

# Liquefaction resistance of gravelly sand under bidirectional cyclic loading

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**ABSTRACT:** This study evaluates the liquefaction resistance of gravel, sand, and gravel-sand mixtures under bidirectional cyclic loading using a bidirectional simple shear device. Four gradations, including clean gravel, clean sand, and mixtures containing 60:40 and 40:60 gravel-to-sand ratios, were examined through drained monotonic tests and undrained cyclic tests under circular stress paths and different cyclic stress ratios. The results show that the cyclic response is strongly governed by the monotonic behavior of the samples. Clean gravel, which exhibited the greatest density dependency and volumetric strain, showed the lowest liquefaction resistance. In contrast, the 60% gravel-40% sand mixture demonstrated the highest liquefaction resistance due to improved particle interlocking and enhanced dilatancy. Liquefaction resistance correction factors, defined as the ratio of bidirectional to unidirectional CRR at the 15th cycle, ranged from 0.52 to 0.82 for pure samples and 0.86 to 1.05 for mixed soils, indicating lower directional sensitivity in well-graded mixtures. Overall, the findings emphasize the role of particle interaction and gradation in controlling the liquefaction potential under multidirectional loading and provide insights for more accurate evaluation of seismic performance.

**KEYWORDS:** liquefaction resistance, bidirectional simple shear, gravel-sand mixture, cyclic loading, correction factors.

## 1 INTRODUCTION

Soil liquefaction, characterized by the loss of soil strength due to rapid pore pressure buildup under cyclic loading, is one of the major geotechnical challenges during earthquakes. The phenomenon is well-understood in clean sands, where extensive research has focused on factors affecting liquefaction potential, such as grain size, density, and the effect of loading conditions (Seed and Idriss, 1971; Dong et al., 2023). However, despite the considerable investigations on sands, the behavior of gravelly soils under cyclic loading remains significantly under-explored. This knowledge gap is particularly concerning as gravelly deposits are widely used for urban development and infrastructure projects in seismically active regions.

Gravel is often considered non-liquefiable due to its high hydraulic conductivity and coarse grain size, which traditionally suggested that it could effectively dissipate pore pressures during seismic events. However, recent field observations have challenged this assumption. For instance, Rollins and Roy (2024) documented cases of liquefaction in gravelly soils during multiple earthquakes, demonstrating that under specific in-situ conditions, these soils can liquefy. The 2008 Wenchuan earthquake further highlighted this issue, showing large-scale liquefaction in gravelly deposits that could have been overlooked based on earlier assumptions (Cao et al., 2011).

Laboratory investigations on liquefaction are largely restricted to unidirectional cyclic loading, which tends to oversimplify the complex stress paths generated during actual seismic motions. Unidirectional loading, though valuable for an initial insight, cannot capture the rotational stress paths and changing principal stress directions experienced in real earthquakes. This limitation has been highlighted in several studies, including those by Kammerer (2002), who demonstrated that bidirectional loading has a notable influence on the pore pressure development and liquefaction response of soils.

Despite these developments, knowledge about the gravelly soils under bidirectional loading is still limited. The majority of the studies so far have focused either on clean sands under bidirectional loading or on gravelly soils under unidirectional loading, with a major gap in the literature concerning the

response of gravelly soils to realistic, multidirectional seismic loading. In addition, gravelly soils are intricate mixtures of coarse gravel and finer fractions, and their liquefaction potential is affected by particle interaction, soil fabric, and stress transfer mechanisms (Pokhrel et al., 2024).

Recent advances in understanding gravel behavior have been achieved through sophisticated testing methodologies. Zekkos et al. (2018) developed a direct simple shear apparatus to investigate the shear behavior of pea gravel under both monotonic and cyclic loading conditions at constant volume. Their findings demonstrated that pea gravel generates significant pore water pressure during both monotonic and cyclic loading, challenging previous assumptions about gravel drainage characteristics. Kavand et al. (2018) investigated the liquefaction resistance of sand-gravel mixtures through cyclic triaxial testing, examining the effects of relative density and gravel content. Their results indicated that the sample containing 75% gravel demonstrates improved resistance. Hubler et al. (2018) examined pea gravel-Ottawa sand mixtures under simple shear conditions, finding that a 40% sand and 60% pea gravel combination exhibits maximum shear resistance and liquefaction resistance. They also identified that the Cyclic Stress Ratio (CSR) significantly influences mixture behavior, with particle contact levels during shear loading being a critical factor.

