Research Resume

Liquefaction and reliquefaction strength of overconsolidated sand considering orientation of sand particles

（砂の粒子配向性を考慮した過圧密された砂の液状化・再液状化強度）

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Abstract

Soil liquefaction is one of the most significant geotechnical hazards associated with earthquakes, causing considerable damage to infrastructure and ground deformation. In addition to the liquefaction history, soils may experience reliquefaction during subsequent seismic events, making it important to understand the factors influencing both phenomena. Natural sand deposits, such as sand dunes, are often formed by aeolian processes, resulting in preferred particle orientations. Furthermore, anthropogenic modifications, including excavation and ground leveling, may change the original particle arrangement and the stress conditions within the soil mass. Therefore, effects of particle orientation and stress history are considered to be important for liquefaction study.

This study examines the liquefaction and reliquefaction strength of overconsolidated sand incorporating with the orientation of sand particles. Triaxial tests were conducted on Toyoura sand specimens prepared at a relative density of 40% with particle orientations of 0°, 45°, and 90°. Here, two stress-history conditions were considered: normally consolidated (OCR = 1) and overconsolidated (OCR = 6). For the overconsolidated condition, specimens were subjected to a higher consolidation pressure and subsequently unloaded to simulate the stress history of natural cutting or excavated ground. The testing program consisted of consolidation, liquefaction, reconsolidation, and reliquefaction processes. Microscopic image analysis was also performed to examine changes in particle arrangement before and after liquefaction.

Experiment results indicate that particle reorientation occurs after the initial liquefaction under normally consolidated conditions, resulting changes in soil structure and influencing subsequent reliquefaction behavior. The results further show that overconsolidation increases liquefaction resistance from the initial liquefaction because of the effects of stress history, which enhanced soil stiffness. However, the reliquefaction response of overconsolidated sand reduced the liquefaction resistance in comparison with the initial liquefaction resistance. The findings suggest that both particle orientation and stress history play important roles in controlling liquefaction behavior. Finally, the study contributes to a better understanding of the liquefaction assessment of overconsolidated sand and provides useful insights for evaluating liquefaction hazards in natural and modified sand deposits.

Keywords: Liquefaction, Reliquefaction, Overconsolidation, Particle Orientation, Cyclic Triaxial Test, Toyoura Sand

1. Introduction

Liquefaction is a major geotechnical hazard that occurs when saturated sandy soils lose their strength and stiffness during earthquake loading due to the generation of excess pore water pressure (Seed & Idriss, 1971;

Kramer, 1996). The resulting reduction in effective stress causes the soil to behave temporarily as a fluid, leading to excessive settlement, lateral spreading, and severe damage to buildings, roads, and other civil infrastructure (Seed & Idriss, 1971; Ishihara, 1996). Because large earthquakes are often followed by aftershocks, liquefied soils may be subjected to repeated cyclic loading, making the evaluation of reliquefaction behavior increasingly important.

The 2024 Noto Peninsula Earthquake caused widespread liquefaction damage in coastal areas of Ishikawa Prefecture, particularly in excavated sand dune deposits. These sand dunes were originally formed by aeolian deposition, producing preferred particle orientations within the soil. Although excavation changed the ground surface, the original particle arrangement may still influence the mechanical behavior of the remaining soil. Furthermore, the removal of overburden during excavation creates overconsolidated ground conditions, which can increase the initial resistance to liquefaction.

Previous studies have shown that overconsolidation generally enhances liquefaction resistance by increasing soil stiffness and cyclic strength (Yasuda et al., 1994). However, the influence of overconsolidation on reliquefaction behavior, particularly when particle orientation is considered, has not been fully clarified. In addition, the mechanisms responsible for the reduction of liquefaction resistance after repeated cyclic loading remain uncertain.

Therefore, this study investigates the liquefaction and reliquefaction behavior of overconsolidated Toyoura sand considering particle orientation. Cyclic triaxial tests were performed under normally consolidated (OCR = 1) and overconsolidated (OCR = 6) conditions. The results are compared using the cyclic resistance ratio (CRR), and their stability is discussed with reference to excavated sand dune deposits for residential area considering seismic motion during the 2024 Noto Peninsula Earthquake.

