Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)

Evaluating liquefaction resistance of recycled geomaterials using energy-based method and stress-based method

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ABSTRACT: A series of consolidated undrained cyclic (CU) triaxial tests were performed to study liquefaction resistance of gravel and Gravel Tire Chips Mixture (GTCM). Samples were prepared at different volumetric fraction of gravel in the mixture and cyclic triaxial tests were conducted under different confining pressure. The energy-based method using the cumulative dissipated energy concept was employed in the liquefaction assessment of GTCM. These were compared to the conventional stress-based method. Results showed that liquefaction resistance are highly influenced by gravel fraction in GTCM. Furthermore, liquefaction resistance was found to increase with decreasing the confining pressure.

1 INTRODUCTION

About 1 billion scrap tires are generated and discarded in all over the world annually. Considerable amount of those waste tires is used for energy production purposes. However, this can increase emission of hazardous gases such as CO, CO_2, and SO_2 to the atmosphere and consequently causes global warming and climate change. Reusing waste tire materials as Scrap Tire-Derived Materials (STDM) can reduce CO_2 release and help preserving our ecosystem. Nowadays, STDMs are being adopted in several civil engineering applications as alternative non-dilative geomaterials with growing advance (Hazarika et al., 2010, Kaushik et al., 2015).

Sand-STDM mixture is being used as a conventional geomaterials for preventing seismic and liquefaction-induced damage (Hazarika et al., 2008, Tsang, 2008, Hazarika and Abdullah, 2016, Otsubo et al., 2016). Many studies can be found in literature on the effectiveness and efficiency of implementing STDM as an additive geomaterials to soil in enhancing dynamic performance and liquefaction potential of soil (e.g. Hazarika et al., 2008, Uchimura et al., 2007, Tsang et al., 2012). A series of undrained cyclic triaxial and 1-g shaking table test were performed by Hazarika et al. to study the effect of reinforcing sand with tire chips on liquefaction potential and residual displacement of quay walls. The results showed that excess pore water pressure ratio decreases with increasing volumetric content ratio of tire chips in the mixture. In addition, they observed that residual lateral displacement of the quay wall was limited in reinforced backfill in compression to that of unreinforced one.

However, low hydraulic conductivity of sand, high liquefaction susceptibility of sand, particles segregation potential of sand and STDM in binary mixture are some of the key issues associated with utilization of sand-STDM mixture in geo-structures (Mashiri et al., 2015, Anvari and Shooshpasha, 2016). Gravel-Tire Chips Mixture (GTCM) has been recently introduced to civil engineering applications with the goal of providing solution for drawbacks of existing methods (Niiya et al., 2012, Chu et al., 2016, Hazarika and Abdullah, 2016). It is well known that gravelly soil possess higher permeability in comparison to that of sandy soil (e.g. Sherard et al., 1984). In addition, footings constructed on gravely soil yields higher bearing in comparison to that of sand (Bowles, 1988). Design, construction and maintenance of structures constructed on the GTCM needs an understanding of dynamic behaviour of these materials. However, there is a lack of study on the dynamic behaviour and liquefaction resistance of GTCM. Therefore, we aimed to investigate the performance of GTCM as a new mitigation measure against liquefaction. Furthermore, this research attempted to identify the important parameters affecting dynamic and liquefaction behaviour of GTCM. The energy-based method using the cumulative dissipated energy concept was employed in liquefaction assessment. The energy-based liquefaction assessment results were compared to the conventional stress-based method. In this study a series of consolidated undrained cyclic triaxial tests were performed on the gravel and gravel-tire chips mixture to assess the new liquefaction mitigation measure.

