Tire chips reinforced foundation as liquefaction countermeasure of residential building

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ABSTRACT: To prevent vibration-induced and liquefaction-induced damage of residential buildings during earthquakes, a low cost technique has been developed and described here, which utilizes tire chips mixed gravel as horizontal reinforcing inclusion under the foundation of residential house. The horizontal reinforcing inclusion refers to a layer made of tire chips and gravel, which is placed horizontally beneath the foundation. Mixture of gravel and tire chips layers provides sufficient bearing capacity to the foundation. In this research, a series of small scale 1g model shaking table tests were performed to evaluate effectiveness of the technique. In addition, cyclic undrained triaxial test were performed to evaluate the liquefaction susceptibility of tire chips-gravel mixtures. Results of model tests indicate that when the thickness of reinforced layer is 10 cm (2 m in prototype) and gravel fraction (percentage of gravel in the mixture) is 50%, the technique yields the best performance. The element tests also indicated that gravel fraction plays an important role. 50%-60% is the best mixing percentage, in which the rise of excess pore water pressure could be significantly restrained without compromising the stiffness of the reinforcing inclusion.

Keywords: Tire chips, gravel, liquefaction, shake table test, horizontal inclusion

1 INTRODUCTION

For the past two decades, research related to the utilization of tires in construction projects has been gaining momentum. Due to their advantageous physical and mechanical characteristics, Tire Derived Geomaterials (TDGM) either in the form of shreds, chips or crumbs have been used as fill material for embankments (Humphrey 2008), as fill material behind retaining walls and abutments (Garcia et al. 2012; Hartman et al. 2013, Reddy and Krishna 2016), as base isolation for buildings (Tsang 2008), and as lining in tunnel construction (Kim and Konagai 2001). The geo-environmental aspects of such materials were thoroughly reviewed by Edil (2008).

On the other hand, the Japanese research covers a wide range of waste tire utilization. Few examples of those include: use of whole tires or in conjunction with other granular materials (Fukutake and Horiuchi 2006) or use of tire chips and tire shreds (Hazarika et al. 2010; Hazarika et al. 2012a; Hazarika et al. 2012b; Niiya et al. 2012; Karmokar et al. 2006; Kikuchi et al. 2008). Also, tire chips mixed with cement-treated clay was used as a sealing material at a waste disposal sites in Tokyo bay (Mitarai et al. 2006). Use of tire chips as a material to prevent liquefaction in soil also was experimented by Yasuhara et al. (2010) and Uchimura et al. (2008).

Japan being one of the most vulnerable countries to earthquake, many techniques for earthquake disaster mitigation using TDGM have been developed (Hazarika et al. 2006; Hazarika et al. 2008; Hazarika, 2012; Hazarika et al. 2012b; Hazarika et al. 2013; Hazarika et al. 2015; Hazarika et al. 2016). One major concern during any earthquake in Japan is the liquefaction induced damage to residential houses. To prevent vibration-induced and liquefaction-induced damage of residential buildings during earthquakes, it is important to adopt low cost ground improvement technique, since house owners cannot afford to go for the expensive ground improvement techniques applied in conventional and large-scale infrastructural projects. One such low cost technique was developed (Hazarika et al. 2009; Hazarika and Abdullah 2015), which utilizes tire chips layer as horizontal inclusion under the foundation of residential housing. Horizontal reinforcing inclusion, refers to a layer made of tire chips which are placed horizontally. Mixture of tire chips and sand as liquefaction prevention materials was also investigated by Hyodo et al. (2008) through cyclic triaxial testing. However, tire chips and sand mixture could result in high differential settlement and inadequate bearing capacity of foundation. Also, most of previous studies on dynamic behavior of sand-TDGM mixtures involved tire chips particles, which are remarkably larger than sand particle ($D_{50,r}$ / $D_{50,s}$)>>1, and this results in segregation of materials due to the differences in shape, size, density and stiffness, especially when the fraction of tire chips in the mixture is high. To overcome those problems, this paper suggests that a mixture of gravel and tire chips layers along with geogrid reinforcement (if necessary) be used, as shown in Fig. 1., which will be more practical as it will provide sufficient bearing capacity to the foundation that otherwise has to rest on highly compressible tire chips layer. To verify the effectiveness of the technique suggested in Fig. 1, in this study, a small scale model shaking table tests were performed.

