Geomechanics and Engineering, *Vol. 38, No. 2 (2024) 165-177*
https://doi.org/10.12989/gae.2024.38.2.165

Analysis of behavioral characteristics of liquefaction of sand through repeated triaxial compression test and numerical analysis

Hyeok Seo[a] and Daehyeon Kim*

Department of Civil Engineering,Chosun Univercity, 309 Pilmundaero, Don-gu, Gwangju, Republic of Korea

(*Received September 3, 2023, Revised May 16, 2024, Accepted July 6, 2024*)

Abstract. Liquefaction phenomenon refers to a phenomenon in which excess pore water pressure occurs when a dynamic load such as an earthquake is rapidly applied to a loose sandy soil ground where the ground is saturated, and the ground loses effective stress and becomes liquid. The laboratory repetition test for liquefaction evaluation can be performed through a repeated triaxial compression test and a repeated shear test. In this regard, this study attempted to evaluate the effects of the relative density of sand on the liquefaction resistance strength according to particle size distribution using repeated triaxial compression tests, and additional experimental verification using numerical analysis was conducted to overcome the limitations of experimental equipment. As a result of the experiment, it was confirmed that the liquefaction resistance strength increased as the relative density increased regardless of the classification of soil, and the liquefaction resistance strength of the SP sample close to SW was quite high. As a result of numerical analysis, it was confirmed that the liquefaction resistance strength increased as the confining pressure increased under the same relative density, and the liquefaction resistance strength did not decrease below a certain limit even though the confining pressure was significantly reduced at a relatively low relative density. This is judged to be due to a change in confining pressure according to the depth of the ground. As a result of analyzing the liquefaction resistance strength according to the frequency range, it was confirmed that there was no significant difference from the laboratory experiment results in the basic range of 0.1 to 1.0 Hz.

Keywords: liquefaction; numerical analysis; poorly graded soil; relative density; repeated triaxial test; well graded soil

1. Background and objective

Liquefaction takes place due to excessive pore water pressure when dynamic loads such as earthquakes are rapidly applied to loose sandy soil ground where the ground is saturated, and the ground loses effective stress and liquefies. In other words, it refers to a phenomenon in which the ground under the earthquake load loses its shear strength and no longer supports the superstructure on the ground.

The laboratory repetition test for liquefaction evaluation can be performed through the repeated triaxial compression test and the repeated simple shear test. In the repeated triaxial compression test, the test specimen is molded, saturated, and the vertical load is loaded under isotropic compression. Unlike the triaxial compression test, it is a test that repeats loading and unloading to find a time point of 5% of the strain at which excessive pore water pressure occurs. In the repeated simple shear test, the saturated sample is placed in a shear box and repeated shear force is applied in the horizontal direction under a vertical load.

Both tests differ in the loading method of the input load or the test to obtain the liquefaction resistance strength.

Some previous studies say that the simple shear test considers the direction of the earthquake load well (Mandokhail *et al.* 2016), but it is the same to find the timing of liquefaction by giving vibration in one direction in one dimension. In the simple shear test, is used when considering the constraint conditions, but in the repeated triaxial compression test, an isotropic compression is applied using and, so the reliability is higher under the constraint conditions. Repeated triaxial compression tests are also widely used when applying laboratory tests or practical applications.

In Korea, liquefaction evaluation is being performed through the two repeated tests mentioned above. In terms of materials, most of the liquefaction evaluation of loose sandy soil as a comparative version uses Jumunjin standard sand, which is sand (SP) with poor particle size distribution under the unified classification method. However, most of the ground in Korea consists of weathered soil (SM) ground under the unified classification method, and when analyzed through particle size distribution tests, it consists of sand (SW) with good particle size distribution and silt (MH) with high plasticity.

Given that most loose sandy soil in Korea is weathered soil (SM), it is necessary to analyze the liquefaction resistance strength of weathered soil (SM) ground as well as Jumunjin standard sand, an SP sample under the unified classification method. In addition, additional analytical verification of the confining pressure conditions and frequency domains, which are limitations of the repeated triaxial compression test, should be made.

