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Performance of sand and shredded rubber tire mixture as a natural base isolator for earthquake protection

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Abstract: The performance of a well-designed layer of sand, and composites like layer of sand mixed with shredded rubber tire (RSM) as low cost base isolators, is studied in shake table tests in the laboratory. The building foundation is modeled by a 200 mm by 200 mm and 40 mm thick rigid plexi-glass block. The block is placed in the middle of a 1m by 1m tank filled with sand. The selected base isolator is placed between the block and the sand foundation. Accelerometers are placed on top of the footing and foundation sand layer. The displacement of the footing is also measured by LVDT. The whole setup is mounted on a shake table and subjected to sinusoidal motions with varying amplitude and frequency. Sand is found to be effective only at very high amplitude (> 0.65 g) of motions. The performance of a composite consisting of sand and 50% shredded rubber tire placed under the footing is found to be most promising as a low-cost effective base isolator.

Keywords: shake table test; base isolation; shredded rubber tire; model test

1 Introduction

One of the challenges in civil engineering is to find an economical and feasible way of designing new structures or strengthening existing ones for the protection from damages during an earthquake. The conventional approach to seismic hazard mitigation is to design structures with adequate strength and ability to deform in a ductile manner. Over the past two decades, newer concepts of structural vibration control including seismic isolation, installation of passive and active/semi-active devices (Soong, 1988; Jangid and Datta, 1995; Nagarajaiah, 1997; Ehrgott and Mastri, 1994) have grown in acceptance. Traditionally, earthquake-resistant design of low- to medium-rise buildings is particularly important, as their fundamental frequencies of vibration are within the range where earthquake-induced force (acceleration) is the highest as found during a number of earthquakes. One possible means to reduce the degree of amplification is to make the building more flexible (Paulay and Priestley, 1992). In a low-to-medium-rise building, this necessary flexibility can be achieved by the use of base isolation techniques, and the primary mechanism for the reduction of shaking level in a base isolation method is energy dissipation.

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The primary scope of the base isolation method is to uncouple the structural motion from the motion of the soil underneath, and therefore reduce the transmitted force on the structure. Due to the increase of the isolated structure's fundamental period, the response of the structure shifts to lower frequencies (much lower than the predominant frequencies of the ground motion), resulting in less earthquake energy absorbed. Rubber bearings offer the simplest method of base isolation and they have been used for the past three decades, with much of the contribution coming from Kelly (1990, 1996). Laminated rubber bearings, which are made by vulcanization bonding of sheets of rubber to thin steel reinforcing plates or lead plugs, are currently the most commonly adopted system. There are many examples of using this strategy for earthquake-resistant construction in the United States, Chile, Indonesia, New Zealand, Italy, China, and Japan.

However, these methods of base isolation are not so affordable in a country like India and, hence, the development of a low-cost, natural base isolation system becomes necessary. The concept of low-cost and effective earthquake protection techniques using natural materials such as sand was looked at by Qamaruddin and Ahmad (2007) and Qamaruddin *et al*. (1986), Li (1984), Ahmad *et al*. (2009) and Nanda *et al*. (2012). The use of a synthetic liner consisting of an ultra molecular weight polyethylene nonwoven geotextile, placed in the foundation of a structure, was also found to be an effective way of reducing seismic ground motion by Yegian and Kadakal (2004) and Yegian and Catan (2004). Soil reinforced with rubber demonstrates an increase in energy dissipation capability (Edil and Bosscher, 1994). The feasibility of using shredded rubber mixed with sand (RSM) as a natural base isolator was investigated experimentally by Xiong and Li (2013) and theoretically by Gray *et al*. (1983), Doudoumis *et al*. (2002), Tsang (2008), Kirtas *et al*. (2009), Kirtas and Pitilakis (2009), Mavronicola *et al*. (2010), and Tsang *et al*. (2012).

This paper presents the results of an experimental investigation into the performance of a layer of sand, and sand mixed with shredded rubber tire (RSM) as low cost base isolation systems.

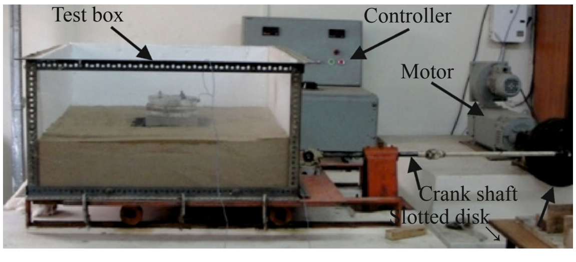
2 Experimental setup

The laboratory model tests are performed on a 1 m by 1 m shake table. The table is shaken sinusoidally in a uniaxial horizontal direction by a 2800 rpm and 7 HP DC motor. A slotted circular mild steel disc of 300 mm diameter and 20 mm thick is bolted to another circular disc of same size (used as a support to the slotted disc). The supported disc is connected to the shaft of a motor (Fig. 1(a)). A steel crank shaft 500 mm long, 20 mm in diameter is connected to the slotted disc by bolts. The other end of the crank shaft is connected to a reciprocating rod, 500 mm long and 20 mm in diameter. The amplitude of sinusoidal motions can be varied by changing the position of the crank shaft in the calibrated slot of the disc. The other end of the reciprocating rod is connected to the shaking table's base plate. The reciprocating rod is kept in the horizontal position during the motion by a bracket support. The speed of the motor can be controlled from a panel board which essentially consists of an electrical variant (Fig. 1(a)). The shaking table has a maximum payload capacity of 5000 kg, a maximum stroke length of 150 mm and a peak frequency of 50 Hz.

