QUSHION: EARTHQUAKE PROTECTION BY RUBBER-SOIL MIXTURES

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ABSTRACT :

This paper presents a promising earthquake protection method by placing rubber-soil mixtures (RSM) around the foundation of structures for absorbing seismic energy and exerting a function similar to that of an earthQuake cUSHION, named hereafter as "QUSHION". The validity of the method has been demonstrated by numerical simulations. A parametric study was carried out to evaluate the effectiveness and robustness of this method.

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 low cost of this proposed seismic isolation methods can greatly benefit developing countries where resources and technology are not adequate for earthquake mitigation using well-developed, yet expensive, techniques.

KEYWORDS: seismic isolation, rubber, soil, developing countries, scrap tire, damping

1. INTRODUCTION

In the past century, earthquakes have killed an average of over 20,000 people a year throughout the world, with 90% of fatalities occurring in developing countries. It is believed to be the most important, yet underrated, challenge that the global earthquake engineering community is facing. It is impossible to prevent earthquakes from occurring, but it is possible to mitigate the disastrous effects of strong earthquake shaking in order to save lives and properties. More efforts are indeed required to address this problem by, for example, forming international networks to promote collaboration and information sharing, putting greater emphasis on small-scale local advocacy, and so forth. Another way is to encourage more research into inadequately engineered construction and low-cost earthquake protection techniques.

1.1. Seismic Isolation for Developing Countries

Seismic isolation aims at reducing seismic loads induced by earthquake excitations, which can greatly minimize the damage induced in a structure, and hence save on costs of repair. However, due to the high cost of implementation, these base isolation techniques are only applied in structures with critical or expensive contents.

There is an increasing interest in applying seismic isolation technology to public housing, schools and hospitals in developing countries where the replacement costs due to earthquake-induced damage could be significant. United Nations Industrial Development Organization (UNIDO) has been instrumental in developing low-cost seismic isolation systems using natural rubber-based bearings for the protection of housing and other structures in earthquake-prone developing countries. Efforts have been put in to develop low-cost isolation systems for developing countries (Kelly, 2002), and several demonstration projects are in place in countries like Indonesia.

In recent years, novel seismic isolation methods have been proposed, of which the flexible or sliding interface is in direct contact with geological sediments and the isolation mechanism primarily involves geotechnics. For example, Kim and Konagai (2001) has proposed a method of covering a tunnel lining with a soft and thin coating for reducing deformation under earthquake shaking. Smooth synthetic liners have been proposed underneath the foundation of structures or between soil layers for dissipating seismic energy through sliding (Yegian and Kadakal, 2004; Yegian and Catan, 2004); and rubber-soil mixtures (RSM) have been proposed around the foundation of structures for absorbing seismic energy and exerting a function similar to that of an earthQuake cUSHION, named hereafter as "QUSHION" (Tsang, 2008). The low cost of these proposed seismic isolation methods can greatly benefit developing countries where resources and technology are not adequate for earthquake mitigation using well-developed, yet expensive, techniques.

The aforementioned seismic isolation methods involving geotechnics could be collectively named "*Geotechnical Seismic Isolation*", in contrast to the commonly used "*Structural Seismic Isolation*". In the following sections, the background and principles of QUSHION will be introduced, followed by the latest research findings. For a newly proposed technology, it is reasonable that some hidden problems may exist and it is essential to carefully evaluate, investigate and criticize the proposed method. Potential problems related to the concept and feasibility of QUSHION, as well as further research directions, will be identified and discussed.

2. BACKGROUND AND PRINCIPLE

The proposed QUSHION is shown schematically in Figure 1. The building structure has a typical dimension [10-storey and 40 m width (w)] of a residential or office building. Surrounding the footing of a low-rise building, a layer of soil was replaced by soil mixed with a designated proportion of rubber (i.e. RSM) of thickness (t) in the order of 10 m. For high-rise building, RSM layer could be placed around the pile cap.

