Investigation of Liquefaction Potential in Sands Mixed with Gravel

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Abstract

Liquefaction is one of the significant hazards associated with earthquakes. It was previously believed to occur mostly in clean sands; however, recent research has shown that liquefaction can occur in specific conditions in sands mixed with fine or coarse particles. Numerous studies have been conducted on clean sand, while limited research has focused on sands mixed with silt. Nevertheless, the liquefaction resistance of sands mixed with coarse particles has received less attention in previous studies. This research investigates the liquefaction potential of sands mixed with gravel using cyclic triaxial testing. The experiments were performed on Ottawa sand mixed with various percentages of gravel. The study evaluates the influence of parameters such as relative density and gravel percentage on the liquefaction resistance of the mixed soil. The results indicate that the gravel percentage and relative density of the samples significantly affect the liquefaction potential.

Keywords: Cyclic triaxial test, Ottawa sand, Gravel, Liquefaction potential.

Introduction

Liquefaction of soil in Central Taiwan was observed after the 1999 Chi-Chi earthquake with a magnitude of 7.6. Although liquefaction predominantly occurred in aquifer layers, fine sands, and silty sands, reports indicated liquefaction in sandy soils in the Yufeng and Nantou regions as well. The common assumption that sandy soils are not prone to liquefaction was challenged by seismic events such as the Chi-Chi earthquake in 1991 and the Armenian earthquake in 1988, raising concerns about saturated sandy soils. Another notable example of sandy soil liquefaction was observed during the Wenchuan earthquake in 2008, where sand boiling and liquefaction affected numerous villages, schools, and factories, causing structural damage and displacement of homes. The phenomenon also led to the blockage of several wells due to the uplift of sand and gravel resulting from the boiling effect. Various tests, including cone penetration testing, dynamic penetration testing (DPT), and surface wave analysis, were conducted on samples extracted from liquefaction-affected sites by Kao and colleagues in 2010. [3]

The occurrence of liquefaction has captured the attention of many engineers, especially in seismic-prone regions such as Alaska and Nigata. The significant damage caused by liquefaction in these areas, notably during the earthquakes in Alaska and Nigata in 1964, led to extensive research and investigations. Numerous studies have been conducted to assess the liquefaction potential.

Liquefaction typically occurs in non-cohesive soils that are saturated and have a moderate to fine particle size distribution. In simple terms, when non-cohesive soils become saturated and undergo rapid loading in conditions of consolidation, there is a tendency for increased pore pressure, resulting in reduced effective stresses. In such conditions, the shear resistance of the sand significantly decreases, and the material may exhibit behavior similar to that of a fluid or viscous slurry, leading to the phenomenon known as liquefaction.

The key characteristic of liquefaction is the generation of pore water pressure in saturated conditions, primarily induced by rapid loading and consolidation. This increase in pore water pressure is the main indicator of liquefaction.

In 2010, Ibrahim et al. investigated the potential improvement of undrained response in one direction of loose clean sand subjected to static liquefaction by blending the sand with separate flexible strands. They demonstrated that the reinforcement action reduces the susceptibility to liquefaction under both triaxial tensile and compressive loading conditions [4].

In 2002, Li and Ding conducted triaxial cyclic loading tests on low plasticity silts. They examined the influence of parameters such as the strand weight ratio, confining stress, and the number of loading cycles on the reinforced soil's shear strength. The results indicated that the shear strength of the reinforced soil is significantly affected by parameters such as the strand weight ratio, confining stress, the number of loading cycles, and shear strain. The shear strength increases with an increase in the strand weight ratio and confining stress but decreases with an increase in the number of loading cycles. They also proposed a hyperbolic function to describe the non-linear stress-strain curve under cyclic loading [5].