*Corresponding author, Professor
E-mail: dkimgeo@chosun.ac.kr
[a]Ph.D.
E-mail: seoh1992@naver.com

ISSN: 2005-307X (Print), 2092-6219 (Online)

Most of the confining conditions use a confining pressure of 100 kPa, the basic value of the equipment, which is very limited to a depth of 5-6 m when calculated by the unit weight of ordinary soil. When evaluating liquefaction in Korea, there is no domestic standard for repeated triaxial-compression tests, so it is generally tested by reflecting the test methods of Japan and the United States. Japan's repeated triaxial-compression test regulations range from 0.1 to 1.0 Hz, and even in Korea, 0.1 Hz is used by applying a load input method by air pressure within this repetitive load cycle. This is not consistent with domestic conditions in which relatively high-frequency earthquakes occur, so an analysis of the liquefaction resistance strength considering a period of 1.0Hz or more is necessary.

The experimental results of the liquefaction evaluation of the weathered soil ground conducted through repeated triaxial compression tests and the analytical verification were compared and analyzed against previous studies to examine the validity of the liquefaction evaluation criteria presented in the revised earthquake resistant general design.

In this study, our previous research on the laboratory experiment part was cited as a reference for analytical verification of this study. The previous work was conducted by the authors, and the liquefaction behavior characteristics of sand was evaluated for the differences from the previous studies including our work. In addition, in order to verify the reliability of this study, numerical analyses were conducted, and the materials property values of the soil used in the analysis were used by citing the contents used in the laboratory experiment.

The liquefaction resistance strength was attempted to be confirmed according to the frequency range, and frequencies up to 1.0 Hz were divided into three sections: 0.1, 0.5, and 1.0 Hz. In addition, in order to confirm the liquefaction resistance strength of 1.0Hz or more, the liquefaction resistance strength for the frequency change of 2.0Hz was confirmed.

It is a well-established fact that liquefaction occurs in loose sand. However, in Korea, the main issue regarding the repeated triaxial test equipment for liquefaction assessment lies in the difficulty of implementing the appropriate confining pressure occurring in the ground. The maximum confining pressure typically used in the repeated triaxial test equipment is 100 kPa. To address these challenges, the confining stresses of 50, 100, and 150 kPa were applied in the numerical studies. Additionally, various ground conditions with loose and dense sands that are poorly graded sand (SP) and well graded sand (SW) and stress conditions were implemented in the repeated triaxial test. The results of laboratory experiments and numerical analyses were compared and analyzed in terms of trends and reliability with existing research. It is expected that these findings will serve as a basis for future research on liquefaction tailored to Korean ground conditions.

In this study, an undrained repeated triaxial compression test was conducted to compare and analyze the liquefaction resistance strength according to the particle size distribution of pure sand and the liquefaction resistance strength according to the increase in fine contents. In order to perform the analytical verification accordingly, the reliability of the repeated triaxial-compression test was verified using FLAC V.7.0, a numerical analysis program. In addition, the liquefaction resistance strength of the sand ground according to the confining pressure condition and frequency range was analyzed for the confining pressure and frequency range that could not be performed in the repeated triaxial compression test.

2. Previous studies

Research on liquefaction began in earnest after the Niigata earthquake (magnitude 7.6) in Japan in 1964 and the Good Friday earthquake (magnitude 8.4) in Alaska in 1964. Later, in 1969, Casagrande proposed a critical void ratio theory, and the liquefaction phenomenon was divided into loose sandy soil and dense sandy soil based on the critical void ratio. Casagrande argued that when a vibration load such as an earthquake is loaded on saturated sand that is looser than the critical void ratio, the volume of the sand decreases, resulting in excess pore water pressure.

Seed and Lee (1966) investigated the damage caused by the Niigata earthquake and claimed that the liquefaction phenomenon occurred when the shear load was repeatedly applied to the saturated and undrained sandy soil ground. In 1971, a simple liquefaction prediction method was proposed through a repeated triaxial compression test. Seed and Idriss (1971) performed an analysis of the liquefaction resistance strength of the seismic wave by reconstructing the irregular seismic wave into a sine wave in order to evaluate the liquefaction phenomenon using the repeated triaxial compression test. Through this, the research results on the content of reproducing input seismic waves as regular sinusoidal waves were published.

Seed (1979) conducted a liquefaction evaluation on the ground by investigating the factors influencing liquefaction occurrence. After that, Seed (1967) proposed a method of evaluating the possibility of liquefaction through field test results and conducted a study comparing it with the liquefaction evaluation results using laboratory tests, and Tokimatsu and Yoshimi (1983) conducted a study on liquefaction evaluation through standard penetration resistance values (N values), which are field test results. In addition, Youd and Perkins (1987) prepared a zone map for the possibility of liquefaction through past earthquake occurrence data and geological research data, and proposed a liquefaction index (LSI) accordingly.

