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Liquefaction Characteristics of Gravelly Soils Prepared by Water Sedimentation Method

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ABSTRACT

Field observations and evaluations from 32 case histories of liquefaction in gravelly soils worldwide, including three in New Zealand, have indicated that gravelly soils in alluvial deposits are the most susceptible to liquefaction. However, replicating these conditions in laboratory tests remains a challenge, particularly in achieving uniform specimen preparation for reliable liquefaction assessment. This study addresses these challenges by using a newly developed water-sedimentation (WS) method for gravelly soil specimens that can reproduce as much as possible the anisotropy and fabric of naturally deposited alluvial sand, enabling a better assessment of liquefaction potential. Notably, this WS method enhances density uniformity and minimises the inherent segregation between small sand and large gravel particles. A series of stress-controlled undrained cyclic triaxial tests were conducted on WS gravelly soil specimens reconstituted at relative densities (*D*r) between 20% and 60% and isotropically consolidated at 100 kPa effective confining stress. The specimens were then subjected to cyclic stress ratios (CSR) ranging from 0.14 to 0.45. Comparisons with specimens prepared by the moist tamping (MT) method showed that soil fabric significantly influences liquefaction resistance, with the WS specimens generally less resistant to liquefaction. In addition, density and gravel content also play a critical role, with liquefaction resistance increasing with both density and gravel content. This study indicates that for a better evaluation of the liquefaction resistance of alluvial gravelly soils, the combined effects of fabric, density state and gravel content must be considered together.

1 INTRODUCTION

Gravelly soils (i.e., gravels, gravelly sands and sandy gravels) are commonly encountered in natural alluvial deposits and reclaimed fills and play a critical role in the seismic performance of infrastructure. However, a persistent challenge in geotechnical engineering is the lack of universally accepted guidelines for characterising and evaluating their liquefaction resistance. Traditionally, gravelly soils have been considered to exhibit higher liquefaction resistance than sandy soils due to their higher permeability, which is believed to inhibit the development of significant excess pore water pressures during earthquakes (Seed et al., 1976). This assumption has led to the general perception that these gravels are less susceptible to liquefaction than clean sands. Nevertheless, increasing field evidence from 32 earthquake events involving widespread liquefaction in gravelly soils, as summarised by Rollins et al. (2021, 2022) and Pokhrel et al. (2024), has challenged the validity of this long-held assumption. Consequently, gravelly soils are often regarded as 'problematic' due to their complex and poorly understood cyclic behaviour.

Previous laboratory studies on the liquefaction resistance of gravelly soils have primarily relied on conventionally reconstituted specimens, prepared using methods such as moist tamping (MT) (Kokusho et al., 2004, 2007; Hara et al., 2004, 2012; Chang et al., 2014) and air pluviation (AP) (Hubler et al., 2018; Evans and Zhou, 1995). While these techniques are widely used, they often fail to reproduce the natural alluvial characteristics of gravelly soils, thus offering limited insight into fabric-related influence on liquefaction resistance. Given that fabric plays a critical role in controlling the cyclic response of gravelly soils, there is a pressing need for novel specimen preparation methods that can better reproduce the natural fabric of alluvial gravelly soil deposits, thus enabling a better evaluation of their liquefaction resistance.

The water sedimentation (WS) method, which allows particles to settle in a manner more representative of natural hydraulic sorting, could offer a promising alternative to conventional specimen preparation techniques (Oda et al., 1978). However, experimental studies examining the liquefaction resistance of gravelly soils prepared using the WS method remain limited, constraining the current understanding of how soil fabric influences the cyclic response and liquefaction resistance of alluvial gravelly soils.

In this study, a systematic and repeatable WS specimen preparation technique was developed to simulate as much as possible the depositional characteristics of alluvial gravelly soils. Specimens prepared using the WS method were then subjected to cyclic undrained triaxial loading to evaluate their liquefaction resistance. The results were compared with those obtained from previous studies employing the conventional MT technique (Pokhrel et al., 2023, 2024) to examine the fabric effects on the cyclic behaviour of gravelly soils, thereby providing a deeper understanding of the liquefaction potential of alluvial gravelly soils and contributing to a more comprehensive understanding of fabric-related effects on their liquefaction resistance.