In order to quantify the reduction in liquefaction resistance due to multidirectional loading, a correction factor (CF) has been introduced, which is defined as the ratio of cyclic resistance under bidirectional to unidirectional loading conditions at a fixed number of cycles (i.e., 15 cycles for a 7.5 magnitude earthquake). This correction factor enables the adjustment of simplified laboratory data (typically obtained from unidirectional tests) to more accurately represent field seismic conditions. Reported values of CF range from 0.5 to 1.3, depending on soil gradation, fines content, initial relative density, and cyclic loading pattern (Ishihara et al. 1980, Kammerer 2002, Rasouli 2020).

Despite these advances, significant knowledge gaps remain regarding the behavior of gravelly soils under multidirectional cyclic loading conditions. Understanding the response of gravelly soils to multidirectional loading is essential for accurate seismic hazard assessment and foundation

design in earthquake-prone regions where gravelly deposits are prevalent. This study addresses the critical knowledge gap by investigating the liquefaction resistance of gravel and gravel-sand mixtures under bidirectional cyclic loading. The research aims to: (1) quantify the effects of bidirectional loading on liquefaction resistance of gravel with varying sand content, (2) develop Liquefaction Resistance Correction Factors (CF) to adjust unidirectional results for bidirectional loading conditions, and (3) assess liquefaction hazard and improved seismic design practices for structures on gravelly deposits.

## 2 METHODOLOGY

### 2.1 Materials

For this study, the Firoozkooch soil was selected as the base material. This soil is a golden siliceous sand commonly used in geotechnical research due to its consistent properties. Two distinct particle sizes were used: D3, a rounded gravel (4–7 mm) representing the coarse fraction, and 161 sand (0.2–0.6 mm) representing the fine fraction. The characteristics of the materials used are summarized in Table 1, which includes the particle size distribution, specific gravity, and other key physical properties.

The tested mixtures consisted of:

- 100% Gravel
- 60% Gravel + 40% Sand
- 40% Gravel + 60% Sand
- 100% Sand

The particle size distribution for all compositions is shown in Figure 1. According to the Unified Soil Classification System (USCS), both gravel and sand are categorized as poorly graded uniform soils. The specific gravity ( $G_s$ ) of both the gravel and sand was consistent, with a value of 2.64, as determined by ASTM D854. The maximum and minimum void ratios were obtained following ASTM D4253 and ASTM D4254. Table 1 also includes the uniformity coefficient ( $C_u$ ) and curvature coefficient ( $C_c$ ) for each mixture.

Table 1. Index properties of the materials

Soil Sample	$e_{min}$	$e_{max}$	$C_u$	$C_c$
Gravel	0.517	0.67	1.245	1.002
Sand	0.595	0.845	1.588	1.151
60% Gravel + 40% Sand	0.284	0.385	18.82	0.097
40% Gravel + 60% Sand	0.37	0.517	3.72	0.406

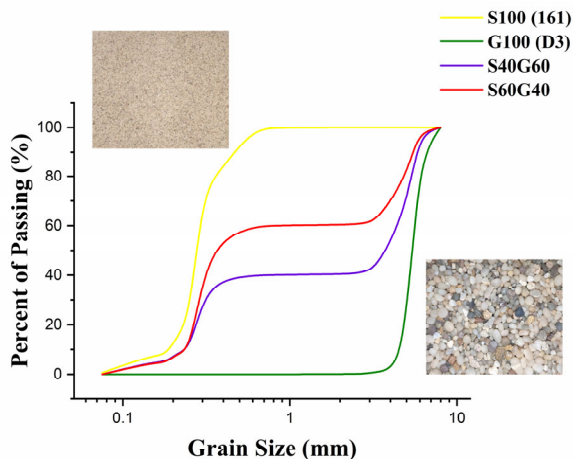


Figure 1. Grain size distribution curve of the materials.