The rationale of this method can be explained by fundamental wave theory, in which transfer function $\mathbf{T}(f)$ can be defined to describe the ratio of displacement amplitudes at the top (surface) and bottom (top of halfspace) of the RSM layer [refer Tsang (2008) for details]. It was shown that only a narrow bandwidth of seismic waves (at around 1–2 Hz) would be amplified, while significant reduction can be seen for other frequency ranges. It is noted that the amplification function is expected to be dependent on the geometry and the material dynamic properties of the RSM layer. The importance of the material damping property leads to the proposed use of rubber, which will be further discussed next.

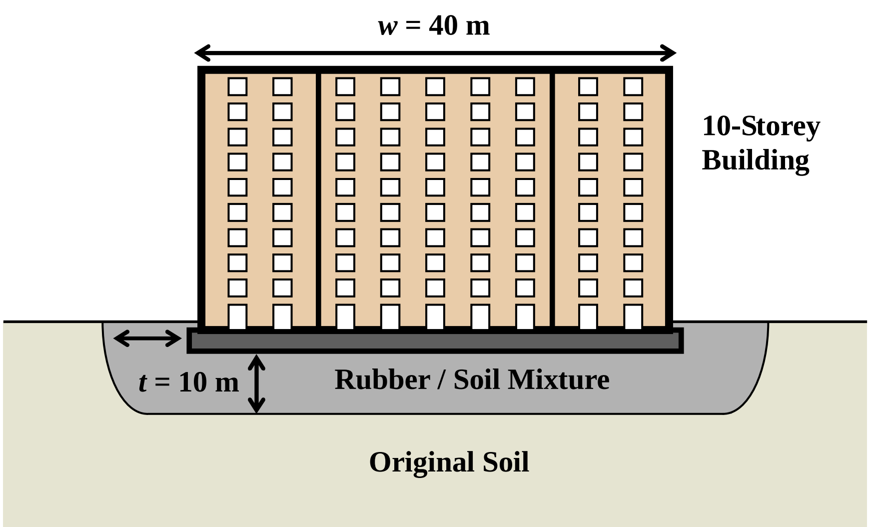

Figure 1 Seismic isolation by a layer of rubber-soil mixture (RSM) (Tsang, 2008).

2.1. 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. More details of the engineering properties of rubber-reinforced soils will be discussed later.

It is generally believed that recycled rubber will become an important component in base isolation in the near future, and scrap tires potentially provide a huge source of rubber material required for the proposed method. 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.

In recent years, the disposal of scrap tires has become a significant environmental problem. Hundreds of millions of scrap tires are disposed every year worldwide as a consequence of the huge increase in the number of vehicles on our roads. Just in the United States, about 300 million scrap tires were generated in 2005 and the number is expected to rise by approximately 2% every year, let alone the whole world.

Since the ban of used tires from landfills in the European Union and several states in the United States, proper uses of scrap tires have become a hot topic among the engineering community. Owing to the high energy content of tires, uses of scrap tires as fuel for energy recovery have been the main outlet of the stockpile 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. From the perspective of sustainability, reusing and recycling of waste tires is preferred to energy recovery. Tire shreds can be applied in civil engineering applications, for instances, highway embankments, landslide stabilization and backfill for retaining walls and bridge abutments.

The use of RSM as QUSHION provides a promising way to reduce the huge stockpile as a large volume of tires can be utilized in each project. Taking the **Reference** scenario in Figure 1 as example, 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% rubber by volume, 25,200 m^3 of solid volume of rubber is required. Since a typical passenger tire weighs 9.1 kg and contains around 70% 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.

3. FINITE ELEMENT MODELING

3.1. 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 in Tsang (2008) are 17.4 and 9.5 kN/m^3 respectively. Given the fact that Poisson's ratio has little effects on the results, different values for different materials were deemed not essential and a single value of 0.3 was chosen.

