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RESPONSE OF SOIL-TYRE MIXTURE SUBJECTED TO CYCLIC LOADING

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Abstract

Typically, base isolators are placed within the building structure for passive vibration control in earthquake prone areas. An economical version of base isolation can be achieved by using natural seismic isolators such as sand placed beneath the foundation. However due to the scarcity of sand and its inability to recover from the deformations suffered during an earthquake, natural seismic isolator made of soil- tyre mixture could potentially be a better solution. This will also serve as a sustainable solution for the recycling of scrap tyres.

To find the suitability of soil-tyre mixture as an effective seismic isolator, a series of strain-controlled cyclic triaxial tests were performed on sand specimens compacted with different percentage of tyre content (0%, 30%, 50% and100%) at a confining pressure of 100 kPa. The results of cyclic triaxil tests shows decrease in the shear modulus values and increase in the hysteretic damping values of sand with the increase in tyre content.

To demonstrate the effective use of sand-tyre mixture as an isolating base layer for buildings, the seismic response of a typical isolated footing embedded in sand-tyre mixture isolator (30% tyre content) was studied using a 3D finite element code ABAQUS. Sand and sand-tyre mixture isolator are modeled as visco-elastic materials. The foundation-isolating layer-soil system was subjected to 1978 Miyagiken Oki earthquake time history of acceleration. It is found that the isolating layer with a thickness of two times the width of footing reduces the peak spectral acceleration by about 40% indicating the promising use of sand-tyre mixture as an isolating base layer for earthquake resistant design of low-rise buildings.

Keywords: Seismic base isolation, sand - tyre mixture, cyclic triaxial test, 3D FE Modelling, ABAQUS.

1. Introduction

Earthquakes can bring devastating effects to life and structures. Earthquake damages to the structures can be minimized by incorporating engineering interventions that could improve the flexibility of building. Introducing base isolation techniques like laminated rubber bearing systems, elastomeric bearing systems and friction pendulum systems can reduce the intensity of earthquake waves on the building to a great extent. Typical base isolation systems use sliders, rotating ball bearing and dampers (oil, steel and rubber). The energy dissipaters placed within the structure can reduce the earthquake response by 40-60% [1]. Advanced techniques of base isolation to minimize damage on buildings during strong shaking are very costly and are hence used only for important buildings. However, in areas with a history of frequent seismic activities, a sustainable and eco-friendly solution is needed for residential and commercial buildings to survive the earthquake damages. Soil-tyre mixture could be an effective solution of seismic isolation due to its low cost and simplicity of incorporating into the field. Utilization of scrap tyre in the geotechnical field would reduce the stockpiling and disposal issues related to the waste rubber tyres that are being dumped worldwide with little recycling and reuse. Experiments conducted on sand to study its feasibility as seismic isolator [2, 3] has found that sand performs well in dampening of the earthquake waves. A sustainable and green technology for seismic isolation can be achieved by adding fragmented scrap tyre to sand which can improve the damping properties of soil.

2. Background of cyclic properties of sand-tyre mixtures

Konagai and Kim [4] proposed to cover tunnel linings with a soft and thin coating (e.g. rubber) for reducing deformation in an earthquake. Kirzhner et al. [5] conducted experiments by replacing soils with softer materials (including rubber or rubber-soil mixture) surrounding a tunnel for noise and vibration absorption. The use of tyre chips for protecting waterfront retaining structures in an earthquake was proposed by Hazarika et al. [6]. For building structures, the concept of vibration screening was initially suggested by Woods [7]. Based on shake table experiments conducted by Xiong [8] using soil-rubber mixture as isolation medium it was reported that the isolators perform well for a higher intensity of earthquake input motions.

Experiments carried out by Nakhaei et al. [9] using large sized cyclic triaxial apparatus (15cm diameter and 30 cm height) has confirmed that shear modulus is primarily governed by confining pressure. The shear modulus increases with increase in confining pressure irrespective of the percentage of rubber content. The damping ratio of the soil-tyre mixture decreases with increase in rubber content for lower confining pressure, But for higher confining pressure, the damping ratio increases with increase in rubber content. Hazarika et al. [10] experimentally investigated the effect of material size (scale effect) on the strength and deformation behavior of tyre-derived geo-materials. The test results confirmed that material size does not significantly affect the material behavior of tyre chips. More recently, works by Mashiri et al. [11] has found that rubber inclusion in soil can decrease its dilatancy properties. Extensive studies were carried out by Anastasiadis et al. [12, 13] on the dynamic behavior of sand-rubber mixture. It was reported that sand-rubber mixture exhibits a reduced shear modulus and higher damping ratio compared to sand.