### 2.2 Device

The multidirectional simple shear device utilized in this study is presented in Figure 2. The cyclic simple shear (CSS) apparatus is equipped with vertical and horizontal load cells and LVDTs for precise displacement measurement. The cylindrical specimen is enclosed in a latex membrane and confined by copper rings, which minimize boundary friction and help maintain lateral constraint during  $K_0$  consolidation. To address stress concentration and non-uniformity issues common in element testing, the specimens were prepared with a height-to-diameter ratio of 0.32 (diameter: 150 mm; height: 48 mm), which satisfies ASTM D6528's requirement of  $\leq 0.4$ , ensuring uniform stress and strain distribution throughout the sample.

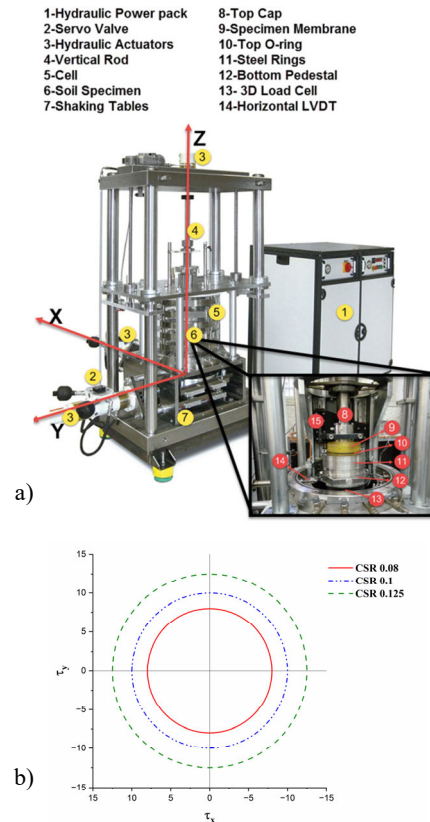


Figure 2. a) Multi-directional simple shear device. b) Shear loading pattern and magnitudes for the clean gravel in bidirectional cyclic tests.

### 2.3 Sample Preparation

The soil specimens were prepared with meticulous care to ensure uniform density and particle distribution. After calculating the target relative density, the sand and gravel were dry-mixed in the specified proportions. To ensure uniform gradation throughout the specimen, sand and gravel were placed in alternating thin layers, and the dry pluviation method was used for specimen deposition. This technique involved pouring the dry soil through a funnel nozzle, allowing it to fall uniformly over the surface of the mold in a spiral pattern. Each soil mixture was consolidated under an initial vertical effective stress of 100 kPa, which is a commonly adopted stress value in liquefaction studies.

### 2.4 Test Procedure

Numerous studies (e.g., Castro & Poulos 1977; Rahman et al. 2014) have identified a correlation between monotonic and cyclic shear responses. Accordingly, 16 drained monotonic

stress-controlled simple shear tests were conducted for each soil composition at four relative densities: loose ( $\approx 20\%$ ), 30%, 70%, and dense ( $\approx 90\%$ ). The primary objective was to characterize the contractive or dilative tendencies of the mixtures under monotonic loading. These tests provided insight into how the samples might behave under cyclic loading. By examining the behavior under monotonic loading, it was possible to observe the tendency of the samples to either contract (resulting in higher pore pressure and a liquefaction potential) or dilate (indicating greater liquefaction resistance).

Cyclic shear tests were performed using two types of horizontal stress paths: linear (unidirectional) loading and circular (bidirectional) loading, both applied along the X and Y axes. The primary focus of this paper is the bidirectional loading results, which simulate the stress conditions encountered during actual earthquakes. During the cyclic tests, a constant height condition is maintained, simulating the undrained condition of the soil. This setup simulates field conditions on level ground, where no initial static shear stress is applied. The Shear stress amplitudes are varied according to predefined cyclic stress ratios ( $CSR = \tau_{cyc} / \sigma_v$ ). For clean sand and sand-gravel mixtures, CSR values of 0.10, 0.125, and 0.15 were applied, while for clean gravel specimens, CSR values of 0.08, 0.10, and 0.125 were used. The frequency and effective vertical stress were kept constant at 0.2 Hz and 100 kPa, respectively. Although the tests are performed on dry specimens, the undrained behavior is simulated through stress interpretation (Martin et al., 1975). Consequently, any reduction of vertical stress to zero during cyclic loading is interpreted as equivalent to the buildup of excess pore pressure in saturated soils, where the effective stress approaches zero, and liquefaction occurs.