2. Background

Liquefaction is a common geotechnical hazard in earthquake-prone regions and frequently occurs in loose, saturated sandy soils. During strong ground shaking, excess pore water pressure increases, reducing the effective stress and causing the soil to lose its strength. In addition to the initial liquefaction, repeated earthquakes or aftershocks may induce reliquefaction, making it important to evaluate the cyclic behavior of soils after the first liquefaction event.

The 2024 Noto Peninsula Earthquake caused extensive liquefaction damage in the coastal areas of Uchinada Town, particularly in the Nishiaraya district. Field investigations revealed that many of the damaged areas were located on excavated sand dunes. Sand dunes are formed by aeolian deposition, where sand particles are naturally deposited along the slope of the dune, resulting in a preferred particle orientation (Oda, 1972; Oda et al., 1985). Even after excavation and land development, the original soil fabric may remain and influence the mechanical behavior of the soil.

Another important characteristic of excavated sand dunes is overconsolidation. Before excavation, the soil is subjected to a higher overburden pressure. After the upper soil layers are removed, the current effective stress decreases while the soil retains the memory of the previous higher stress. This stress history creates an overconsolidated (OC) condition, which is generally associated with increased stiffness and higher liquefaction resistance.

Previous studies conducted in the Geotechnical Engineering Laboratory demonstrated that particle orientation significantly influences the liquefaction resistance of normally consolidated sand (Yoshimine et al., 1998; Oda et al., 1985). However, the combined effects of overconsolidation and particle orientation on both liquefaction and reliquefaction behavior have not been fully clarified. Therefore, further investigation is required to improve the understanding of cyclic soil behavior and to enhance the evaluation of liquefaction hazards in excavated sand dune areas