2 METHODOLOGY

2.1 Test Materials

In this study, New Brighton Sand (NB Sand), Dalton River Washed Sand (DRW Sand), and rounded Pea Gravel were used to prepare well-graded sand-gravel mixtures for testing. To create a less uniform host sand and minimize gap-grading, the two sands were mixed in equal proportions by mass (50%-50%). The pea gravel was then added to the host sand to produce sand-gravel mixtures (SGM) with 10% and 25% gravel content (G_C) by mass (i.e., SGM with sand-dominated structures).

As reported in Table 1, index properties were evaluated for the test soils and mixtures according to relevant standards from the Japanese Geotechnical Society (JGS) and New Zealand Standards (NZS). They include the maximum (e_{max}) and minimum (e_{min}) void ratios, specific gravity (G_s), mean grain size (D_{50}), coefficient of uniformity (C_u), and coefficient of curvature (C_c). In Figure 1, the particle size distribution curves are reported.

Table 1: Material properties

Materials	G_s	e_{max}	e_{min}	D_{50} [mm]	C_u	C_c
NB Sand	2.66	0.623	1.016	0.20	1.64	0.93
DRW Sand	2.65	0.598	0.900	0.68	3.14	0.95
Pea Gravels	2.66	0.482	0.665	5.60	1.38	1.11
0% GC	2.66	0.563	0.906	0.26	2.50	0.90
10% GC	2.66	0.739	0.494	0.29	2.77	0.66
25% GC	2.66	0.632	0.415	0.41	4.50	0.42

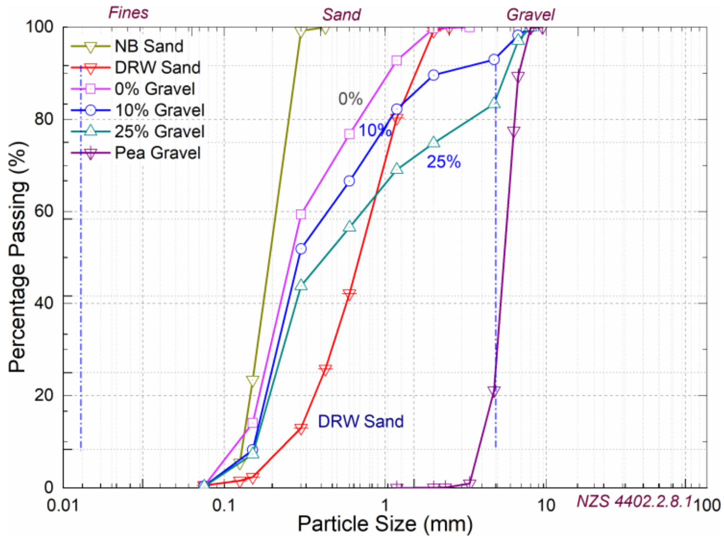

Figure 1. Particle size distribution curves of tested materials (adapted from Pokhrel et al., 2024).

2.2 Specimen Preparation Method

Specimens of 60 mm diameter and 137 mm height were reconstituted by a new WS method developed by the authors (Figure 2a). In this method, sand-gravel mixtures were carefully poured into a pluviation device with a constant drop height and water level, at a constant rate, to create a uniform 'sand rain.' This pluviation system was derived from insights gained from previous research by Vaid and Negussey (1988) and Lagioia et al. (2006), with some necessary adjustments and modifications. Specifically, to minimize inherent segregation between sand and gravel grains, the multi-layer deposition method proposed by Dobry (1991) was adopted, and specimens were built in 10 identical layers.