On the other hand, investigation of dynamic behavior of GTCM is necessary to establish the technique described above. Therefore, this study also aims to investigate the influence of gravel fraction on dynamic properties as well as liquefaction resistance of GTCM. For that purpose, a series of stress controlled consolidated undrained cyclic triaxial tests were conducted on GTCM with different gravel fractions.

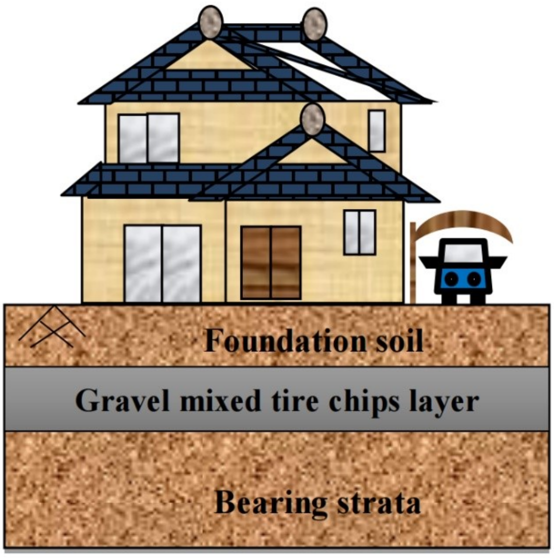


Figure 1. Liquefaction induced damage prevention of building using horizontal inclusion.

2 VALIDATION OF HORIZONTAL INCLUSION TECHNIQUE

To evaluate the effectiveness of the technique illustrated in Fig. 1, a series of 1g model shaking table tests were performed, using the shaking table test assembly of Kyushu University, Fukuoka, Japan.

2.1 *Model shaking table test*

The test model (prototype to model ratio of 20) is shown in Fig. 2. Model test box was 600 mm in length, 300 mm in width and 500 mm in height. Toyoura sand was used as foundation soils of a model house. Pure tire chips (2mm in size) or tire chips mixed gravel (size almost similar to tire chips) were used in preparing the horizontal inclusion. Keeping the height of the ground in the soil box up to 300 mm, the relative density of base layer and the layer containing horizontal inclusion was adjusted to be around 50%. The layer immediately below the foundation was made of gravel, which replicates the top layer of building foundation normally improved by some sorts of ground improvement techniques.

A total of seven test cases were examined under three different conditions of the horizontal inclusion, which are shown in Table 1. In the Table, Case 0 represents the conventional foundation soil. Case 1, Case 2-1 and Case 2-2 represent the cases in which the thickness of horizontal inclusion was 10 cm. Case 3-1 and Case 3-2 represent the conditions in which the thickness of horizontal inclusion was reduced to 5 cm.

Finally, in Case 4, the reinforced layer was located between the upper and lower sand layers. In the Table TC refers to tire chips and gf (gravel fraction) refers to the percentage of gravel in the mixture by volume. 30 %, 50 % and 70 % gravel fractions (gf) were used. A sinusoidal acceleration of 300 Gal with 3 Hz frequency was imparted into the model for 45 seconds, and the responses were measured using the LVDT, accelerometers and pore water transducers, which were installed at various locations within the foundation soils shown in Fig. 2.