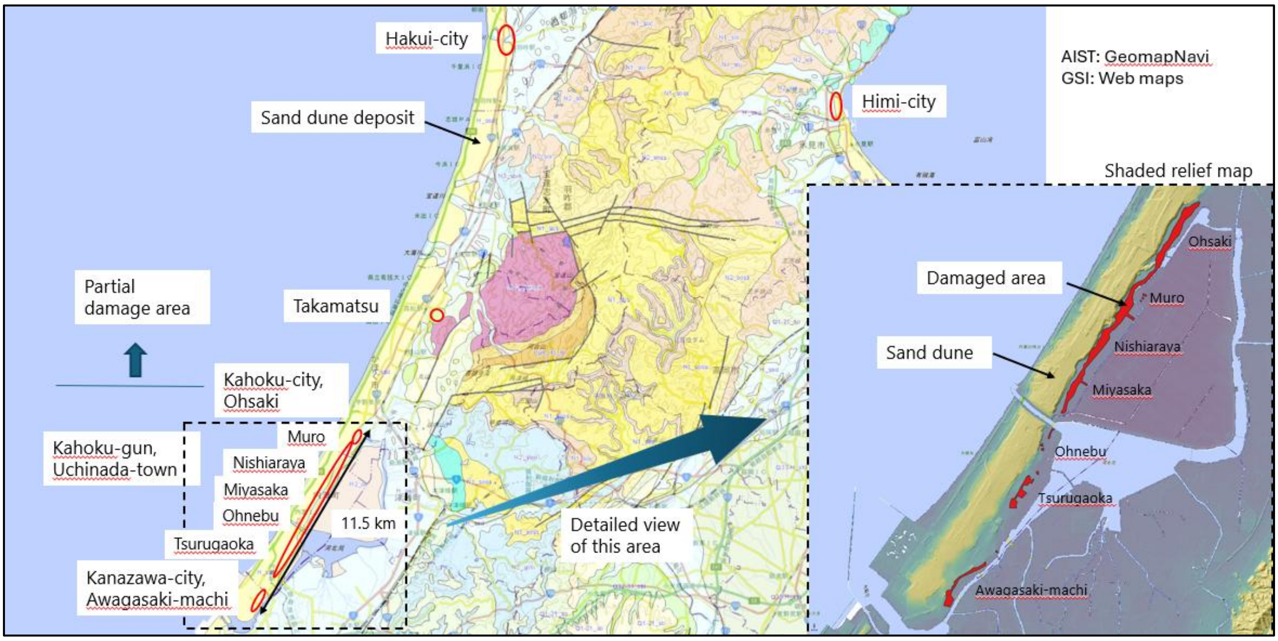

Figure 1: Sand dune deposits in the Noto Peninsula region

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3. Objectives

The objective of this study is to investigate the influence of overconsolidation on the liquefaction and reliquefaction behavior of Toyoura sand while considering the orientation of sand particles.

The specific objectives are:

1. Comparison of liquefaction and reliquefaction strengths between normal consolidation (OCR=1) and overconsolidation (OCR=6).
2. Understanding of overconsolidation (OC) effects on liquefaction strength based on the particle orientation of sand.

4. Methodology

The experimental program was designed to investigate the liquefaction and reliquefaction behavior of overconsolidated Toyoura sand considering the orientation of sand particles. Figure 2 shows the overall research methodology adopted in this study. The experimental procedure followed conventional cyclic triaxial testing methods commonly used in liquefaction research (Seed et al., 1985; Youd et al., 2001).

First, cylindrical Toyoura sand specimens (50 mm diameter and 125 mm height) were prepared at a relative density of 40% using the air pluviation method. After specimen preparation, the samples were saturated using the double negative pressure method and isotropically consolidated. Two consolidation conditions were examined: normally consolidated (OCR = 1) and overconsolidated (OCR = 6).

For the OCR = 1 specimens, the soil was consolidated under an effective confining pressure of 50 kPa for one hour. A cyclic triaxial test was then performed to determine the first liquefaction strength (Liquefaction-1). After the first liquefaction, the specimen was reconsolidated at 50 kPa for one hour and subjected to a second cyclic loading test to evaluate the reliquefaction strength (Liquefaction-2).

For the OCR = 6 specimens, the soil was first consolidated at 50 kPa for one hour. The effective pressure was then increased upto 300 kPa and maintained for two hours (Yasuda et al., 1994). Subsequently, the pressure was reduced to 50 kPa and maintained for another two hours to establish the overconsolidated condition (OCR = 6). The specimens were then subjected to the same liquefaction and reliquefaction testing procedures as the OCR = 1 specimens.

The liquefaction and reliquefaction strengths were evaluated using the Cyclic Resistance Ratio (CRR), and the experimental results obtained from the OCR = 1 and OCR = 6 specimens were compared to clarify the influence of overconsolidation and particle orientation on cyclic soil behavior.