The mechanism of liquefaction initiation can be observed by studying the behavior of sand under cyclic loading in cyclic triaxial tests. In 1960, Sayed introduced the cyclic stress ratio (CSR) method for assessing liquefaction potential. Other methods, such as cyclic strain by Dobry et al. [2] and probabilistic methods by Lee et al. [3], were also developed but received less attention than the CSR method. The evaluation of liquefaction potential involves estimating the cyclic shear stress generated during an earthquake in terms of the cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR) of the soil. The reliability factor against liquefaction, considering these two parameters, can be calculated using the following formula.

F.S. Liq = CRR/CSR

The determination of the cyclic resistance ratio (CRR) can be obtained through both laboratory and field methods. Youd et al. [6] described various field methods for calculating resistance to liquefaction. Among these methods, standard penetration test (SPT), cone penetration test (CPT), and shear wave velocity (Vs) are the most widely used and applied [6]. Laboratory tests are generally faster for calculating CRR. Tests such as cyclic triaxial (CTX), cyclic simple shear (CSS), and cyclic torsional shear (CTOR) are typically performed in an undrained condition under controlled stress conditions. However, the best option for calculating CRR in the field is to use undisturbed samples (e.g., frozen sampling). The use of reconstituted samples is generally not reliable, but with the right sampling method, similar results to undisturbed samples can be achieved [7]. Yin et al. in 2004 investigated the liquefaction resistance of sandy soils using the large penetration test (LPT) and shear wave velocity tests. Since the presence of coarse particles can hinder the penetration of standard penetration test tools and cone penetration test, they used the correlation between shear wave velocity and the large penetration test (LPT) to estimate the liquefaction resistance of sandy soils. They utilized sandy deposits that had liquefied during the Chi-Chi earthquake. To estimate the liquefaction resistance of sandy soil samples, they employed both tools, and additionally, by using a large-scale cyclic triaxial test (with a diameter of 15 cm and a height of 30 cm), they investigated and improved the correlation between these two tests. The results indicated that these mentioned tests are suitable methods for estimating the liquefaction resistance of sandy soils. Moreover, the results obtained from shear wave velocity were closer to the real results compared to the LPT method [8]. Stokoe et al. in 1988 investigated the liquefaction resistance of liquefied sandy soils during the Idaho earthquake peak using the Spectral Analysis of Surface Waves (SASW) method [9]. The initial relative density (Dr) and the percentage of sand (GC) are two influential parameters in determining the liquefaction resistance of sandy soils. They tested soil samples at different relative densities and percentages of sand to examine how these parameters affect liquefaction resistance. The results of the experiments by Iovance and Cho (1995) demonstrated that the resistance to liquefaction significantly increases with the addition of sand [10].

Materials and Test Procedure

The utilized material is a type of crushed silica sand. This sand has a yellow to golden color, and it exhibits uniform particle size distribution. The sand, along with gravel with a maximum diameter of 1.5 centimeters, was used. According to ASTM standard D 5311, the maximum particle size should be less than one-sixth of the sample diameter. Hence, this sand was used with varying percentages of gravel. The effect of increasing the gravel percentage and relative density on the liquefaction resistance of the mixed soil was investigated.

The sample preparation method significantly affects the results of triaxial tests and soil behavior. Therefore, various methods have been proposed for sample preparation. Among these methods, the moist tamping method is preferred due to its ease of compaction control and the ability to produce samples with low density. In this research, the moist tamping method was employed for sample preparation. The samples were constructed with a diameter of 100 millimeters and a height of 200 millimeters. After sample preparation, a confining pressure of less than 35 kilopascals was applied to the sample [11].

The purpose of the saturation stage is to replace the air in the soil pores with water. To achieve this, CO_2 gas is passed through the sample for at least 30 to 45 minutes to remove all the air from the sample, and then the CO_2 gas is replaced with water saturated with air. After completing this stage, water saturated with air is passed through the sample. To prevent soil particle disturbance, water is injected from the bottom and extracted from the top with low-pressure gravity flow. According to the Skempton relationship, complete saturation of the sample occurs when the ratio of pore water pressure to changes in all-around pressure is greater than or equal to 95%.