This paper looks into the cyclic behavior of the soil-tyre mixture by conducting cyclic triaxial tests on sand-granulated tyre mixture samples. The variation of shear modulus and damping ratio with strain is studied for various percentage of granulated tyre content. A seismic response of isolated footing resting on sand-granulated tyre mixture layer was studied using 3D Finite Element code ABAQUS**.** The strain-dependent shear modules and damping properties obtained from the cyclic triaxial tests are used in the modelling of sand-granulated tyre mixture layer. The numerical results are analyzed in terms of time history of acceleration and response spectra at the surface of foundation.

3. Determination of cyclic properties of sand-rubber tyre mixtures

3.1 Materials used

In the present study, river sand collected from Chennai city (India) is used. The grain size distribution curve for sand is shown in Fig.1. The soil is classified as Poorly graded Sand (SP) as per Indian Standard Classification system. The rubber tyre used in this study is obtained from local scrap tyre recycling units where the steel reinforcements inside the automobile tyre are removed, and the scrap tyre is fragmented into fine particles with angular shape. Granulated tyre particles passing 4.75mm size sieve is used in the preparation of sand -rubber tyre mixture samples. The particle size distribution curve of the granulated tyre is also presented in Fig.1. The index properties of sand and granulated tyre are summarized in Table1.

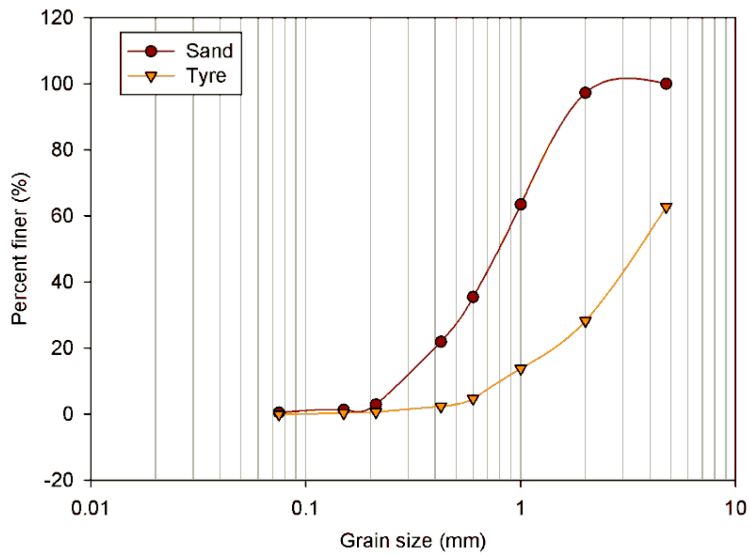

Fig.1 – Particle size distribution curve of sand and granulated tyre

Table 1 – Properties of sand and rubber tyre

Material	Specific gravity	Coefficient of uniformity (Cu)	Coefficient of curvature (Cc)	Classification
Sand	2.65	3.3	1.1	Poorly graded Sand (SP)
Tyre	1.1	5.5	3.2	Equivalent of Poorly graded Sand (SP)

3.2 Sample preparation

For the present study, cyclic triaxial test samples are prepared for sand with and without granulated tyre. Sand and granulated tyre are mixed uniformly to get a homogenous mixture as shown in Fig.2. Cylindrical soil specimen of 50mm diameter and 100m height is prepared for the cyclic triaxial test setup. The sample is made in a split mould with a rubber membrane carefully attached to it. Dry deposition method proposed by Ishihara [14] is adopted for sample preparation. Sample specimen is poured into the split mould using a funnel, maintaining a height of fall of 10cm followed by tamping. A relative density of 80-85% is maintained during sample preparation.