In foreign countries, Lade *et al.* (2009) identified the behavior of sand with non-plastic fines content and conducted triaxial compression tests with stepwise addition of fines content to study the effect of liquefaction occurrence. Heidari and Andrus (2010) calculated LPI based on CPT data, a liquefaction risk study was conducted for South Carolina. Valverde-Palacios *et al.* (2014) conducted a liquefaction risk study on the Spanish metropolitan area, and evaluated and analyzed the liquid phase for the Tokimatsu and Seed method and the Pradel method. Rahman *et al.* (2015) conducted a liquefaction risk study on Dhaka, Bangladesh using standard penetration test values, and at this time, the risk was prepared using the Zonation technique reflecting the ground and regional characteristics.

For the reinforcement of liquefied ground, Zeybek *et al.* (2017) studied the mechanism of liquefaction deformation due to air injection, and reported that air injection is effective in reducing the deformation of the foundation and surrounding ground through centrifugal model experiments on sandy soil ground with high liquefaction potential under shallow foundations. Sonmezer (2019) found that sand containing fibers was more resistant to liquefaction than typical sand, and that fiber content had a greater effect on liquefaction resistance than fiber length. Amanta *et al.* (2021) conducted a repeated triaxial strength test to compare the dynamic characteristics of fully saturated samples and air injection samples, and the air injection samples remain unsaturated 30 days after air injection, significantly improving soil liquefaction resistance.

In the case of Korea liquefaction research, research on the risk of earthquakes began in earnest after the revision of the earthquake-resistant design (1997) by the Ministry of Construction and Transportation along with the 1995 Kobe earthquake in Japan. At the beginning of the liquefaction study, Shin *et al.* (1999) studied the improvement of the liquefaction evaluation technique considering the seismic characteristics in Korea through repeated triaxial tests, Kwak (2001) calculated the liquefaction potential index (LPI) to create a liquefaction risk map centered on coastal landfill areas in Korea.

Since the 2017 Pohang earthquake, research on liquefaction in Korea has been conducted on the resistance strength of liquefaction and the LPI range. With the revision of the liquefaction evaluation criteria in 2018, the reliability of laboratory experiments, a detailed liquefaction evaluation, and steps for the LPI index were added. The study on the liquefaction resistance strength analysis, which is a laboratory experiment, was mainly conducted to analyze the liquefaction resistance strength of sand in Pohang.

In the study of LPI, Kim (2018) created a liquefaction zone map using Pro-shake, a one-dimensional ground response analysis program, by applying the Hachinohe earthquake wave in the long period and the Ofunato earthquake wave in the short period to evaluate the liquefaction of the Incheon coastal landfill. Beek *et al.* (2018) compared the risk of liquefaction based on LPI with the actual damage area to examine the limitations and problems of the existing method. Ahn *et al*. (2018) prepared a liquefaction risk for Pohang earthquake using Deep Soil v6.0, a one-dimensional ground response analysis program, and Choi *et al.* (2018) evaluated the liquefaction risk through Pro-Shake for power districts in the southeastern region, judging that the liquefaction phenomenon of the ground can directly affect not only the structure on the surface but also the underground. Ha *et al.* (2017) conducted a study to apply the earthquake vulnerability evaluation by applying the liquefaction possibility index (LPI) to domestic river embankment.

Mandokhail *et al.* (2016) derived a liquefaction resistance curve based on the results of the study on the resistance strength of liquefaction after the Pohang earthquake using Ottawa sand and Jumunjin standard sand. Mun *et al*. (2018) confirmed the effect of the relative density and particle size distribution between the sand at the liquefaction site in Pohang and the existing West Coast silt sand, and Park *et al.* (2018) studied the liquefaction resistance characteristics of Pohang sand based on the difference in relative density and effective confining pressure.

