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SEISMIC ISOLATION USING RECYCLED TIRE-RUBBER

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Abstract

Geotechnical seismic isolation using rubber-soil mixtures appears to be a promising alternative to protect structures deployed over large extensions of land, such as low-income condominiums or industrial plants. The use of isolating soil layers may have several advantages and trade-offs in comparison with conventional seismic isolation. It is apparent that some of the advantages are the protection given to whatever is erected on top of a mixed soil layer, the avoidance of maintenance needed for the isolation system, the reuse of an environmentally unfriendly material through recycling, and the potentially lower cost per square meter. The usefulness of the proposed geotechnical seismic isolation concept is demonstrated by means of an inelastic model consisting of a simple linear structure underlain by a non-linear rubber-soil mixture. Layers of variable depths are considered and evaluated for a suite of 60 different seismic records. It is shown that an underlying layer of rubber–soil mixture of about 2 meters in thickness could reduce significantly the seismic demands on the structure. Indeed, the reduction ratio R of the peak acceleration obtained at the base of a structure for the three different rubber-soil mixtures (denoted as RSM-A, RSM-B and RSM-C) are R = 0.82, 0.60, and 0.46, respectively. In general, a thickness for the RSM layer between 2 and 3 meters is likely to achieve adequate levels of acceleration reduction. This is in stark contrast to the large thicknesses recommended elsewhere in the literature. Although the reduction in structural response is enhanced as the rubber content in the mixture is increased, a rubber content as low as 15-25% is found to be enough to attain useful reductions in response.

Keywords: Geotechnical seismic isolation, non-linear inelastic modeling, rubber-soil mixture, recycled tire-rubber,

1. Introduction

In the light of the intensive consumption of tires by modern society, which after the tires wear out are discarded without much ado and accumulate into huge piles, it is imperative to find alternative uses for that waste. A common strategy to recycle tires consists in shredding and grinding these into small rubber particles of varying sizes. One then employs the resulting granular material for miscellaneous industrial and civil engineering applications [1]. In geotechnical engineering, the mix of shredded tires with sand is known as rubber-sand mixture, or RSM, which has a relatively low cost in comparison with other soil aggregates, and is an attractive way of helping reduce the mountains of scrap tires [2]. An application in earthquake engineering consists in placing a shallow and resilient layer of RSM underneath a structural foundation, a mechanism that is known as a geotechnical seismic isolation (GSI) system. Its goal is to reduce the seismic demands on the superstructure by decoupling, to the extent possible, the structure from the ground motion. While a GSI system is conceptually similar to that of conventional elastomeric seismic isolation based on rubber bearings placed at discrete points underneath a building, it differs from it in that the RSM is continuously distributed along the contact surface separating the structure from the ground, and it is thus much easier and economical to construct.

Although this concept is not new, it has yet to be tried in real projects in practice, and this despite its promise from a recycling perspective. Still, efforts are now underway to demonstrate their efficacy in the laboratory [3]. Most of the numerical models available in the literature are based on quasi-linear models. Although such engineering models are widely-used and are adequate when the soil strains remain small, they fail when the material undergoes large inelastic deformations and slip, in which case a truly inelastic model is necessary. This task is taken up herein, where we briefly document the performance of a GSI system inferred from rigorous, non-linear, inelastic models.

2. Mechanical properties of rubber-soil mixtures (RSM)

In general, rubber-soil mixture is characterized by a lower stiffness and a higher damping than pure soil. For this reason, it is expected that when a RSM is used for seismic isolation, it will effect an elongation of the fundamental natural period of the system and elicit also strong inelastic processes which dissipate energy, both of which are thought to cause reductions in the acceleration demands on the structure during an earthquake. For this reasons, it has been suggested that when low-to-medium rise buildings are isolated by means of a GSI, both the horizontal and vertical accelerations could be lowered by an average of 40-60% [4].

Studies on the mechanical properties of various mixtures of sands and/or gravel with rubber have indeed been conducted by various researchers [5, 6]. Moreover, those studies have also examined the effects on stiffness and strength exerted by the size of the shredded rubber particles, which has been accomplished by carrying out tests in which the rubber content, the size of particles, and the distribution of the grain size have been varied in a controlled fashion. Indeed, triaxial as well as torsional resonant column tests have been used to measure the small-strain shear module G_0 and the damping ratio ξ_0 for various rubber-soil mixtures. These reported results should be interpreted with some caution because most laboratory tests can only measure the mechanical properties of soils for shearing strains up to 1%, and no more. Indeed, by the time that the resonant column tests reach the shear strength of the soil, the variation of shearing stress with distance to the torsional axis of the specimen is no longer linear, or even approximately so. Then again, since what matters in a seismic isolation system is the ability of the isolation layer to sustain and dissipate energy through slippage, it then follows that knowledge of the all-important behavior of the rubber-soil mix at very large strains where the material steadily slips along some given failure plane is paramount, yet that behavior can only roughly be surmised via extrapolations from small-strain tests.

Laboratory tests have generally revealed that when the rubber content of a soil mix is gradually increased, all of the following effects are observed, at least up to some moderately large fractions of rubber in the mix, but not when the rubber is the sole material, or it dominates the mix:

- The unit dry weight of the mixture decreases with the rubber content (the mix becomes a lighter material).
- The void ratio of the mixture decreases, which translates into a less porous matrix.
- The small strain shear modulus G_0 steadily decreases with rubber content and this despite the decrease in void ratio. This is because the shear stiffness of clean rubber is some hundred times smaller than that of clean granulated soil, so the overall stiffness of the soil-rubber mix can only decrease.
- The small strain damping ratio ξ_0 increases with the rubber content.
- The shear strength at first increases in tandem with the fraction of rubber, but only up to some maximum percentage, after which it decreases again rather rapidly and the mixture changes from sand-like to rubber-like behavior [7].
- Inasmuch as rubber is largely incompressible, when its fraction is increased, it can be expected that the Poisson's ratio of the mix will also increase.
- The shear velocity v_s decreases with the rubber content.

As is well known, the (moderately) large strain behavior of particulate soils can be characterized by a pair of soil degradation curves $G(\gamma)/G_0$ and $\xi(\gamma)$, namely the secant modulus normalized by the small strain shear modulus and the damping ratio. Both of these parameters depend, in addition to the material characteristics such as the mean grain sizes of soil and rubber D_{50s}/D_{50r}, on the mean confining pressure σ'_m. Thus, the same material will exhibit different degradation curves depending on the depth at which it is lain. Laboratory results for these two degradation curves as function of maximum strain, for different values of σ'_m, quotient D_{50s}/D_{50r}, and a wide range of rubber contents, were presented earlier [5,6].