Dynamic properties of soils are well known for their significant dependence on soil shear strains. The computer program used in this study, *QUAD4M* (Hudson, 1994), employs the commonly adopted 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. *QUAD4M* is a dynamic, time-domain, two-dimensional finite element program, and is a robust analysis tool that has been used extensively.

The dynamic properties of RSM have been investigated by Feng and Sutter (2000). The maximum values of shear modulus of soil (G_{max}) [when shear strains are very small (10^{-5} – 10^{-3} %)] adopted for sand and RSM75 are 222 and 7.5 MPa respectively. The strain dependent G/G_{max} ratio (degradation of the shear modulus) and damping ratio have been plotted in Figure 2. Large uncertainty in estimating the dynamic properties of soil materials is unavoidable, and thus tolerance of around plus and minus 10% has been allowed in modeling the shear modulus degradation and damping. The notional upper bound and lower bound curves have been plotted with dashed lines in Figure 2.

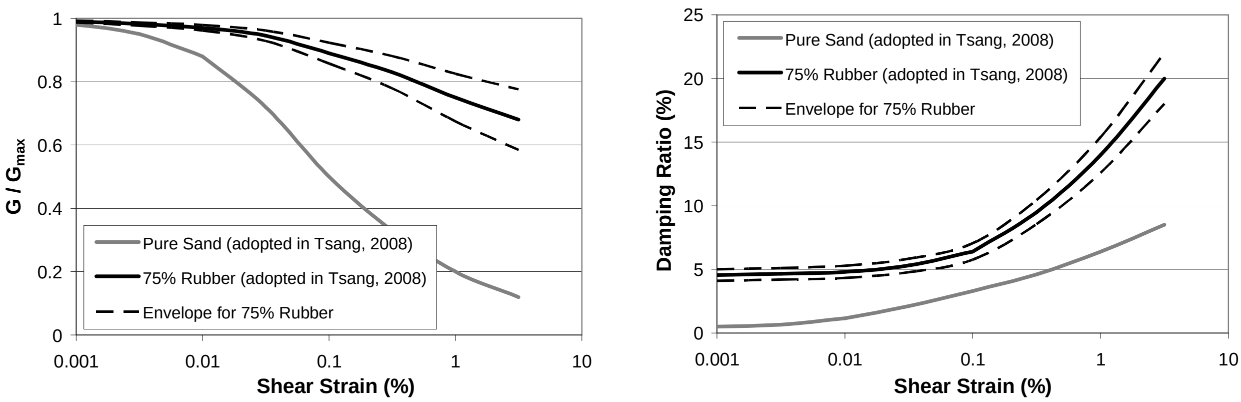

Figure 2 (a) Shear modulus degradation curves and (b) damping curves (Tsang, 2008).

3.2. Numerical Simulations

To demonstrate the feasibility of QUSHION, a series of numerical simulations was performed. The configuration described in Figure 1 was adopted as the **Reference** model. Robustness analysis was conducted to examine a number of important variables, which included number of storeys and width of the building, depth of underground structure (annotated as ***F*** in Figure 3), thickness of RSM, discrepancies in dynamic properties of RSM, earthquake ground motions with different shaking levels and frequency contents. Details can be found in Table I. 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 (bolded in Table I). The purpose of this comparative analysis was to test the robustness of the results to each input parameter.

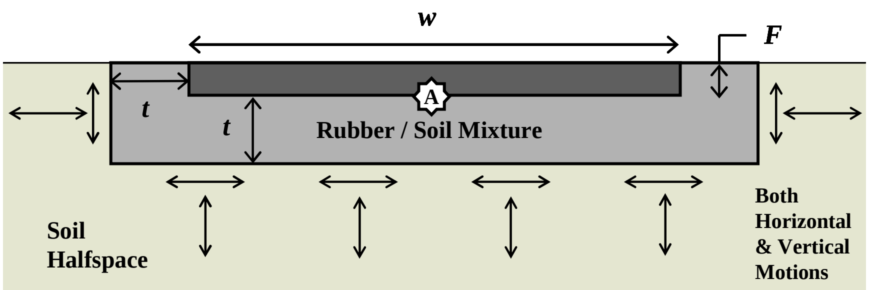

Figure 3 Simplified model for finite element analysis using *QUAD4M*.