The cyclic tests were initiated under an effective vertical stress of 100 kPa and continued until the failure threshold was reached. In this study, the criteria for liquefaction are based on strain limits. The onset of liquefaction was defined by one of the following strain thresholds (Kammerer 2002):

1. double-amplitude shear strain  $\geq 3\%$ , or
2. single-amplitude shear strain  $\geq 6\%$

For each test, the number of loading cycles required to reach the specified strain-based liquefaction criteria was obtained. The results were used to evaluate the liquefaction resistance of the specimens under bidirectional cyclic loading and to quantify the role of sand content in strengthening or weakening the resistance of gravel. The results of the bidirectional simple shear test are given in Table 2.

### 3 RESULTS

#### 3.1 Monotonic

The monotonic tests were conducted to observe the contractive and dilative behavior of the soil samples. The results revealed clear trends in the contraction and dilation behaviors of the samples, which are critical to understanding their cyclic behavior and can provide an initial prediction of the liquefaction resistance of the samples. Figure 3 shows the volumetric strain versus shear strain, plotted for samples in relative densities in loose and dense states (e.g.,  $\approx 20\%$  and 70%). All materials demonstrate a decreasing trend in volume strain with increasing relative density. At very low relative density ( $Dr \approx 20\%$ ), all specimens exhibit a dilative response, and the differences between mixtures are pronounced. While at higher densities, the curves become contractive. This behavior aligns with the principle of the critical state of soil mechanics, where denser granular materials require less contraction to reach the dilation phase.

The monotonic simple shear test outcomes revealed significant composition-dependent variations in volumetric behavior. The G100 sample showed the greatest dilative behavior. This reflects the large void ratios in uniform gravels and their potential for particle rearrangement.

The S40G60 sample demonstrated the most stable volumetric response during monotonic shear loading. Suggesting that the gravel part provides the framework to maintain the stability, while the sand fraction fills the internal voids, which results in a more uniform response to density variations.

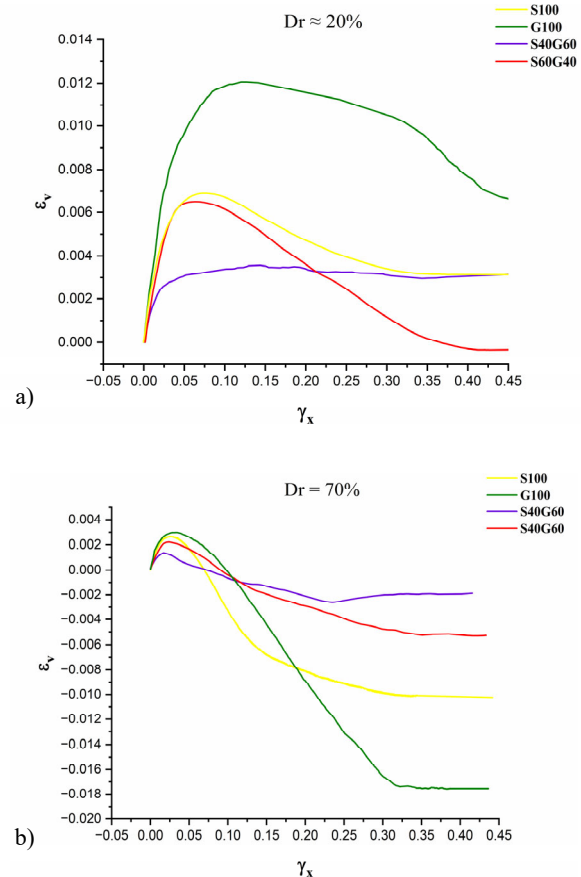


Figure 3. Volumetric strain  $\epsilon_v$  versus shear strain  $\gamma_x$  for clean gravel, clean sand, and sand-gravel mixtures at two representative relative densities: a)  $Dr \approx 20\%$  and b)  $Dr = 70\%$ .