2 MATERIALS AND TESTING PROCEDURE

A series of large cyclic triaxial tests were carried out on specimens of 100mm in diameters by 200mm in height to assess liquefaction resistance of gravel and GTCM. Particle size distribution of the gravel and tire chips is measured following the standard specification in JGS 0131 and plotted in Figure 1. 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 JGS 0131, gravel is classified as poorly graded (GP). Regarding shape and maximum grain size of Scrap Tire-Derived Materials (STDM), they are classified as tire chips (TC). Specific gravities (Gs) of gravel and TC were obtained 2.81 and 1.17 respectively. The variation of specific gravity of GTCM is plotted in Figure 2a. To proceed with the preparation of specimens for CD triaxial tests at desired relative density, a series of vibratory test were conducted on Gravel as well as Gravel Tire Chips Mixture (GTCM) mixtures according to JGS 0161 standard.

The following empirical correlation has been proposed to estimate maximum and minimum void ratio of GTCM:

$$e_{\min,\,GTCM}, e_{\max,\,GTCM} = A + B/\left(1 + 10^{(C-(GF\%)\times D)}\right) \qquad (1)$$
$$D_{50,Tc}/D_{50,G} \approx 1.2,\ D_{50,Tc} = 6\text{mm}$$

Table1. Fitting parameters for maximum and minimum void ratio

Parameters	A	B	C	D
Maximum Void Ratio	0.83	0.35	41.39	−0.05
Minimum Void Ratio	0.56	0.42	43.26	−0.03

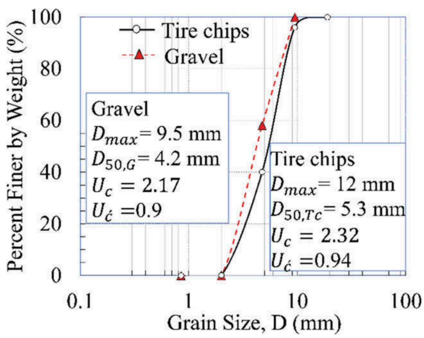

Figure 1. Particle size distribution of Gravel and tire chips.

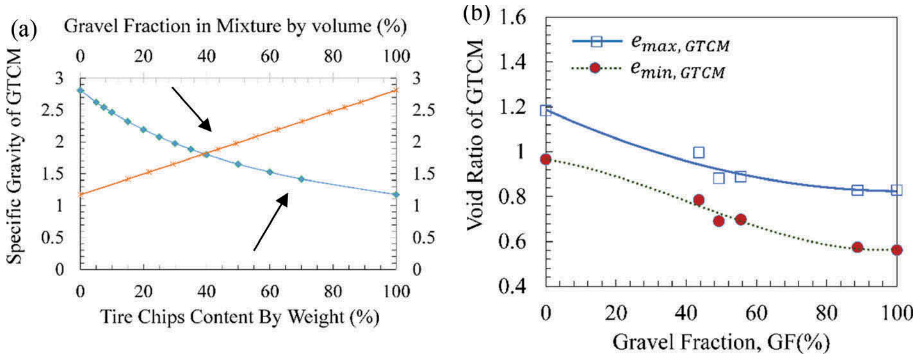

Figure 2. Physical properties of GTCM: (a) Specific gravity of GTCM particles (b) Maximum and minimum void ratio of GTCM.

Where $e_{min, GTCM}$, $e_{max, GTCM}$ are minimum and maximum void ratio of GTCM for a given gravel fraction (GF=V_G/V_T) in mixture. Where A, B, C, D are fitting parameters listed in Table 1. As can be seen in Figure 2b, the value of void ratio decreases as the gravel fraction increases in the GTCM. Considering theory of packing of a binary mixture, minimum and maximum void ratio of GTCM decreases with increasing gravel fraction. Because large particles are surrounded with small particles of the same size, no packing phenomena occurs (Reid et al., 1998).

The under-compaction method was used for the preparation of specimens (Ladd, 1978). Gravel and tire chips were mixed carefully by hand and placed into mold and sequentially compacted in 10 layers until the target relative density D_r was achieved. Samples were saturated by allowing de-aired water to flow through from the bottom of the sample. 200 kPa back pressure was applied for a day to reduce the remained air within the specimen and increase the degree of saturation (B>0.95).

