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Technical Paper

Tire-chip reinforced foundation as liquefaction countermeasure for residential buildings [☆]

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Abstract

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

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Keywords: Tire chips; Gravel; Liquefaction; Shake table test; Horizontal inclusion

1. Introduction

Soil liquefaction can cause severe damage to buildings, such as a loss in the foundation's bearing capacity, tilting, overturning of the structure, and differential settlements. According to the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT 2015), approximately

27,000 houses were damaged due to liquefaction during the 2011 off the Pacific coast of Tohoku earthquake, about half of which were located in the Tokyo Bay area. The zones of damaged homes in Urayasu City, Chiba Prefecture are shown in Fig. 1. Liquefaction occurred widely in the Tokyo Bay area, owing to high underground water levels and reclaimed land that was filled with loose sandy soils (Yasuda et al. 2012). Similarly, a large number of residential buildings in Kumamoto Prefecture suffered from liquefaction-induced damage during the 2016 Kumamoto earthquake. Liquefaction mostly occurred along the old river estuaries. The damage caused by liquefaction in Mashiki City, Kumamoto Prefecture is shown in Fig. 2.

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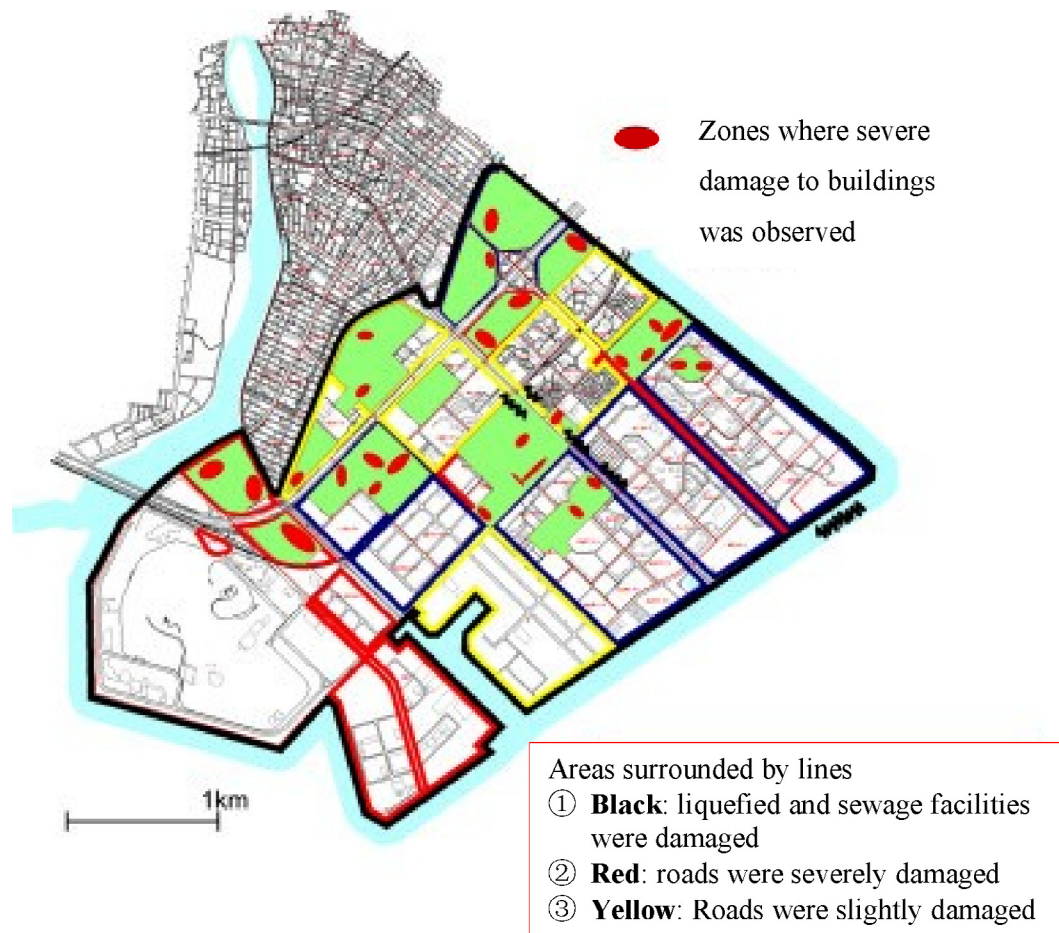


Fig. 1. Zones where houses were severely damaged in Urayasu City (Partially modified from report by JGS Technical Committee on 2011 Urayasu liquefaction).

The severe damage to buildings resulting from liquefaction due to past earthquakes has demonstrated the importance of preventive measures to protect buildings and the infrastructure by minimizing ground settlement and lateral spreading.

On the other hand, in recent decades, research related to the utilization of waste tires in construction projects has been gaining momentum. Due to their advantageous physical and mechanical characteristics, Tire Derived Geomaterials (TDGM), 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, 2015), as base isolation for buildings (Tsang 2008), and as linings in tunnel constructions (Kim and Konagai 2001). As shown in Fig. 3, the share of thermal recycling of tires in Japan is four times than that of the material recycling and thermal recycling releases four times more CO₂ than material recycling. Therefore, the thermal recycling of used tires has already caused severe environmental problems, and an adjustment to the recycling pattern from thermal to material is necessary for the sustainable use of the material. The geo-environmental aspects of such materials were thoroughly reviewed by Edil (2008).

Many researchers in Japan have conducted a wide range of research on the waste tire utilization. A few examples of the studies include: the use of whole tires or the use of tires in conjunction with other granular materials (Fukutake and Horiuchi 2006) or the 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). In addition, tire chips mixed with cement-treated clay have been used as sealing material at waste disposal sites in Tokyo Bay (Mitarai et al. 2006). The application of tire chips as a material to prevent liquefaction in soil has also been conducted by Yasuhara et al. (2010) and Uchimura et al. (2008). Studies on the physical and mechanical behavior of soil-tire derived materials have shown that the shear strength behavior, dilatancy, and volumetric response of the mixtures are highly influenced by their tire content (Chiaro et al., 2019a; Chiaro et al., 2019b; Pasha et al., 2018).