#### 3.2 Cyclic

In the bidirectional condition, due to the simultaneous shear loading in the X and Y axes, the resultant shear strain ( $\gamma_R$ ), calculated by Equation (1), was used in the analyses.

$$\gamma_R = \sqrt{\gamma_x^2 + \gamma_y^2} \quad (1)$$

As expected, when the shear stress increases, the excess pore water pressure reaches 1 more rapidly. The locked-up condition occurred at shear stresses of 8 and 10 kPa. Locked-up state is when the  $r_u$  will not reach 1 and oscillate around a certain value until the shear strain gradually builds up and the specimen reaches the liquefaction threshold. In this series of tests, this constant value was found to be approximately 0.9. As shown in Figure 4, although  $r_u$  remained below 1, shear strain continues to increase until the liquefaction threshold is reached, which is the 6% strain (cyclic mobility failure). When the shear stress is increased to 12.5 kPa, the liquefaction mode changes, leading

to flow liquefaction failure and abrupt shear strains, as shown in Figure 4.

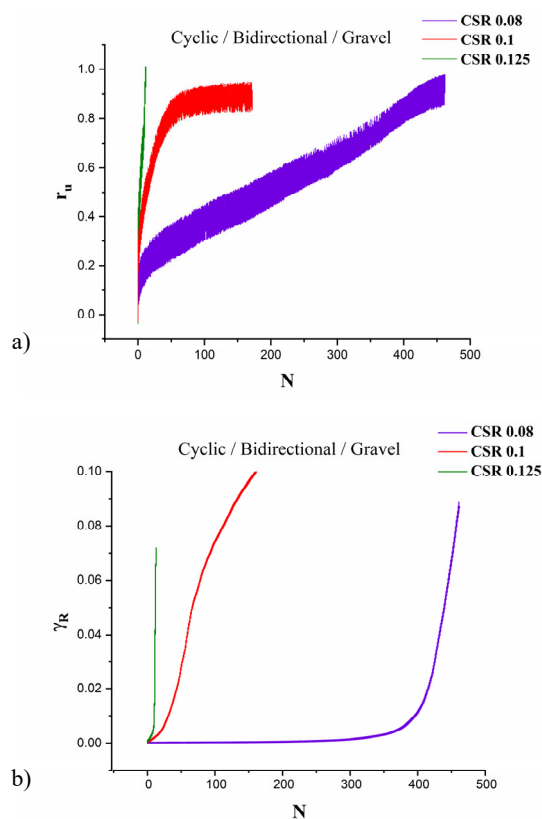


Figure 4. a) pore water pressure generation and b) Shear strain accumulation in gravel during bidirectional loading.

### 3.3 Effect of Increasing Sand Content on the Cyclic Behavior of Mixed Soil

Increasing the sand content in a gravelly sand mixture will have a significant effect on the liquefaction resistance of the soil. The addition of sand reduces void spaces and enhances particle interlock through increased friction, leading to a more dilatant response under cyclic shear loading. The enhanced dilatancy helps the soil build up greater shear resistance, which delays liquefaction onset. However, when sand dominates the mixture, the soil loses its cohesive properties, resulting in a more erratic and unstable response to cyclic loading conditions. Therefore, identifying an optimal gravel-to-sand ratio remains essential for maximizing liquefaction resistance.

The results indicate that adding sand to gravel enhances soil dynamic behavior up to a specific threshold, after which further sand addition reduces shear resistance. Circular loading tests revealed that the mixture containing 60% gravel and 40% sand demonstrates optimal performance with the highest dynamic resistance. The cyclic response of this sample shows a significantly slower rise in excess pore pressure and a higher number of cycles to reach liquefaction compared to the other mixtures, indicating that the added sand improved the soil's overall resistance. Figure 5 illustrates how the excess pore water pressure ratio and shear strain change under a specific cyclic shear stress ratio, facilitating comparison among the different samples. The data clearly show that the 60% gravel and 40% sand mixture has better cyclic behavior, with smooth and gradual changes throughout the loading process.

The observed relationship between monotonic and cyclic behavior is consistent with the steady-state framework established by Castro and Poulos (1977) and validated by

numerous subsequent studies. Based on the dilatant and contractive response of samples in monotonic tests, the least liquefaction resistance is expected from the clean gravel sample and the highest from the S40G60. By plotting the liquefaction resistance of specimens under bidirectional simple shear loading, the same result was obtained.