The laboratory model tests are performed inside a 1 m × 1 m × 0.5 m (length × width × height) rectangular test box made up of 12 mm thick Perspex glass sheets (Fig. 1(b)). The sides of the box are fixed rigidly with steel angles to prevent any movement. The model box is fixed to the base plate of the shaking table with bolts so that no relative movement can occur. This base plate is fitted with very smooth wheels which slide in the horizontal direction on two parallel rails. The two sides, vertical to the direction of the motion and the backside of the box are covered with 30 mm thick thermocol sheets to minimize the reflection of the waves at the boundary (Fig. 1(b)). No thermocol is placed on the front side of the box but it is lightly lubricated with grease to enable one to see inside through it. Sand particles are glued to the bottom surface of the model box to generate surface roughness, so that there is no slippage along the bottom surface during shaking. The complete test setup is shown in Fig. 1.

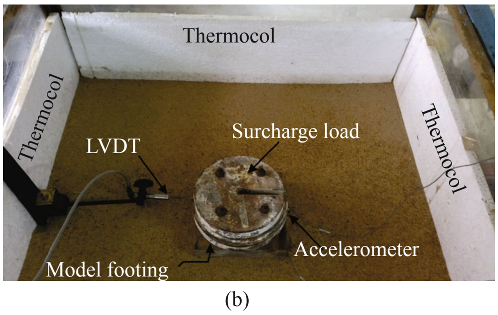
In the laboratory model tests, a typical isolated building foundation, a square footing, is scaled down 10 times (scale factor, λ = 10) geometrically and modeled by a 200 mm by 200 mm and 40 mm thick, rigid plexi-glass block (Fig. 1(b)). A 1-g scaling law (Ramu *et al*., 2011; Iai, 1989) is utilized in this study. The mass density of the foundation soil and acceleration are not scaled in this study. However the frequency is scaled by $\lambda^{-0.5}$ and time is scaled by $\lambda^{0.5}$. The scaling factors used to convert various quantities between prototype scale and model scale are given in Table 1.

The basic objective of the study is to find a low cost yet effective base isolator for medium storied (2 – 5 storied) buildings. For this reason, the transmissibility of the base isolator under the foundation is of the major concern. Hence, the overall complex response of the structure-foundation-ground is not studied. It may be noted that the role of the particular dynamic characteristics of the superstructure is not so important, as long as the modified period of the base-structure system is shifted towards larger values outside the predominant period range of the earthquake. The normal stress (normal load) on the foundation due to the super structure is imparted by a number of steel plates (weights) bolted on top of the plexi-glass block (Fig. 1(b)). A typical normal stress of 4 kPa has been considered here on top of the footing. This vertical load represents scaled column load coming from a typical 2 storied residential building. A coarse sand paper is glued to the bottom side of the footing block to model the roughness of the footing.



(a)

Fig. 1(a) Test setup



(b)

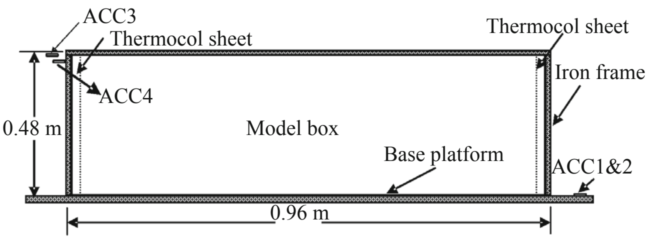
Fig. 1(b) A top view of the test set up showing the instrumentation (LVDT and accelerometers) and the model footing with surcharge load on top of it

Table 1 1-g scaling law

Quantities	Model	Prototype
Length/Width	L_m	$\lambda \times L_m$
Force	F_m	$\lambda^3 \times F_m$
Area	A_m	$\lambda^2 \times A_m$
Stress	S_m	$\lambda \times S_m$
Acceleration	a_m	$\lambda \times a_m$
Density	γ_m	$\lambda \times \gamma_m$
Frequency	f_m	$\lambda^{-0.5} \times f_m$
Time	t_m	$\lambda^{0.5} \times t_m$
Surcharge load	q_m	$\lambda \times q_m$

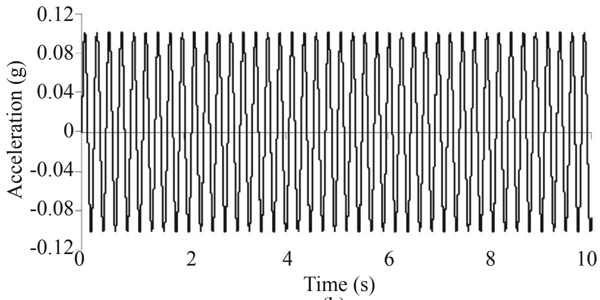
In the laboratory shake table tests, the test container is first filled with sand up to 200 mm height and compacted to the relative density of 65%. The model footing is then placed in the middle of the test box on top of the compacted sand foundation. The test box along with the sand foundation and the model footing are shaken by sinusoidal motions of given amplitude and frequency. The acceleration responses during shaking are measured using Delta Tron accelerometers (B& K Type 4507). Two accelerometers (ACC1 & ACC2) are mounted on the base plate of the shake table to measure the horizontal and vertical vibrations (Fig. 2(a)). The measurement in the vertical direction is made only to keep track of the vertical component of the motion, if any, generated by the table. Two other accelerometers (ACC3 & ACC4) are fixed on the walls of the test box. The Bruel and Kjaer (B&K) Pulse 6.1 system (Type 3560c) sound and vibration meter is used for data acquisition.