Fig. 2 – Soil-tyre mixture used for the cyclic triaxial test

3.3 Test procedure and program

The strain controlled consolidated undrained cyclic triaxial tests are carried out on sand-rubber tyre mixture specimens using Wykeham Farrance International (UK) make, a servo-controlled cyclic triaxial testing facility (Fig.3) available in the Geotechnical Engineering Laboratory of Indian Institute of Technology Madras. The specimen prepared at a specific relative density is saturated by letting de-aired water from the bottom of the specimen and by incrementing the back pressure. The specimen is saturated until the Skempton's pore pressure parameter B becomes greater than or equal to 0.95. The sample is subjected to isotropic consolidation under a confining pressure of 100 kPa. Under the undrained conditions the specimen is subjected to cyclic deviator stress in the axial direction. The tests are conducted at a frequency of 1 Hz for a constant cyclic strain rate up to 100 no of cycles. The tests are repeated for varying cyclic strain amplitudes. During the testing, the axial load, axial strain and excess pore water pressure were measured. Mixtures of sand replaced with granulated tyre by dry weight in the order of 0%, 30%, 50% and 100% are used for sample preparation. In this study, 0% and 100% replacements indicate pure sand and pure granulated tyre samples respectively.

Fig. 3 – Cyclic triaxial test setup

3.4 Results and discussions

3.4.1 Hysteresis stress-strain behavior of sand- tyre mixtures

Under undrained conditions, the volumetric strain will be zero. Hence, the axial strain measued in the triaxial testing will be equal to shear strain γ_c and deviator stress (q) will be equal to shear stress τ_c (Atkinson and Bransby[15]). A typical shear stress- shear strain response of soil-tyre mixture specimens with 30% tyre content obtained from the cyclic triaxial tests at 1st, 3rd, 10th and 100th loading cycle is shown in Fig.4. The inclination of hysteresis loop, i.e., degradation of stiffness with increase in the number of cycles of loading can be observed from Fig.4. The shape of hysteresis stress-strain loop stabilizes after three cycles. But at a larger number of cycles (100th cycle) the hysteresis loop is found to be further inclined indicating further degradation of the stiffness of soil-tyre mixture. However, in the typical earthquake loading applications, the soil layers are subjected to less number of cycles and hence the shear modulus and damping are obtained from the hysteresis loop corresponding to the 3rd cycle of loading.

The equivalent linear shear modulus, G and the damping ratio, ξ of the soil-tyre mixture are obtained from the hysteresis loop at different strain levels using Eq. (1) and Eq. (2) (Kramer [16]).

$$G = \frac{\tau_c}{\gamma_c} \tag{1}$$

where, τ_c and γ_c are the shear stress and the shear strain amplitudes, respectively.

$$\xi = \frac{W_D}{4\pi W_S} = \frac{1}{2\pi}\frac{A_{loop}}{G{\gamma_c}^2} \tag{2}$$

where, W_D is the dissipated energy, W_S the maximum strain energy, and A_{loop} is the area of the hysteresis loop.

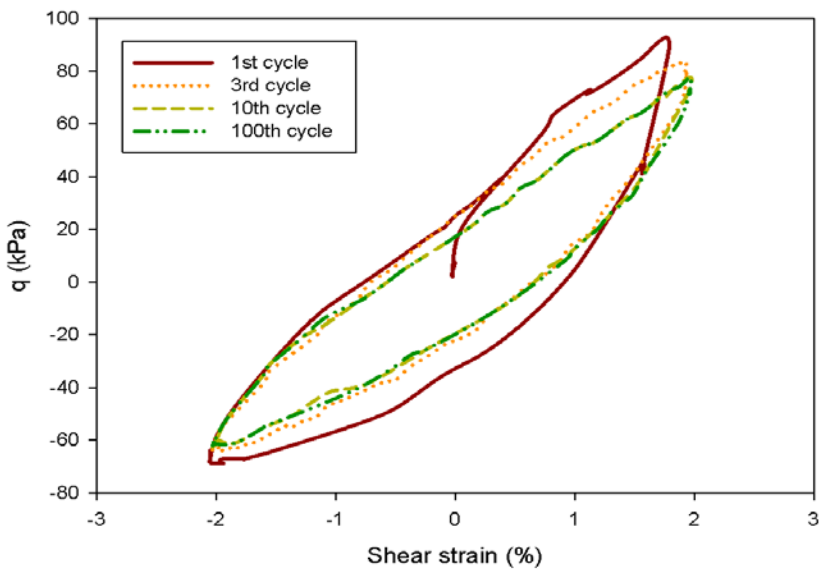

Fig.4 – Hysteresis loop of soil-tyre mixture for different cycles of loading (30% tyre content)

3.4.2 Shear modulus curves

The variation of shear modulus with shear strain for sands with various percentage of tyre content is presented in Fig. 5. It can be noticed from Fig.5 that at relatively small to medium strain levels the shear modulus of the sand decreases drastically with increase in tyre content. But it is interesting to notice that the degradation of stiffness with increase in strain level is less for sand-tyre mixture specimens compared to sand specimen. It could also be observed that sand-tyre mixture with 30% tyre content gives a higher shear modulus value compared to the same with 50% and 100% tyre content.