In most cases, the most severe damages were caused by near-field earthquakes with strong ground shaking, so ground motions which are rich in high frequency seismic wave components were the focus of the analysis (Tsang, 2008). Peak and root-mean-square ground accelerations, both horizontal and vertical, were chosen for the comparison of the effectiveness in different scenarios. Normally, the location where earthquake motion is applied for structural analysis is at the base of the footing or pile cap. Hence, the acceleration time histories were collected at the point annotated by the letter "A" in Figure 3. For simplicity, the weight of the whole building structure was condensed to the footing, leading to different "equivalent" densities of elements for different scenarios listed in Table I. This simplification is reasonable provided that ground accelerations, but not structural responses, were chosen for comparison.

Table I Input parameters used in the parametric study (Tsang, 2008).

Input Parameter		**Reference**		
Thickness of RSM ***t*** (m)	5	**10**	20	
Dynamic Properties of RSM	– 10%	**Median**	+ 10%	
Building Width ***w*** (m)	20	**40**	80	
Number of Storeys	5	**10**	15	
Depth of Underground Structure ***F*** (m)		**3**	7	10
Peak Horizontal Acceleration (g)	0.45 – 3.56 (refer Table II)			
Peak Vertical Acceleration (g)	0.33 – 2.10 (refer Table II)			

The model was subjected to three earthquake ground excitations, which cover different frequency contents and a wide range of ground shaking levels, both horizontal and vertical, as shown in Table I. They are, respectively, 1994 Northridge, California earthquake, 1985 Valparaiso, Chile earthquake and 1999 Duzce, Turkey earthquake. An additional set of strong-motion data was obtained by multiplying the 1994 Northridge, California earthquake by a factor of two (equivalent to around one unit increase in earthquake magnitude), in order to give a stronger shaking level.

Figures 4(a)–(b) show the *Fourier* amplitude spectra (*FAS*) of the horizontal and vertical ground accelerations respectively, in which the *FAS* of the scenarios of placing RSM and pure sand were plotted. Figures 4(c)–(d) present the corresponding normalized horizontal and vertical ground acceleration time histories of the two scenarios. Each time history was normalized by the respective maximum absolute ground acceleration of the scenario with pure sand for convenient observation of the reduction ratio and for direct comparison.