A system calibration test was performed to check the performance of the experimental set up before starting the experimental work (A detail description of the calibration process is given in Giri and Sengupta (2009)). The objective is to verify that the amplification produced by the system is negligible. The loading sequence used for system calibration consists of 10-s horizontal sinusoidal motions with peak acceleration of 0.1 g at 4.2 Hz frequency, and is shown in Fig. 2(b). The response of the accelerometer (ACC3) fixed to the model box is shown in Fig. 2(c). It is observed that no significant amplification of the system is registered during the loading and the system appears to behave linearly throughout the loading history. The responses of the accelerometers are found to be sinusoidal with predominant frequency of 4.2 Hz. This corresponds to a payload of 2 kN (weight of the base plate and the empty model box). The vertical vibration of the shaking base plate and the model box is also measured. The magnitude of the vertical vibration (0.0075 g) of the base



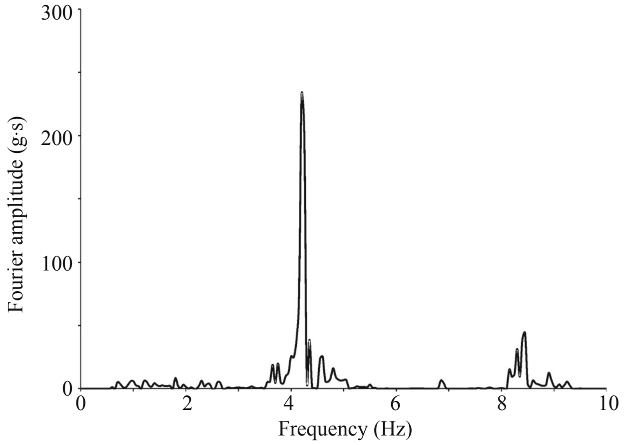
(a)

Fig. 2(a) Schematic diagram of the model test setup showing the positions of accelerometers during system calibration



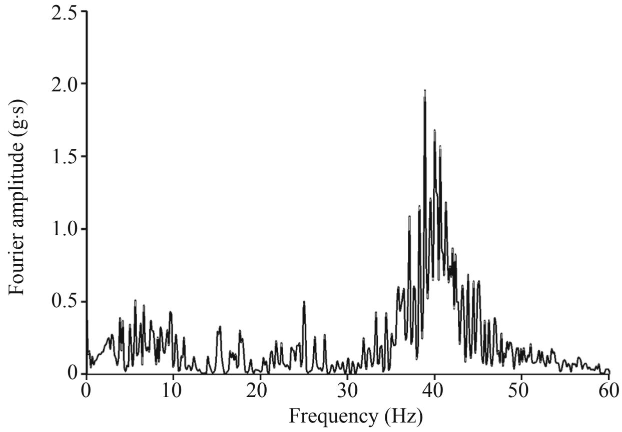
(b)

Fig. 2(b) Base motions during system calibrations



(c)

Fig. 2(c) Responses of the accelerometer (ACC3) during calibration



(d)

Fig. 2(d) Natural frequency of the whole setup

plate is very small as compared to the horizontal input motion and cannot significantly affect the test results.

The natural frequency of the base plate along with the test container and the soil slope is determined experimentally by subjecting the whole test setup to a motion and then allowing it to shake freely until it stops by its own. It is found to be around 40 Hz (Fig. 2(d)). As the natural frequency of the system is much higher than the predominant frequencies of the input motions that will be examined in the study (1.5, 3.5 and 4.5 Hz), the platform-box system's dynamic response will not affect the test results.

The first series of tests are performed with the model footing placed on top of the sand layer at the middle of the container. In this case, an accelerometer is placed in the foundation sand 20 mm below the footing and another one on top of the footing. The second series of the tests are performed with the shredded rubber tire and sand mixture (RSM) in different proportions as base isolator under the model footing. In this case also, one accelerometer is placed just below the RSM layer and one at the top of the footing (Fig. 3(a)). In both series, the relative movement of the footing during a test is measured by a spring-less LVDT (linear variable displacement transducer) fixed to the test box on one side and attached to the model footing on the other end. Before the second series of tests, a 20 mm deep square excavation in the sand of the size 250 mm by 250 mm is constructed. The shredded rubber tire and sand in predetermined proportion (by weight) are first mixed thoroughly by hand. The excavation in the sand foundation is then filled with the shredded rubber tire and sand mixture in three equal layers. Each of the layers is compacted by hand tools to the desired density to avoid undesirable settlements. The model footing is then placed over the shredded tire and sand mixture (RSM).

Several proportions of shredded tire in the RSM were considered, but only the performances of 50% RSM are reported in detail below as this combination yielded the best result.

3 Base motions

The shake table along with the experimental setup is shaken in the horizontal direction by sinusoidal motions of amplitude 0.15, 0.3, 0.4, 0.5, 0.6, 0.8 and 1 g. The frequency of motion is varied from test to test to study the effectiveness of the seismic isolators at various frequencies of motion, and the frequencies considered are 1.5, 3.5, 4 and 4.5 Hz. For each specified motion, the vertical and the horizontal accelerations of the shake table in addition to those on top of the foundation sand layer and on top of the model footing are also recorded. Each of the motions is monitored for at least 5 cycles to ensure that the system has reached steady state condition. A typical input base motion is shown in Fig. 3(b). In all cases only the results for the first few cycles are shown for clarity of presentation.

4 Experimental results

4.1 Model footing resting on top of foundation sand

The performance of sand as a base isolator has been studied for the given base motions mentioned earlier. In this case, the model footing is resting directly on top of 200 mm deep sand layer within the test tank. The sand used in the study is local uniform medium sand (Kansai River sand). It is classified as poorly graded sand (SP) as per the Unified Soil Classification System. The specific gravity of the sand is 2.7. The maximum and minimum dry unit weights are 16.6 and 14.1 kN/m^3, respectively. The grain size distribution of the sand is shown in Fig. 4. In all the tests, the relative density of the sand foundation within the test chamber is maintained at 65%. The shear strength (effective cohesion, c' and effective friction angle, ϕ') of the sand, as obtained from the direct laboratory tests, are $c' = 0$ and $\phi' = 36^{\circ}$.