After saturation, the consolidation stage begins. In this stage, the all-around pressure is increased to the desired value. The tested samples in this research were consolidated under a stress of 100 kilopascals. To apply cyclic loading, according to ASTM standard D 5311, a sinusoidal cyclic wave with a frequency of 0.2 hertz was applied to the sample to initiate cyclic loading [12-17].

Results and Discussion

Samples were compacted at three different relative densities and various stress ratios with different gravel percentages. Below are the graphs corresponding to the samples compacted with a relative density of 30% and a gravel content of 10%, where CSR (Cyclic Stress Ratio) is 0.15, and the liquefaction occurred after 39 cycles. The variations in axial strain, pore water pressure (ru), and the stress-strain path are observable. Graphs and figures depicting axial strain, pore water pressure, and stress-strain path for samples with 30% relative density, 10% gravel content, and CSR of 0.15 after 39 liquefaction cycles are presented.

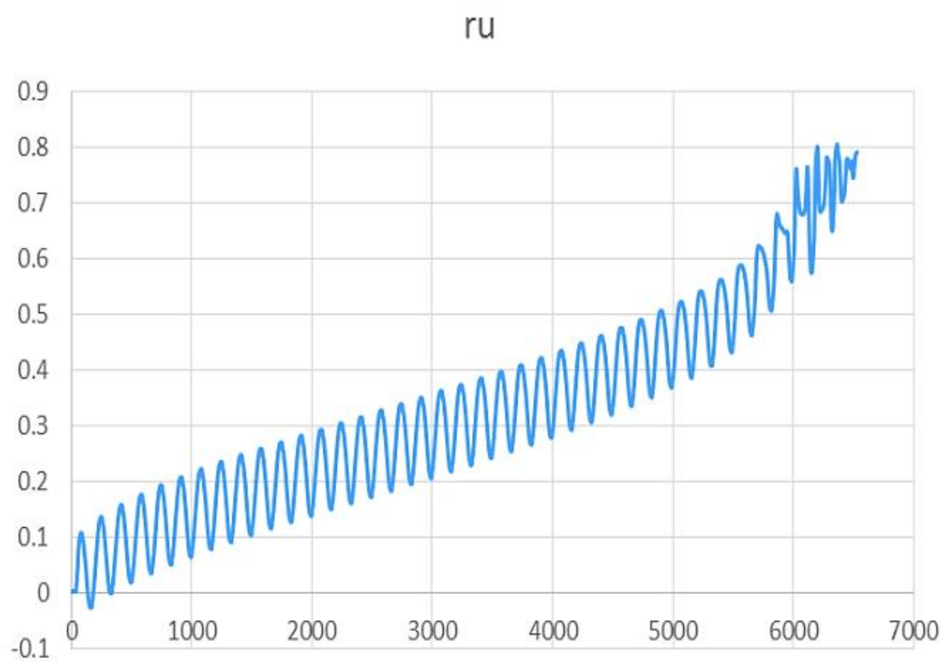

Figure 1 – Changes in Pore Water Pressure (ru) over Time

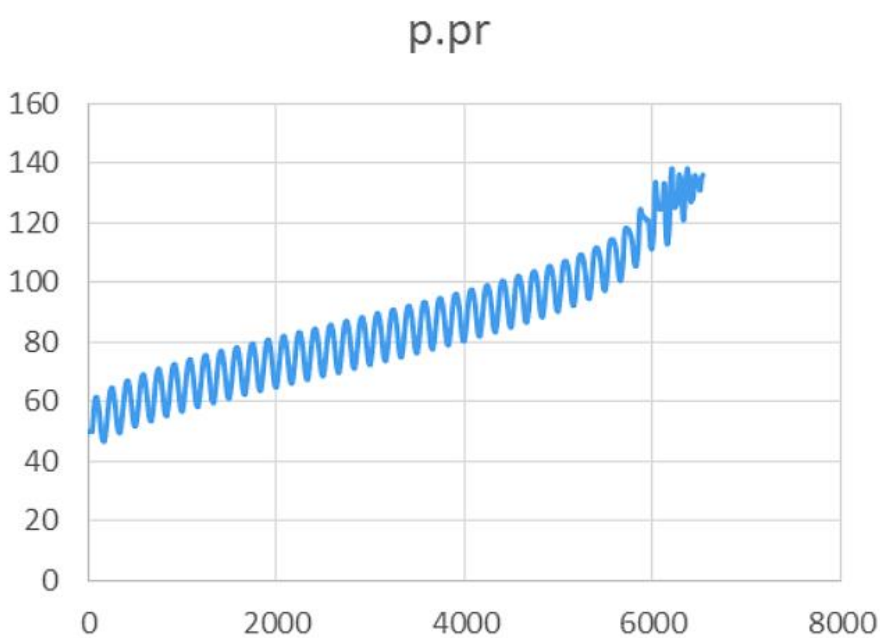

Figure 2 – Changes in Excess Pore Water Pressure over Time

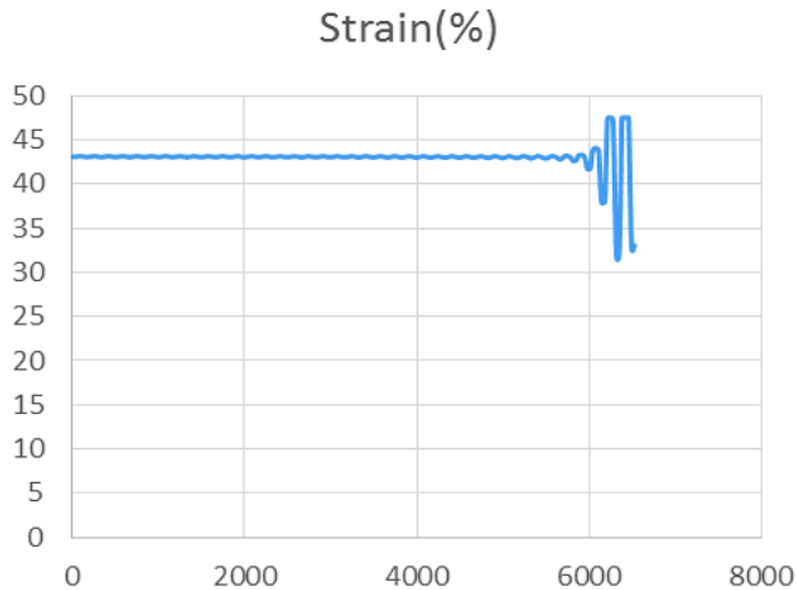

Figure 3 – Changes in Axial Strain of the Sample over Time

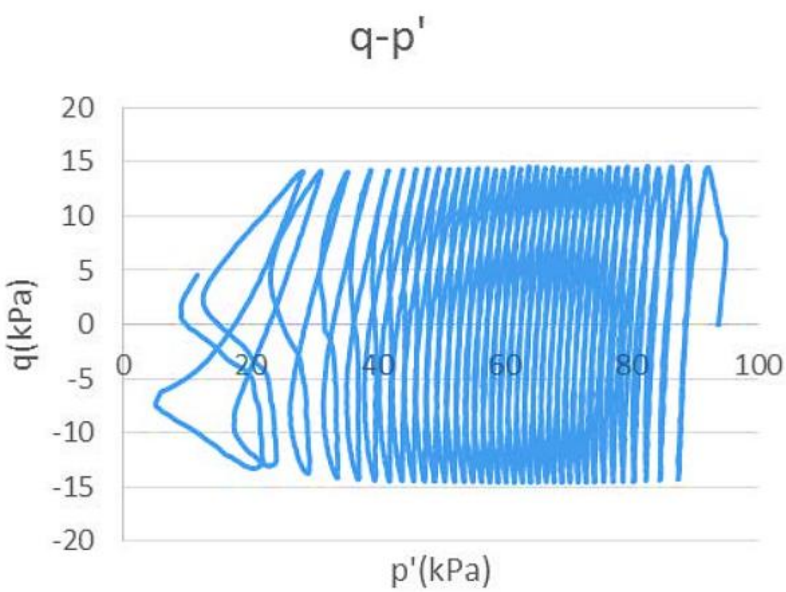

Figure 4 – Stress Path Diagram during Loading

