefit developing countries where resources and technology are inadequate for hazard mitigation using well-developed, yet expensive, techniques.

The potential of the method has been demonstrated by numerical modeling using various recorded earthquake ground motions. For a newly proposed technology, it is reasonable that some hidden problems may exist and hence it is essential to carefully evaluate, investigate and criticize the proposed method. Potential problems related to the concept and feasibility, which can be considered as further research directions, will be identified and discussed.

USE OF RUBBER AND SCRAP TIRES

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.

It is believed that recycled rubber will become an important component in earthquake protection in future, and scrap tires potentially provide a huge source of rubber material required. The durability of tires is ensured, for instance, they are termite proof, fireproof and do not outgas once they are buried. Possible environmental effects will be discussed in a later section.

The Problem of Scrap Tires

In recent years, the disposal of scrap tires has become a significant environmental problem. 800 millions of scrap tires 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 tires were generated annually and the number is expected to rise by approximately 2% every year (refer Fig. 1). The problem would become more severe due to the rapid economic growth of a number of developing countries, including China, India, and so forth. It is seen in Fig. 1 that the number of new tires produced in China has drastically increased since the beginning of this century.

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

Civil Engineering Applications of Scrap Tires

From the perspective of sustainability, reusing and recycling of waste tires is preferred to energy recovery. Due to their relatively low weight and high permeability, tire 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 tire utilization in civil engineering applications is relatively narrow and the amount of tires used in these applications is limited. It is essential to seek other beneficial and practical uses to consume huge scrap tire stockpile.

Using Scrap Tires for Energy Dissipation

The damping property of rubber within waste tires 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. Laminated rubber bearing is currently the most commonly adopted seismic isolation system, but the application is not extensive due to the tremendous costs with implementation. There has been increasing interests in the development of alternative low-cost earthquake protection systems for use in developing countries, where there are affordability issues with employing expensive resources and state-of-the-art technology for infrastructure protection. Utilizing rubber tires in earthquake hazard mitigation can be a viable approach of resolving the chronic problems associated with waste tire disposal and costly provisions for earthquake protection of the infrastructure.

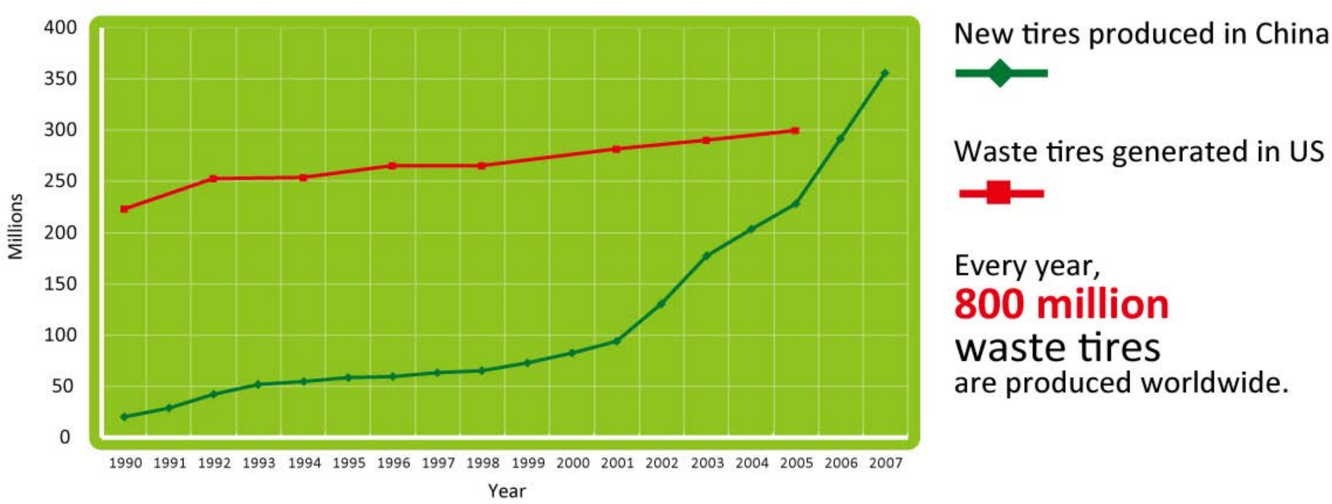

Fig. 1. The scrap tire problem in the United States and China.