Figure 5 shows the transmitted peak accelerations at the top of the footing resting on sand with respect to the peak acceleration of the base motions for different amplitude of motions (keeping the frequency constant at 3.5 Hz). The figure shows that at and around 0.6 g amplitude of base motions, the sand beneath the model footing starts to reduce the base motions. This is accompanied by a sliding movement of the model footing. Figure 6 shows the footing response at 1 g amplitude of base

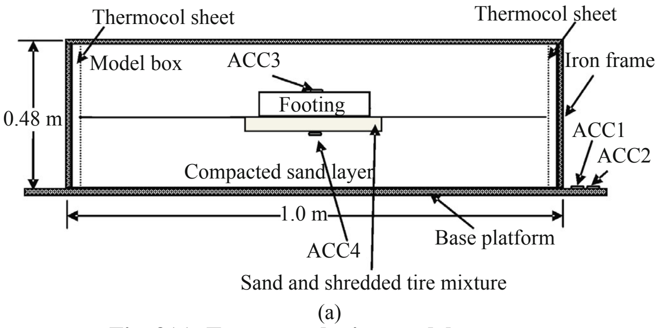


Fig. 3(a) Test setup during model tests

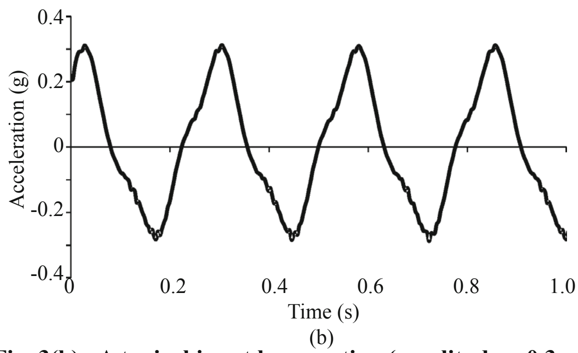


Fig. 3(b) A typical input base motion (amplitude = 0.3 g and frequency = 3.5 Hz)

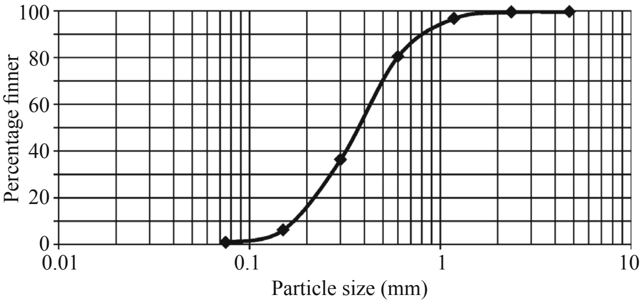


Fig. 4 Grain size distribution of Kansai River sand

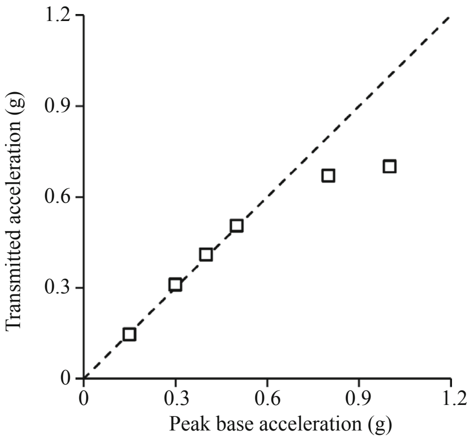


Fig. 5 Comparison of transmitted acceleration at the top of the footing resting on sand for base motions with various acceleration amplitudes and frequency 3.5 Hz

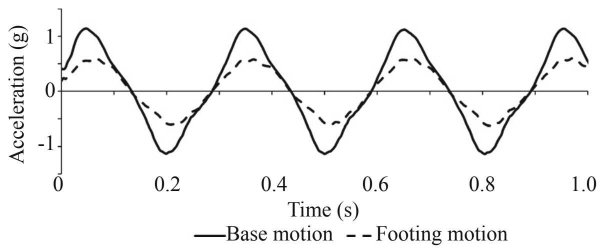


Fig. 6 Comparison of transmitted acceleration at the top of the footing resting on sand for a base motion of amplitude 1 g and frequency 3.5 Hz

motion. The damping effect of the sand in the foundation at this high amplitude of motions can be easily observed from the figure. The maximum amplitude of the footing response reduces to 0.7 g for the 1 g base motions. The relative displacement of the footing is also noticeable at this high amplitude of motions. Figure 7 shows the relative displacements of the footing when shaken at 1 g. The footing is found to displace back and forth by ± 5.43 mm during the 1 g base motions.

For high-amplitude base motion, relative displacement of the footing over the sand foundation triggers frictional resistance at the interface. When the dynamic interface frictional resistance (about 0.6) is exceeded, the footing starts to slip over the sand which in turn absorbs some of the energy of the base motions and this results in the dampened response of the footing as observed in Fig. 6. Figure 8 shows the response spectra of the model footing resting on the sand at various amplitudes of motion. Note the shifting of the response curve to the right side at high amplitudes of motion. This shifting of the response curve may be due to the slight reorientation (slippage) of the footing on the sand bed. It is clear from these figures and tables that the sand layer in the foundation behaves as an effective base isolator only at very high amplitudes (above 0.6 g in these cases) of base motion.