Among the simplest theoretical models for the interpretation of experimental cyclic test results is the so-called modified hyperbolic model, which uses two parameters to define the non-linearity of the initial loading curve, i.e. the virgin or backbone curve. One of these is the reference strain γ_{ref} defining the strain at which $G/G_0 = 0.5$, and the other parameter is the curvature a, which defines the slope of the curve, or the degree of non-linearity:

$$G/G_0 = 1/(1+\gamma/\gamma_{ref})^a \tag{1}$$

Experiments have indicated that the rubber content has little influence on the value of a, but that the reference strain γ_{ref} does increase with this parameter. When these observations are then supplemented by the observation that the initial shear modulus G_0 generally decreases with the rubber content, it becomes clear that the mixed material must exhibit a more "linear behavior" when cycled at comparable maximum strains, i.e. that the mix requires larger cyclic strains for the non-linear behavior to become manifest. To illustrate these concepts with an actual example, consider a poorly graded dry sand $D_{50s} = 0.5$ mm that has been mixed together with a uniformly graded rubber $D_{50r} = 2.8$ mm. When the rubber content is varied from 0% (pure sand) to 10%, 20% and 35% mixtures of rubber by weight and each mix is subjected to a mean confining pressure of 100 kPa, the experimental results for the small strain shear modulus and the degradation curves are depicted in Figure 1. As can be seen, G_0 is reduced by almost five times (as shown on the top-left subplot) while γ_{ref} increases by up to three times (shown in the top-right subplot) when the maximum amount of 35% rubber is added. For convenience, the strain-shear degradation curves are also plotted at the lower subplot, where the curve for 35% rubber is farthest to the right, i.e. there is much less degradation with strain.

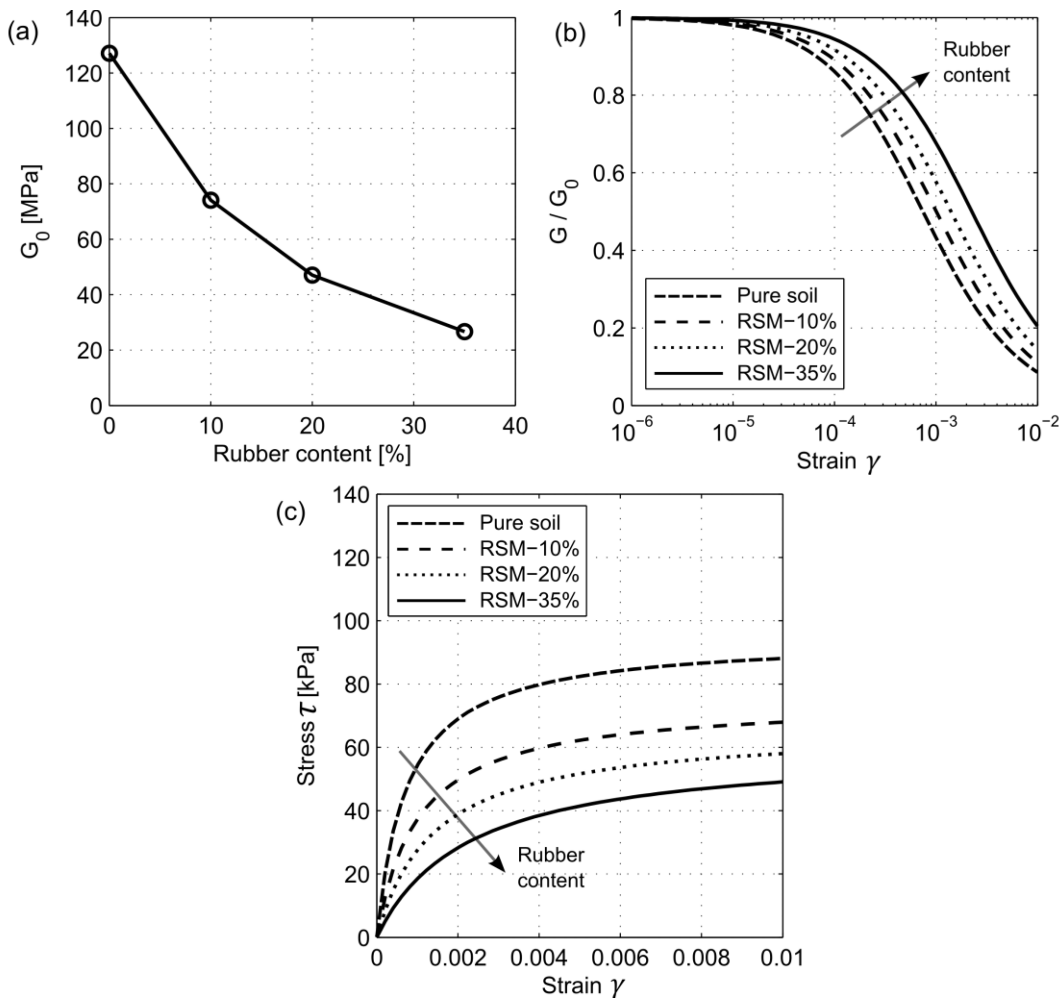

Fig. 1 – Effect of increasing rubber content in the shear properties of a typical soil (a) Initial shear modulus G_0; (b) Shear stiffness degradation curve G/G_0; (c) Stress-strain backbone curve. (Figure taken from [8])

Although a soil without rubber generally dissipates more energy than a mixture of soil and rubber when it is cycled at some given maximum strain (this is because the hysteresis loop is bigger), then again that soil also has a larger stiffness and strength, so that it is very unlikely that it will undergo large levels of deformation when used in the context of a seismic isolation system. Thus, the lower stiffness and strength of the RSM layer allows that layer to experience large shear strains, and therefore, it opens the door for large, energy dissipating deformations to take place, or at least to prevent the transmission of that energy into the superstructure.