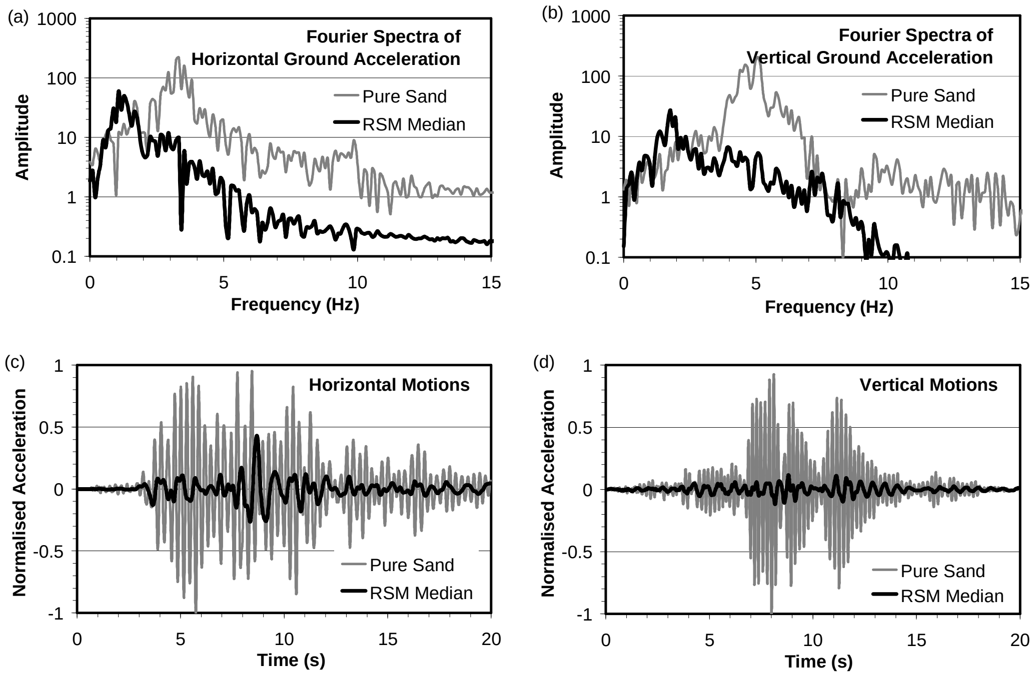

Figure 4 The *Fourier* amplitude spectra (*FAS*) of the (a) horizontal and (b) vertical ground accelerations; and the corresponding normalized (c) horizontal and (d) vertical ground acceleration time histories for the **Reference** scenario (Tsang, 2008). *Notes*: In each figure, the scenarios of placing RSM and pure sand were plotted. Each time history was normalized by the respective maximum absolute ground acceleration of the scenario with pure sand.

In Figures 5(a)–(f), the effectiveness of acceleration reduction is shown. The "Acceleration Ratio" (in %) refers to the ratio of the ground acceleration obtained from the model with RSM to that obtained from the model with sand. It is obvious that QUSHION can effectively reduce both horizontal and vertical ground accelerations in all cases, even for the worst-case scenarios presented. On average, the acceleration ratio is in the order of 30–40% for horizontal motion and 10–20% for vertical motion. The importance of vertical ground motion will be further discussed in the following sub-section.

It is noted in Figure 5(b) that the result is most sensitive to the thickness of RSM. In particular, the horizontal acceleration ratio changes from around 20% to 60% with respect to the thickness of RSM of 5 to 20 m. In Figures 5(c)–(d), significantly higher effectiveness can be observed in reducing horizontal acceleration for heavier structures which are represented by a greater height or width of building, but the vertical acceleration ratio only varies slightly. On the other hand, increasing the depth of underground structure is relatively ineffective in the reduction of acceleration (Figure 5(e)). A clear trend is yet to be seen in different earthquake scenarios which include a wide range of shaking levels and frequency contents (Figure 5(f)).