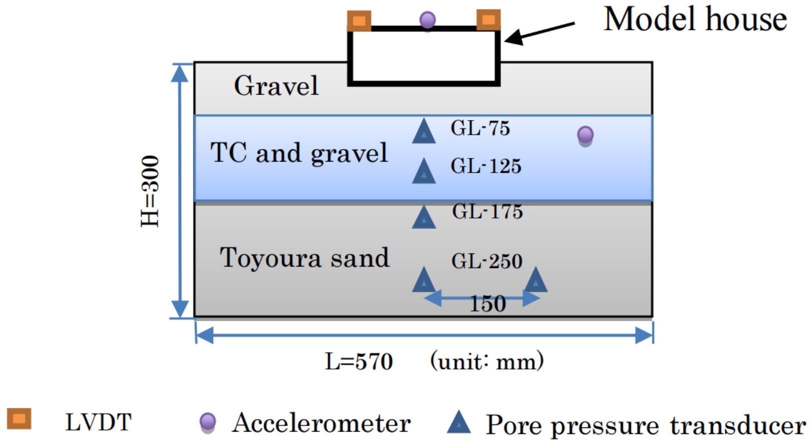


Figure 2. Model test setup.

Table 1. Different configurations of the model test.

Depth (mm)	**Case 0**	**Case 1**	**Case 2-1**	**Case 2-2**	**Case 3-1**	**Case 3-2**	**Case 4**
50	Gravel	Gravel	Gravel	Gravel	Gravel	Gravel	Gravel
100	Sand	Pure TC	TC + gravel (gf=50%)	TC + gravel (gf=30%)	TC + gravel (gf=50%)	TC + gravel (gf=70%)	Pure sand
150					Sand	Sand	TC + gravel
200		Sand	Sand	Sand			Sand
250							
300							

2.2 *Test results*

The maximum of excess pore water pressure ratios at various depths within the foundation soils are shown in Fig. 3. In the unreinforced foundation (Case 0) the excess pore water pressure exceeds 1.0 at all the depths indicating liquefaction in the foundation soils. Except for Case 4, in all the other cases the liquefaction was restrained in the reinforced layer. While Case 2-1 is the most effective in restraining liquefaction, Case 2-2 and Case 3-2 also display no liquefaction throughout the depth. These results imply that when the thickness of reinforced layer is 10cm, liquefaction can be prevented using the proposed horizontal inclusion technique. However, when the layer thickness is reduced to 5cm, the gravel fraction has to be over 70% to ensure its function. This may be attributed to the light weight nature of tire chips, which may not exert enough overburden pressure on the layers underneath.

The average final settlements of the model house due to the cyclic loading for each case are shown in Fig. 4. From this figure it is clear that the settlement of the house reinforced by pure tire chips (10 cm thick inclusion) can be reduced to half that of the non-reinforced foundation. However, when comparing with the gravel mixed tire chips reinforced foundation (10 cm thick inclusion), it can be observed that the settlement of the house was reduced further to half as compared to the foundation reinforced with pure tire chips. This implies that mixing gravel to tire chips can decrease the differential settlement due to enhanced bearing capacity. In addition, the settlement decreases with the increase in the thickness of reinforced layer and the amount of gravel fraction. Furthermore, Case 2-1, in which the reinforced layer thickness was 10 cm and gravel fraction was 50%, the settlement is significantly less. In Case 4, the settlement was found to be even larger than the unreinforced foundation. This implies that this particular pattern of reinforcement is not appropriate for the model considered in this study. In other words, the location and thickness of the horizontal inclusion are also important design consideration in this technique.