Samples were consolidated to the effective confining pressure of 50 kN/m and 100 kN/m^2. Stress-controlled undrained cyclic triaxial tests were conducted at a constant frequency of 0.1 Hz, relative density of 50% and different cyclic stress ratios ($\sigma_d/2\sigma'_{3c}$).

3 RESULTS AND DISCUSSION

3.1 *Stress paths*

Typical results (stress paths) on cyclic behaviour of GTCM with different gravel fractions at stress ratio ($\sigma_d/2\sigma'_{3c}$) of 0.3, relative density of Dr=50% and confining pressure of $\sigma'_3 = 100$kPa are shown in Figure 3. As is evident, the effective mean stress (p') decreases with cyclic deviator stress (q), however, none of the GTCM samples did reach the state of zero mean effective stress at the conclusion of cyclic loading. Therefore, it can be concluded that initial liquefaction of GTCM samples were not achieved. The decrease in the effective mean stress (p') occurs due to the rapid generation of excess pore water pressure during stress controlled cyclic loading.

For GTCM specimens with GF=100% and GF=87%, strain softening occurrence starts from very first cycle of loading. The subsequent unloading from the peak point of deviatoric stress leads to extensive increase in pore water pressure moving the GTCM towards to state of zero mean effective confining pressure. Reloading in the extension region of the stress cycle causes the GTCM to undergo further deformation and its mean effective stress moves along failure envelope. Repetition of loading and unloading cycles causes a progressive increase in cyclic deformation following rapid loss of shear strength due to the accumulation of excess pore water pressure. This mechanism of the failure is similar to that of flow failure.

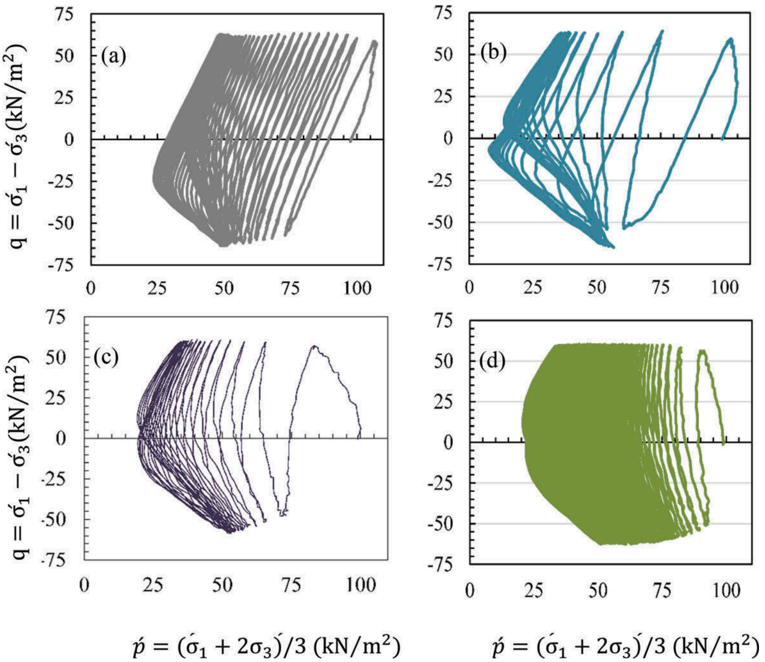

Figure 3. Cyclic stress paths of GTCM at cyclic stress ratio of $\sigma_d/2\sigma'_{3c} = 0.3$ and Relative density of Dr=50% and confining pressure$\sigma'_3 = 100\text{kN/m}^2$:(a) GF=100%;(b) GF=87%; (c) GF=55%; (d) GF=30%.

In the case of GTCM specimens with GF=55% and GF=30%, the cyclic deformation increases progressively due to the gradual increase in pore water pressure without strain softening. It should be noted that the magnitude of permanent deformations depends on the duration of loading and for the samples subjected to the cyclic loadings of long duration, cyclic mobility can generate damaging levels of soil deformations (Kramer, 1996). The medium dense and dense sandy and gravely soils show similar liquefaction behaviour under cyclic loading. This mechanism of the failure is similar to that of cyclic mobility failure.