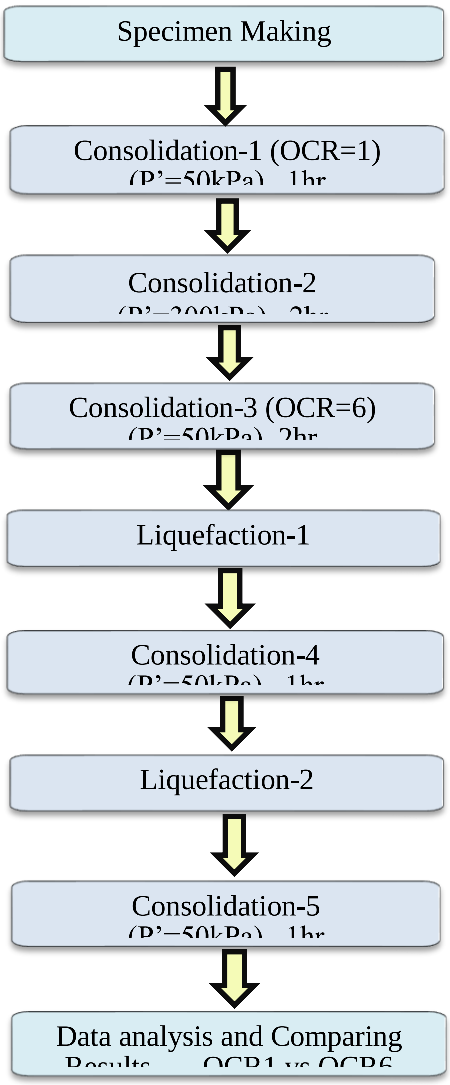

Figure 2: Methodology flowchart

5. Results and Discussion

5.1 Effect of Overconsolidation on Liquefaction Strength

Figure 3 presents the liquefaction resistance obtained from cyclic triaxial tests for the OCR = 1 and OCR = 6 specimens. The results indicate that the overconsolidated specimens exhibited higher liquefaction resistance than the normally consolidated specimens during the first liquefaction stage.

The increase liquefaction resistance can be attributed to the stress history imposed on the OCR = 6 specimens. During the overconsolidation process, the specimens experienced a higher effective stress before being unloaded to the testing stress level. This stress history resulted in a more stable soil structure and increased resistance to cyclic loading. Consequently, a greater number of cycles were required to reach liquefaction in the OCR = 6 specimens compared with the OCR = 1 specimens. These observations are consistent with previous studies, which reported that overconsolidation improves the cyclic resistance of sandy soils by increasing stiffness and reducing contractive behavior during cyclic loading.

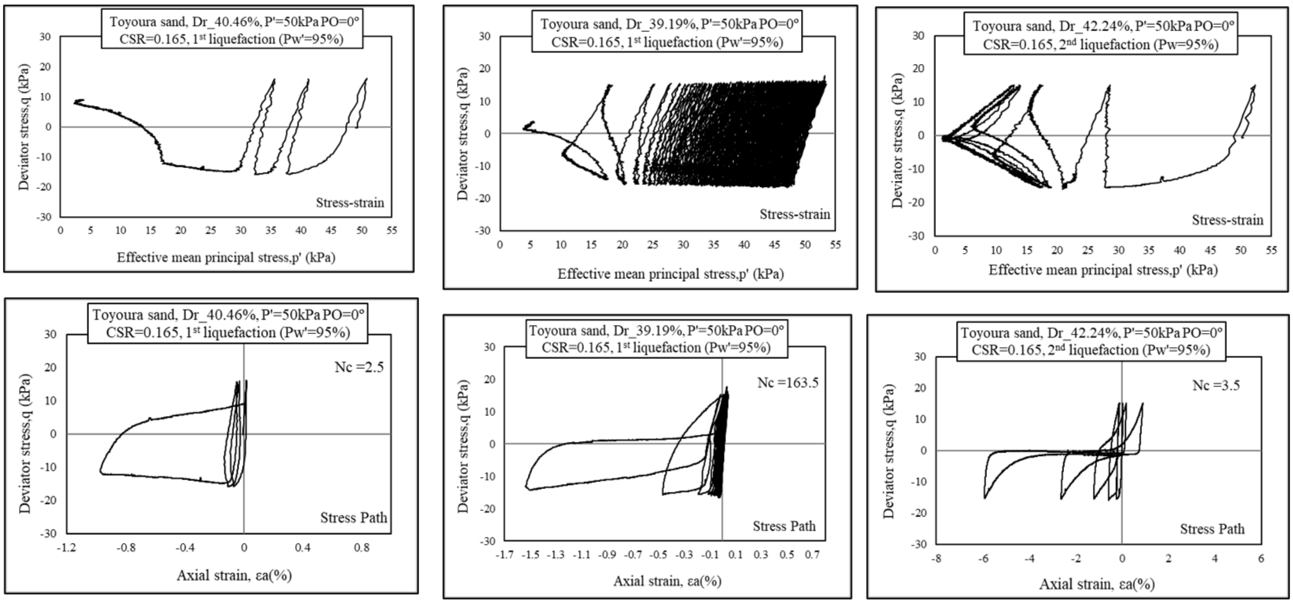

Figure 3: Comparison of (a)1st liquefaction of OCR1 (b) 1st liquefaction of OCR6 (c) 2nd liquefaction of OCR6 of PO 0°with CSR 0.165

5.2 Reliquefaction Behavior

After the first liquefaction event, all specimens were reconsolidated and subjected to a second cyclic loading test to evaluate reliquefaction resistance.