Japan is one of the most vulnerable countries to earthquakes; and thus, many techniques for earthquake disaster mitigation using TDGMs have been developed (Hazarika et al. 2006; Hazarika et al. 2008; Hazarika 2012; Hazarika et al. 2012b; Hazarika, 2013; Hazarika and Abdullah 2015; Hazarika and Fukumoto, 2016). One



Fig. 2. Liquefaction-induced damage to buildings during 2016 Kumamoto earthquake: (a) Inclination of residential house, (b) Sand boiling and settlement, (c) Differential settlement of house, and (d) Settlement of building.

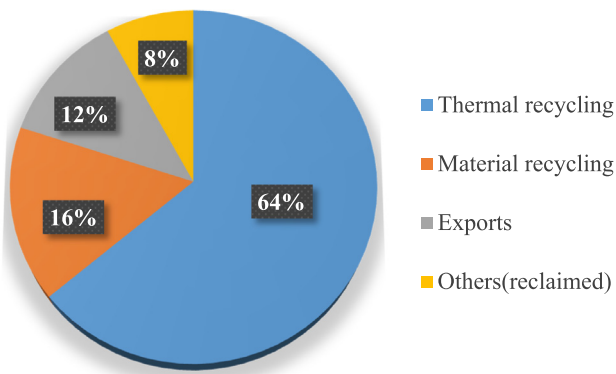


Fig. 3. State of recycling of used tires in Japan as of 2018 (Based on data from JATMA (Japan Automobile Tire Manufacturers Association)).

major concern during any earthquake in Japan is the liquefaction-induced damage to residential houses. To prevent vibration-induced and liquefaction-induced damage to residential buildings during earthquakes, it is important to adopt low-cost ground-improvement techniques, since most homeowners cannot afford to adopt the expensive ground-improvement techniques applied in conventional

and large-scale infrastructural projects. One such low-cost technique was developed, which utilizes a layer of tire chips as the horizontal inclusion under the foundation of residential housing (Hazarika et al. 2009; Hazarika and Abdullah 2015). Horizontal reinforcing inclusion refers to a layer of tire chips which is placed horizontally.

Mixtures of tire chips and sand as liquefaction prevention materials have also been investigated by Hyodo et al. (2008) through cyclic triaxial testing. However, mixtures of tire chips and sand can result in the high differential settlement and inadequate bearing capacity of the foundation. Moreover, most of the previous studies on the dynamic behavior of sand-TDGM mixtures involved the use of tire chip whose particle size is remarkably larger than sand ($D_{50,r}/D_{50,s} \gg 1$ (where $D_{50,r}$ and $D_{50,s}$ are the mean diameter of the tire and the soil particles, respectively)). This results in the 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 solve these problems, this paper suggests that a layer comprising a mixture of gravel and tire chips, along with geogrid reinforcement (if necessary), be used, as shown in Fig. 4. This will be more practical as it will provide

sufficient bearing capacity to the foundation that otherwise has to rest on a highly compressible layer of tire chips.

Senetakis et al. (2012) carried out a study on dry gravel-rubber mixtures to evaluate the pure dynamic properties of such mixtures, in which the effects of the confining pressure, rubber contents, and physical characteristics of the grains were clarified. Their findings showed that the small strain shear modulus (G_0) is increased by a decrease in the rubber content in the mixture as well as the confining pressure (σ'_{3c}). On the other hand, the small strain damping ratio (D_0) of gravel-rubber mixtures increased with higher rubber fractions in the mixture. However, in practical applications, such as liquefaction mitigation, the results from the above research based on dry conditions cannot provide sufficient information on the undrained behavior of the mixing materials.

Therefore, to establish the above-described liquefaction mitigation technique, a detailed investigation of the dynamic behavior of gravel-tire chip mixtures (GTCMs) under undrained conditions is necessary, so that those properties can be used in the application-oriented physical modeling (such as shaking table tests or centrifuge tests) and the numerical modeling. Therefore, another aim of this study is to investigate the influence of the gravel fraction on the dynamic properties as well as the liquefaction resistance of GTCMs. For this purpose, a series of stress-controlled consolidated undrained cyclic triaxial tests were conducted on GTCMs with different gravel fractions. The results of the element tests supplement not only the necessary information in the preparation of the models in the model shaking table tests, but also serve as an important source of the material parameters in the numerical simulation. It is worthwhile to mention that the numerical simulation is beyond the scope of this research.

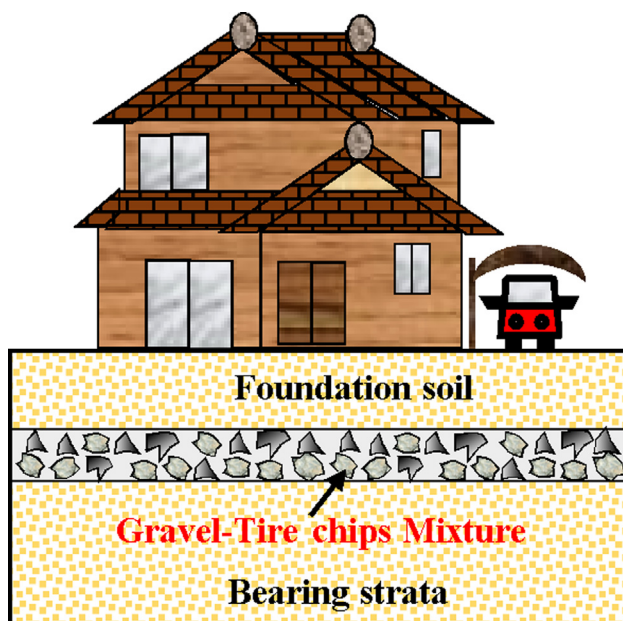


Fig. 4. Prevention of liquefaction-induced damage to building using horizontal inclusion.

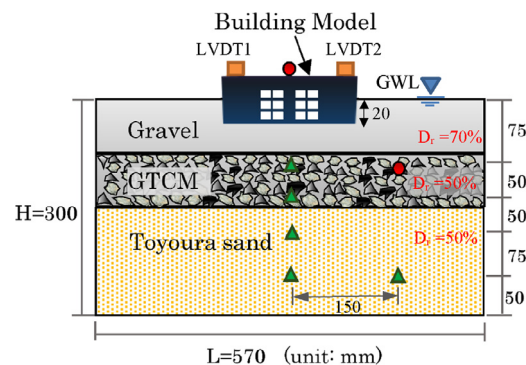
2. Validation of horizontal inclusion technique

To evaluate the effectiveness of the technique illustrated in Fig. 4, a series of 1 g model shaking table tests was performed using the shaking table test assembly at Kyushu University, Fukuoka, Japan.