We consider three different types of RSM in our analyses, which we denote as RSM-A (with D_{50s}=0.5 mm, D_{50r}= 2.8 mm), RSM-B (with D_{50s} = 3.0 mm, D_{50r} = 2.8 mm) and RSM-C (with D_{50s} = 7.8 mm, D_{50r} = 2.8 mm). Figure 2 shows a particular case of these three types of mixtures when they are all subjected to a confining pressure of 100 kPa and the void ratio of the intact soil is e = 0.5 . The left subplot shows the ratio between the small strain shear moduli G_0^{RSM}/G_0^{PS} of the mix and of the pure soil as the content of rubber is increased. Clearly, when the rubber content is zero (pure soil), this ratio is unity for all the types of RSM. When the content of rubber is 35%, we observe that G_0^{RSM}/G_0^{PS} is equal to 0.2, 0.1 and 0.05 for the RSM-A, RSM-B and RSM–C, respectively, which means that the small strain shear modulus of that mix is five, ten, and twenty times lower, respectively, than that of the pure soil used for the mix. On the other hand, the right subplot shows the shear degradation curves for the three rubber-soil mixtures referred to previously when they have 35% of rubber content, and as expected, the value of γ_{ref} increases for all three mixtures. More specifically, the reference strain is observed to have increased up to 3 times for RSM-A, 4.5 times for RSM-B and 8 times for RSM-C.

3. Previous work in GSI and outline of current model

Previous research on the use of RSM layers for seismic isolation [9] have suggested that the concept is promising and that by using such systems one could expect a significant reduction in structural accelerations, and thus in structural forces. However, available analyses are limited by their reliance on material linearity, which is implicit in their use of iterative dynamic models cast in the frequency domain where the soil stiffness and damping are estimated on the basis of the expected levels of strain – as is done in the well-known computer program SHAKE for the analysis of wave amplification. In addition, since such models operate with frequency-independent parameters and damping is assumed to be constant for all frequencies, they grossly overestimate the dissipation of energy associated with high frequency, secondary hysteresis loops [10]. Another limitation in the models published is that they rely on excessively thick layers of rubber-soil mixtures, to the tune of 5 to 15

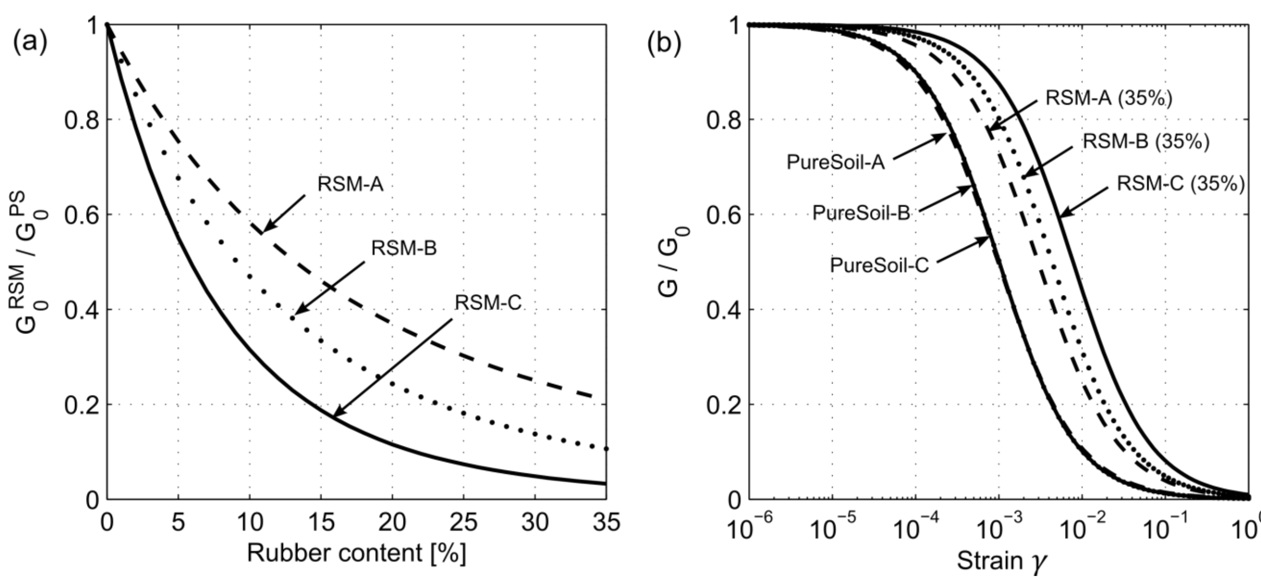

Fig. 2 – Pure soil and RSM curves used for analyses with σ_m=100 kPa: (a) Ratio between small-strain shear moduli of the mix and the pure soil; (b) Stiffness degradation of pure soil and RSM with 35% rubber content. (Figure taken from [8])

meters. These are not only impractical and costly, but require large excavations and fill, and also interfere with space needed for basements and parking facilities. In addition, such very thick RSM layers, which in some cases are made of pure TDA, contravene ASTM recommendations, and are best avoided.

In the light of the previous comments, in the remainder of this article we go on to explore the use of a thin layer of RSM and to assess its performance as a seismic isolation system by means of rigorous, non-linear, inelastic models. The non-linear material characteristics of the RSM are inferred from published data, taking into account the relative percentages of TDA and sand as well as the confining pressure that results from the overburden load emanating from the weight of the upper layers and of the building being supported. In addition, we subject the system to various earthquakes with varying characteristics.

Starting from the experimental, cyclic soil degradation curves for a given soil mix, such as those shown in Figure 2, we use these curves to infer the parameters that define a backbone (or virgin) stress-strain curve, and more specifically, when that curve obeys a hyperbolic model with given shear strength and low-strain shear modulus. We then go on to use this curve in the context of a Massing non-linear model [11], which defines the non-linear behavior at reversal points in terms of the backbone, but which we conveniently implement in terms of the fully equivalent and well known inelastic model proposed by Iwan [12], which consists in a large set of elasto-plastic springs in parallel. The advantage of the Iwan over the Massing model is that it greatly simplifies the algorithmic details in programming, which was carried out in Matlab.

In the analyses presented herein and as shown in Figure 3, the structures as well as the soil profile are modeled as lumped mass, multi–degree of freedom systems subjected to vertically propagating shear waves (i.e. SH waves). Each material, namely the structure, the natural soil and the RSM layer are discretized into thin layers whose thickness h_j is small in comparison to the typical wavelength in the seismic motion. The structure and the nonlinear soil elements are modeled as a set of elasto–plastic springs in parallel in the style of Iwan's model, while the equations of motion are integrated directly in the time domain using the Central Differences Method. The geometric and mechanical properties of each layer can be altered as needed to assign appropriate parameters to the system.