The effect of confining pressure on the stress path of GTCM with GF=100% at relative density of 50% and stress ratio ($\sigma_d/2\sigma'_{3c}$) of 0.3 is shown Figure 4. GTCM sample with lower effective confining pressure exhibits comparatively higher liquefaction resistance, which usually could be observed in denser specimens.

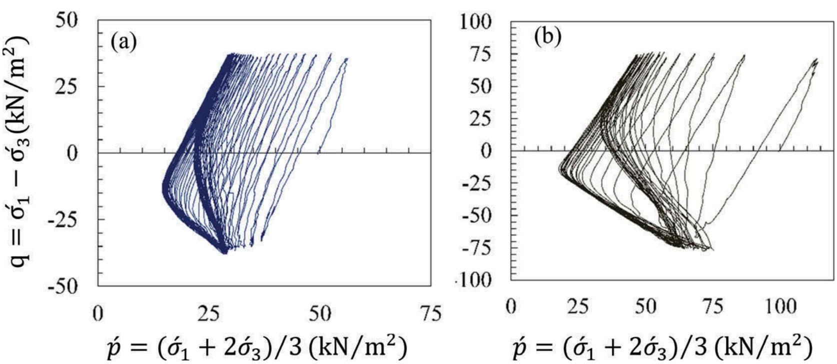

Figure 4. Cyclic stress paths of GTCM with GF=100% and relative density of Dr=50% at cyclic stress ratio of$\sigma_d/2\sigma'_{3c} = 0.3$: (a) σ'_3= 50kN/m^2; (b) σ'_3= 100kN/m^2.

4 EVALUATION OF LIQUEFACTION RESISTANCE

4.1 *Stress-based assessment*

The most common technique to evaluate liquefaction resistance is stress-based method (Seed and Idriss, 1971). The effect of gravel fraction on the evolution of excess pore water pressure ratio ($\mathrm{Ru} = \Delta\mathrm{u}/\sigma'_{3\mathrm{c}}$) during the cyclic loading for GTCM specimens at$\sigma'_3 = 100\mathrm{kN/m^2}$, Dr=50% and CSR=0.3 is shown in Figure 5. As is mentioned in previous section, for GTCM specimen with GF=87%, soil skeleton is still mainly formed by gravel and considering tire chips soft inclusions as voids in the mixture, GTCM specimen exhibits gravel like behavior in relatively loose state. For GTCM specimens with GF<87%, the number of cycles leading to $R_u = 0.8$ increased by decreasing gravel fraction in mixture.

For further analysis on liquefaction resistance of GTCM, maximum value of Ru at $\sigma_d/2\sigma'_{3c} = 0.3$ and confining pressure of$\sigma'_3 = 100\mathrm{kN/m^2}$ is plotted (Figure 6) for a given number of cyclic loading (Nl=20). Optimum value of gravel fraction in which GTCM sample shows remarkable improvement in liquefaction resistance of mixture was around 50%. The effect of confining pressure on liquefaction resistance of GTCM with different gravel fraction is shown in Figure 7. the increase in effective confining pressure remarkably suppressed dilative behavior and reduced liquefaction resistance of representative GTCM specimen. Similar finding was reported by (Vaid et al., 1985) on the liquefaction resistance of sandy soil. Furthermore, studies on permeability of sand and sand-tire chips revealed the reduction in the hydraulic conductivity of mixture with the effective confining pressure (e.g. Edil and Bosscher, 1994).