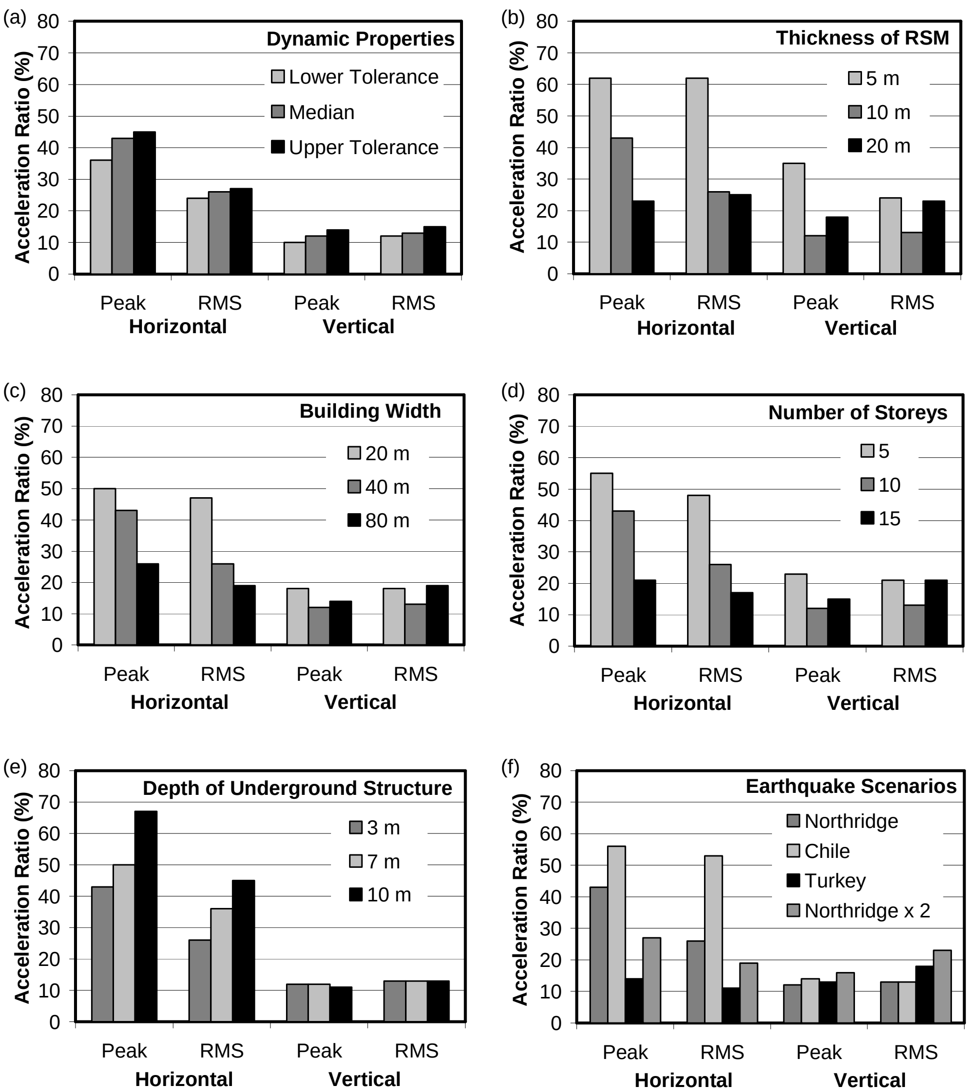

Figure 5 Comparison of the acceleration ratio, with respect to different (a) dynamic properties of RSM; (b) thicknesses of RSM; (c) building widths; (d) number of storeys; (e) depths of underground structure; and (f) earthquake scenarios (Tsang, 2008). *Notes*: Only one input parameter was varied in each case, while all other input parameters were held constant at the default values specified for the **Reference** scenario.

3.3. Vertical Ground Motion

In the past few decades, characteristics of horizontal earthquake ground motion, as well as their effects on structures, have been extensively examined. It was not until recently that investigations on vertical ground motion were initiated. Strong vertical ground motion was studied by Papazoglous and Elnashai (1996) and field evidence from recent earthquakes on their destructive effects on structures was collated. It was discovered that vertical motion might increase axial column forces, moment and shear demands and also reduce the ductility level in columns and moment/shear capacity in beams.

It was also learnt that the ratio of vertical to horizontal (V/H) response spectra increases with decreasing source-site distance at high frequencies (Bozorgnia and Niazi, 1993). This means that the effects of vertical ground motion are more critical to structures with short natural periods under near-field earthquakes. In view of such characteristics, both short-period structures and near-field earthquakes with strong shaking levels were chosen for demonstration in this study.

4. DISCUSSION

4.1. Nonlinear Site Response

It is well recognized that nonlinear response behaviour can be resulted from soils yielding at moderate to high levels of strains. As stated in Hauksson and Gross (1991), most damage was caused by soft, near-surface ground conditions. Hence, it might be reasonable to deduce that RSM may not be beneficial in reducing the level of ground shaking. However, Trifunac (2003) illustrated that buildings on softer soils were damaged to a lesser degree under strong shaking (e.g. peak ground velocity > 200 mm/s) due to energy absorption of incident seismic waves by nonlinear soil response. 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 wave components. Considering the excellent energy absorption capability of rubber, it is therefore believed that QUSHION should be feasible.