A case study was considered in which reference parameters were established. The set of top layers represent a two-story building of 2.5m inter-story height with a density of ρ_{ST} = 400 kg/m3 and a linearly elastic shear modulus G_{ST} = 1600 MPa. The value for the density was chosen so that the weight of each floor is 1000 kgf/m^2, which is a typical value for the masonry or reinforced concrete buildings with heavy tiled roofs, which are common in Chile. The intermediate set of layers represent the RSM seismic isolation system with a total depth of H_{RSM} = 2 m. The bottom layers, which represent soil placed below the RSM layer, were considered to have a total depth of H_{PS} = 3 m. The isolating layer is assumed to be constituted by either the RSM-A, RSM-B or RSM-C type, whose mechanical characteristics were briefly described previously. The sand phase in the mix was assumed to have a density ρ_{PS}= 2000kg/m^3, void ratio e = 0.6, and coefficient of lateral pressure at rest K_0 = 0.5.

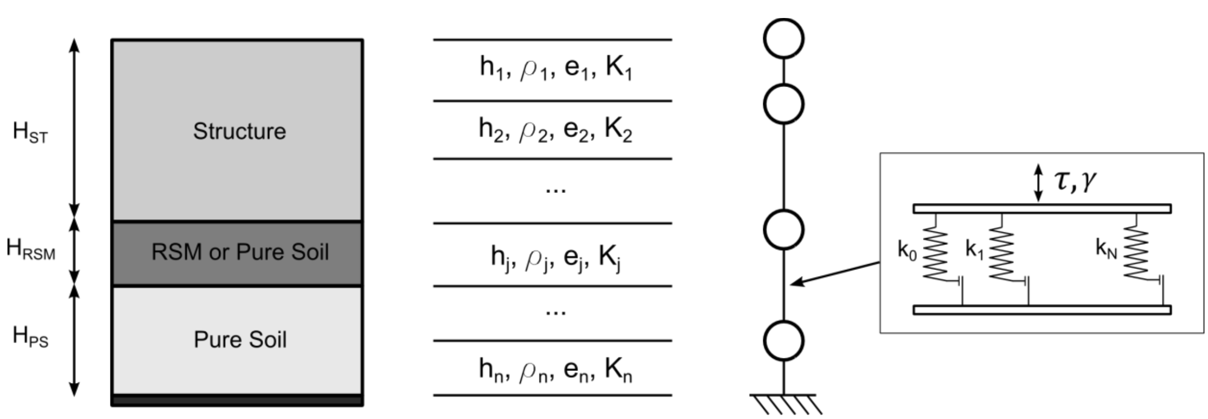

Fig. 3 – Idealization of the structure and soil profile as a multi degree of freedom system. (Figure taken from [8])

Subjecting the non-linear model to seismic motions of varying amplitude and frequency content, the response of the system was evaluated throughout in terms of accelerations, displacements, shear strains and stresses in all of the layers. The seismic motions chosen were taken from acceleration records obtained during various earthquakes in North America, Japan and in Chile. A summary of the seismic motions considered together with their peak accelerations is shown in Table 1, which range between 0.083g (Goldengate N-E, 1957) and 1.778g (Tarzana E-W, 1994). For convenience, the seismic records are sorted in ascending order of PGA, and each record is assigned an ID number that will be used to identify the results presented later on.

Table 1 – Seismic records considered in the analyses

ID	Seismic record	PGA [g]	Earthquake	ID	Seismic record	PGA [g]	Earthquake	ID	Seismic record	PGA [g]	Earthquake
1	Goldengate N-E	0.083	USA 1957	21	Olympia E-W	0.280	USA 1949	41	Talca H2	0.471	Chile 2010
2	Goldengate S-E	0.105	USA 1957	22	Matanzas H1	0.286	Chile 2010	42	Capitola N-S	0.472	USA 1989
3	Casablanca E-W	0.113	Chile 2010	23	Peñalolen E-W	0.293	Chile 2010	43	Llayllay N-S	0.474	Chile 1985
4	Valparaíso H1	0.132	Chile 2010	24	Peñalolen N-S	0.298	Chile 2010	44	Curicó N-S	0.475	Chile 2010
5	Cerro El Roble H1	0.133	Chile 2010	25	Valparaíso H2	0.301	Chile 2010	45	Corralitos H2	0.479	USA 1989
6	Helena E-W	0.145	USA 1935	26	Zapallar E-W	0.305	Chile 1985	46	Maipú E-W	0.488	Chile 2010
7	Casablanca N-S	0.145	Chile 2010	27	Llolleo H2	0.325	Chile 2010	47	Melipilla E-W	0.528	Chile 1985
8	Helena N-S	0.146	USA 1935	28	Viña H2	0.331	Chile 2010	48	Constitución H2	0.538	Chile 2010
9	Olympia N-S	0.165	USA 1949	29	Matanzas H2	0.344	Chile 2010	49	Llolleo H1	0.557	Chile 2010
10	Pichilemu E-W	0.178	Chile 1985	30	El Centro S-E	0.348	USA 1940	50	Maipú N-S	0.560	Chile 2010
11	Cerro El Roble H2	0.188	Chie 2010	31	Llayllay E-W	0.352	Chile 1985	51	Constitución H1	0.626	Chile 2010
12	Ventanas N-S	0.213	Chile 1985	32	Park Field N-S	0.355	USA 1966	52	Kobe E-W	0.629	Japan 1995
13	El Centro S-W	0.214	USA 1940	33	Viña E-W	0.363	Chile 1985	53	Corralitos H1	0.630	USA 1989
14	Viña H1	0.219	Chile 2010	34	Hualane H2	0.382	Chile 2010	54	Melipilla N-S	0.686	Chile 1985
15	Ventanas E-W	0.227	Chile 1985	35	Capitola E-W	0.398	USA 1989	55	San Isidro E-W	0.710	Chile 1985
16	Quillota E-W	0.237	Chile 1985	36	Curicó E-W	0.414	Chile 2010	56	Llolleo E-W	0.712	Chile 1985
17	Viña N-S	0.237	Chile 1985	37	Talca H1	0.415	Chile 2010	57	San Isidro N-S	0.721	Chile 1985
18	Pichilemu E-W	0.259	Chile 1985	38	Park Field E-W	0.434	USA 1966	58	Kobe N-S	0.834	Japan 1995
19	Quillota N-S	0.260	Chile 1985	39	Llolleo N-S	0.445	Chile 1985	59	Tarzana N-S	0.990	USA 1994
20	Zapallar N-S	0.270	Chile 1985	40	Hualane H1	0.451	Chile 2010	60	Tarzana E-W	1.778	USA 1994

4. Simulations with non-linear inelastic models

The model described was used in the context of the parametric analyses alluded to in the previous section, and an assessment was made on the effectiveness of the RSM layer as a seismic isolation system. Out of many analyses we present typical results obtained for one particular case, as described next.