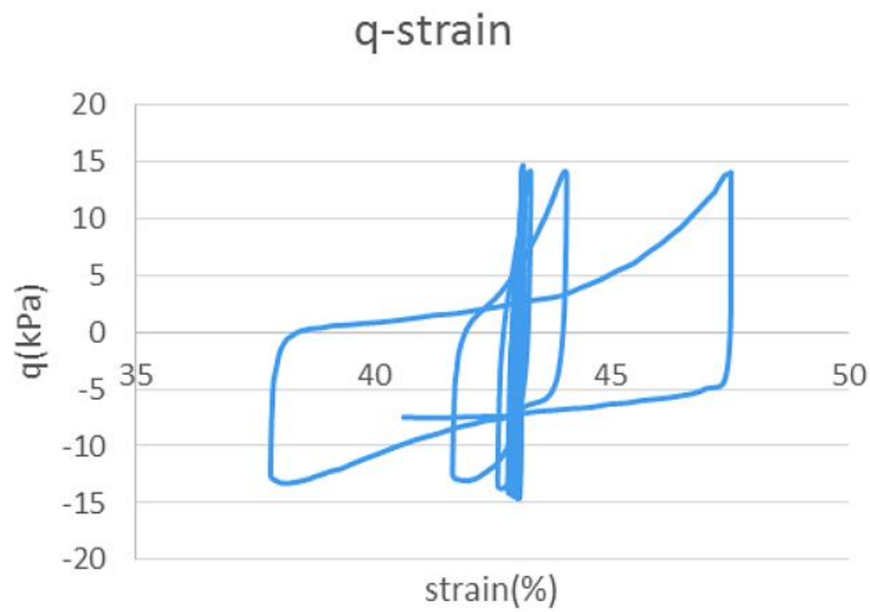

Figure 5 – Stress-Strain Diagram

In the following graphs, we observe that with an increase in the relative density of the samples and an increase in the cyclic stress ratio applied to the specimen, the resistance to liquefaction increases. As mentioned, the experiments were conducted at three different relative densities and two different percentages of sand. The results are observable in the following graphs. At a sand percentage of 10%, an increase in relative density has a slight effect on reducing liquefaction potential, while with an increase in the sand content from 10% to 30%, there is a noticeable increase in resistance to liquefaction.