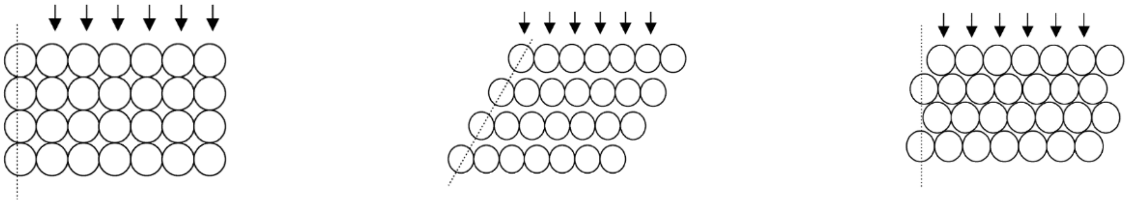
In addition, Lee (2019) studied the intensity constant and liquefaction resistance strength of the sand in the area where the liquefaction occurred (Songdo, Heunghae) and Park (2020) studied the liquefaction resistance characteristics of the Busan sand (7 locations).

Recently, Na *et al.* (2022) conducted a study on the occurrence of liquefaction in Pohang using GPR exploration techniques, Lee *et al.* (2022) conducted a study on the comparison of liquefaction evaluation according to the Korean standard of repeated triaxial compression tests. Yoo *et al.* (2023) analyzed the reinforcement effect and applicability of the reinforcement method for liquefaction generation ground, and Ha *et al.* (2023) confirmed the possibility of liquefaction of the ground due to particle size distribution and soil plasticity. In addition, Park and Ha (2023) conducted a study on the evaluation of the relative liquefaction destruction risk of soil dams in Korea.

As such, in the early stages of research on liquefaction, research was conducted focusing on evaluation methods and standards, and additional research on reinforcement methods and risks was gradually conducted. However, since liquefaction is an area where the classification of soil and its evaluation criteria are very important, this study tried to focus on the contents of Korea's liquefaction evaluation standards, methods, and analysis methods.

In the case of Korea liquefaction evaluation, most of them were performed through repeated triaxial-compression tests. This is meaningful in that it is possible to accurately simulate isotropic compression conditions using and compared to a simple shear test. In addition, in most previous studies, liquefaction evaluation experiments have been conducted by adding fine grains to Jumunjin standard sand (SP) with poor particle size distribution. Although Jumunjin standard sand is used a lot in that it has uniform particle size and representative physical properties, it is necessary to analyze the detailed liquefaction resistance strength of the weathered soil in that it is most typical weathered soil (SM) in Korea. Liquefaction mainly occurs within about 20 m, but few studies on liquefaction resistance evaluation for shallow depths have been done. Liquefaction generally occurs in the ground within 20 m, but since most laboratory experiments apply the confining pressure to 100 kPa (5-6 m depth of ground), this study attempted to confirm the liquefaction behavior at a shallow depth by adding 50 kPa (3-4 m depth of ground).

Therefore, this study analyzed the ground behavior evaluation of grain size distribution and fine grain content using repeated triaxial-compression tests with similar confining conditions to the site, and conducted a liquefaction evaluation on the weathered soil (SM) representing the Korean ground. In addition, the ground behavior evaluation was analyzed considering low



(a) Loose condition (b) Condition under sheer deformation (c) Rearranged state

Fig. 1 Liquefaction process

confining conditions for the liquefaction resistance evaluation of shallow depth, and the analysis results were verified by comparing the experimental values in a low frequency range of 0.1 Hz, which is the standard for liquefaction laboratory experimental evaluation. The ground behavior evaluation according to the loading speed was analyzed by increasing from 0.1 Hz to 2.0 Hz using the verified constitutive model

3. Theory of liquefaction

Liquefaction can be defined as a phenomenon in which the excess pore water pressure generated by the shear stress acting in the ground becomes the same as the initial effective stress that binds the soil particles, resulting in zero effective stress. In other words, under repeated loads, soil particles deform and rearrange, but due to the constant volume retention of saturated soil, excess pore pressure occurs as much as the strain and rearrangement of soil particles. If the generated pore pressure reaches the same level as the effective stress in the soil, the shear resistance in the soil is completely lost, and the saturated sandy soil leads to liquefaction.

Fig. 1 shows the process of liquefaction.

4. Laboratory experiment and results

The experimental results of section 4 are a procedure for verifying the reliability of the numerical analysis of section 5 of this study, and the part conducted in the previous study was cited as a reference.

4.1 Characteristics of specimens

This research conducted experiments using sand (SP) with poor particle size distribution, sand (SW) with good particle size distribution, and fine particle size (MH), and specific gravity and particle size tests were conducted to verify the physical properties of the sample. For fines, a sample passing through #200 sieve was used, and the specimen was molded by mixing the dry weight ratio of weathered soil at 100:0%, 90:10%, 80:20%, and 70:30%. The relative density was carried out up to 30% for fine particles and 40%, 55%, and 70% for relative density less than 80% according to the previous research and the liquefaction exemption criteria in Korea.