Consider a two-story building underlain by a 2m depth RSM-B layer with 35% rubber content, which is subjected at the base to the Corralitos H2 (1989) earthquake. The stress – strain loops response are shown in Figure 4. The subplots on the left show the response of the soil without rubber (i.e. non-isolation layer), while the subplots on the right show the response for the isolating case. The upper row of subplots show the stress–strain response of the building, measured at mid height in the structure, which is some 40% lower for the isolating case and results from the isolation effect of the RSM layer. As can be seen in the second row of subplots, the RSM material yields at a lower stress than the sand layer, has much larger deformations and dissipates much more energy. Indeed, the RSM layer reaches a peak strain of 0.0884, which is ten times the value for soil alone, namely a peak strain of 0.0081. It is also interesting to observe from the third row of subplots that the response of the bottom layer decreases too. The probable explanation is that the isolation layer attenuates significantly the incident motion, in which case the amplitude of the waves that feed back to the bottom have decreased amplitude, i.e. not all of the energy returns down.

Figure 5 shows the time history of the acceleration in the structure and also the dissipated energy of the underneath layers. Once again the subplots on the left show the non-isolated case, while the subplots on the right show the isolated case. The upper row of subplots shows the acceleration measured at the bottom of the building (i.e. at the top of the RSM layer) when normalized by the peak acceleration of the non-isolated case (i.e. pure soil). As can be seen, the peak acceleration of the RSM case is only 55% as large, which represents a significant reduction in the seismic demand on the structure. The second row of subplots shows the cumulative dissipated energy of the middle (RSM) and bottom layers (i.e. the area within the hysteresis loops) during the seismic motion, which in the graph is normalized by the total energy dissipated by the pure soil case. As can be seen, the value of the total dissipated energy in the right case corresponds to 1.7 times of that in the left one, what is consistent with the seismic isolation concept. The middle layer of the isolated case (i.e. RSM layers) dissipates almost all of the energy, while in the pure soil case the middle layer contributes with only 1/3, and the bottom layer completes the other 2/3.

This procedure was repeated for all seismic motions listed in Table 1, and for all RSM types considered; a summary of these results obtained is depicted in Figure 6. The upper subplot shows the ratio R of the peak acceleration obtained at the base of the structure both with and without the isolation layer. The X-axis identifies

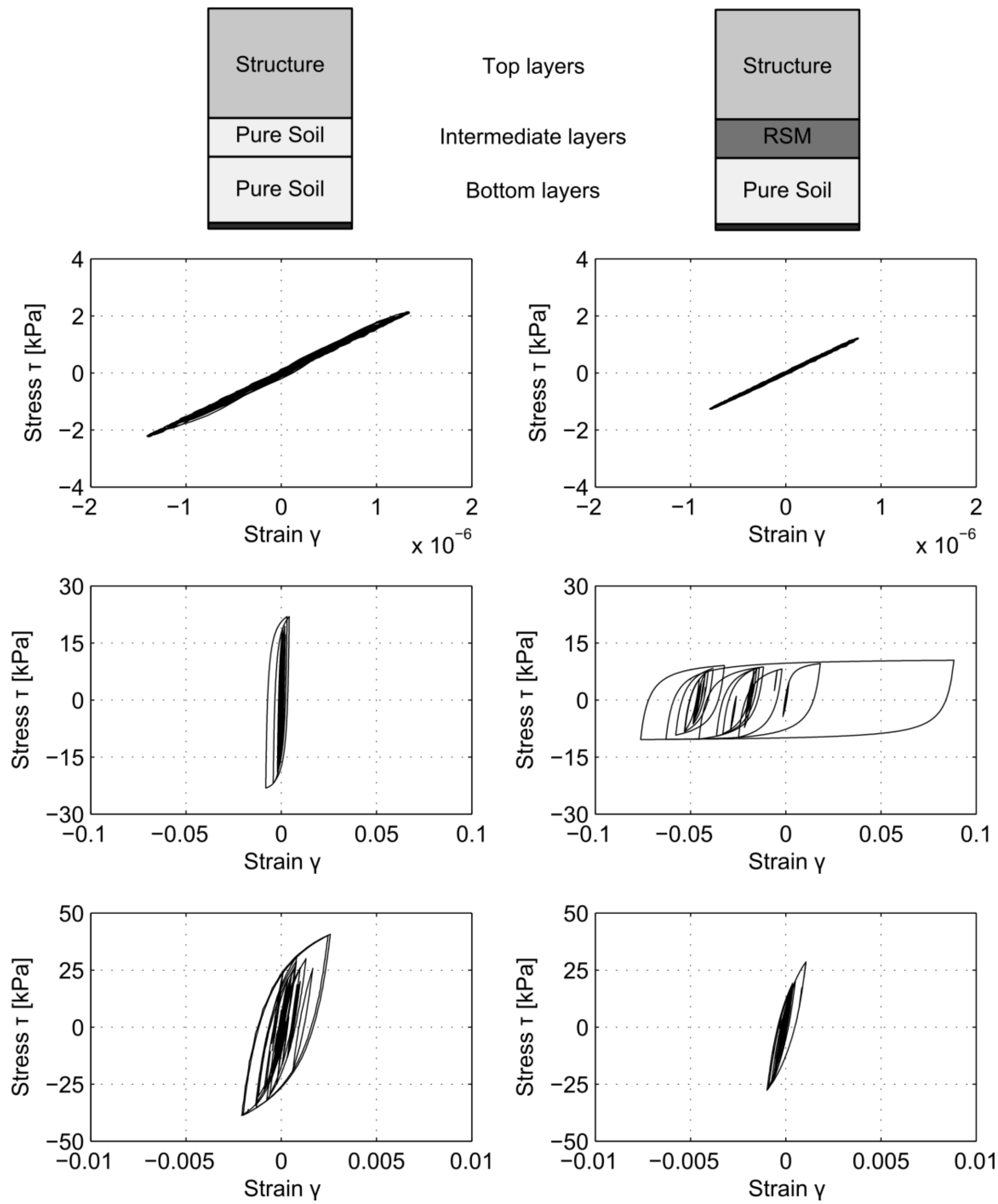

Fig. 4 – Comparison of the stress-strain response between the isolated and the non-isolated case when the system is subjected to Corralitos H2 seismic record. (Figure taken from [8])

the earthquake used and numbered as in Table 1. As shown in all cases examined, the RSM layer effects a reduction of the acceleration response of the building. There is a couple of exceptions in the RSM-A layer case when it is subject to seismic motions 2, 3, 7 and 11, in which R is slightly higher than unity, i.e. the response of the isolated case is very similar to that of the non-isolated one, mainly because the acceleration is not large enough to cause inelastic effects.