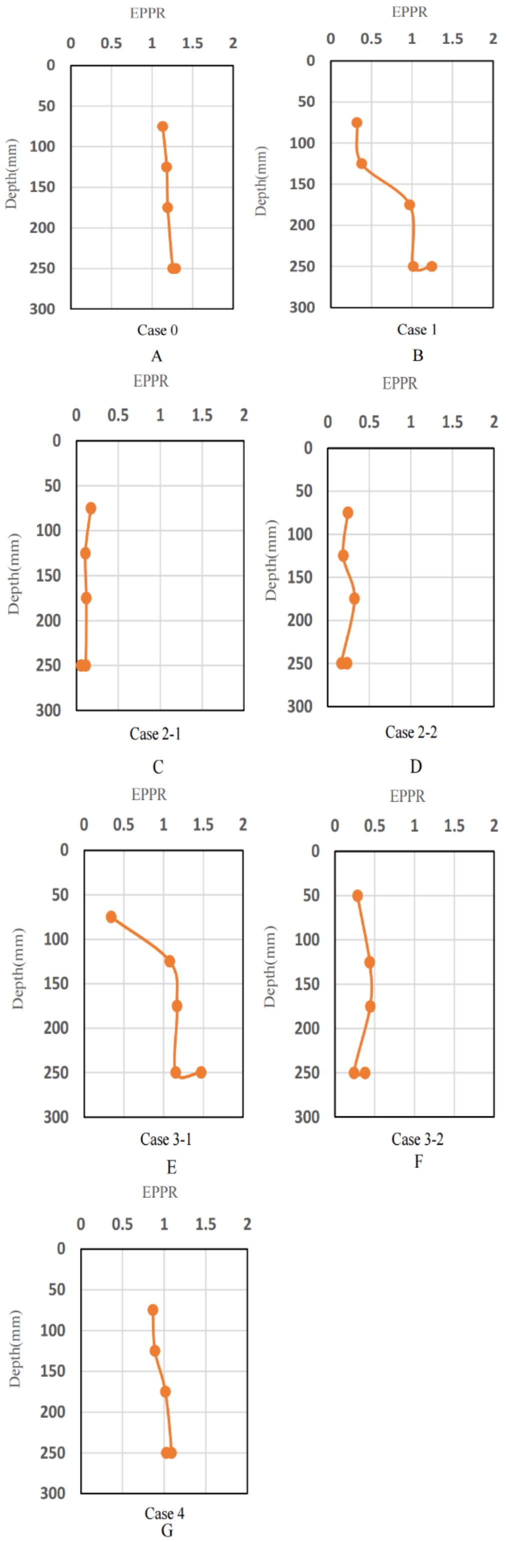


Figure 3. Liquefaction potentials of the foundation in each case.

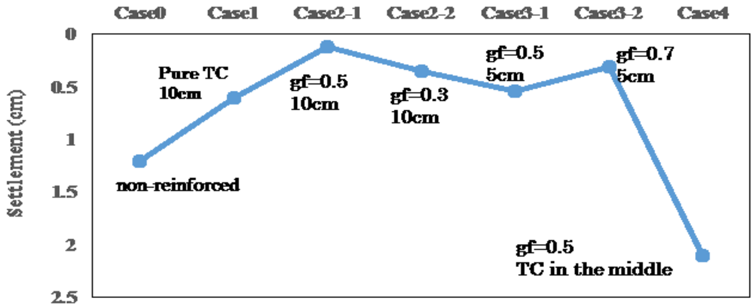


Figure 4. Comparisons of the settlement of model house in each case.

3 DYNAMIC PROPERTIES AND LIQUEFACTION POTENTIAL OF GRAVEL-TIRE CHIPS MIXTURE (GTCM)

Using the large cyclic triaxial testing apparatus of Yamaguchi University, Ube, Japan. Consolidated undrained (CU) tests were carried out on specimens of 100mm in diameters by 200mm in height to determine liquefaction resistance and large strain shear modulus of gravel tire chips mixtures (GTCM).

3.1 *Materials and test procedures*

Fig. 5 demonstrates the particle size distribution of gravel and tire chips (TC) used in this study. Other physical characteristics of materials such as maximum diameter of gravel and tire chips particles (D_{max}), coefficient of curvature (U_c), coefficient of uniformity ($U_{c'}$) are also displayed in Fig.5. The maximum grains size of TC and gravel were limited to less than 1/6 of specimen diameter to avoid the effect of sample size on the results of experiments. According to the Japanese Geotechnical Society Standard (JGS 0131), this type of gravel is classified as poorly graded (SP). The specific gravities (G_s) of gravel and TC were determined as per the Japanese Geotechnical Society (JGS 0111) recommendations, and they were found to be 2.81 and 1.17 for gravel and TC respectively.