4.2 Model footing resting on top of a mixture of shredded rubber tire and sand

The shredded rubber tire used for the study is obtained from a local shop. The shredded rubber tire is very heterogeneous in nature. Each thread has a different aspect ratio. The maximum length of a rubber thread is 10 mm with a diameter of about 1 mm. The heterogeneous nature of the shredded rubber and coarse sand, in fact, actually helps in reducing the void ratio and achieving a desirable compaction to reduce settlement of the model footing. In the present study, four different proportions (by weight) of shredded rubber tire in sand,

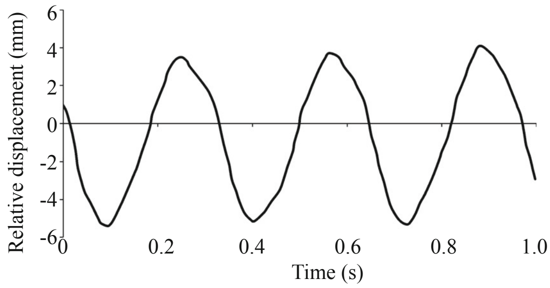


Fig. 7 Relative displacements of the footing for a base motion of amplitude 1 g and frequency 3.5 Hz

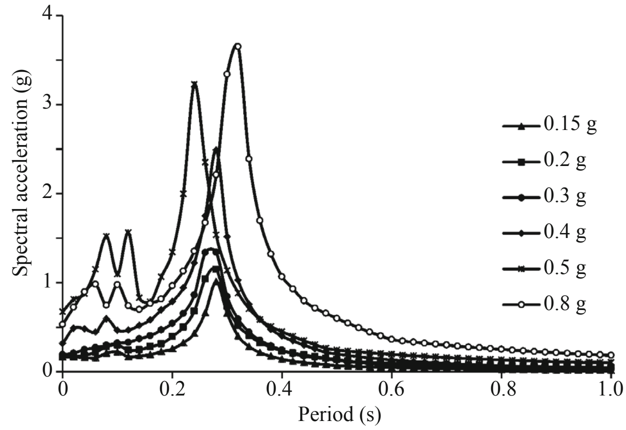


Fig. 8 Response spectra of the footing resting on sand at various amplitude of base motions keeping frequency constant at 3.5 Hz

viz., 10%, 20%, 30% and 50%, have been considered as potential low cost base isolators under the model footing. However, for the most part only the results for the 50% shredded rubber tire-sand mixture (50% RSM) are presented in detail here since this case exhibits the best results under the present scenario.

In all the cases involving RSM placed under the model footing, a 250 mm by 250 mm and 20 mm deep square excavation in the sand is constructed before the tests. This excavation is then filled with the shredded rubber tire and sand mixture in correct proportions in three equal layers. The model footing is then placed over the shredded tire and sand mixture after proper compaction with hand tools. As done for the previous cases, in these cases also the whole test setup is shaken on the shake table for the previously stated sinusoidal motions.

The static shear strengths of the sand and sand mixed with different proportions of shredded rubber tire are determined in our laboratory by standard direct shear tests. Figure 9 shows the results of direct shear tests for different percentages of RSM. As the percentage of shredded tire mixture increases, the effective friction angle (ϕ') is found to be increasing slightly for the 20% RSM and then decreasing for the higher percentages of RSM. The effective cohesion (c') of the mixture is found to be increasing with increasing percentage of shredded rubber tire.

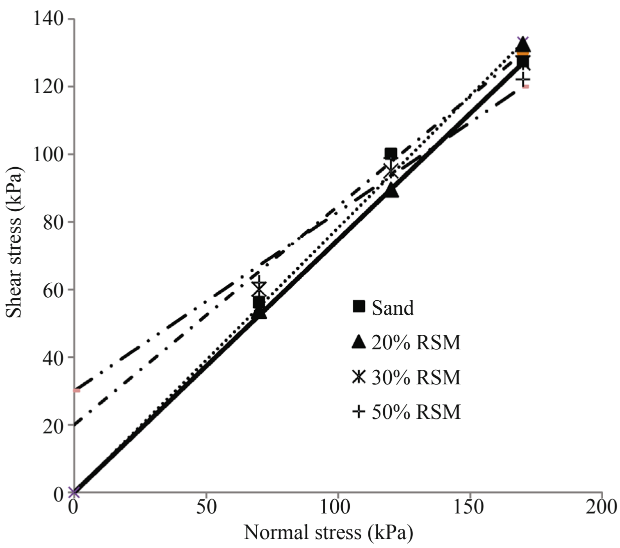


Fig. 9 Results of direct shear tests on sand and various percentages of RSM

Table 2 summarizes the unit weight and shear strengths of the sand and sand mixed with different proportions of shredded rubber tire. In particular, for the sand mixed with 50% (by weight) shredded rubber tire, the shear strength is given by c' = 30 kPa and ϕ' = 30° (as compared to those for sand only, c' = 0 and ϕ' = 36°). The maximum and minimum dry unit weights are 10.0 and 7.72 kN/m^3, respectively. The laboratory test results show that the unit weight and the effective friction angle decreases with the addition of shredded tire in the sand. However, the cohesion starts to pick up with increase in the percentage of shredded tire in the sand. Thus the net bearing capacity, though decreases initially with the addition of shredded tire, actually increases significantly for 30% and 50% shredded tire mixture due to increase in cohesion. But as the percentage of shredded tire in sand increases beyond 50%, the unit weight and effective friction angle decrease significantly and settlement (punching failure) and rocking motion of the foundation during the loading become an issue.