It is interesting to observe the consistent tendency revealed by these results. By and large, the greater the PGA, the more effective the isolation layer becomes, i.e. the value of R decreases steadily. An alternative way of interpreting this is to realize that as the PGA decreases in value, so do also the inelastic deformations in the isolation layer, in which case the system remains in the linear elastic range, less energy is dissipated, and the response becomes "similar" to that of the pure soil case. That means that GSI systems are ineffective for small levels of shaking. It would seem then that on the basis of the results obtained herein, the benefits of the GSI will become manifest only for PGA values in excess of 0.2g.

As also seen in the first subplot of Figure 6, the smallest reduction is observed with RSM-A, intermediate results are obtained with RSM-B, and the best results are achieved with a RSM-C. Typical reductions in these cases are $R_{RSM\text{-}A}$= 0.82, $R_{RSM\text{-}B}$ = 0.60 and $R_{RSM\text{-}C}$ = 0.46, i.e. reductions of 18%, 40% y 54%, respectively. This follows from the fact that the small-strain shear modulus G_0 of RSM-C decays faster with rubber content than that of RSM-B, which is in turn decays faster than that of RSM-A, as shown in Figure 2. In other words, the RSM-C layer is the most compliant of the three mixtures and exhibits the greatest tendency to experience large inelastic deformations. As a result, it reaches its shear resistance limit rather quickly, dissipates more energy during the earthquake and provides greater seismic isolation capacity to the complete system.

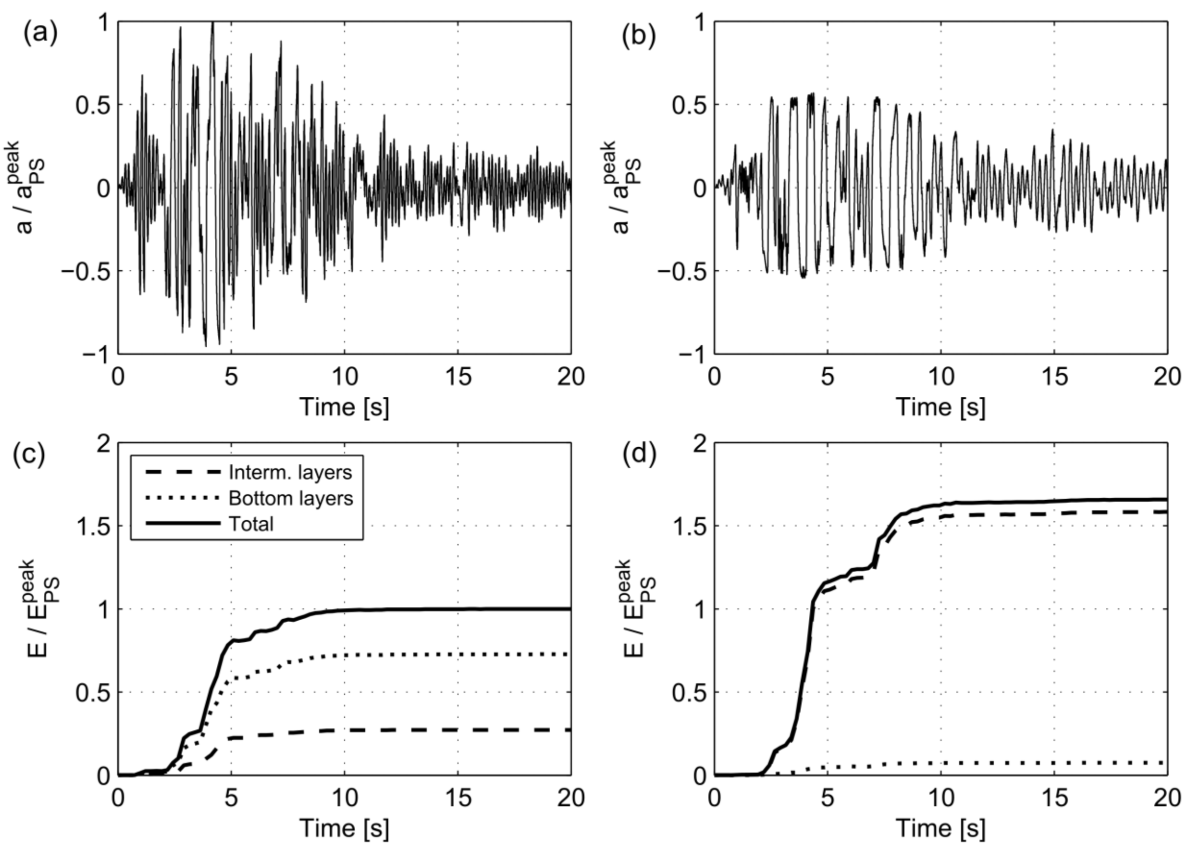

Fig. 5 – Comparison of the response of the system between the isolated and the non-isolated case, when it is subjected to the Corralitos H2 seismic record: (a) and (b) acceleration in the bottom of the building; (c) and (d) dissipated energy of the intermediate and bottom layers. (Figure taken from [8])

The previous observations are further corroborated in the middle subplot, which shows the maximum displacement experienced by the building during the earthquake. Clearly, the peak displacement is very small when the earthquake is small (about 1cm, during which the layers are kept mainly in an elastic range), and tends to increase with increasing intensity of the earthquake, reaching 28cm for the most demanding non-Chilean earthquake (quake 58, Kobe N-S) and 10 cm for the most demanding Chilean earthquake (quake 51, Constitución H2). It is observed in the graph that larger peak displacements are obtained due to non-Chilean earthquakes, and it is explained because these seismic motions present response spectrums which in general have higher levels of pseudo accelerations and displacements compared with the Chilean earthquakes. In general, RSM-B and RSM-C mixtures exhibit larger displacements than an RSM-A mix. Also, the residual displacements or drift observed after the earthquake is over are shown on the third subplot. Although the trend of that drift seems less clear and appears to be more random, there is indeed a correlation with PGA. Still, the magnitude of