After pluviation was completed, the deposit was left resting for approximately 12 hours. Following this, the water level was lowered down to the top of the deposited specimen. Fresh deposits were densified to the target *Dr* by vibration induced by a hammer impact around the sides of the deposition tube. To mitigate disturbance during handling, specimens were frozen in a freezer before being transferred to a triaxial cell for testing. To do so, excess free water in the deposited specimen was drained prior to freezing. Special attention was given to temperature control when handling the frozen specimen tube, particularly during PVC tube removal, drilling of bender element holes, and trimming of the top surface. Shear wave velocity (Vs) was measured for all specimens, and unique sets of values were obtained for the different specimens prepared at the same Dr and G_C, confirming the suitability of the developed WS method to create uniform specimens.

2.3 Testing Procedure

Once the frozen specimen was positioned on the triaxial pedestal (Figure 2b), a rubber membrane was carefully placed around the specimen, which was then thawed under 20 kPa cell pressure for 12 hours. The diameter and height of the specimen were measured both before and after thawing. To achieve a B-value ≥ 0.95, a multi-step saturation process was conducted, including carbon dioxide percolation, followed by de-aired deionized water saturation under double vacuum, and finally by application of 200 kPa back pressure. The specimen was then isotropically consolidated to a target 100 kPa effective confining pressure in 20 kPa increments.

Stress-controlled undrained cyclic triaxial tests were conducted on specimens subject to constant-amplitude sinusoidal axial load with a cyclic stress ratio (CSR) ranging from 0.14 to 0.45 at a frequency of 0.05 Hz using a pneumatic loading system (Figure 3c). The CSR was calculated as per Equation 1:

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} = \frac{\sigma_d}{2\sigma'_c} \tag{1}$$

where σ_d = target single-amplitude axial stress; and σ'_c = mean principal effective stress at the end of consolidation.

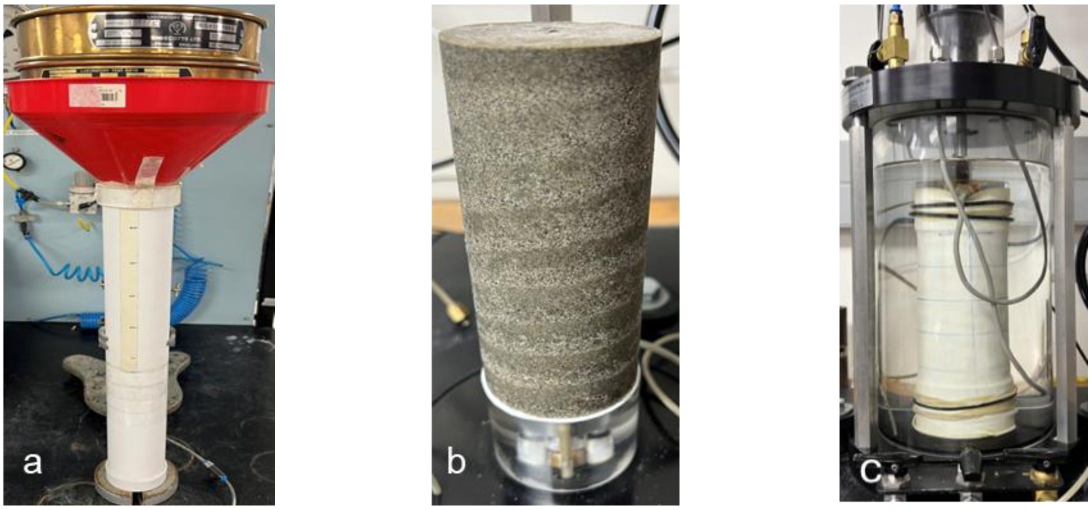

Figure 2. Specimen preparation and testing: (a) setup of the WS method developed in this study; and (b) example of layered frozen specimen prepared by the WS method; (c) a specimen tested in the triaxial device