In order to calculate the weight of the sample according

Table 1 Void ratio according to sand type and relative density

Classification	e_{max}	e_{min}	D_r	e
SP	0.934	0.656	40	0.823
			50	0.781
			70	0.7.9
SW	0.711	0.470	40	0.615
			55	0.578
			70	0.542

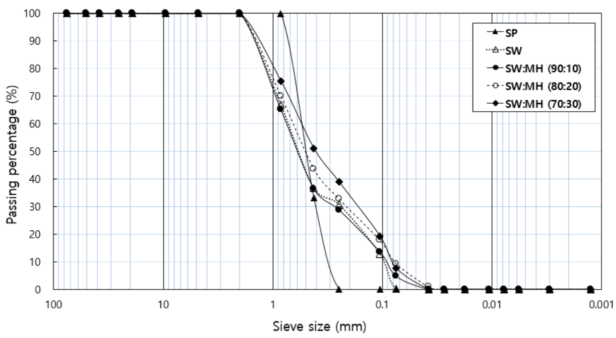


Fig. 2 Particle size distribution curve of soil

to the relative density, a void ratio test was performed, and the maximum void ratio (e_{max}) and the minimum void ratio (e_{min}) of sand were derived accordingly, and the void ratio was calculated using Eq. (1).

$$\mathrm{e} = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{1}$$

Where D_r are the Relative density, e are the Void ratio, e_{max} are the Maximum void ratio, e_{min} are the Minimum void ratio.

Table1 shows the result of calculating the void ratio (e) according to the particle size distribution and relative density of sand, and Fig. 2 shows the result of the particle size distribution test.

4.2 Repeated triaxial compression test conditions

The size of the specimen is 50×100 mm (D×H), and the membrane is first put on the lower part, the porous plate is inserted, and then sealed with an O-ring. Then, the vacuum molding is combined with box with the lower body. Then, the membrane is covered on the vacuum molding box and the membrane is closely attached to the vacuum molding box by applying vacuum pressure.

(a) Join membrane (b) Join cells

Fig. 3 Process of preparing test specimen for repeated triaxial compression test

The sample was divided into a total of five layers, and was divided into several layers without a drop height and molded. For each layer, the sample was molded according to the required relative density by slightly hitting the molding box with a rubber hammer in four directions.

As shown in Table 1, six different cases were planned on SP and SW specimens. For each case, three confining stresses were applied, resulting in a total of 18 repeated triaxial tests.

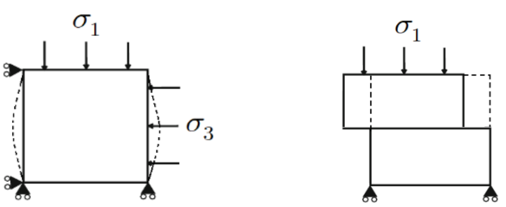
The weight of the specimen according to the relative density was derived by multiplying the cross-sectional area (A) and height (H) of the specimen after deriving the dry unit weight of the soil using Eq.(2).

$$\gamma_d = \frac{G_s \gamma_w}{1+e} \qquad (2)$$

The Where γ_d are the Dry unit weight, G_s are the Specific gravity, γ_w are the Unit weight of water, e are the Void ratio.

In general, repeated triaxial compression tests are mainly used when evaluating liquefaction. Compared to a simple shear, there is a difference in the method of loading, but one-dimensionally, the same is used to confirm the time point of failure of the sample by applying repeated stress in one direction.

Fig. 4 shows the confining pressure conditions of the repeated triaxial compression test and the simple shear test. In the case of a simple shear test, a vertical load is applied on the upper part of the specimen as in the direct shear test, but in the case of a repeated triaxial compression test, an isotropic confining pressure condition can be implemented, making it more reliable under the confining condition (a confining stress of 100 kPa).



(a) Repeated triaxial compression test (b) Cyclic simple shear test

Fig. 4 Stress conditions of repeated triaxial test and simple shear test

4.3 Cyclic resistance ratio (CRR)

The cyclic resistance ratio (CRR) derived through the repeated triaxial compression test can be defined as shown in Eq.(3). The CRR can be defined as a value obtained by dividing the maximum repeated shear stress by the isotropic confining pressure (Park. 2015).

$$CRR = \frac{q_{cyc}}{2\sigma_{3c}} \qquad (3)$$

Where $q_{cyc}/2$ are the Maximum cyclic shear stress, σ'_{3c} are the Isotropic confining pressure.