The use of RSM provides a promising way to reduce the huge stockpile as a large volume of tires can be utilized in each project. For a typical building considered in Tsang (2008), the bulk volume occupied by RSM is around 42,000 m^3. Assuming a bulk density of 0.8 of the RSM, for RSM with 75 percent rubber by volume, 25,200 m^3 of solid volume of rubber is required. Since a typical passenger tire contains around 70 percent of rubber (Dhir *et al.*, 2001), over four million passenger tire equivalents (equivalent to 40,000 tons) can be consumed, given the density of rubber of 1,100 kg/m^3. This amount is well beyond the consumption of scrap tires in typical civil engineering projects.

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 modeling are 17.4 and 9.5 kN/m^3 respectively. Given that Poisson's ratio (ν) has little effects on the performance of RSM in terms of its energy dissipation and isolation characteristics, a single value of $\nu = 0.3$ was adopted in the study.

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 modeling soil dynamic properties, in which the non-linear 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 (degradation of the shear modulus) and damping ratio have been plotted in Fig. 2.

FINITE ELEMENT MODELING

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 behavior of a soil-foundation-structure system (refer Fig. 3). The superstructure is modeled 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.

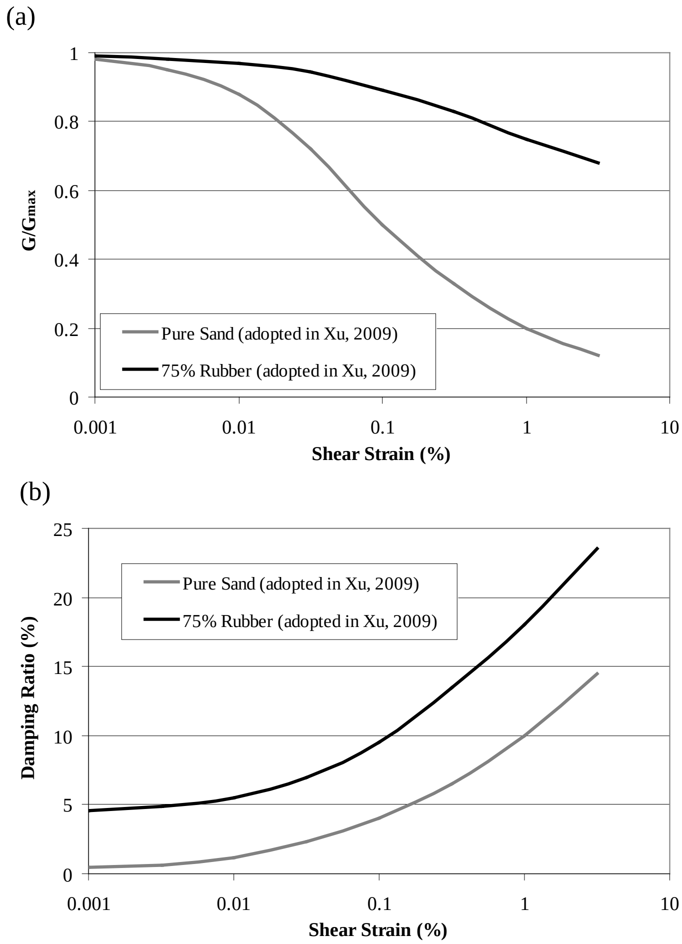

Fig. 2. (a) Shear modulus degradation curves and (b) damping curves of RSM75 (Xu, 2009).

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 Fig. 3. The soil layers surrounding the foundation (pile system as shown in Fig. 3) 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 Fig. 3 (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/).