3 RESULTS

3.1 Undrained Cyclic Response

Typical undrained cyclic responses are reported in Figure 3 for a loose specimen (*D*r = 30%) with 10% G_c, in terms of deviator stress, *q* (Figure 3a), excess pore water ratio, r_u (Figure 3b), and axial strain (Figure 3c). For completeness, the corresponding effective stress paths (Figure 3d) and stress-strain relationship (Figure 3e) are represented for the same specimen. Pore water pressure and axial strain increased progressively with increasing cycles of loading (N_c) until the r_u was equal to or greater than 0.95. The loading program was terminated when 5% single-amplitude axial strain was reached, and the specimen failed, typically under extension shear loading conditions. As expected, in the case of the denser specimens (*D*r > 30%), a higher N_c under the same CSR was required to result in similar failure conditions (i.e., $r_u \geq 0.95$ or 5% double amplitude axial strain, ε_{DA}).

In this study, the state of initial liquefaction was defined as either $r_u \geq 0.95$ or $\varepsilon_{DA} = 5\%$, and cyclic resistance ratio (CRR_{15}) was defined as the CSR value at 15 cycles of loading (N_C). The liquefaction resistance curves of sandy soil and 10% gravel content cases based on 5% ε_{DA} and $r_u \geq 0.95$ are plotted in Figure 4.

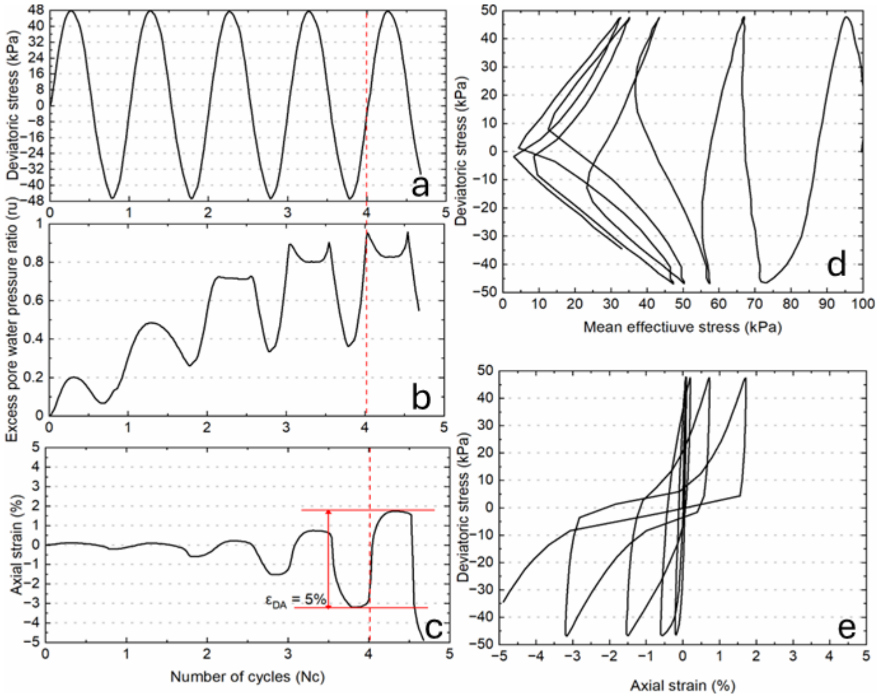

Figure 3. Typical undrained cyclic triaxial response of a loose specimen (Dr = 30%) with 10% gravel content.