2.1. Model shaking table tests

The test model (prototype to model ratio of 20) is shown in Fig. 5. The model test box was 600 mm in length, 300 mm in width, and 500 mm in height. Toyoura sand was used for the foundation soil of a model house. The building model was 300 mm in length and 180 mm in width and had a total weight of 27 N. The scaling factors for the different variables were calculated based on the scaling relationships proposed by Iai (1989) and shown in Table 1. Pure tire chips (2 mm in size) or tire chips mixed with gravel (almost similar to tire chips in size) were used in preparing the horizontal inclusion (Table 2). Keeping the height of the ground in the soil box at 300 mm, the relative density of both the base layer and the layer containing the horizontal inclusion was adjusted to be around 50%. To achieve the desired relative density, the dry pluviation technique was used to prepare uniform and consistent layers of sand. The gravel-tire chip layers were prepared using the usual compaction method. The layer immediately below the foundation was made of gravel, which replicates the top layer of the building foundation normally improved by some sorts of ground-improvement techniques. The sample was saturated by introducing water from the bottom of the soil box at a very slow flow rate.

A total of seven test cases were examined under three different conditions of horizontal inclusion, which are listed in Table 3 and shown Fig. 6. In the table, Case 0 represents conventional foundation soil. Case 1, Case 2-1, and Case 2-2 represent the cases in which the thickness of the horizontal inclusion was 10 cm. Case 3-1 and Case 3-2 represent the conditions in which the thickness of the horizontal inclusion was reduced to 5 cm. Finally, in Case 4, the



■ LVDT ▲ Pore pressure transducer ● Accelerometer

Fig. 5. Model test setup.

Table 1
Physical properties of materials used in this study.

Material	Mean grain size D_{50} (mm)	Maximum grain size D_{max} (mm)	Coefficient of curvature (U_c)	Coefficient of uniformity ($U_{c'}$)	Specific gravity (G_s)	Maximum void ratio (e_{max})	Minimum void ratio (e_{min})
Gravel	4.2	9.5	2.17	0.9	2.81	0.829	0.562
Tire chips	5.3	12	2.32	0.94	1.17	1.183	0.966

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 a frequency of 3 Hz was imparted to the model for 45 s, and the responses were measured using linear variable differential transformers (LVDTs), accelerometers, and pore water transducers, which were installed at various locations within the foundation soil, as shown in Fig. 5.

2.2. Test results

Fig. 7 shows the time history of the input excitation for Case 0 and the time history of the excess pore water pressure beneath the horizontal inclusion for Case 0, Case 1, Case 3-1, and Case 4. It is to be noted that, since the onset of complete liquefaction was observed within 30 s of cyclic loading for the unreinforced case (Case 0), the duration of input excitation was reduced to 30 s for the reinforced cases in the test series. In other cases, the pore water pressure remained constant, which indicates that liquefaction was effectively prevented by the presence of the reinforced gravel-tire chip layer. This is due to the fact that the effective stress within the foundation soils varied owing to differences in the thickness and gravel fraction in the reinforcement layer. In Cases 3-1 and 4, the maximum excess pore water pressure reached the same value as that of the unreinforced foundation. Case 1, with the reinforced layer of pure tire chips, yielded the lowest excess pore water pressure value. Furthermore, the dissipation of the pore water pressure started earlier and was faster in the case of the reinforced foundation in comparison to the unreinforced foundation.

The maximum excess pore water pressure ratios at various depths within the foundation soils are shown in Fig. 8. In the unreinforced foundation (Case 0), the excess pore water pressure exceeds 1.0 at all depths, indicating liquefac-

Table 3
Scale factors for 1 g shaking table tests.

Quantity	Prototype/Model	
Length	N	20.0
Density	1	1.0
Time	$N^{0.75}$	9.5
Acceleration	1	1.0
Velocity	$N^{0.75}$	9.5
Displacement	$N^{1.5}$	89.4
Stress	N	20.0
Strain	$N^{0.5}$	4.5
Water pressure	N	20.0

tion in the foundation soils. In all the other cases, except for Case 4, 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 the reinforced layer is 10 cm, liquefaction can be prevented by using the proposed horizontal inclusion technique. However, when the thickness of the layer is reduced to 5 cm, 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. Time histories of the vertical displacements at the locations of LVDT1 and LVDT2 for all model tests are plotted in Fig. 9. Due to the malfunction (going out of the measuring range) of the displacement sensors, arising from the excessive settlement of the ground, the vertical displacement could not be measured digitally in some cases (Case 0, Case 3-1, and Case 4). Therefore, the final values for the vertical displacements in those cases were measured manually, at the end of shaking, using the markers installed on the surface.

The average final settlements ($(LVDT1 + LVDT2)/2$) of the model house due to the cyclic loading for each case are shown in Fig. 10. From this figure, it is clear that the