The waveform used was a sine wave, and the vibration load was a stress control method. In addition, the timing of liquefaction was considered to occur when the excess pore pressure became the same as the effective stress in the sample, that is, when the effective stress reached '0'. This is the time when the ratio of the confining pressure and the pore pressure is 95% or more and the axial strain is 5% or more.

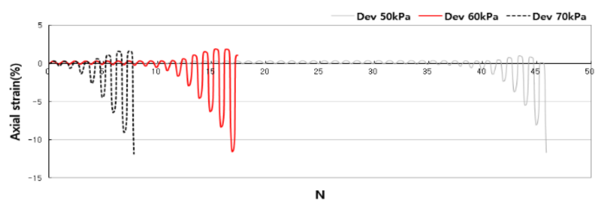
4.4 Results of repeated triaxial compression test

4.4.1 Relationship between axial strain rate and pore pressure according to the number of repetitions

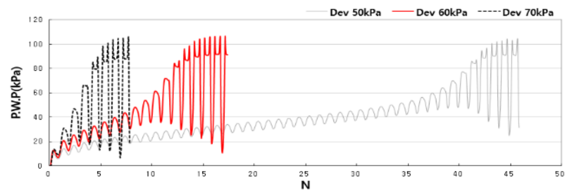
As a result of the repeated triaxial compression test, a total of four graphs could be derived from the axial strain according to the number of repetitions, the pore pressure ratio according to the number of repetitions, the deviator stress according to the axial strain, and the deviator stress according to the effective confining pressure.

Fig. 5 shows the relationship between the axial strain and the pore pressure according to the number of repetitions. First, in the graph of the axial strain according to the number of repetitions, the timing of liquefaction according to the change in the strain rate can be determined, where liquefaction occurs when the strain reaches 5%.

The basis for supporting this can be confirmed by the pore pressure ratio according to the number of repetitions. Liquefaction means that the loose sandy soil ground loses its shear strength and excess pore pressure occurs. Fig. 5.

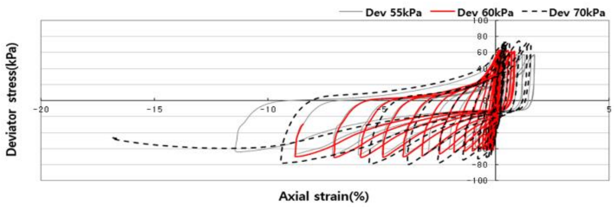


(a) N - Axial strain

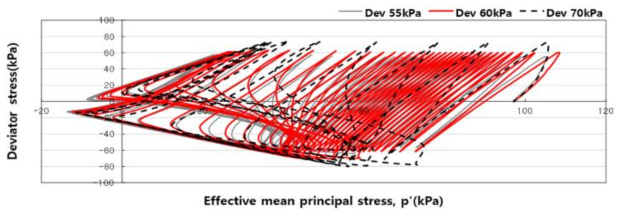


(b) N - P.W.P.

Fig. 5 Liquefaction process



(a) Axial strain – Deviator stress



(b) Deviator stress – P'.

Fig. 6 Liquefaction process

shows the relationship between the axial strain and the pore pressure according to the number of repetitions. As shown in Fig. 5(b) below, it can be determined that liquefaction may occur at the time of excess pore pressure.

4.4.2 Relationship between axial strain and effective confining pressure according to deviator stress

Among the graphs derived through the results of the repeated triaxial compression test, the change in effective stress due to the increase in strain can be confirmed through the stress-strain curve and the stress-path curve.

Fig. 6 shows the relationship between the axial strain and the effective confining pressure according to the deviator stress.

Looking at the stress path of the occurrence of liquefaction, the strain increases as the deviator stress increases. At this time, the effective stress approaches '0' as the pore pressure also increases. This means a state in which the ground loses its shear strength and is rearranged when liquefaction occurs.

4.5 Repeated resistance stress ratio according to grain size distribution and relative density of sand

Fig. 7 shows the CRR values of SP samples and SW samples according to relative density under the same confining pressure conditions. As the relative density increased, Cyclic Resistance Ratio (CRR) values increased by 21%-28% for SP samples, and CRR values increased by 5% for SW samples. In addition, based on the same relative density, the liquefaction resistance strength was found to be 23%, 35%, and 66% higher for relative density of 40%, 55% and 70% for SW samples compared to SP samples.