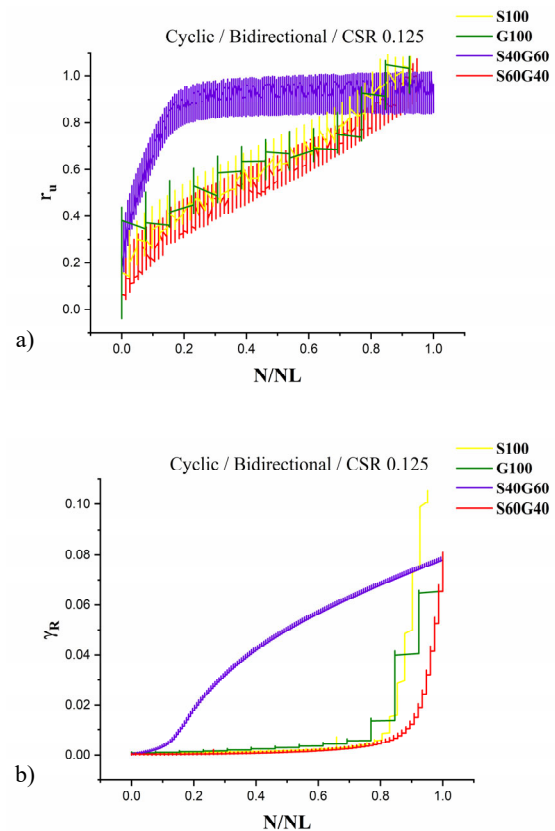


Figure 5. Comparing a) pore water pressure generation and b) Shear strain accumulation for each sample under the shear strain of 12.5 kPa.

This finding indicates that rounded gravel particles, despite their larger size, move more freely when subjected to shear forces. This increased mobility leads to greater soil contraction and higher generation of excess pore water pressure. As a result, the soil becomes more susceptible to liquefaction, reaching this critical state in fewer loading cycles and at lower shear stress levels. However, incorporating an appropriate amount of sand into the gravel mixture helps reduce the negative impact of particle roundness. This addition improves the soil's stability and enhances its overall resistance to liquefaction. Figure 6 compares the liquefaction resistance of samples under bidirectional simple shear loading.

Previous research has demonstrated that mixed soils exhibit an optimal sand-to-gravel ratio for achieving maximum liquefaction resistance. Kavand et al found that river gravel and Firouzkouh sand performed best at 75% gravel and 25% sand, while Hubler et al. reported optimal results with 60% pea gravel and 40% Toyora sand. The current study reveals that for the materials tested, a 60% gravel and 40% sand composition provides the highest shear resistance under circular loading conditions.

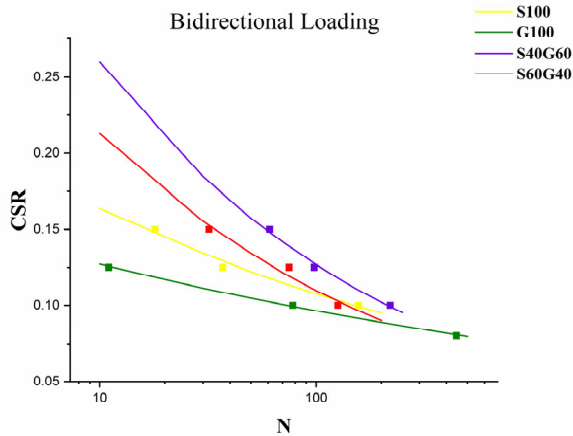


Figure 6. Liquefaction resistance curves of each mixture in the circular stress path.

By fitting the obtained curves shown in Figure 6, the liquefaction resistance of all mixtures can be examined, and the CRR value, which is the CSR value at the 15<sup>th</sup> cycle, equivalent to the seismic demand of an Mw = 7.5 earthquake, can be calculated. By dividing the CRR values into bidirectional and unidirectional loadings, the Liquefaction Resistance Correction Factor (CF) can be obtained (Equation (2)). Using this factor, results from unidirectional cyclic behavior research can be easily extended to multidirectional loading conditions. The correction factors obtained in this research are shown in Table 2.

$$CF = CRR_{multi} / CRR_{uni} \quad (2)$$

The CF values for 40 cycles of earthquake are shown in Figure 7 for specimens. The results show that mixed samples generally exhibit lower directional sensitivity at low cyclic demands. However, as the number of cycles increases, representing stronger or longer-duration earthquakes, their liquefaction resistance becomes more affected by the directionality of loading. In contrast, pure samples (clean sand or clean gravel) tend to show more consistent liquefaction resistance across different loading paths as the number of cycles increases. Overall, the results suggest that soil gradation plays a crucial role in directional sensitivity. Well-graded or optimally mixed soils, such as S40G60, perform better and show more resilience under multidirectional seismic loads.