4.2 *Energy based evaluation of GTCM liquefaction resistance*

Studies on energy-based liquefaction evaluation technique has shown that dissipated energy during the dynamic loading is an important factor governing the pore water pressure or

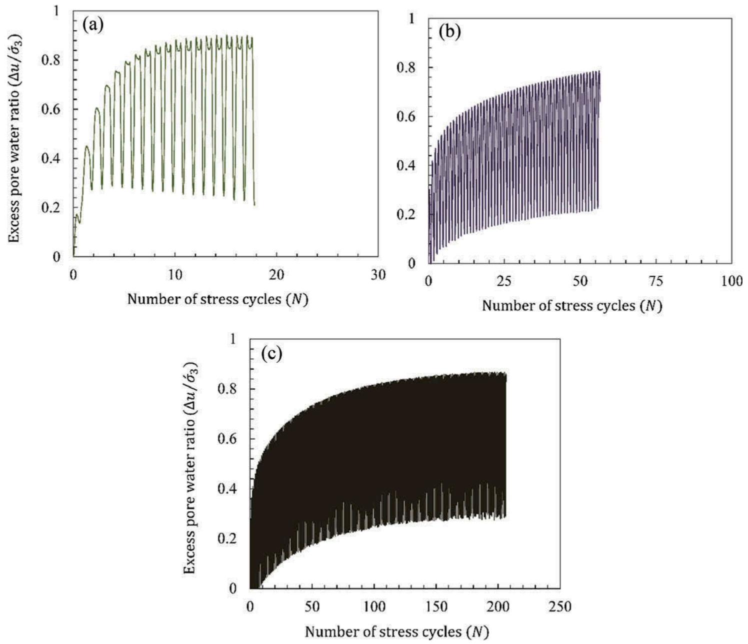

Figure 5. The effect of gravel fraction on the evolution of excess pore water ratio of GTCM with different GF at Dr=50%, CSR=0.3, $\sigma'_3 = 100\mathrm{kN/m^2}$: (a) GF=87%; (b) GF=44% (c) GF=30%.

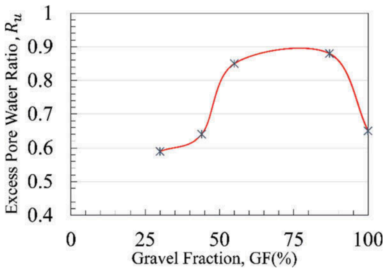

Figure 6. Excess pore water ratio (Ru = u/σ'_{3c}) of GTCM specimens at cyclic stress ratio $\sigma_d/2\sigma'_{3c} = 0.3$, σ'_3= 100kN/m^2 and number of cycles (Nl= 20).

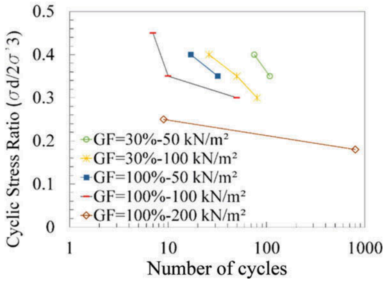

Figure 7. The effect of confining pressure on liquefaction resistance of GTCM at Dr=50%.

induced strain generated during the liquefaction (Kokusho & Kaneko, 2018). Figure 8a displays typical stress-strain relationship obtained in undrained cyclic loading triaxial test on GTCM specimen. Figure 8b shows the schematic shear stress-strain ($\tau - \gamma$)diagram of GTCM. Dissipated energy (ΔW) for each loading cycle can be obtained as:

$$\Delta \mathrm{W} = \sum_{\mathrm{S}} \tau \Delta \gamma = \oint^{\tau d\gamma} \tag{2}$$

Where $\sum_S \tau\Delta\gamma$ is the summation of slices such as ABCD over small strain width of $\Delta\gamma$ in a single dynamic loading cycle and $\oint^{\tau} d\gamma$ is the equivalent integral over the shear strain γ. The cumulative dissipated energy can be calculated as the summation of ΔW_i loading cycles from i=1 to desired number of cycles and can be represented as consistent integral to the corresponding cycles:

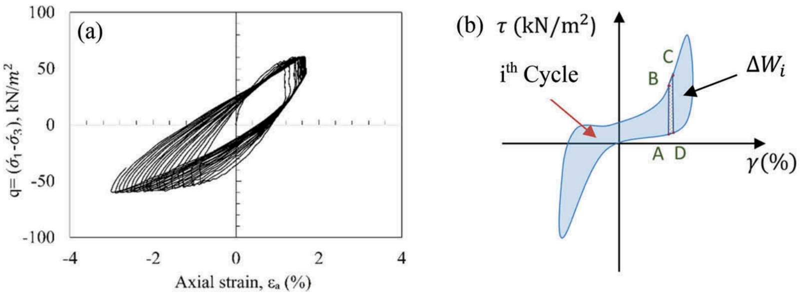

Figure 8. (a) Stress-strain hysteresis loop of GTCM with GF=44%, σ'_3 =100 kN/m^2 (b) definition of dissipated energy.

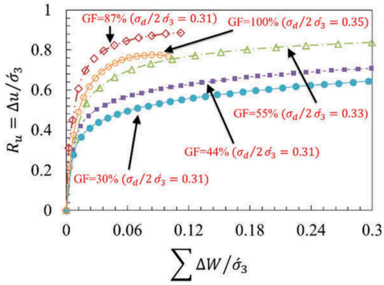

Figure 9. pore water pressure ratio (R_u) versus normalized dissipated energy ($\sum \Delta W/\sigma'_3$) for GTCM specimens at Dr=50% and $\sigma'_3 = 100\text{kN/m}^2\text{kN/m}^2$.

$$\sum^{\Delta} \text{W} = \sum_i \Delta \text{W}_i = {}^{\tau d\gamma} \tag{3}$$

Correlation between pore water pressure ratio (R_u) and normalized cumulative dissipated energy ($\sum \Delta W/\sigma'_3$) is displayed in Figure 9. The R_u values are well correlated with normalized cumulative dissipated energy ($\sum \Delta W/\sigma'_3$) for all tests of GTCM with different gravel fraction at stress ratio CSR≈0.3 – 0.35. The pore water pressure buildup for GTCM with GF=87% is slightly faster than the sample with GF=80% for the sample level of dissipated energy. However, for the samples with GF<87%, the pore water pressure buildup seems to be delayed with decreasing GF for same level of dissipated energy. The effect of gravel fraction on pore water pressure ratio (R_u) versus ($\sum \Delta W/\sigma'_3$) correlation is more pronounced for GTCM specimens with GF≤55%.

Because at this percentage of GF, the tire chips particles dominate the soil matrix and GTCM shows tire chips like behavior which is non-liquefiable and non-dilative materials. In the other hand, energy dissipation capacity of GTCM tends to increase with decreasing gravel fraction in mixture.

5 CONCLUSION

A series of undrained cyclic triaxial tests were carried out to evaluate liquefaction resistance properties of gravel-tire chips mixture using conventional stress-based method and energy-based method using the cumulative dissipated energy concept. The following conclusion can be drawn:

- The liquefaction resistance of GTCM specimens is remarkably influenced by gravel fraction in the mixture. For higher gravel fractions (GF>87%), Soil matrix is mainly formed by gravel. Therefore, adding a small amount of tire chips decreases liquefaction resistance due to a reduction in gravel inter-particle contacts during cyclic loading. However, for specimens with the GF<87%, liquefaction resistance increases with a decrease in gravel fraction in the mixture. GTCM exhibits gravel-tire chips like behavior or tire chips like behavior with higher permeability (non-liquefiable materials).
- GTCM specimens exhibit higher liquefaction resistance in lower effective confining pressures. the main reason for this phenomenon is that permeability of the mixture decreases with confining pressure. Furthermore, dilation of the mixture is suppressed at higher confining pressures.
- The energy dissipation capacity of GTCM specimens was found to increase with decreasing gravel fraction for the mixtures with GF<87%.

ACKNOWLEDGEMENT

First author would like to thank Prof. Takaji Kokusho fo his advice and many insightful discussions and suggestions throughout this research.

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