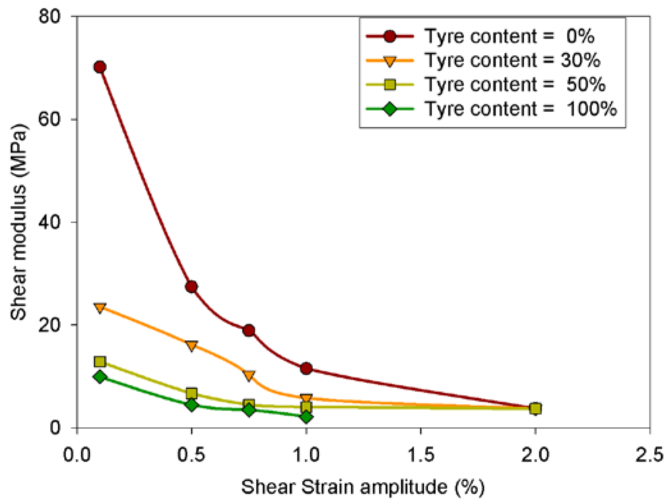

Fig.5 – Shear modulus degradation curve for different proportions of soil-tyre mixture

3.4.3 Damping curves

The variation hysteretic damping, ξ of sand- tyre mixtures with the shear strain is plotted in Fig.6. It is noticed from Fig.6 that the strain dependent damping values of sand increases with increase in tyre content. The shape of damping curves for sand-tyre mixture with 30% tyre content is found to be similar to the pure sand but at a high percentage of tyre content, the nature of damping curves differ from that of pure sand.

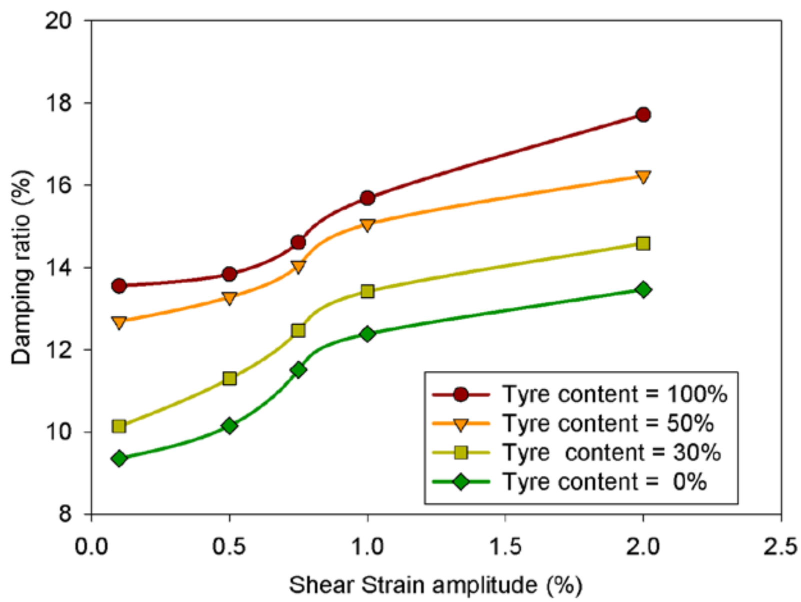

Fig.6 – Damping curves for different proportions of soil-tyre mixture

4. Seismic response of footings on sand-tyre mixture isolator

To demonstrate the effectiveness use of sand-tyre mixture as an isolating base layer for buildings, the seismic response of a typical isolated footing embedded in sand-tyre mixture isolator is considered. The isolating footing considered is a square concrete footing with 1 m x 1m size and 1m thickness. It is found from Section 3 that sand-tyre mixture with 30% tyre content is found to have relatively higher stiffness and adequate damping properties. Hence, sand-tyre mixture with 30% tyre content is considered as the base isolator for the footing. The thickness of the isolator layer below the footing and side of the footing is adopted as 1m, i.e. equal to the width of the footing. The soil layer below the base isolator layer is considered as a thick homogeneous soil layer. The schematic representation of the isolated footing on sand -tyre mixture isolating layer is illustrated in Fig.7.