Table 2
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							

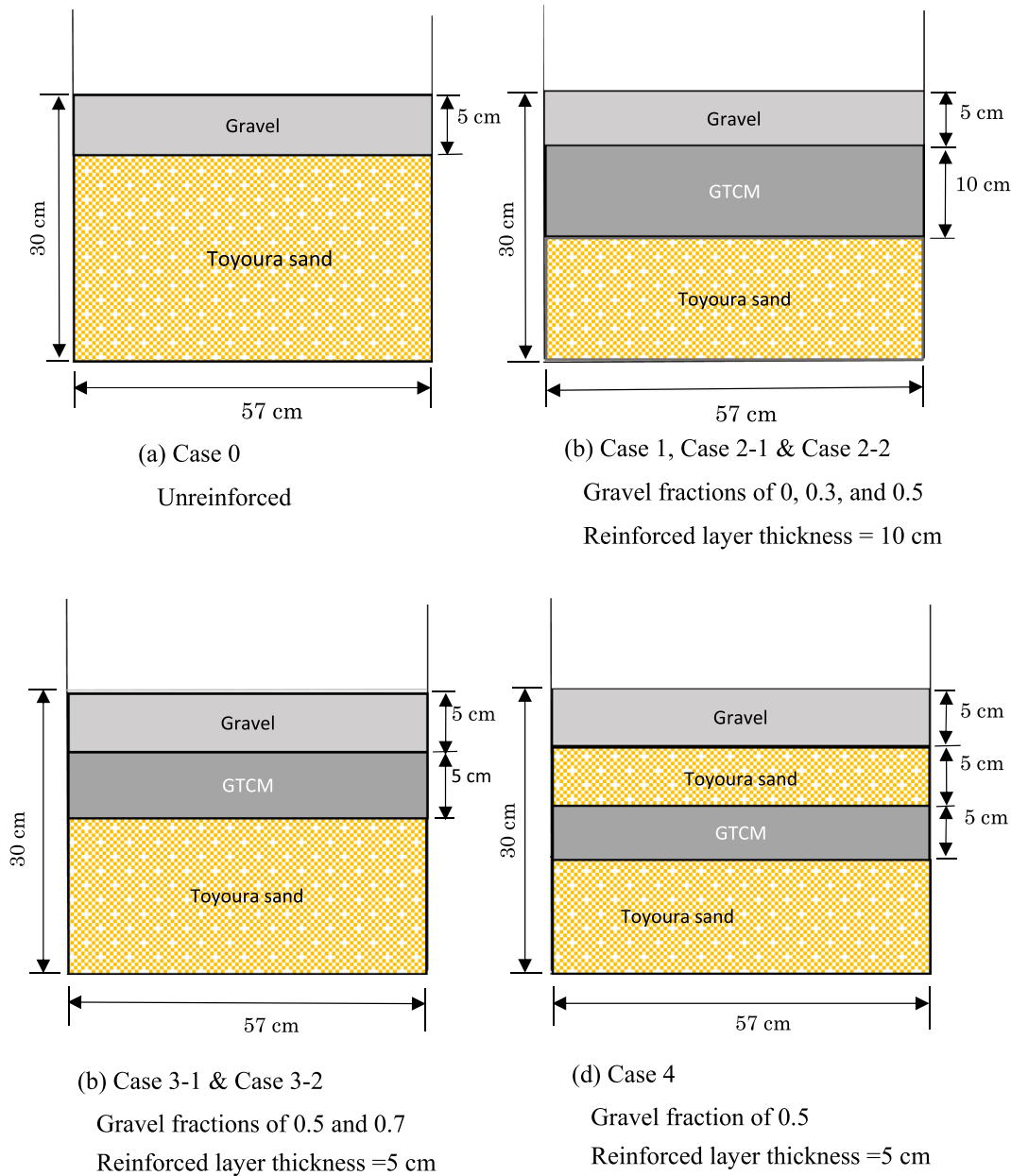


Fig. 6. Influence of various factors in model tests.

settlement of the house reinforced by pure tire chips (10-cm-thick inclusion) was reduced to half that of the non-reinforced foundation. However, when compared with the foundation reinforced with gravel mixed with tire chips (10-cm-thick inclusion), it is seen that the settlement of the house was reduced to half that of the foundation reinforced with pure tire chips. This implies that mixing gravel with tire chips can decrease the differential settlement due to enhanced bearing capacity. In addition, the settlement decreased with the increase in the thickness of the reinforced layer and the amount of gravel fraction. Furthermore, in Case 2-1, in which the reinforced layer thickness was 10 cm and the gravel fraction was 50%, the settlement was 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 considerations in this technique.

3. Dynamic properties and liquefaction potential of gravel-tire chip mixtures (GTCMs)

The large cyclic triaxial testing apparatus at Yamaguchi University, Ube, Japan was used in this test series. Consolidated undrained (CU) tests were carried out on specimens, 100 mm in diameter by 200 mm in height, to determine the