The bearing capacity and settlement of the model footing at the end of a cyclic test are shown in Table 1. In India, design guidelines for shallow foundation are given in IS 1904-1986 (Code of practice for design and construction of foundations in soils: general requirements, 3rd rev., Bureau of Standards, New Delhi, India). As per this code, for multistoried buildings (RC or steel framed buildings with panel walls), maximum allowable settlement is 60 mm for isolated foundation and 75 mm for raft foundation in sand and hard clay. The maximum allowable differential settlement is 0.002 L where, L is the length of the distorted part of the footing or raft. The permissible angular distortion for isolated footings is 1/500 and that for raft is 1/400. In the present case, the total settlement is less than 4 mm, which means that the settlement in a prototype foundation is less than 40 mm. This is well within the permissible limit. The differential settlement of the footing resting on top of 50% RSM was found to be 0.1 mm which is well within

Table 2 Material properties, net bearing capacity & settlement of sand & RSM

Material	Unit weight (kN/m^3)	Cohesion, c' (kPa)	Friction angle ϕ' (deg.)	Net bearing capacity* (kPa)	Settlement+ of the foundation block at the end of motion (mm)
Sand	16.7	0	36	173	0.85
20% RSM	14.5	0	34	120	2.38
30% RSM	12.0	20	32	1037	3.02
50% RSM	10.0	30	30	1235	3.33

*For the model footing.

+Differential settlement found to be negligible for all the cases.

the permissible limit. However when RSM contains more than 50% shredded tire, rocking motion was noticed which led to instability.

Several researchers (Feng and Sutter, 2000; Senetakis *et al*., 2012; Nakhaei *et al*., 2012; Hazarika *et al*., 2008) have looked into the dynamic properties of RSM. The shear strength results of sand mixed with different proportions of shredded rubber tire are in agreement with the published results (Ahmed, 1993; Shariatmadari *et al*., 2007; Youwai and Bergado, 2003) and Balachowski and Gotteland, 2007). In particular, Ahmed (1993) found increasing shear strengths with increasing percentage of shredded rubber tire up to 39%. Beyond 39%, he noticed a decline in shear strength. The difference between Ahmed's and our study in the proportion of rubber tire in the mixture after which it becomes unstable, might be due to the different types of sand used in the studies.

A comparison of the peak acceleration at the top of the model footing resting on 20%, 30% and 50% RSM and the peak acceleration of the input (measured during the tests) base motion are shown in Fig. 10. The test results show that, unlike in sand, even at small amplitudes of base motion, the responses of the model footing are remarkably less than the original base motions (Figs. 10 and 12). The results show clearly that the response (acceleration) at the top of the model footing decreases with increasing percentages of shredded rubber tire in the foundation. When the percentage of shredded rubber tire in the foundation is increased beyond 50%, a rocking motion is experienced and the model footing with 4 kPa surcharge pressure on top becomes unstable.

Figure 11 shows the response spectra of the footing resting on various percentages of RSM and compares them with the response spectra of the footing resting on the sand. The initial peaks in the response curves are most probably due to the vibration of the system at low frequency range and they may be ignored. The response curves show increase in damping behaviour due to the increase in percentage of shredded rubber tire in the sand. When compared with the response of the footing resting on sand, a shift in the natural frequency becomes noticeable. This might be due to the introduction of 20 mm thick layer of sand and shredded rubber tyre mixture under the model footing. A comparison of the peak motion measured on top of the footing and the base motion is shown in Fig. 12 for the case. This figure also attests to the effectiveness of the 50% RSM as base isolator. The relative displacement of the model footing for the case of footing resting on sand and 50% shredded rubber tire is found to be about ±1.8 mm for 0.3 g base motions at 3.5 Hz frequency and shown in Fig. 13. The test results show that, unlike in sand, even at small amplitude of base motions, the response of the model footing is remarkably less than the base motion. In these cases, the sand rubber mixture dissipated base motion energy through slip deformation, and also some amount of energy is absorbed by the sand rubber mixture which results in dampened response of the footing. The isolating layer consisting of 50% RSM is quite effective in dampening the cyclic base motions.

Figures 10 – 13 attest to the effectiveness of the 50% RSM as a base isolator for cyclic motions. The response of the model footing resting on 50% RSM to 0.3 g base motions at various frequencies is shown in Table 3. The effect of frequency on the response of the footing is not conclusive at least for this case and other cases investigated. The responses of the footing resting on sand and on RSM for the same base motion are also compared in the table. The effective of RSM on the base of the footing can be very well observed. Table 4 shows the response of the footing to base motions of various amplitudes keeping the frequency constant at 3.5 Hz. The effect of the base isolation is very clear from this

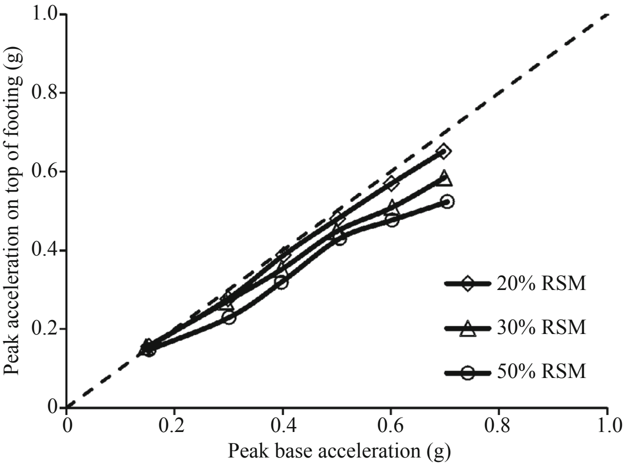


Fig. 10 Comparison of transmitted accelerations at the top of the footing resting on 20%, 30% and 50% RSM for base motions of various acceleration amplitudes and frequency 3.5 Hz