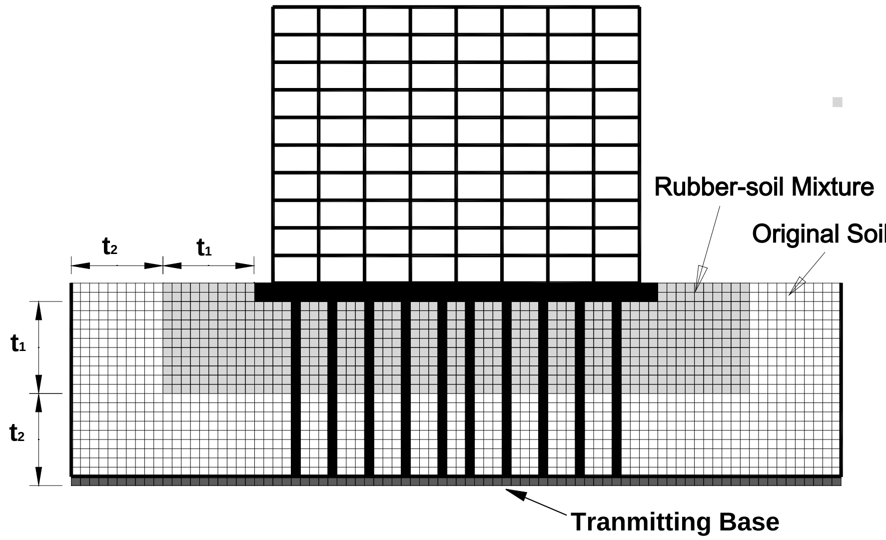

Fig. 3. Schematic drawing of the finite element mesh for modeling the proposed earthquake protection scheme.

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 4(a) and (b) show the corresponding normalized roof and footing horizontal acceleration time histories of the reference scenario. Each of these time-histories has been normalized with respect to the maximum absolute acceleration of the control scenario in which pure sand was used for the construction of the foundation. Figure 4(c) shows the inter-storey drift time-history of the first floor (which has been normalized 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 Fig. 4(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).