For the same relative density of 40%, the CRR of SP and SW was 0.193 and 0.321, where the CRR of SW was 60% higher than that of SP. For the relative density of 55%, the CRR of SP and SW was 0.248 and 0.336, repectively, where the CRR of SW is 35% higher than of SP. In addition, for a relative density of 70%, the CRRs of SP and SW were 0.301 and 0.371, indicating that the CRR of SW was 23% higher than that of SP.

This can be judged by the difference in the void ratio of

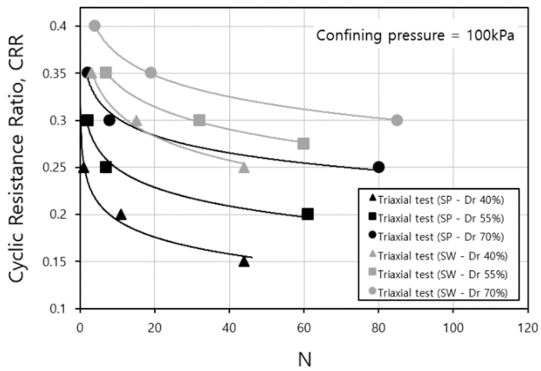


Fig. 7 Analysis of cyclic resistance stress ratio according to distribution and relative density of sand (SP : SW)

sand, and the particle size of sand with good particle size distribution is evenly spread compared to sand with poor particle size distribution, so the less particle crushing of the well graded sample occurred.

In order to confirm the liquefaction resistance strength according to the increase in the confining pressure, the results of the previous studies and this study experiment were compared and analyzed according to the degree of loose and dense relative density.

Park *et al.* (2018) and Hwang (2020) conducted repeated triaxial compression tests using sand (SP under the unified classification method) in Pohang, where liquefaction occurred due to the earthquake, and analyzed the results with the experimental results conducted in this study as shown in Fig. 8(a). As a result of the analysis, at loose relative density, the CRR value was similar to sand with poor particle size distribution. When the relative density was dense, the CRR value of sand with poor particle size distribution was confirmed to be nearly 50% higher.

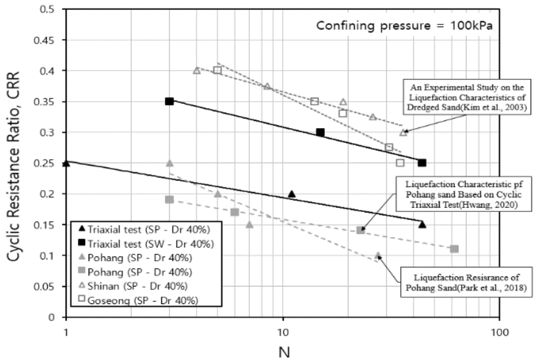
This can be seen that the liquefaction strength does not increase significantly even if the relative density of sand in the Pohang area increases. In a state where the relative density is loose, an engineering simulation of the liquefaction shape of Pohang can be performed using the Jumunjin standard sand, but the effect of the equal coefficient should be confirmed on the ground where the relative density is dense.

Kim *et al.* (2003) conducted repeated triaxial compression tests using sand (SP under the unified classification method) collected near Shinan-gun, Jeollanam-do and Goseong-gun, Gyeongsangnam-do, and compared and analyzed the results with the experimental results conducted in this study as shown in Fig. 8(b). As a result of the analysis, when comparing the sample (SW) and CRR values used in this study, the liquefaction strength was 15% higher at loose relative density and 6% or higher at dense relative density.

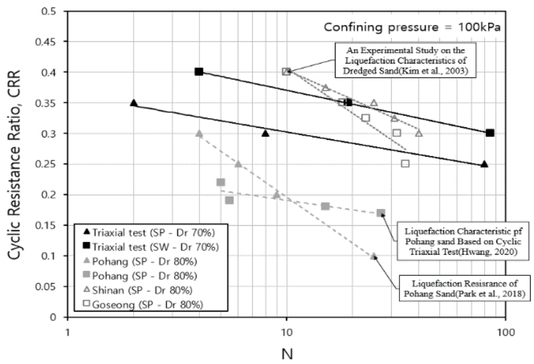
This can confirm that the liquefaction resistance strength can be measured differently depending on the particle size distribution of sand, and that even with the same SP sample, the CRR value increases in the case of SP samples similar to SW samples.