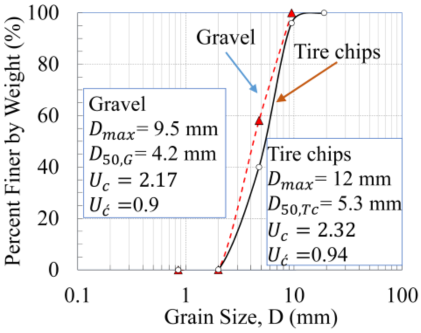


Figure 5. Particle size distribution of gravel and tire chips

3.2 *Test results*

Typical results (stress paths) on cyclic behavior of GTCM at stress ratio ($\sigma_d/2\sigma'_{3c}$) of 0.3 with different gravel fractions for relative density of D_r=50% and confining pressure of σ'_{3c} =100kPa are shown in Fig. 6. As it is evident, effective mean stress (p') decreases with deviator stress (q), but does not reach zero. Therefore, it can be concluded that initial liquefaction of GTCM samples did not occcur. The decrease in the effective mean stress (p') occurs due to the rapid excess pore water pressure generation during stress controlled cyclic loading. Furthermore, mechanism of the failure for GTCM with gf=100% and gf=87% is similar to that of flow type failure in which the samples exhibit combination of contractive and dilative behavior. The samples underwent excessive deformation leading to complete loss of shear strength due to the rapid building up of excessive pore water pressure during the cyclic loadings. For the GTCM samples with gf=44% and gf=30% similar mechanism to that of cyclic mobility type of failure is observed.

The effect of confining pressure on the pore water generation of GTCM with gf=30% and D_r=50% at ($\sigma_d/2\sigma'_{3c}$) of 0.35 is shown Fig. 7. The GTCM samples exhibit higher liquefaction resistance even at low confining pressure. This behavior is similar to that of denser sand samples at higher confining pressure. The reduction in effective confining pressure remarkably enhances liquefaction resistance of representative GTCM samples with gf=30%. This might happen due to the reduction in the hydraulic conductivity of mixture with the effective confining pressure (Edil and Bosscher 1994).

In Fig. 8, for a given number of cycles (Nl=20), the maximum of excess pore water ratio (Ru=u/σ'_{3c}) of GTCM samples with relative density of Dr=50% is plotted at stress ratio ($\sigma_d/2\sigma'_{3c}$) =0.3 and confining pressure of σ'_{3c} =100 kN/m^2 for different gf. It can be seen that liquefaction resistance decreases with decreasing gravel fraction from 100% to 87% and then increases with further decrease in gravel fraction. This is possibly due to the fact that in GTCM with gf=100% (pure gravel) the soil sample is in medium dense state, and, therefore, it exhibits relatively high dilative behavior resulting in high liquefaction resistance. When small amount of tire chips is added to the mixture, GTCM matrix is still formed by gravel particles. However, some of the solid gravel particles are replaced by soft tire chips particles with relatively low stiffness. Presence of those soft tire chips inclusions in the voids of the mixture, GTCM sample with gf=87% shows gravel like behavior in relatively loose state, which results in relatively low liquefaction resistance in comparison to that of gf=100%.