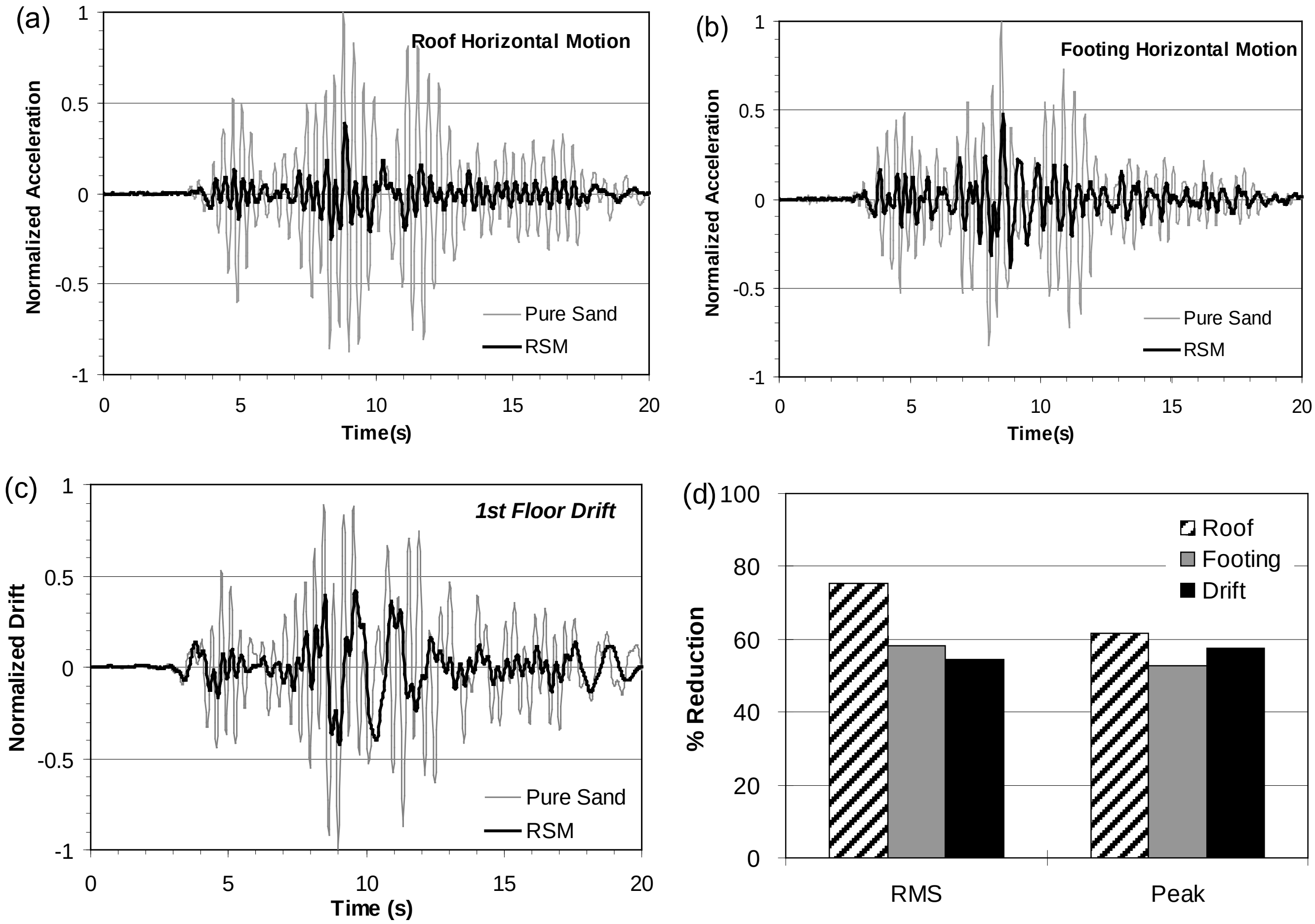

Fig. 4. Normalized time histories of (a) roof and (b) footing horizontal acceleration, and (c) first-floor inter-storey drift for the reference scenario. (d) Root-mean-square (RMS) and peak acceleration and drift percentage reduction values.

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.

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 also applies to the worst-case scenarios considered in the parametric study.

DISCUSSION

For a newly proposed technology, it is sensible that some hidden problems may exist and it is essential to carefully evaluate, investigate and criticize the proposed method. In this section, key considerations associated with the conception and implementation of the proposed earthquake protection method using RSM are outlined under separate sub-headings to prompt further discussions and investigations.

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 Stories	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.*
RMS = Root-mean-square.

Liquefaction

The two most important factors accounting for the occurrence of liquefaction include (i) the cohesiveness and density of the soil deposits and (ii) the intensity of the earthquake shaking. As this isolation method requires partial replacement of the soil materials with RSM, it is essential to consider whether it would increase the risks of liquefaction in a severe earthquake.

As the density of RSM is reduced from 17.4 kN/m^3 (of pure sand) to 9.5 kN/m^3, this may lead to a decrease in the shear strength and potentially increase the risks of liquefaction. Preliminary studies by Promputthangkoon and Hyde (2007) have shown that the addition of small quantities of tire chips would reduce the cyclic shear strength of RSM. However, experimental investigations show that shear strength of loose sand with an addition of more than 10% of tire chips could be greater than that of dense sand (Edil and Bosscher, 1994).

Various studies of the engineering properties of RSM have also demonstrated a significant increase in the cohesion intercept (commonly referred to as the *c*–value) (Masad *et al.*, 1996). Moreover, rubber normally has higher frictional angles (commonly referred to as the ϕ–value) than normal soils (Edil and Bosscher, 1994) and the ϕ–value increases with the percentage of shred contents in the mix (Foose *et al.*, 1996). In addition, randomly mixing tire chips can reinforce sand, resulting in greater shear strength than that of pure sand at its densest state. Densification can be carried out to reduce the void ratio and thus increase the density in order to minimize liquefaction.