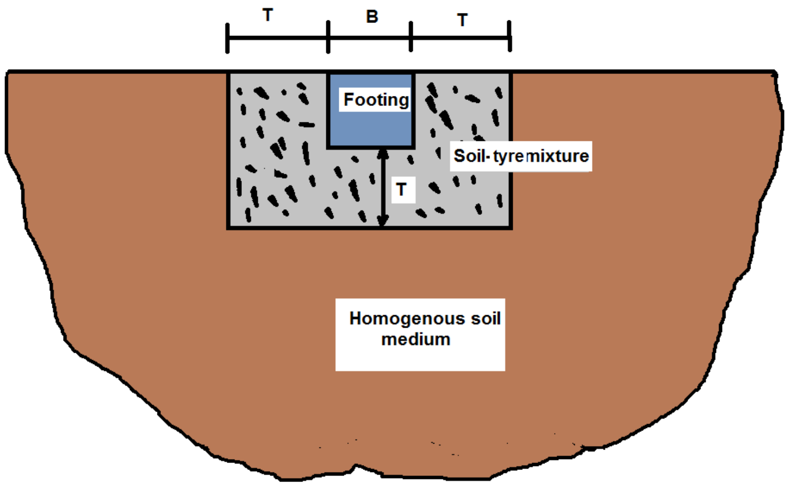

Fig.7 – Seismic isolation system using soil-tyre mixture

4.1 Finite Element Modeling

A three-dimensional finite element model is developed using ABAQUS 6.12 to study the response of footing placed on soil-tyre mixture subjected to an earthquake. A square footing of size 1m (B) x1m (B) and depth 1m (B)is used in the analysis. The footing is embedded into the soil up to a depth of B, where B is the width of the footing. The sand-tyre mixture is placed beneath and around the footing for a thickness of B. The entire footing and soil-tyre isolators are placed on a soil mass of size 400B (length) x 40B (breadth) x 40B (depth). To avoid reflections of waves the length of the soil mass is chosen as 400B. The whole model is discretized using 8-node continuum elements (C3D8R). The 3-D finite element model of the seismically isolated system employed in the present study (Fig.8) involves an isolated footing placed at the center of the soil mass at the ground surface surrounded by the soil-tyre isolation layer.