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 to as soil resonance. Considering the replacement of certain thickness of surface geological deposits with RSM, the stiffness (and in turn the natural frequency) of the materials beneath the structure would be significantly modified and the potential harmful effects should not be ignored. Although this problem could not be seen in the numerical simulations mentioned in the previous section, further investigation on soil resonance effects is required.

If the natural frequency of the site can be modified, with specific design of the configuration and properties of the RSM layer, to a frequency which is not close to the dominant frequency of the incident seismic waves, the level of shaking can then be further reduced in addition to energy dissipation by RSM. This is actually the underlying philosophy of the commonly adopted seismic isolation system.

4.3. Liquefaction

Liquefaction is the state when saturated sandy soil loses shear strength and effective stresses are reduced as a result of increased pore water pressure. The two most important factors accounting for the occurrence of liquefaction include (1) the cohesiveness and density of the soil deposit and (2) the level of shaking. As this isolation method requires partial replacement of the soil materials with RSM, it is essential to consider whether it would increase the liquefaction potential during earthquakes.

As mentioned in the previous section, 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 enhance the possibility of liquefaction occurrence. Preliminary studies by Promputthangkoon and Hyde (2007) have shown that the addition of small quantity of tire chips reduces the cyclic shear strength of RSM. However, there is evidence to show that the shear strength of loose sand becomes greater than that of dense sand with an addition of more than 10% tire chips (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 content 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 ground accelerations can be lowered by the damping effects of RSM, thus reducing the probability of liquefaction occurrence. Nevertheless, remedial measures against liquefaction could still be carried out during the construction process.

4.4. 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. Although an embankment constructed with pure tire shreds settles slightly more than that constructed with soils, embankment sections composed of tire shreds that are overlain with a soil cap (of the order of 1 m thickness) can significantly reduce the compressibility and deflections, performing equally well as those constructed with soils. Also, settlement can be decreased by compaction, through which soil particles are packed more closely and air voids are reduced with the addition of either static or dynamic forces.

4.5. 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, 2000), 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, 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 is also a common concern. However, iron level is only specified in the aesthetic drinking water standard (taste), rather than of health concern. Furthermore, manganese is naturally present in ground water in many areas. It can thus be concluded that there is little or no likelihood of significant leaching of substances that are of specific public health concern from tire chips.

5. NEW CLASSIFICATION OF SEISMIC ISOLATION SYSTEMS

An interesting feature of the two new types of geotechnical seismic isolation systems (smooth synthetic liners and QUSHION) is that they are analogous to the conventional structural seismic isolation systems using spherical sliding bearings and laminated rubber bearings respectively (refer Figure 6 for comparison). Both laminated rubber bearings and QUSHION decouple the building or structure from ground motions by interposing elements or materials of low stiffness in between. While the rubber bearings shift the fundamental frequency of the isolated structure and concentrate the deformation and energy dissipation demands in the isolation system, QUSHION modifies the dominant frequency of the incident seismic waves and dissipates the seismic energy of high frequency components in particular. On the other hand, both spherical sliding bearings and geosynthetic liners limit the transfer of shear across the isolation interface which has a low level of frictional resistance, and hence, the levels 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 the conventional systems which are based on isolation of certain discrete supporting points. Further research can be directed to the development of the *distributed seismic isolation system*.