Concerning the intensity of ground shaking, it is noted from the previous section that both the peak and root-mean-square (RMS) ground accelerations can be lowered by the beneficial energy dissipation (damping) actions of RSM which in turn would lower the risks of liquefaction developing.

Non-linear Site Response

It is well recognized that non-linear site response behavior can be resulted from soils experiencing moderate to high levels of shear strains. As stated in Hauksson and Gross (1991), most damage is caused by soft, near-surface ground conditions. Hence, it may be reasonable to infer that RSM might not be beneficial in terms of reducing the level of ground shaking. However, a more recent study by Trifunac (2003) illustrated that buildings on softer soils were damaged to a lesser degree under strong ground shaking (e.g. peak ground velocity > 200 mm/s) due to energy absorption of incident seismic waves by virtue of the non-linear behavior of the soil. In fact, soft soils can potentially act as a natural mechanism for passive isolation, especially for near-field earthquakes that are rich in high-frequency contents. In view of the excellent energy absorption capability of rubber, the proposed use of RSM is expected to realize its potential in terms of mitigating site responses.

Internal Heating of Scrap Tires

The possibility of internal heating of scrap tires had been of such a great concern, its civil engineering applications were once almost halted. Self-heating reactions were noted in tire shred fills in 1995 (Humphrey, 2005), leading to the development of guidelines for limiting internal heating. Following these incidents, a considerable number of projects have been completed, in accordance with those guidelines and the (subsequently published) Standard Practice for Civil Engineering Applications of Scrap Tires (ASTM D6270-98), to alleviate the potential problems. The success of these projects have boosted the number of scrap tires used in civil engineering applications ever since.

Ground Settlement

Since tire shreds and RSM are highly compressible (Promputthangkoon and Hyde, 2007), they are prone to ground settlement. However, it has been demonstrated that the compressibility of tire shreds decreases substantially upon the application of loads (Edil and Bosscher, 1994). Preloading can thus be adopted after the construction of fill to eliminate plastic compression resulting in permanent settlement. Although an embankment constructed with pure tire shreds settles slightly more than that constructed with normal soil fills, embankment sections made up of tire shreds and overlain with a soil cap (in the order of 1 m thick) can significantly reduce compressibility of the fill (and performing as well as a normal embankment on soil fills).

Environmental Effects

Long term environmental issues associated with the use of recycled rubber, such as groundwater contamination and impacts on local ecology, have been the subject of intense debate. From previous laboratory tests and field studies (Liu *et al.*, 2000), both the concentrations of metallic components and organics were found to be well below the standards specified in two protocols in the United States, namely, Toxicity Characteristics Leaching Procedure Regulatory Limits and Extraction Procedure Toxicity, proving that recycled scrap tire is not a hazardous recycled material.

The increase in iron and manganese levels arising from the use of scrap tires has also been a common cause of concern. However, iron level is only an issue with the aesthetic (and taste) of the water for domestic consumption as opposed to being a health concern. Furthermore, naturally occurring manganese is common in ground water in many areas. It can be concluded that there is little or no likelihood of significant leaching of substances from tire chips that are of specific public health concern.

NEW CLASSIFICATION OF SEISMIC ISOLATION SYSTEMS

The two new types of geotechnical seismic isolation systems (smooth synthetic liners and rubber-soil mixtures) can be analogous to the conventional structural seismic isolation systems using spherical sliding bearings and laminated rubber bearings respectively (refer Fig. 5 for comparison) (Tsang, 2009). Both laminated rubber bearings and RSM layer decouple the building structure from ground motions by interposing elements or materials of low stiffness in between. The conventional approach of base-isolating a building using rubber bearings is based on shifting the fundamental frequency of the structure away from the dominant frequencies of the applied excitations and to channel, and dissipate, most of the energy at the bearings. In contrast, the RSM layer is designed to modify the dominant frequency of the incident seismic waves and dissipate their energy (particularly energy associated with the high frequency wave components) prior to these waves reaching the structure. On the other hand, both spherical sliding bearings and geosynthetic liners are designed to limit the transfer of shear across the isolation interface where frictional resistance is low, and hence, the level of shaking transmitted to the structure could be reduced.