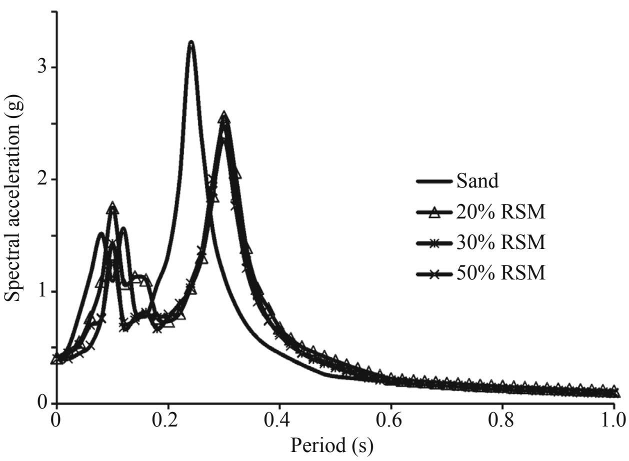


Fig. 11 Responses of the footing resting on sand and on 20%, 30% and 50% RSM for a base motion of amplitude 0.4 g and frequency 3.5 Hz

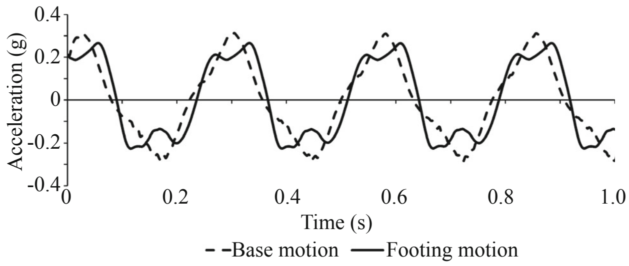


Fig. 12 Comparison of the accelerations on top of the footing resting on sand and 50% RSM for a base motion of amplitude 0.3 g and frequency 3.5 Hz

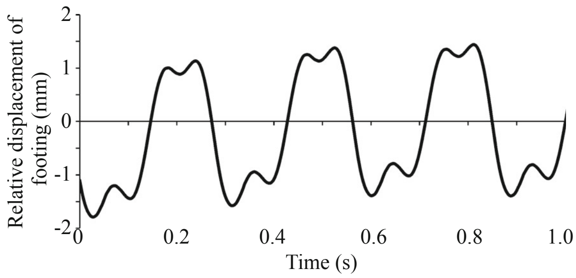


Fig. 13 Relative displacements of the model footing resting on sand and 50% RSM for a base motion of amplitude 0.3 g and frequency 3.5 Hz

Table 3 Peak acceleration at the top of footing at a constant amplitude of 0.3g and different frequencies of base motion

Frequency (Hz)	Peak base acceleration (g)	Peak transmitted acceleration (g) on top of footing	
		Resting on 50% RSM	Resting on sand
1.5	0.3	0.2	0.3
2.5	0.3	0.25	0.3
3.5	0.3	0.23	0.3
4.5	0.3	0.22	0.3

Table 4 Peak acceleration at the top of footing at a constant frequency of 3.5 Hz and different amplitude of base motion

Frequency (Hz)	Peak base acceleration (g)	Peak transmitted acceleration (g) on top of footing	
		Resting on 50% RSM	Resting on sand
3.5	0.2	0.15	0.2
3.5	0.3	0.23	0.3
3.5	0.4	0.32	0.4
3.5	0.5	0.43	0.5
3.5	0.6	0.48	0.6
3.5	0.7	0.52	0.62
3.5	0.8	0.54	0.67
3.5	1.0	0.56	0.70

table even at small amplitudes of motion. The table also shows the corresponding response of the footing resting on sand. The numbers are again convincing, showing the effects of RSM at the base of the footing.

4.3 Effects of surcharge load and layer thickness

To study the effects of the RSM layer and the surcharge pressure on the response of the model footing, a test was performed with the surcharge pressure increased from 4 kPa to 8 kPa and the thickness of the isolating layer of 50% RSM increased from 20 mm to 50 mm. The base motion had an amplitude of 0.4g and a frequency of 3.5 Hz. Figures 14(a) and 14(b) show the responses of the model footing with 4 kPa and 8 kPa surcharge pressures, respectively. These figures indicate that the amplification in acceleration at top of footing decreases with an increase in surcharge pressure: The peak acceleration on top of the footing with 4 kPa surcharge load is 0.34g while that for the footing with a surcharge load of 8 kPa is 0.27 g. Figures 15(a) and 15(b) show the responses of the footing resting on top of 20 mm and 50 mm thick 50% RSM. The results indicate that the amplification in acceleration response at the top of the model footing decreases with the increase in the isolating layer thickness. However, as can be seen from Fig. 16, displacement of the model footing relative to the base increases with the increase in the layer thickness. When the thickness of the 50% RSM layer under the model footing is increased from 20 mm to 50 mm, the relative displacement of the footing increased also from 4mm to 5 mm. The peak response of the footing decreases from 0.32 g to 0.27 g. Note that such relative displacement is mainly concentrated within the layer, but not on the structure. Hence, it would not increase the displacement demand (in terms of inter-storey drift) on real structures.