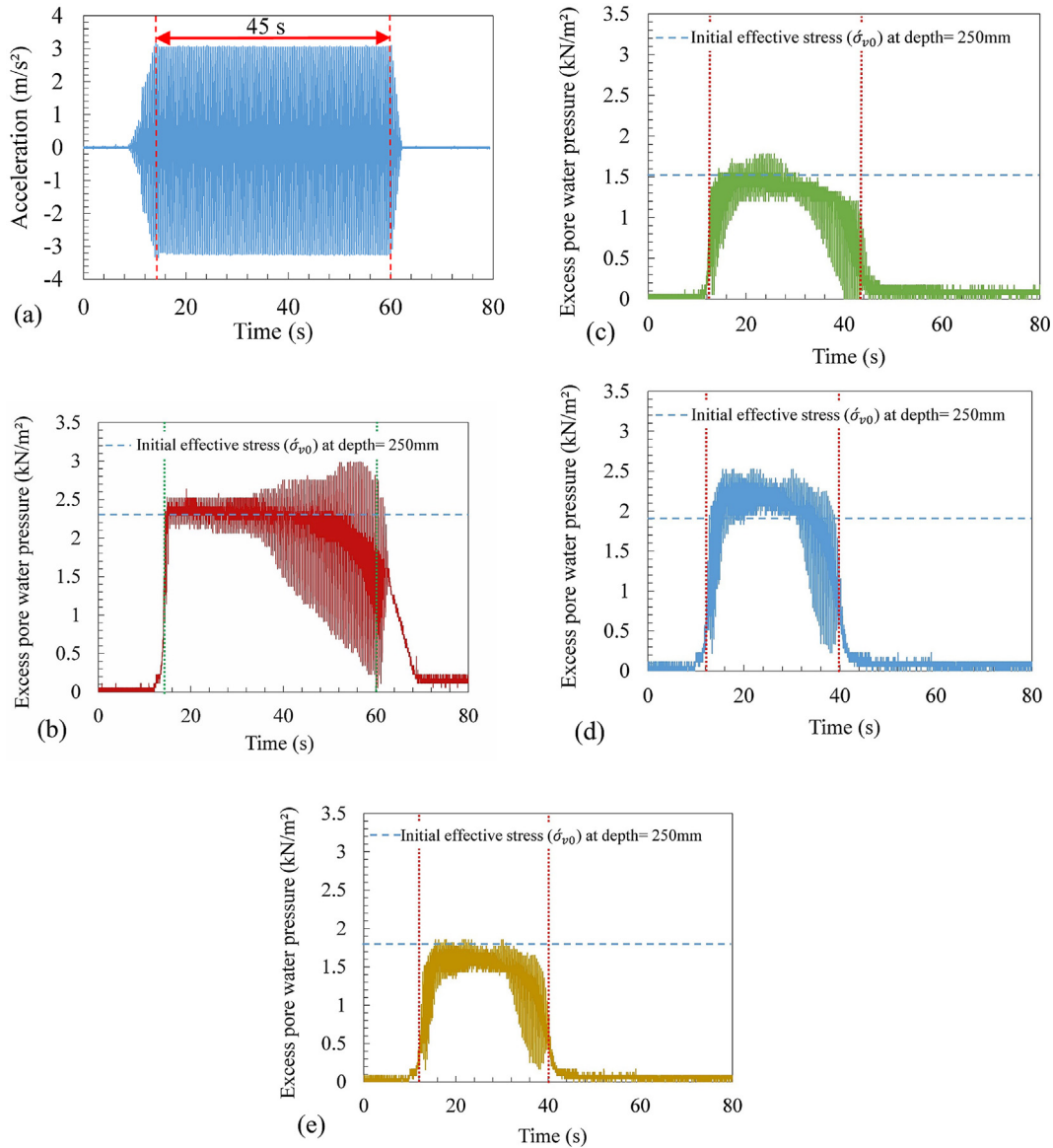


Fig. 7. (a) Time history of input excitation for Case 0 and time history of excess pore water pressure at depth of 250 mm for: (b) Case 0, (c) Case 1, (d) Case 3-1, and (e) Case 4.

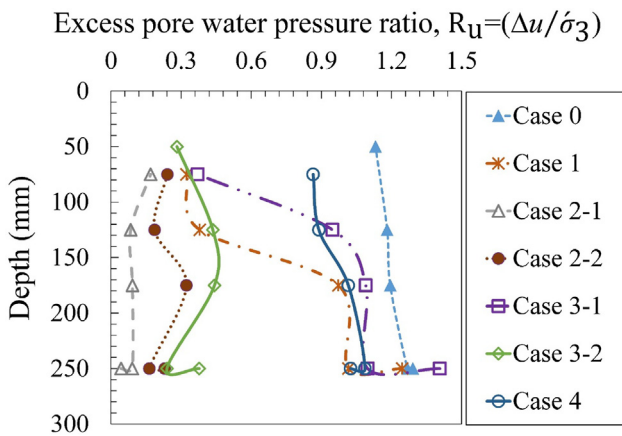


Fig. 8. Liquefaction potentials of foundation in each case.

liquefaction resistance and large strain shear modulus of gravel-tire chip mixtures (GTCMs).

3.1. Materials and test procedures

Fig. 11 shows the particle size distribution curves of the gravel and the tire chips (TC) used in this study. Other physical characteristics of the materials, such as the maximum diameter of the gravel and tire chip particles (D_{max}), the coefficient of curvature (U_c), and the coefficient of uniformity (U_u), are listed in Table 1. The maximum grain size of the TC and the gravel were limited to less than 1/6 of the specimen diameter to avoid the effect of the sample size on the results of the experiments. According to the Japanese Geotechnical Society Standard (JGS 0131), this type of

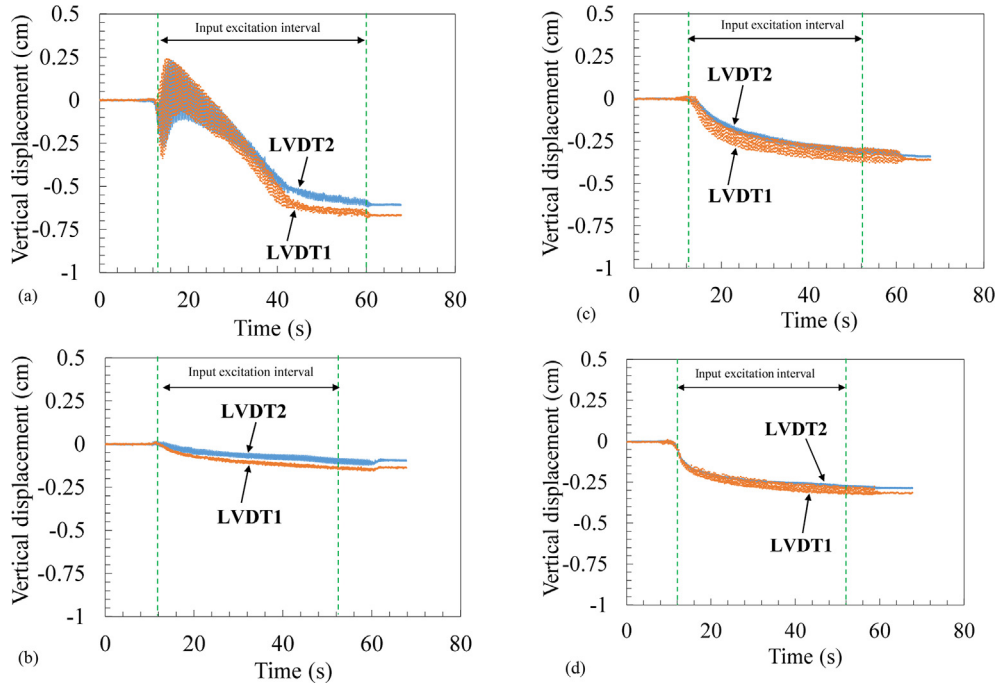


Fig. 9. Time histories of vertical displacement measured by LVDT1 and LVDT2 for: (a) Case 1, (b) Case 2-1, (c) Case 2-2, and (d) Case 3-2.

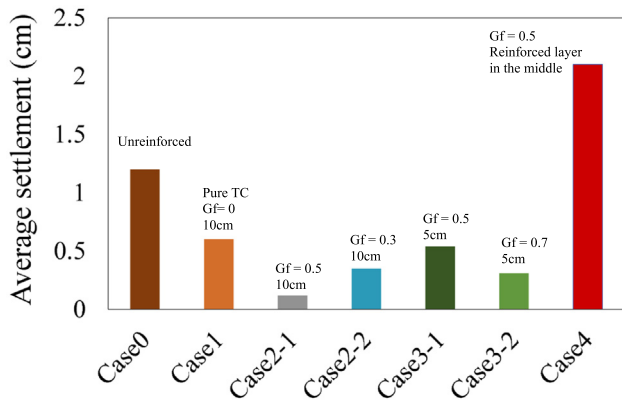


Fig. 10. Comparison of settlements of model house in each case.