On the other hand, the two geotechnical seismic isolation methods can be generalized as a *distributed seismic isolation system*, which involves isolating the entire contact surface of the foundation structure. This feature is clearly distinctive from conventional systems which are based on isolation at certain discrete supporting points.

CONCLUSIONS

This paper presented a promising 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 tires as the rubber material can provide an alternative way of consuming huge stockpiles of scrap tires 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. In addition, five important issues regarding the concept and feasibility of the proposed method have been identified and discussed.

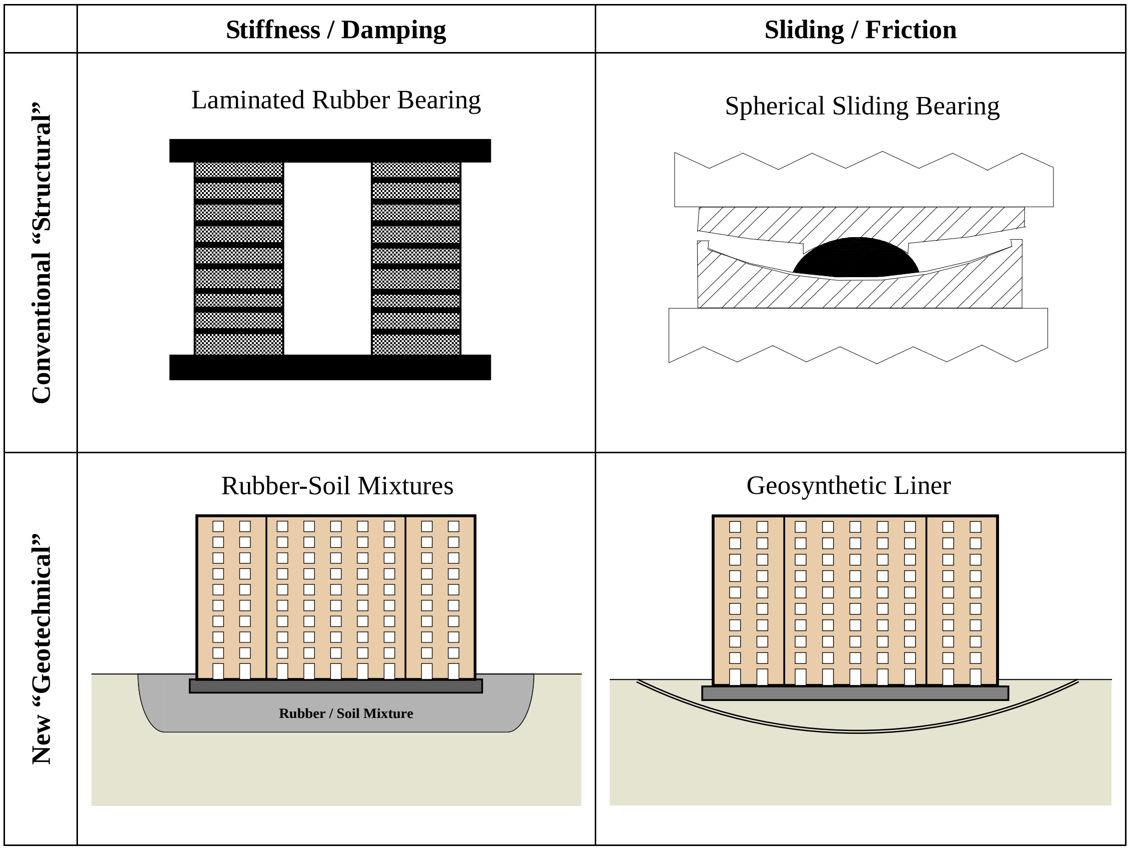

Fig. 5. Proposed classification of seismic isolation systems (Tsang, 2009).

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