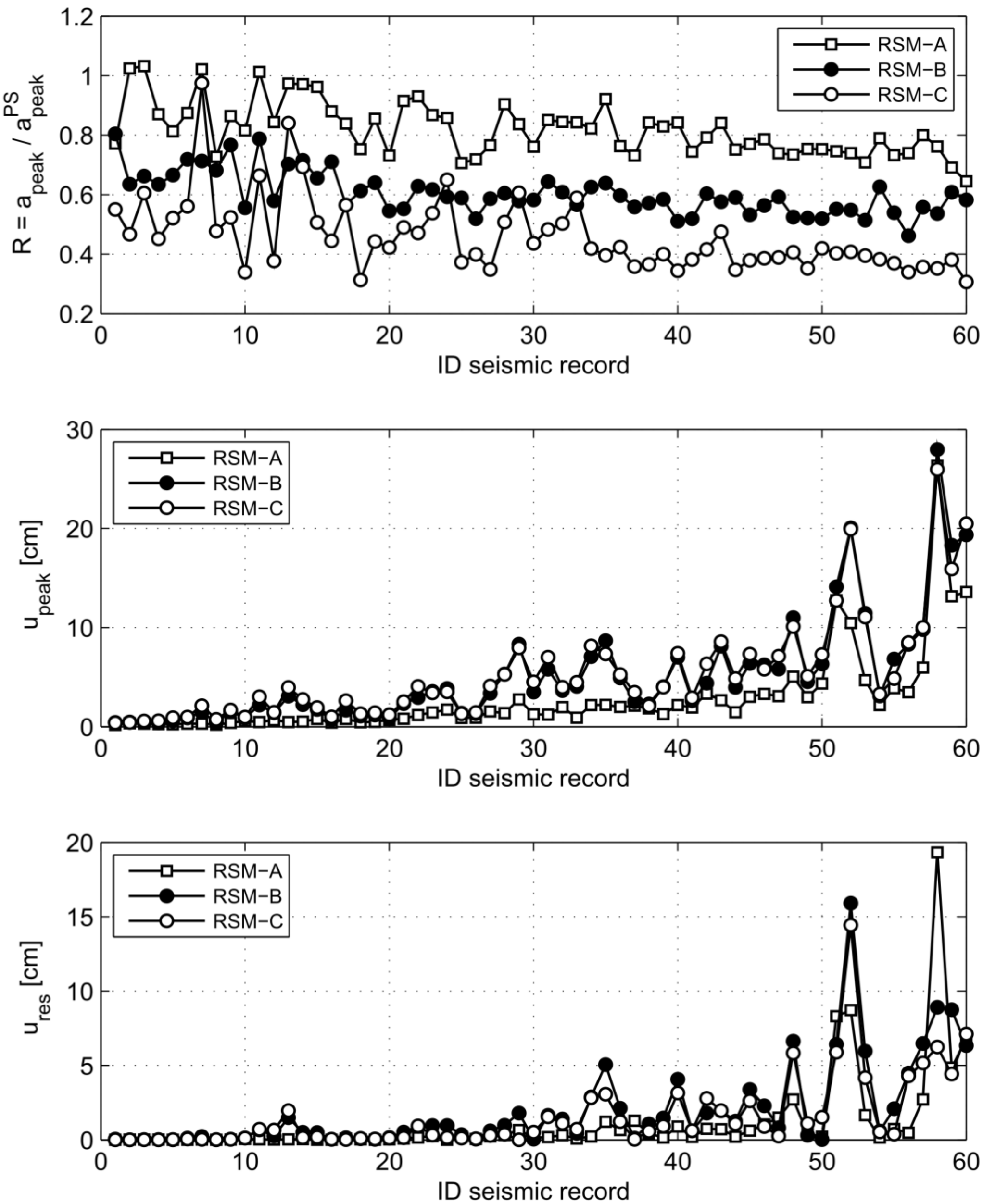

Fig. 6 – Acceleration reduction, peak displacement and residual displacement of the structure when varying the applied seismic record. (Figure taken from [8])

the drift depends also on the characteristics of the input earthquake, such as the dominant frequency and especially the duration. In this particular case, the larger residual displacement is about 20 cm for the Kobe N-S earthquake (RSMA layer), and 15 cm approximately for the case of Kobe E-O (RSM-B and –C layers).

Inasmuch as one of the main goals of this study is to find optimal values for the thickness of the RSM layer, several models were run in which the thickness of that layer was varied between 0 and 5m and for various rubber contents. Figure 7 shows the peak acceleration measured in the structure (normalized by the peak acceleration of the pure soil case) for the three types of soil mix considered herein and when subjected to the Corralitos H2 earthquake. Each line represents a simulation with a different rubber content used in the mix, which was varied from 0% (i.e. pure soil) to 35%, every 5% each step. It can be seen that good reductions can be achieved with an RSM layer whose thickness is on the order of two meters. Furthermore, increasing this variable much beyond this threshold does not seem to accomplish any significant reductions in the response of the structure. This is good news because a 2m thick RSM layer not only suffices to attain an effective seismic isolation system, but it also satisfies ASTM recommendations and minimizes the construction costs.

Figure 7 illustrates also the effect of rubber contents on the effectiveness of the system as seismic isolation system. As anticipated, the more rubber is added to the mixture (up to the maximum content of 35% by weight considered herein), the more the reduction attained. However, comparable reductions can also be achieved with relatively lower quantities of rubber. In the case of the RSM-B, for example, it can be seen that comparable results are obtained when the rubber contents is in the range between 15% and 35%. In the case of the RSM-C, the range of percentages for comparable performance is 25% to 35%. The case of the RSM-A mixture is less clear, inasmuch as the higher the percentage of rubber, the larger will be the degree of reduction. In summary, depending on the soil mixture used, good levels of reductions can be achieved with rubber contents in the range of 15-25% by weight of mixture.