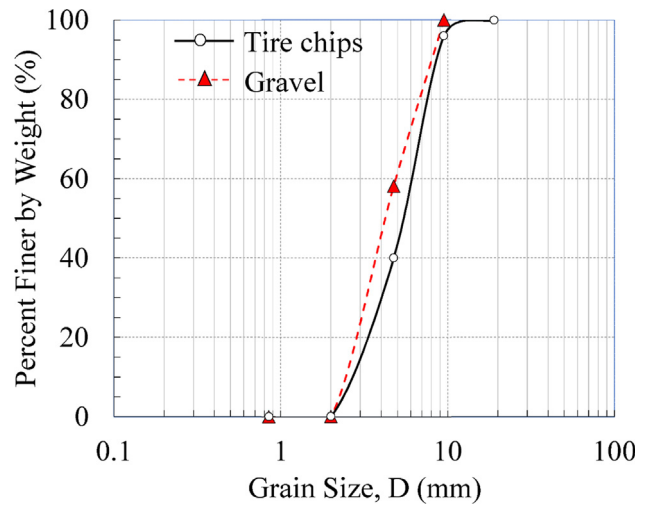


Fig. 11. Particle size distribution curves of gravel and tire chips.

gravel is classified as poorly graded (SP). The specific gravities (G_s) of the gravel and the TC were determined as per the Japanese Geotechnical Society (JGS 0111) recommendations, and they were found to be 2.81 and 1.17 for the gravel and the TC, respectively.

In order to produce homogenous samples, the under-compaction method was used for the preparation of the specimens (Ladd 1978; Pasha et al. 2019). Mixtures of the desired relative densities were obtained by mixing manually and carefully and placing the mixtures into the mold by compacting them in 10 layers. The saturation of specimens was accomplished first by percolating carbon dioxide gas through the samples for a period of 30 to 60 minutes. After the percolating carbon dioxide gas through the

specimen, water was introduced slowly to allow the replacement of the carbon dioxide. The back-pressure technique was adopted to enhance the degree of saturation of the samples. Full saturation was assumed to have been achieved when Skempton's B parameter ($\Delta u / \Delta \sigma_3$) was greater than 0.95. An isotropic consolidation pressure was applied to the samples, while maintaining constant initial back pressure (200 kN/m^2). Samples were consolidated to the effective confining pressures of 50 kN/m^2 and 100 kN/m^2 . A sinusoidal cyclic axial loading was applied to the samples at a frequency of 0.1 Hz under undrained condition. All tests were conducted on the isotopically

consolidated samples at relative density of 50%, and different cyclic stress ratios ($\sigma_d/2\sigma'_{3c}$).

3.2. Test results

Typical results (stress paths) on the cyclic behavior of the GTCM for different volumetric proportion of gravel in mixture at a stress ratio ($\sigma_d/2\sigma'_{3c}$) of 0.3, a confining pressure of $\sigma'_{3c} = 100 \text{ kN/m}^2$ are shown in Fig. 12. As is evident, the effective mean stress (p') decreases with the cyclic deviator stress (q); however, none of the GTCM samples reaches the state of zero mean effective stress at the conclusion of cyclic loading. The decrease in the effective mean stress (p') occurs due to the rapid build up of excess pore water pressure during the stress-controlled cyclic loading. Furthermore, the mechanism of failure for the GTCMs with $G_f = 100\%$ and $G_f = 87\%$ is similar to that of the flow-type failure in which the samples exhibit a combination of contractive and dilative behavior. The samples experienced excessive deformation leading to a 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 $G_f = 44\%$ and $G_f = 30\%$, a similar

mechanism to that of the cyclic mobility type of failure is observed.

The effect of confining pressure on the pore water generation of GTCMs with $G_f = 30\%$ and $D_r = 50\%$ at ($\sigma_d/2\sigma'_{3c}$) of 0.35 is shown Fig. 13. The GTCM samples exhibit higher liquefaction resistance even at low confining pressures. This behavior is similar to that of denser sand samples at higher confining pressures. The decrease in effective confining pressure remarkably enhances the liquefaction resistance of the representative GTCM samples with $G_f = 30\%$. This might have been caused by the decrease in the hydraulic conductivity of the mixture with the effective confining pressure (Edil and Bosscher, 1994).

In Fig. 14, for a given number of cycles ($N = 20$), the maximum excess pore water ratio ($R_u = u/\sigma'_{3c}$) of the GTCM samples with a relative density of $D_r = 50\%$ is plotted at a stress ratio ($\sigma_d/2\sigma'_{3c}$) = 0.3 and a confining pressure of $\sigma'_{3c} = 100 \text{ kN/m}^2$ for different G_f . Since all the testing conditions, including relative density (D_r), loading frequency, cyclic stress ratio ($\sigma_d/2\sigma'_{3c}$), and the number of the cycles, were the same for the GTCM samples with different gravel fractions, the same input energy was applied to the samples. Therefore, the lower the maximum