The results showed that the reliquefaction behavior differed from the initial liquefaction behavior. For the OCR = 1 specimens, the cyclic resistance ratio (CRR) during the second liquefaction stage changed compared with that of the first liquefaction stage. This indicates that the first liquefaction altered the internal structure of the soil, resulting in a different response during subsequent cyclic loading.

For the OCR = 6 specimens, the increase in liquefaction resistance observed during the first liquefaction stage was significantly reduced after the soil experienced liquefaction. The CRR values obtained during the second liquefaction stage became approximately equal to those obtained for the OCR = 1 specimens. This result suggests that the beneficial effect of overconsolidation was largely eliminated after the first liquefaction event.

This trend differs from that reported by Toyota and Takada (2017), in which loading history continued to influence the subsequent liquefaction resistance. The discrepancy may be attributed to differences in stress history, particle orientation, specimen preparation, and the associated changes in soil fabric during the first liquefaction event. Further investigation is required to clarify the governing mechanism.

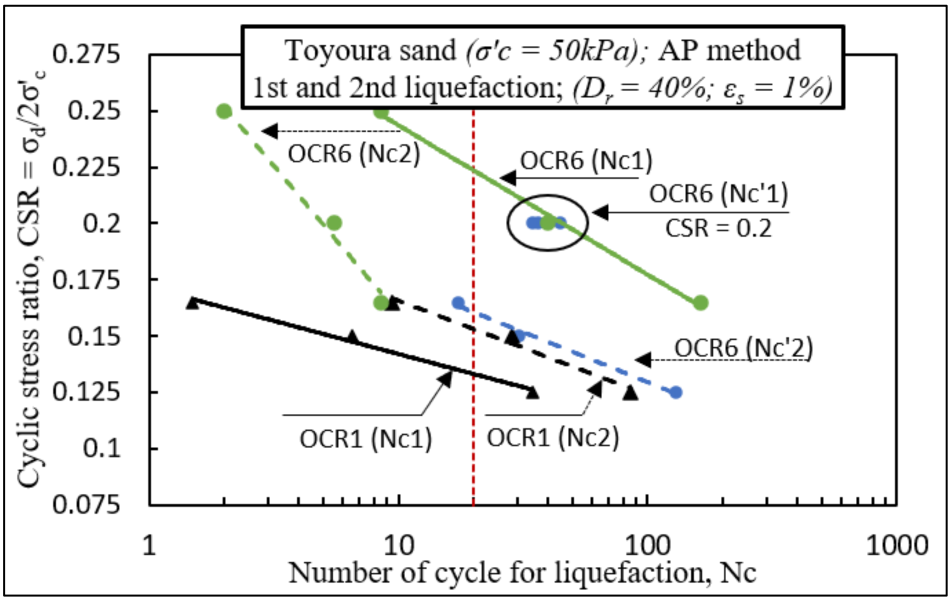

Figure 4: Comparison of liquefaction and reliquefaction results of PO 0° with different CSR

5.3 Influence of Particle Orientation

Previous studies conducted in the Geotechnical Engineering Laboratory demonstrated that particle orientation strongly influences the liquefaction resistance of sand. Sand particles deposited under different orientations develop different soil fabrics, resulting in variations in cyclic resistance. During the first liquefaction event, particle rearrangement occurs as a consequence of cyclic loading and excess pore water pressure generation. This rearrangement modifies the original soil fabric and changes the orientation of the sand particles.

The observed reduction in the difference between OCR = 1 and OCR = 6 specimens after liquefaction suggests that particle reorientation plays an important role in controlling reliquefaction behavior. Once the original soil structure is disturbed, the influence of stress history becomes less significant.