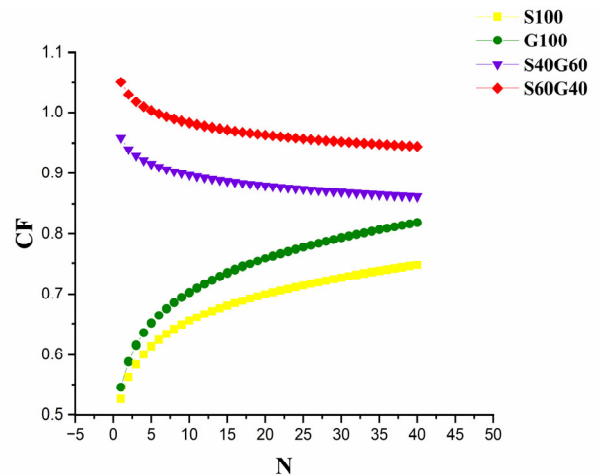


Figure 7. The Liquefaction Resistance Correction Factor (CF) during 40 cycles of earthquake.

Table 2. Summary of test conditions, results, and liquefaction resistance corrected for a magnitude 7.5 earthquake

Test No.	Test Code	Soil Sample	CSR	Dr (%)	N <sub>liq</sub> (Number of Cycles)	CRR (Mw = 7.5)	LM*
1	C/BI-G100-0.08	Gravel	0.08	73	445	0.735	CM
2	C/BI-G100-0.1		0.1	71	78		CM
3	C/BI-G100-0.125		0.125	71	11		FL
4	C/BI-S100-0.1	Sand	0.1	73	157	0.68	CM
5	C/BI-S100-0.125		0.125	75	37		FL
6	C/BI-S100-0.15		0.15	77	18		FL
7	C/BI-S40G60-0.1	40% Sand+ 60% Gravel	0.1	60	220	0.886	CM
8	C/BI-S40G60-0.125		0.125	66	98		CM
9	C/BI-S40G60-0.15		0.15	60	61		CM
10	C/BI-S60G40-0.1	60% Sand+ 40% Gravel	0.1	70	126	0.97	FL
11	C/BI-S60G40-0.125		0.125	67	75		FL
12	C/BI-S60G40-0.15		0.15	65	32		FL

\*Liquefaction mode: FL = Full liquefaction and CM = Cyclic Mobility

#### 4 CONCLUSIONS

The cyclic behavior and liquefaction resistance of four soil samples were investigated using a bidirectional simple shear device. The samples included clean gravel, clean sand, and two gravel-sand mixtures to evaluate the influence of gradation on liquefaction resistance.

The monotonic tests provided valuable insights into cyclic performance. Materials with higher contraction showed lower cyclic resistance. This relationship provides a practical method for estimating cyclic behavior from simpler static tests.

Clean gravel's rounded particles caused higher mobility and excess pore pressure generation. This sample showed the most contractive behavior and the lowest liquefaction resistance

among all samples. Adding 40% sand significantly reduced the contractive tendency of gravel and improved its resistance to liquefaction. This composition performed best under both monotonic and cyclic loading, highlighting the critical role of soil fabric and inter-particle interaction.

To quantify the effect of loading direction, correction factors (CF) were calculated for each material. The CF values revealed that mixed compositions have less sensitivity to directional changes and more stable behavior under complex loading patterns.

These findings can inform the geotechnical design of foundations and structures in seismic regions. However, further research should explore other types of gravel, particle shapes,

and stress conditions, and comparisons with field observations are needed to validate the laboratory results.

Overall, assessing the liquefaction resistance of gravel and gravel-sand mixtures is a complex process affected by various factors. These include the dilative or contractive behavior of the soil, particle shape and angularity, gradation and soil fabric, as well as the direction and magnitude of cyclic loading. Therefore, reliable assessment requires considering the combined effects of all these factors.

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