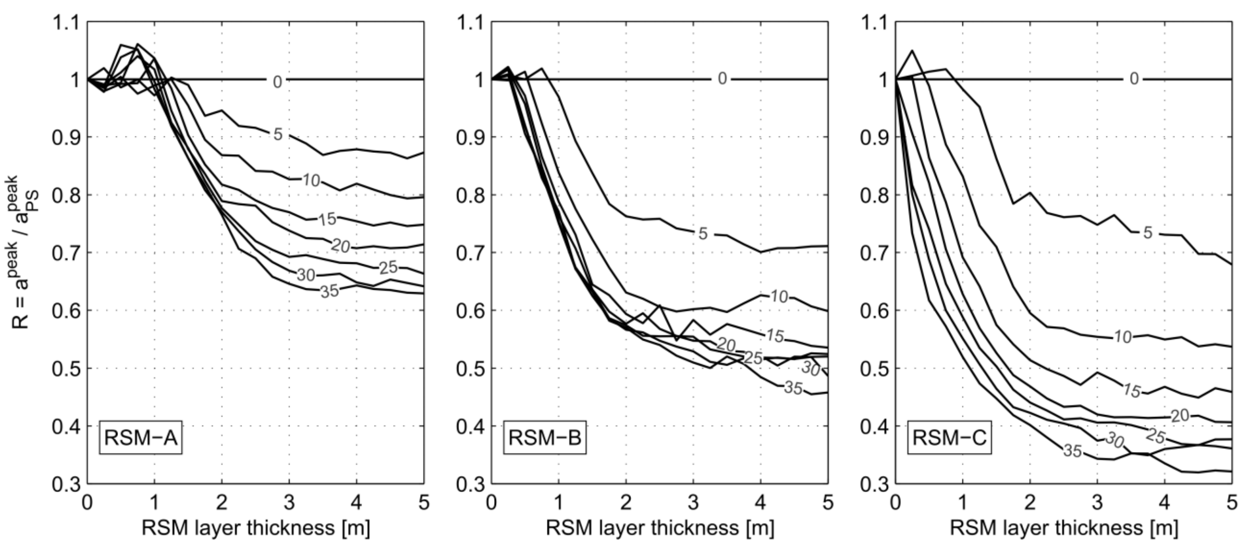

Fig. 7 – Peak acceleration measured at the bottom of the building normalized by the peak acceleration of the non-isolated case, when varying the thickness of the RSM layer. (Figure taken from [8])

5. Conclusions

The results of the analyses presented in this article lead to the following conclusions:

- A rubber–soil mixture layer placed underneath a structure could reduce significantly the seismic demand on it. This concept was validated based on several simulations with nonlinear inelastic models, subjected to vertically propagating shear waves (SH). It would be necessary to complement these results with 2D or even 3D analyses to correctly simulate a MDOF structure and their interaction with the surrounding soil, and include also the vertical component of acceleration; however the results obtained herein are deemed to be very successful for a first rigorous approach to this complex problem.

- The information used in this article to model the hysteresis curves of the pure soil and rubber–soil mixtures is based on experimental data obtained via resonant column and triaxial tests involving relatively low shear deformations. It may thus be necessary to carry out further tests to assess the behavior and shear resistance of the mixture for large deformations.
- The ratio R of the peak acceleration obtained at the base of the structure with and without the isolation layer, when the system was subjected to 60 different seismic motions, is R = 0.82 for the RSM-A case, R = 0.60 for the RSM-B case, and R = 0.46 for the RSM-C case. The best reduction was achieved with the RSM-C layer because the shear modulus of this mixture decays faster than that of the others, exhibiting the greatest tendency to experience inelastic deformations.
- The isolation effectiveness of the GSI become manifest only for PGA values in excess of 0.20-0.25g, after which large inelastic deformation of the rubber-soil mixture materialize. Low levels of shaking are not able to induce non-linear response of the mixture, and hence, reduction of the seismic response of the structure is not evident.
- A thickness for the RSM layer between 2 and 3 meters is likely to achieve adequate levels of acceleration reductions, which supersedes the large thicknesses proposed earlier in the literature. A shallow depth has advantages from an economic and constructive perspective, and it satisfies the ASTM recommendations.
- By and large, as the rubber content in the mixture is increased, larger reductions of the response of the structure are achieved, at least up to a limit of 35% considered herein. Still, comparable results were obtained with rubber content as low as 15-25% when the adequate type of RSM layer was used.

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7. References

[1] Humphrey D (1999): Civil engineering applications of tires shreds. *In: Proceedings of the tire industry conference, Hilton Hill, North Carolina*.

[2] Hazarika H, Yasuhara K (2007). Scrap tire derived geomaterials: opportunities and challenges. *Proceedings of the international workshop on scrap tire derived geomaterials. Yokosuka, Japan*

[3] Xiong W, Yan M, Li Y (2014): Geotechnical seismic isolation system further experimental study. *Applied Mechanics and Materials; 580-583: 1490-3*

[4] Tsang H, Lo S, Xu X, Sheikh M (2012): Seismic isolation for low-to-medium-rise buildings using granulated rubber soil mixtures, numerical study. *Earthq Eng Struct Dyn: 41:2009-24*

[5] Anastasiadis A, Senetakis K, Pitilakis K (2012): Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures. *Geotech Geol Eng 2012; 30(2): 362-82*

[6] Senetakis K, Anastasiadis A, Pitilakis K, Souli A, Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. *Soil Dyn Earthq Eng 2012: 33:38-53*

[7] Zornberg J, Cabral A, Viratjandr C (2004): Behavior of tire shred sand mixtures. *Can Geotech J 2004; 41:227-41*

[8] Brunet S, De la Llera J, Kausel E (2016): Non-linear modeling of seismic isolation systems made of recycled tire-rubber. *Soil Dynamics and Earthquake Engineering 85 (2016): 134-145*

[9] Senetakis K, Anastasiadis A, Trevlopoulus K, Pitilakis K (2009): Dynamic response of SDOF systems on soil replaced with sand/rubber mixture. *In:Proceedings of the ECCOMAS thematic conference on computational methods in structural dynamics and earthquake engineering*.

[10] Kausel E, Assimaki D, Seismic simulation of inelastic soils via frequent-dependant moduli and damping. J Eng Mech 2002: 128(1):34-47

[11] Massing G. Eigenspannungen und verfestigung beim messing (1926). *In: Proceedings of the 2nd international congress for applied mechanics.*

[12] Iwan W (1996). A distributed element model for hysteresis and its steady-state dynamic response. *J Appl Mech 1966; 33(4) 893-900*