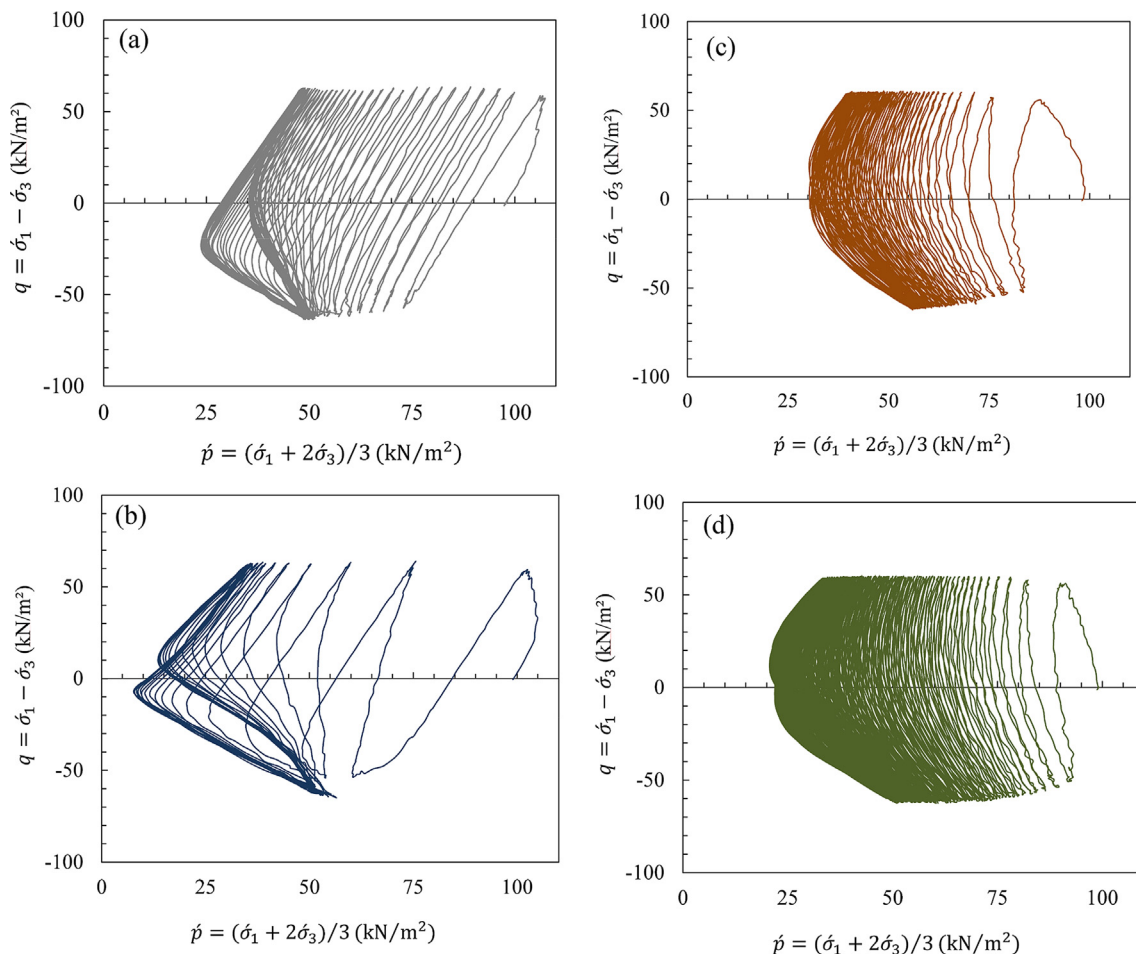


Fig. 12. Cyclic stress paths of GTCM at $\sigma_d/2\sigma'_{3c} = 0.3$, $D_r = 50\%$, and $\sigma'_{3c} = 100 \text{ kN/m}^2$: (a) $G_f = 100\%$, (b) $G_f = 87\%$, (c) $G_f = 44\%$, and (d) $G_f = 30\%$.

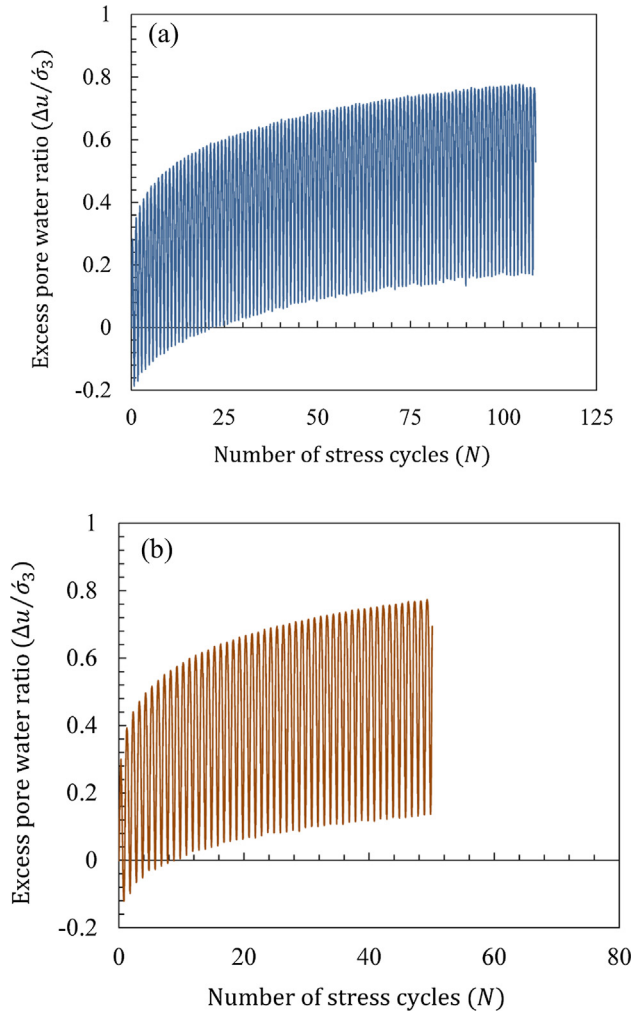


Fig. 13. Effect of effective confining pressure on evolution of excess pore water ratio of GTCM against number of stress cycles (N) at $G_f = 30\%$ and $\sigma_d/2\sigma'_{3c} = 0.35$: (a) $\sigma'_{3c} = 50 \text{ kN/m}^2$ (b) $\sigma'_{3c} = 100 \text{ kN/m}^2$.

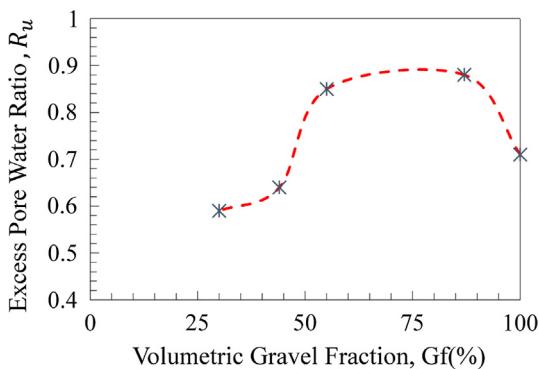


Fig. 14. Maximum excess pore water ratio of GTCM with different $G_f(\%)$ at cyclic stress ratio $\sigma_d/2\sigma'_{3c} = 0.3$, $\sigma'_{3c} = 100 \text{ kN/m}^2$ and number of stress cycles ($N = 20$).

excess pore water pressure, the higher the liquefaction resistance of the samples. It can be seen that the liquefaction resistance decreases with the decreasing gravel fraction

from 100% to 87% and then increases with any further decrease in the gravel fraction. Possibly, in the GTCM with $G_f = 100\%$ (pure gravel), the soil sample is in the medium dense state and exhibits relatively high dilative behavior resulting in high liquefaction resistance. When a small amount of tire chips is added to the mixture, the GTCM matrix is still formed by the gravel particles. However, some of the solid gravel particles are replaced by soft tire chip particles with relatively low stiffness. With the presence of those soft tire chip inclusions in the voids of the mixture, the GTCM sample with $G_f = 87\%$ shows gravel-like behavior in the relatively loose state, which results in relatively low liquefaction resistance in comparison to that of the sample with $G_f = 100\%$. The optimum value of the gravel fraction in which the GTCM sample shows remarkable improvement in the liquefaction resistance of the mixture was around 50%.