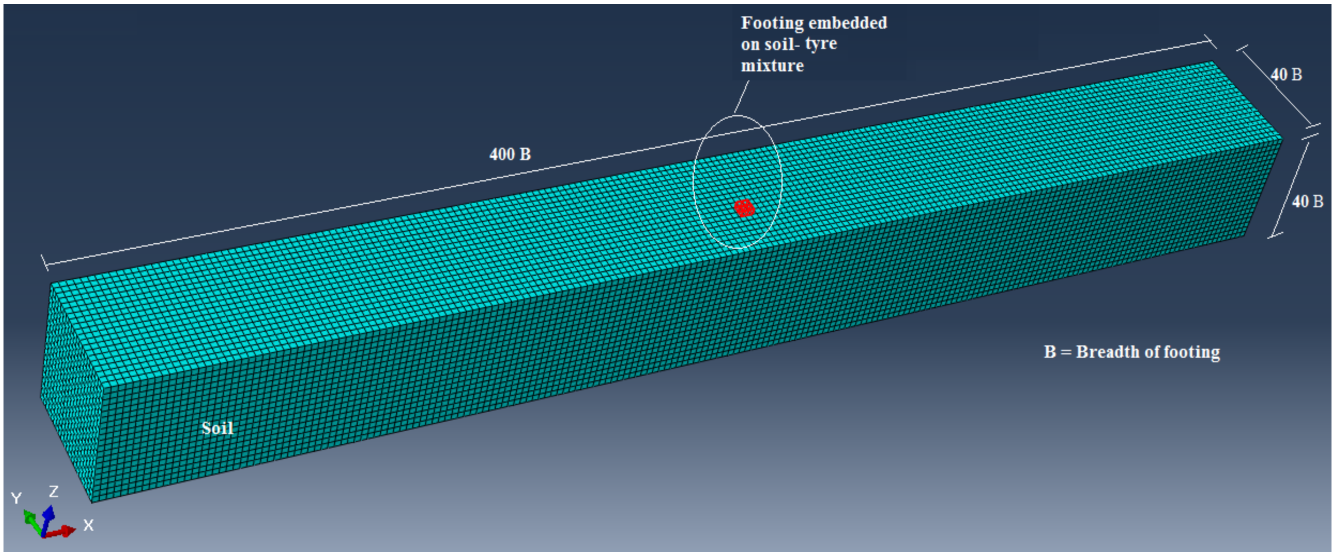

Fig.8 – Finite element model of the seismically isolated system.

Soil and sand -tyre mixture isolator is modeled as visco-elastic materials. Young's modulus of sand and sand-tyre mixtures is obtained from cyclic triaxial tests which are presented in Table 2. The assumed Poisson's ratios of sand and sand-tyre mixtures are also given in Table 2. The Rayleigh damping constants α and β which is a function of natural frequency and damping ratio are used to incorporate the damping properties of soil and soil-tyre mixture in the model. The Rayleigh damping for soil and sand-tyre mixture used in FE analysis is given in Table 2. The concrete footing is modeled with liner elastic properties as listed in Table 2.

Table 2 – Material Properties used in ABAQUS

Properties		Soil	Soil-Tyre	Concrete
Young's modulus (MPa)		180	100	30000
Poisson's ratio		0.3	0.35	0.2
Density (kg/m^3)		1600	1500	2400
Damping coefficient	α	0.4534	1.8420	-
	β	0.0055	0.1357	-

The initial stress conditions are established by applying the boundary conditions of roller supports to the sides and fixed support at the base of the model. The gravity loads are applied in the next step. The footing is considered at the centre of the model to avoid boundary effects. The dynamic analysis was carried by implicit method. The time history of acceleration corresponding to the 1978 Miyagiken Oki earthquake with PGA of 0.063g was applied as input motion at the base of soil medium.

4.2 Results and discussion

4.2.1 Peak Ground acceleration at foundation level

The time history of acceleration is estimated at the top foundation i.e. foundation input motion to the superstructure for the considered isolated footing with and without the sand-tyre isolator. Typical acceleration-time history corresponding to seismically isolated system without isolator and with isolator (T/B = 1) are shown in Fig.9 (a) & (b). The peak ground acceleration obtained from the time history at the top of foundation for the sand tyre isolated layer with thickness T/B=1 and T/B= 2 are presented in Table 3. It can be easily noticed from Table 3 that the value of peak ground acceleration for isolator layer with thickness equals to twice the width of footing (T/B=2) decreases by about 20% in comparison to the footing system without isolating layer.