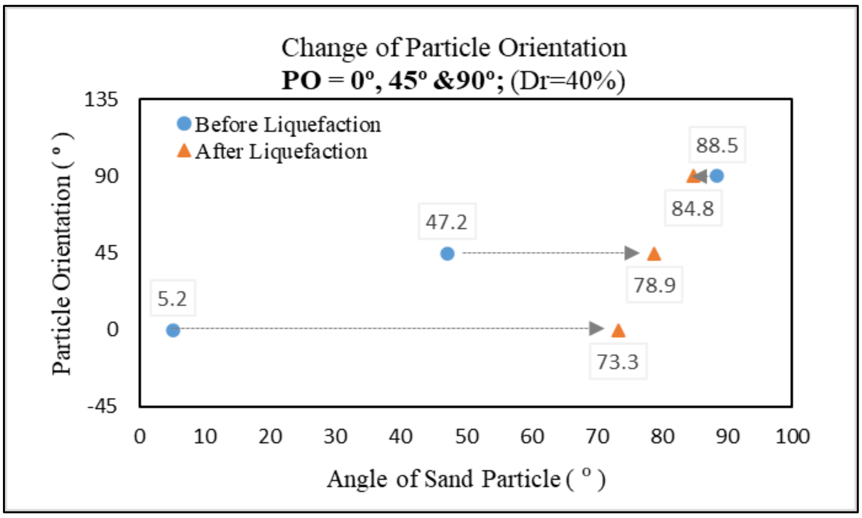

Figure 5: Comparison of microscopic analysis results of OCR1 for both before and after liquefaction

Therefore, both particle orientation and soil fabric evolution should be considered when evaluating the long-term cyclic behavior of sandy soils.

5.4 Engineering Implications

The findings of this study have important implications for the assessment of liquefaction hazards in excavated sand dune deposits.

Field investigations conducted after the 2024 Noto Peninsula Earthquake indicated that severe liquefaction damage occurred in the Nishiaraya area of Uchinada Town, where large-scale excavation of sand dunes had been carried out. The removal of approximately 15 m of overburden soil likely created overconsolidated ground conditions.

Based on the liquefaction resistance analysis, the present ground condition can be regarded as overconsolidated. When the OCR effect is considered, the calculated liquefaction resistance is higher than that obtained under normally consolidated conditions. Therefore, ignoring stress history may lead to an inaccurate evaluation of liquefaction potential.

Further, according to historical topographic data, extensive land modification had been in Nishiaraya area. Sand was excavated and used for reclamation purposes, creating complicated ground conditions. Hence, the ground experienced significant unloading due to excavation, the current soil state differs from a normal consolidated condition.

However, the experimental results also indicate that the beneficial effect of overconsolidation may diminish after liquefaction occurs. Consequently, the potential for reliquefaction should be considered when assessing the long-term seismic performance of excavated sand dune deposits (Toyota & Takada, 2017). By considering these facts, 1st liquefaction normal consolidation should be used in this ground's next liquefaction assessment.

6. Conclusions

This study investigated the liquefaction and reliquefaction behavior of overconsolidated Toyoura sand considering the orientation of sand particles through a series of cyclic triaxial tests. Based on the experimental results, the following conclusions were obtained:

1. **Overconsolidation significantly increased the initial liquefaction resistance of Toyoura sand.** The OCR = 6 specimens required a greater cyclic resistance ratio (CRR) to reach liquefaction than the normally consolidated (OCR = 1) specimens, demonstrating the beneficial effect of stress history.

2. **The first liquefaction event altered the internal soil structure and particle arrangement.** These structural changes influenced the cyclic behavior of the sand during subsequent loading, resulting in different reliquefaction characteristics.

3. **The beneficial effect of overconsolidation was largely eliminated after the soil experienced liquefaction.** Based on the cyclic resistance ratio (CRR), the reliquefaction resistance of the OCR = 6 specimens became approximately equal to that of the OCR = 1 specimens.

4. **The findings have practical implications for excavated sand dune deposits.** Since excavation can create overconsolidated ground conditions, the overconsolidation Ratio (OCR) should be considered when evaluating liquefaction potential. However, the reduction in OCR effects after liquefaction indicates that the possibility of reliquefaction should also be taken into account in long-term seismic hazard assessments.

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