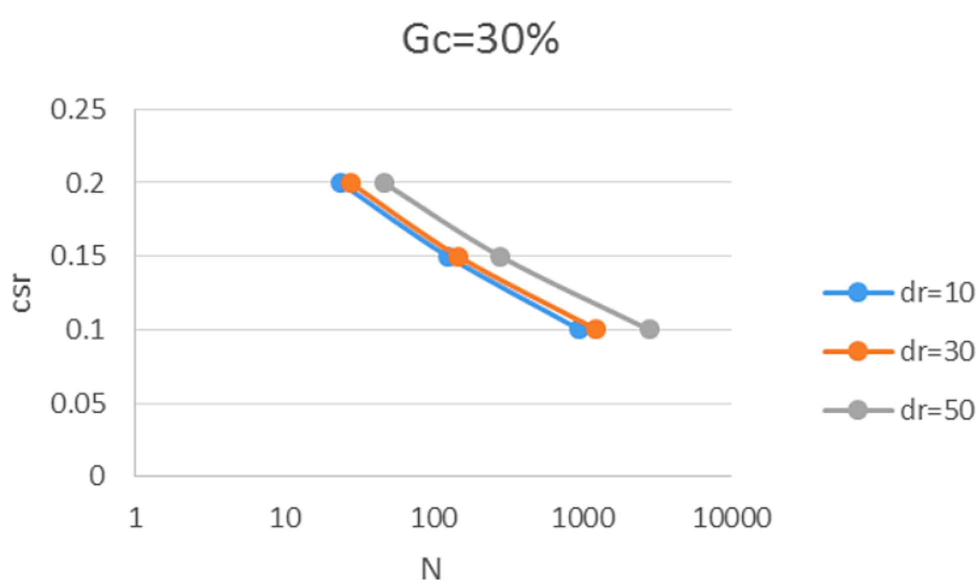

Figure 6 – The Effect of Increased Density on Liquefaction Resistance at 30% Sand Content

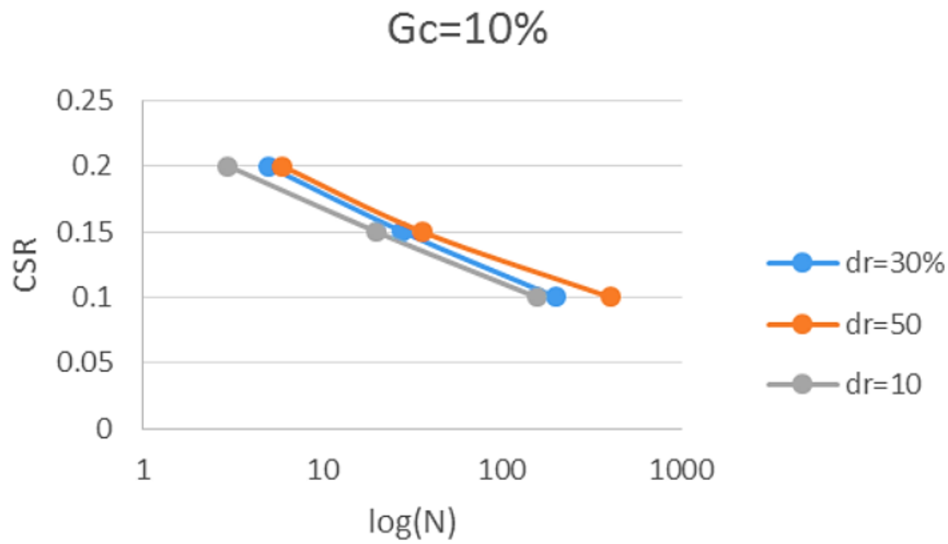

Figure 7 – The Effect of Increased Density on Liquefaction Resistance at 10% Sand Content

Conclusion

The liquefaction issue is one of the significant concerns following an earthquake. The common perception is that sandy soils are not susceptible to liquefaction. However, reported cases from several earthquakes have raised concerns about saturated sandy soils. The present study investigates the liquefaction potential of sand mixed with various percentages of gravel, using cyclic triaxial testing. The experiments were conducted on Ottawa sand mixed with different percentages of gravel. As mentioned earlier, the tests were performed at three different relative densities and two different sand percentages. The results indicate that an increase in relative density and cyclic stress ratio leads to an increase in liquefaction resistance. Additionally, at lower gravel percentages, an increase in relative density has a minimal effect on reducing liquefaction potential, while at higher gravel percentages, the increase in resistance against liquefaction is more pronounced. The optimal arrangement of piles in a foundation system provides minimal internal energy, maximizing stiffness for a specific material fraction. Additionally, research has demonstrated improved performance for piles situated in liquefaction-prone soils [18]. The findings suggest that higher relative density and cyclic stress ratio contribute to increased resistance against liquefaction [19-20].

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