The variations in the shear modulus of the GTCM samples with different $G_f(\%)$ are shown in Fig. 15. For the GTCM specimens with $G_f = 100\%$ and $G_f = 87\%$, the shear modulus decreased drastically with the shear strain within a few cycles of loading. This reduction in shear modulus with an increase in shear strain can be attributed to the decreased gravel inter-particle contacts after the rapid development of pore water pressure during cyclic loading. The tire chip content did not significantly affect the shear modulus of the specimen for $G_f = 55\%$, 44%, and 30%, and the shear modulus of the specimens at higher shear

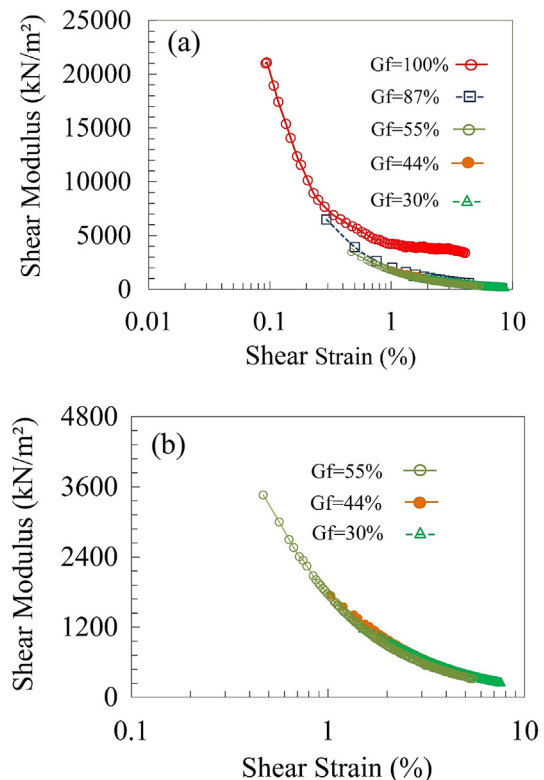


Fig. 15. Effect of gravel fraction on shear modulus of GTCM: (a) $30\% \leq G_f \leq 100\%$ and (b) $30\% \leq G_f \leq 55\%$.

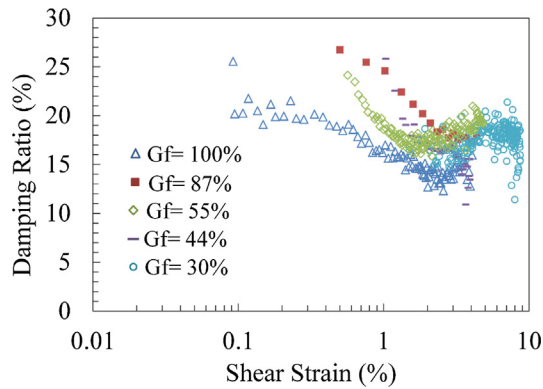


Fig. 16. Evolution of damping ratio with shear strain for GTCM specimens.

strains were almost identical. This may be due to the fact that the gravel inter-particle contact is minimal (especially at very high shear strains $> 1\%$) where the GTCM matrix is mainly formed by tire chip particles with relatively low stiffness in comparison to that of gravel particles.

The variation in the damping ratios of the GTCM mixtures with shear strain is shown in Fig. 16. The damping ratios increase slightly with the decreasing gravel fraction in the mixture. The decrease in the damping ratio values with shear strain may occur due to the rapid development of pore water pressure during cyclic loadings. The inter-particle contact significantly decreases with the pore water pressure, resulting in a reduction of frictional energy loss in the soil skeleton with the number of cycles.

4. Conclusions

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

- (1) Tire chips have been found to be an excellent material for the prevention of liquefaction. However, due to their compressible nature, their direct use may result in the unwanted settlement of structures resting on such materials. When the horizontal inclusion is made of gravel-mixed tire chips, the shear stiffness in the reinforced layer will be increased; and thus, the settlement will be reduced.
- (2) When the thickness of the horizontal inclusion is 10 cm (2 m in prototype) and the gravel fraction is 50%, the liquefaction mitigation technique yields the best performance, as the rise in excess pore water pressure can be significantly restrained. This ultimately leads to a reduction in the earthquake-induced settlement of the structure.
- (3) Two behavioral zones (with gravel-like and gravel-tire chip-like behavior) of GTCMs can be used to explain the liquefaction potential as well as the dynamic behavior of GTCM specimens.
- (4) The liquefaction resistance of GTCM specimens is remarkably influenced by the gravel fraction in the mixture. For higher gravel fractions ($G_f > 87\%$),

the soil matrix is mainly formed by gravel; and thus, adding a small amount of tire chips decreases the liquefaction resistance due to the reduction in the gravel inter-particle contacts during loading. However, for $G_f < 87\%$, the liquefaction resistance increases with a decrease in the gravel fraction in the mixture. This is because the mixture tends to exhibit gravel-tire chip-like behavior or tire chip-like behavior (non-liquefiable materials).

- (5) The undrained cyclic behavior of the gravel-tire chip mixtures was found to be highly stress-dependent. The decrease in the effective confining pressure increases the liquefaction resistance of the GTCM mixture.
- (6) The gravel fraction plays an important role in the dynamic behavior and liquefaction resistance of GTCMs. 50–60% is the best mixing percentage, in which the rise in excess pore water pressure can be significantly restrained without compromising the stiffness of the reinforcing inclusion.

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

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