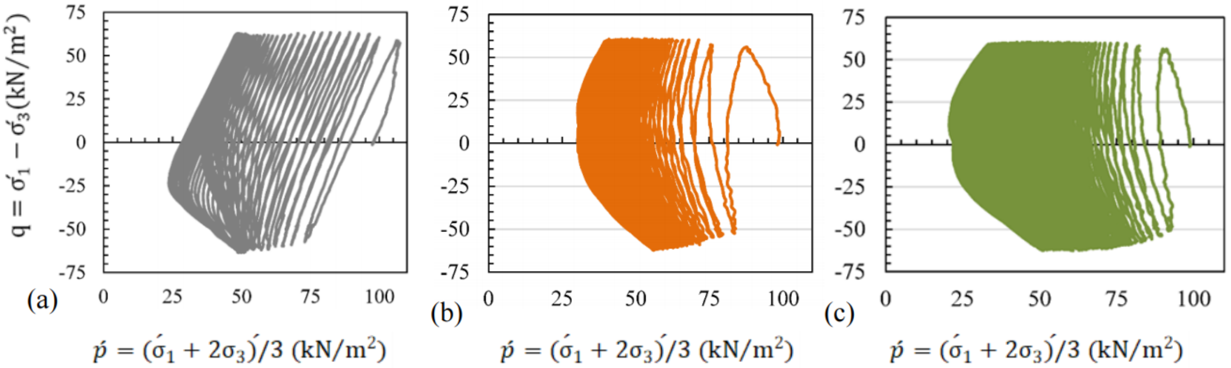
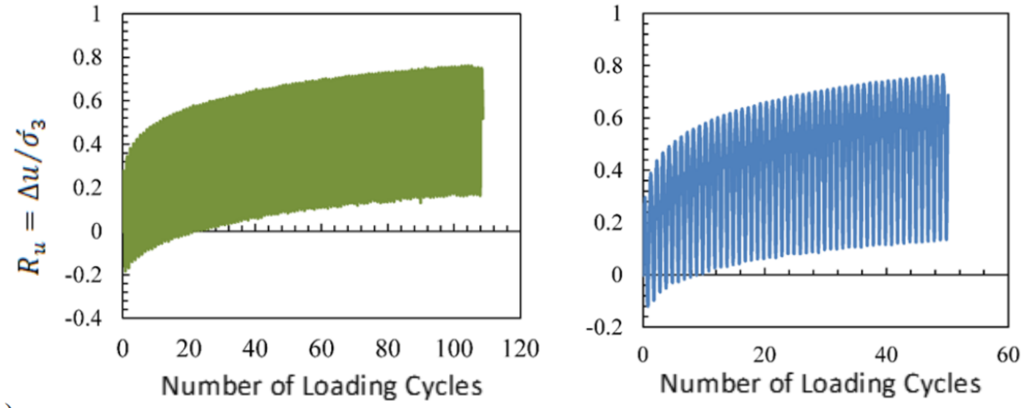


Figure 6. Cyclic stress paths of GTCM at $\sigma_d/2\sigma'_{3c} = 0.3$, D_r=50% and σ'_{3c}=100 kN/m^2: (a) gf=100%; (b) gf=44%; (a) gf=30%.



(a)

(b)

Figure 7. The effect of effective confining pressure on the evolution of excess pore water ratio of GTCM against number of stress cycles at gf=30% and $\sigma_d/2\sigma'_{3c} = 0.35$ (a) σ'_{3c}=50 kN/m^2 $\acute{\sigma}_3 = 100\ kN/m^2$; (b) σ'_{3c}=100 kN/m^2

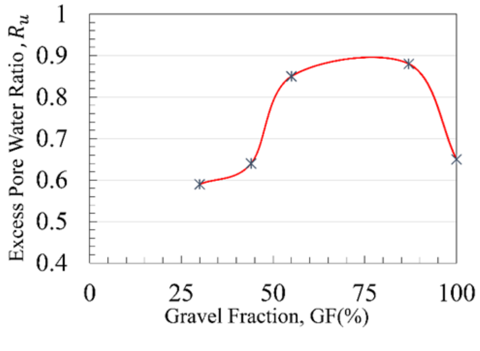


Figure 8. Maximum excess pore water ratio of GTCM with different gf(%) at Cyclic Stress Ratio $\sigma_d/2\sigma'_{3c} = 0.3\sigma_d/2\sigma_{3c} = 0.3$, σ'_{3c}=100 kN/m^2 and number of cycles (Nl= 20).

The shear modulus variations of GTCM samples with different gf(%) are shown in Fig. 9. For the GTCM specimens with gf=100% and gf=87% shear modulus decreased drastically with the shear strain within the few cycles of loading. This reduction in shear modulus with an increase in shear strain can be attributed to the decrease in the gravel inter-particle contact due to rapid building up of pore water pressure during the cyclic loading. Tire chips content did not significantly affect the shear modulus of specimen for gf=44% and 30% and shear modulus of specimens at higher shear strains are almost identical. This is probably because gravel inter-particle contacts are minimal (especially at very high shear strains >1%) where GTCM matrix is mainly formed by tire chips particle with relatively low stiffness in comparison to that of gravel particles.