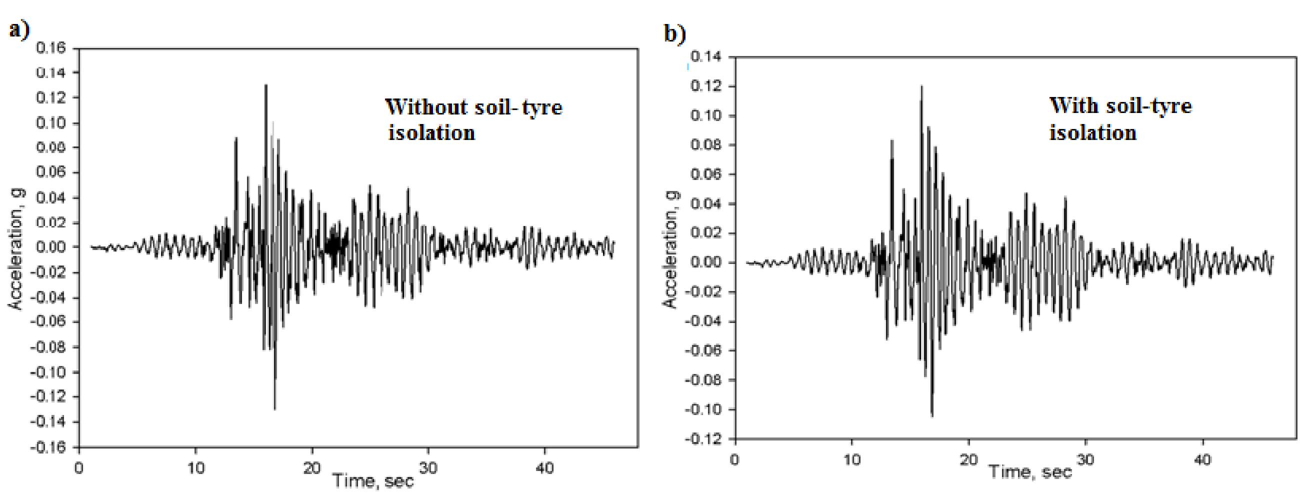

Fig.9 – Time history of acceleration at the top of foundation (a) Without isolator. (b)With isolator (T/B=1)

Table 3 – Peak Ground Acceleration (PGA) and Peak Spectral Acceleration at the top of foundation

Description		Peak ground acceleration, g	Peak spectral acceleration, g
Without soil-tyre isolator		0.130	0.52
With soil-tyre isolator beneath and around the footing	T/B=1	0.120	0.44
	T/B=2	0.105	0.33

4.2.2 Response Spectra at foundation level

The acceleration response spectra obtained from the time history of acceleration level for the foundation system considered with and without isolators are presented in Fig.10. The similar shape of response spectra for footing system with and without isolators as shown in Fig.10 indicates that there is no change in the frequency content due to the introduction isolating layer. However, the amplitude of spectral acceleration is reduced in the case of foundation embedded in the sand-tyre mixture isolating layer. The estimated values peak spectral accelerations are presented in Table 3 which points out the drastic decrease of peak spectral acceleration for the foundation system with isolators. For foundation isolated with the sand-tyre mixture having T/B=2, the peak spectral acceleration is found to be about 40% that of the foundation without isolating layers which in turn indicates the effectiveness of sand-tyre mixture system as a base isolation system for buildings.

The present study needs to be further modified and analyzed for different earthquake input motions and material models to optimize the thickness of soil-tyre mixture isolators and to bring out the full efficiency of the soil-tyre isolation system.

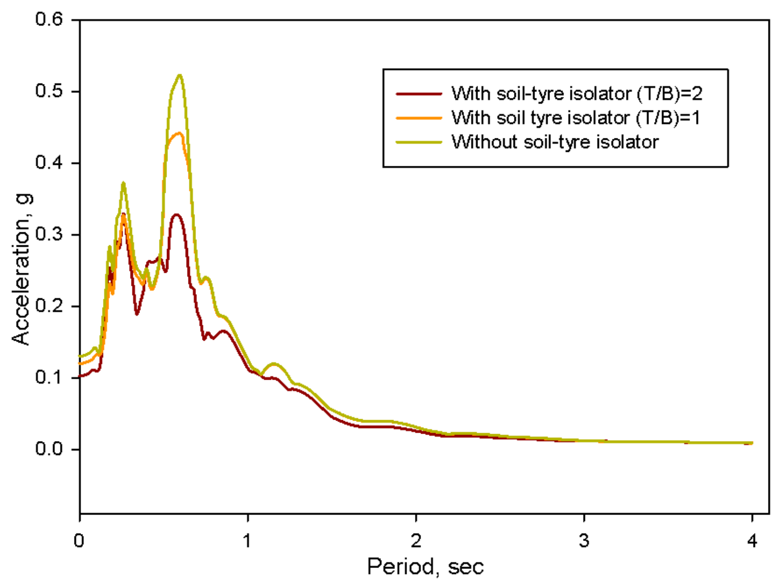

Fig.10 – Response spectra at the foundation level

5. Conclusion

In the present paper, an attempt was made to study the use of sand-tyre mixture as a base isolating layer for buildings subjected to earthquakes. Strain-controlled, cyclic triaxial test was carried out to establish the strain dependent shear modulus and damping curves for sand-tyre mixture. It is found that use of sand-tyre mixture with 30% of tyre content is more effective in seismic isolation since it satisfies both stiffness and damping requirements.

The seismic response of typical isolated footing embedded in sand-tyre isolating layer with 30% tyre content is carried out using 3D finite element code ABAQUS. It is found that the isolating layer with a thickness of two times the width of footing reduces the peak spectral acceleration by about 40% indicating the promising use of sand-tyre mixture as an isolating base layer for earthquake resistant design of low-rise buildings.

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