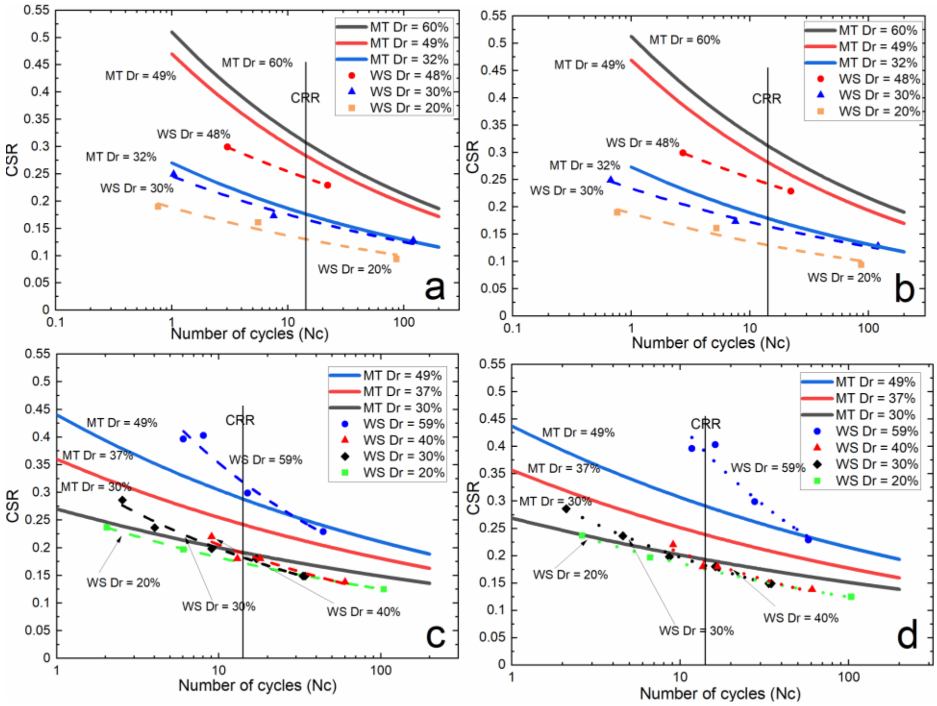

Figure 4. Liquefaction resistance curves (a) sandy soil, 95% ru; (b) sandy soil, 5% εDA; (c) 10% gravel, 95% ru; (d) 10% gravel, 5% εDA.

The liquefaction resistance curves for specimens with 10% GC, defined based on the 95% r_u and 5% ε_{DA} criteria, are nearly identical within the *D*r range of 20% to 40%. This suggests that 95% r_u and 5% ε_{DA} thresholds were reached at approximately the same time during cyclic loading. This behaviour reflects the typical undrained cyclic response of loose specimens. However, at Dr = 59%, the CSR curve based on the 5% ε_{DA} criterion becomes noticeably steeper than that based on the 95% r_u criterion, leading to different CRR values, as shown in Figures (4c) and (4d). Notably, the significant divergence between the two initial liquefaction criteria at higher densities has also been reported in previous studies (Pokhrel et al., 2024). Therefore, in this study, the $r_u \geq 0.95$ criterion was adopted to define initial liquefaction and determine the CRR_{15} value of specimens.

3.2 Effects of Relative Density and Soil Fabric on Liquefaction Resistance

To evaluate the fabric effects on liquefaction resistance, comparisons with experimental data available for specimens prepared by the MT method by Pokhrel et al. (2024) are made in Figure 4.

At the same *D*r, for any given value of Nc and CSR, the cyclic resistance of sandy soil specimens prepared by the WS method is lower than that of specimens prepared by the MT method, indicating a significant influence of specimen fabric on the liquefaction resistance.

However, for the 10% G_C case, the cyclic resistance ($r_u = 0.95$) of WS specimens is not consistently lower than that of the MT specimens. For instance, for Dr = 30% and 40%, the liquefaction curves of WS specimens are steeper than those of MT specimens (Figure 4c). It appears that at Nc > 10, the WS specimens exhibit a weaker cyclic resistance, while at NC < 10, the resistance of WS specimens exceeds that of the MT specimens. A similar trend is also observed for denser specimens (Dr = 59%), with the transition occurring at $N_C = 25$.