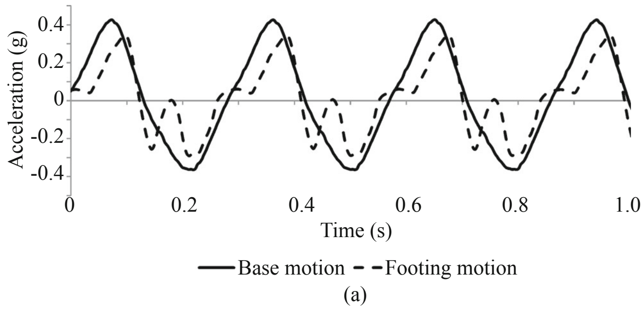


Fig. 14(a) Response of the footing with 4 kPa surcharge pressure on top and resting on sand and 50% RSM for a base motion of amplitude 0.4 g and frequency 3.5 Hz

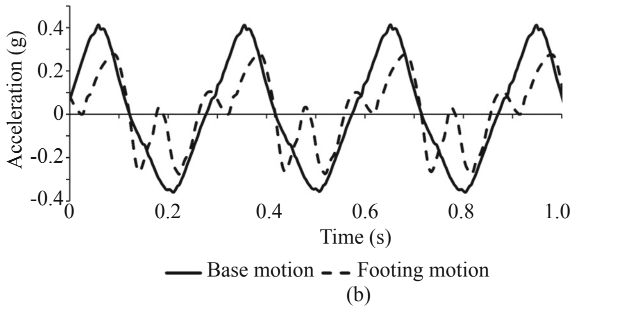


Fig. 14(b) Response of the footing with 8 kPa surcharge pressure on top and resting on sand and 50% RSM for a base motion of amplitude 0.4 g and frequency 3.5 Hz

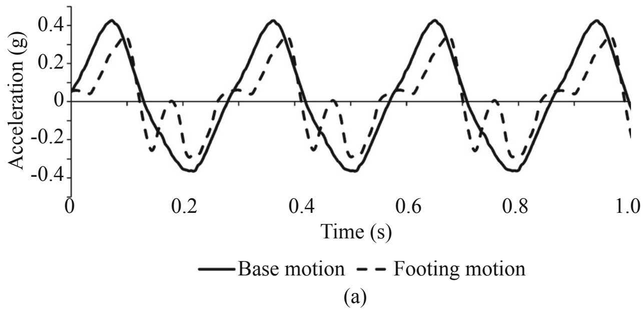


Fig. 15(a) Response of the footing resting on a 20 mm thick RSM layer for a base motion of amplitude 0.4 g and frequency 3.5 Hz

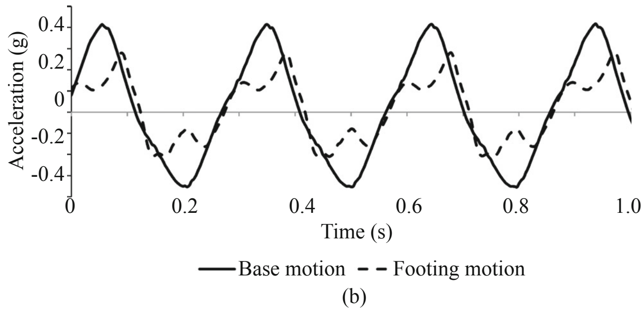


Fig. 15(b) Response of the footing resting on a 50 mm thick RSM layer for a base motion of amplitude 0.4 g and frequency 3.5 Hz

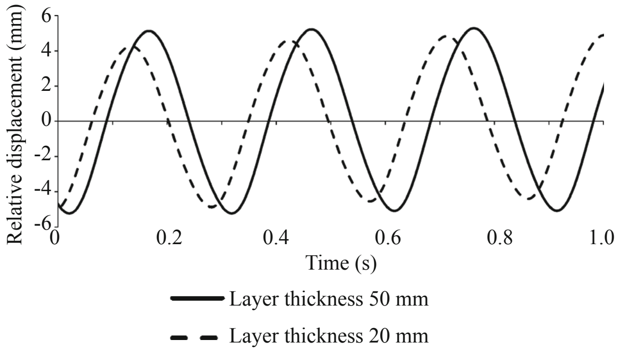


Fig. 16 Relative displacement of the footing resting on 20 mm and 50 mm thick RSM layer for a base motion of amplitude 0.4 g and frequency 3.5 Hz

5 Conclusions

A base isolating system can be effective in two ways: (1) By reducing the input motion that the structure is subjected to; and (2) by shifting the predominant frequency of the structure from that of its base motion so as to avoid resonance. The objective of this communication is to demonstrate that shredded rubber tire, usually considered a waste worldwide, could be utilized effectively as part of a low cost base-isolation scheme by reducing the shaking motion.

With regard to (1), sand in the foundation of the model footing is found to be ineffective as a base isolator at low amplitudes (< 0.6 g) of base motion. However, at higher amplitudes (> 0.6 g), it is quite effective in reducing the motion transmitted to the footing. At 0.8 g and 1 g, the accelerations of the model footing decreased significantly. The decrease was accompanied by slip/displacement of the footing over the sand foundation. At 1 g motion, the amplitude of this displacement was found to be about ±5.43 mm.

Shake table tests with the model footing resting on a 20 mm thick layer of sand and shredded rubber tire mixture (i.e., RSM) show that the proportion of shredded rubber tire should be 50% (by weight) to yield significant benefits. At this proportion the response of the model footing was found to be significantly less than that of the base. However, with the percentage of rubber in the mixture further increased, rocking motion started to dominate and the model footing was found to be unstable.

Shake table tests with different surcharge pressures on the model footing indicate that amplification in the acceleration response of the footing decreases with increasing surcharge pressures. Amplification in the acceleration response of the model footing is found to decrease with increasing RSM layer thickness, whereas the relative displacement of the model footing with respect to the base increases with increasing layer thickness.

With regard to (2), since all the input motions of the shake table are sinusoidal with a given frequency, the shifting of the frequency of the model footing during a test could not be studied. It is hoped that this important aspect of the base isolation system can be looked at in the next phase of the study.

Finally, the proposed scheme of low cost base isolation using 50% RSM is in a very preliminary stage of testing. Its performance has been studied in an ideal (laboratory) condition, and more studies, including field testing, are definitely needed.

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