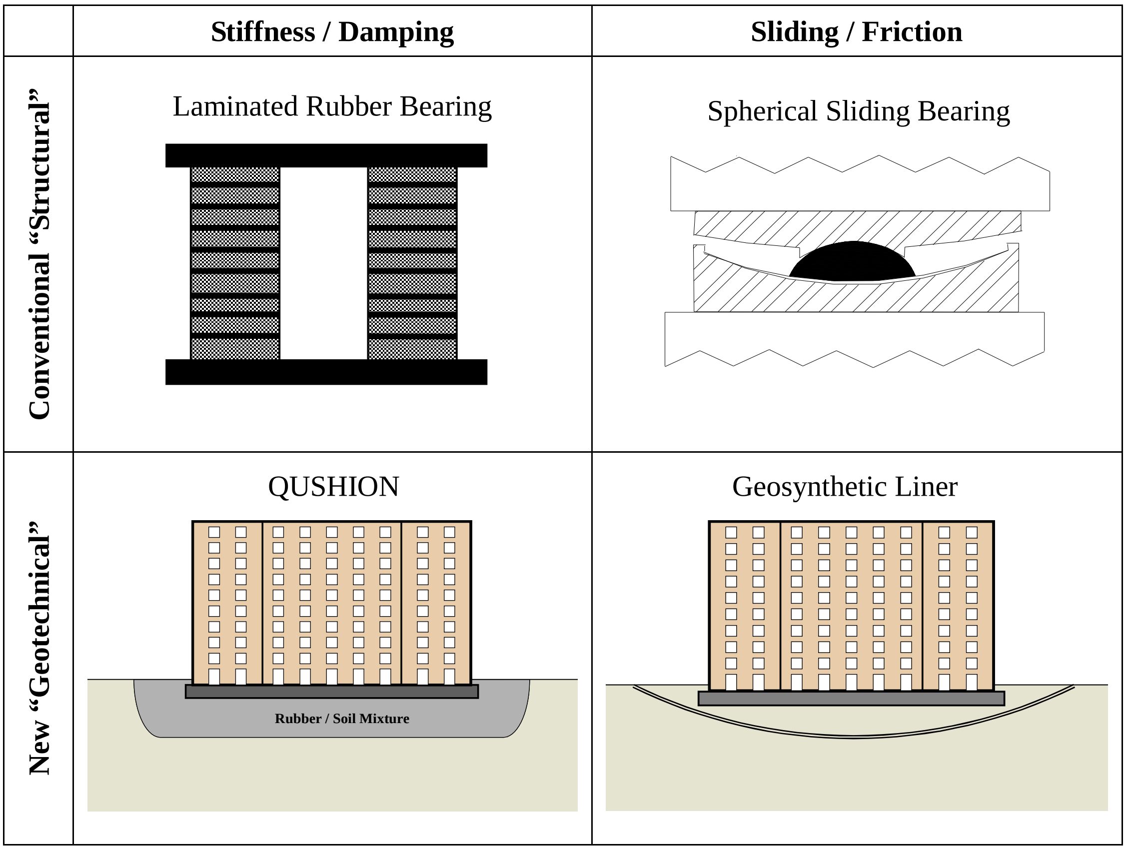

Figure 6 Proposed classification of seismic isolation systems

6. CLOSING REMARKS

Undoubtedly, earthquakes have been causing unacceptably large numbers of deaths and injuries in developing countries. The vulnerability of megacities in the developing world is much greater where the average number of victims can be 150 times larger than that in the developed world, and the economic loss (as a percent of Gross National Product) 20 times greater (Wenzel *et al.*, 2007).

In the past few decades, rapid urbanization can be seen all over the world, while most of this has occurred in developing countries, owing to the breakdown of the rural economy and the consequential migration of rural population to urban areas, leading to the emergence of megacities, such as Mumbai, Dhaka and Jakarta. It is foreseen that the vulnerability in developing countries will continue to increase. Severe devastation and high death tolls could result if a major earthquake occurs in one of these megacities, where fragile buildings and infrastructures prevail.

It is time for us all, as earthquake professionals, to meet the most important challenge ahead and to make the built environment safer worldwide. ***If not now, when? If not us, who?***

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