3.3 Effects of Gravel Content on Liquefaction Resistance

Based on the liquefaction curves shown in Figure 4, CRR_{15} was defined for all mixtures investigated in this study and by Pokhrel et al. (2024), prepared at different Dr and Gc = 0, 10 and 25% G_C. The results for the 25% G_C specimens are not yet complete and will be presented in full detail elsewhere in the future. Linear correlations between the CRR_{15} and void ratio (*e*) are obtained for each tested G_C configuration, as shown in Figure 5. The test results shown in Figure 5 indicate that the fabric effects are negligible for loose density conditions (i.e., higher void ratio values); however, as the density increases (i.e., void ratio decreases), the difference in liquefaction resistance between the two specimen preparation methods increases, with the MT specimens becoming progressively stronger than the WS ones.

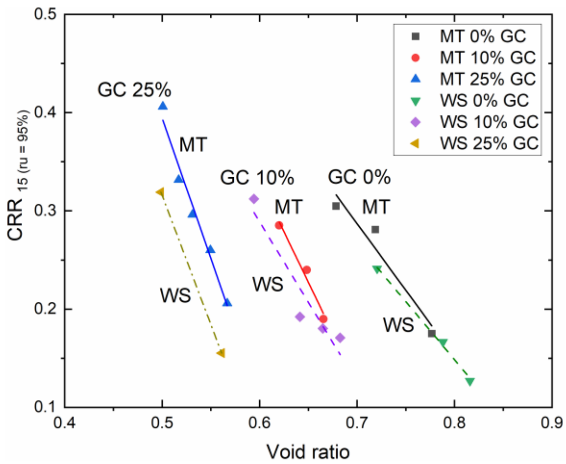

Figure 5. Correlation between CRR_{15} and void ratio for specimens prepared by different preparation methods.

It is clear from Figure 5 that fabric, Dr and G_C play a key role on the liquefaction resistance of alluvial gravelly soils. Therefore, to more accurately evaluate the liquefaction resistance of alluvial gravelly soils, the combined effects of these three key factors must be considered all together.

4 CONCLUSIONS

In this study, a series of undrained cyclic triaxial tests were conducted to investigate the combined effects of fabric, relative density (Dr) and gravel content (G_c) on the liquefaction resistance of sandy gravelly soils. To do so, a new water sedimentation (WS) method was developed for gravelly soils, and the specimens were prepared using the same materials and sand-gravel mixtures tested by Pokhrel et al. (2023, 2024), who employed the moist tamping (MT) method, and tested under the same triaxial testing conditions.

It is found that the proposed water-sedimentation (WS) method for gravelly soils allows the preparation of specimens with uniform density and minimises the inherent segregation between small sand and large gravel particles, thus mimicking as much as possible the fabric of naturally deposited alluvial sands. Therefore, it enables a better assessment of the liquefaction potential of alluvial gravelly soil.

The experimental results show that in the case of sandy soils, the liquefaction resistance of those prepared by WS is less than those prepared by MT, irrespective of the density state. However, for the 10% Gc case, the cyclic resistance of WS specimens is not consistently lower than that of the MT specimens. Specifically, for Dr = 30% and 40%, it appears that for cycles loading number (Nc) > 10, the WS specimens exhibit a weaker cyclic resistance, while at Nc < 10, the resistance of WS specimens exceeds that of the MT specimens. A similar trend is also observed for denser specimens (Dr = 59%), with the transition occurring at Nc = 25. Moreover, irrespective of the density state, it is observed that the fabric effects are negligible for loose density conditions; however, as the density increases, the difference in liquefaction resistance between the two specimen preparation methods increases, with the MT specimens becoming progressively stronger than the WS ones.

It is evident that fabric, Dr and G_C play a key role on the liquefaction resistance of alluvial gravelly soils. Therefore, to more accurately evaluate the liquefaction resistance of alluvial gravelly soils, the combined effects of these three key factors must be considered all together.

The results of ongoing laboratory investigations on specimens, prepared with higher Gc (i.e., 25% and 40%) across a broader range of Dr, will provide further useful information to better characterise the cyclic response of alluvial gravelly soils and the combined effects of fabric, Dr and GC on their liquefaction resistance.

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