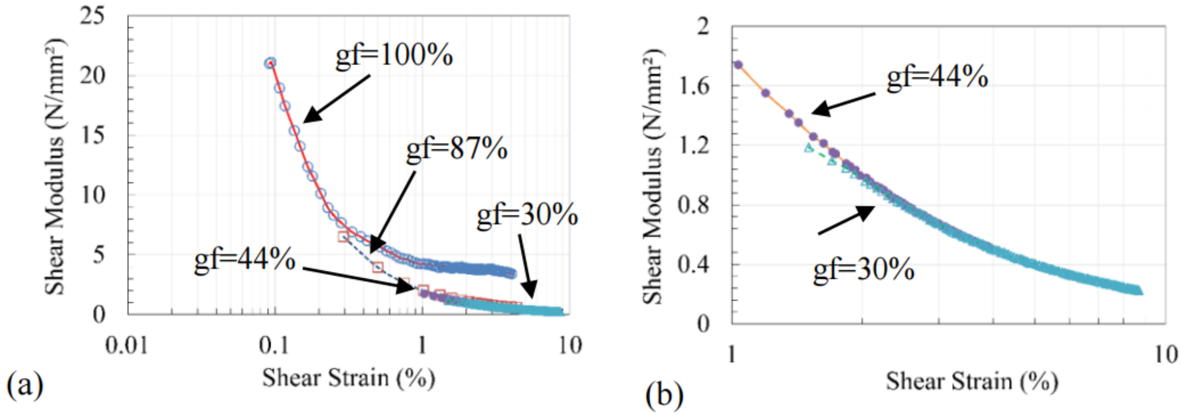


Figure 9. Effect of gravel fraction on shear modulus of GTCM: (a) 30%≤GF≤100% (b) 30%≤GF≤44%

4 CONCLUSIONS

The following are the some of the main conclusions derived from this research.

1. Tire chips was found to be an excellent liquefaction mitigating material. However, due to its' light weight nature, it may also cause unexpected settlement of the structure. When the reinforced layer is mixed with gravel, the shear stiffness in reinforced layer will be increased, and thus the settlement will be reduced.
2. When the thickness of horizontal inclusion is 10 cm (2 m in prototype) and gravel fraction is 50%, the liquefaction mitigation technique yields the best performance, as the rise of excess pore water pressure could be significantly restrained. This ultimately leads to the reduction of earthquake induced settlement of the structure.
3. Two behavioral zone (gravel like and gravel-tire chips like behavior) of GTCM can be used to explain liquefaction potential as well as dynamic behavior of GTCM specimens.
4. Liquefaction resistance of GTCM specimens are remarkably influenced by gravel fraction in mixture. For the higher gravel fractions (gf>87%), soil matrix are mainly formed by gravel, and thus, adding small amount of tire chips decreases the liquefaction resistance due to reduction in gravel inter-particle contacts during loading. However, for gf<87%, liquefaction resistance increases with a decrease of gravel fraction in the mixture. This is because the mixture tends to exhibits gravel-tire chips like behavior or tire chips like behavior (non-liquefiable materials).
5. The level of effective confining pressure make a remarkable contribution to the liquefaction resistance of GTCM.
6. Gravel fraction plays an important role in the dynamic behavior and liquefaction resistance of the GTCM. 50%-60% is the best mixing percentage, in which the rise of excess pore water pressure could be significantly restrained without compromising the stiffness of the reinforcing inclusion.

Using optimum tire and gravel mixture in the reinforcement layer as well as optimum thickness and proper location of the layer, liquefaction countermeasure described here can lead to the prevention of liquefaction induced settlement of buildings. The technique possesses tremendous potentials for adopting in developing and emerging economies, where alarming rate of car usage as the mode of commuting are already creating problems of stockpiling and illegal dumping, which in turn are placing a huge burden on our environment. To implement the technique, prototype testing using centrifuge model test, and numerical simulation using the material behavior described in this paper will be essential. Mapping of constitutive relationship of the material using Artificial Intelligence (Pasha et al. 2018) could be an useful tool in that direction.

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