Table 2 Properties according to the characteristics of sand

Classification	G_s	#200 sieve percent finer(%)	D_{10}	D_{30}	D_{60}	C_u	C_c	e_{max}	e_{min}
SP	2.630	0	0.30	0.40	0.56	5.5	1.14	0.93	0.66
SW	2.651	0	0.10	0.26	0.73	2.5	0.72	0.71	0.47
Pohang A	2.520	6	0.09	0.18	0.36	4.0	1.00	0.98	0.70
Pohang B	2.500	2	0.12	0.17	0.23	1.9	1.05	-	-
Shinan	2.660	10	0.11	0.25	0.34	3.1	1.69	-	-
Goseong	2.649	9	0.11	0.26	0.35	3.2	1.85	-	-



(a) Loose sand



(b) Dense sand

Fig. 8 Analysis of repeated resistance stress ratio according to the particle distribution of sand

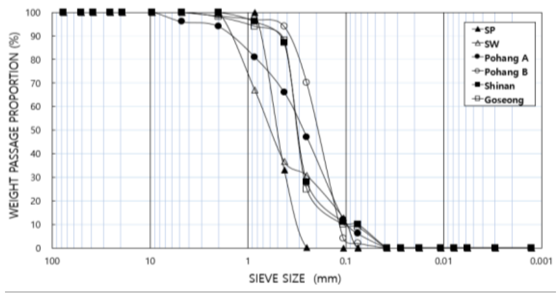


Fig. 9 Particle size distribution curve of sand

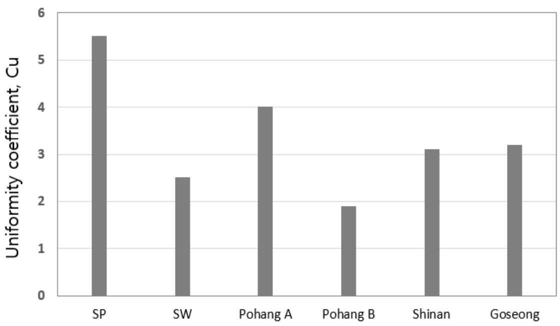


Fig. 10 Comparison of uniformity coefficients of sand

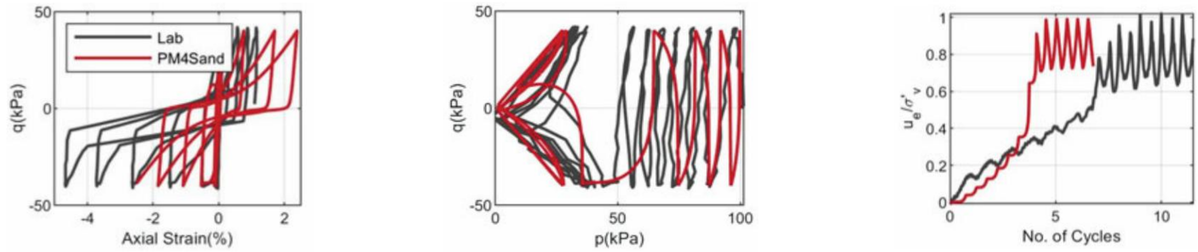
Fig. 9 shows the results of the particle size distribution test, and Figure 10 represents the uniformity coefficient of sand. It is clear that the strength of liquefaction resistance varies depending on the degree to which the particle size distribution of sand is good or bad. However, as shown in Figs. 8(a) and 8(b), in the case of SP close to SW, the resistance strength to liquefaction is confirmed to be quite high. In order to confirm the relationship of particle size distribution to these results, as shown in Figs. 9 and 10, the uniformity coefficient according to the particle size distribution of sand was compared.

As a result, even with the same SP sample, a large difference in the uniformity coefficient can be confirmed. In some cases, the uniformity of the SP smaple is measured lower than that of the SW sample. This simply indicates that it is not reasonable to infer the liquefaction resistance strength of sand according to particle size distribution, and it shows the importance of the detailed evaluation method such as the repeated triaxial test for the liquefaction evaluation process.

The reliability of laboratory experiments on liquefaction may vary slightly in precision due to the proficiency of the engineer performing the experiment, and the sample preparation process and test are accompanied by considerable time and cost, but repeated triaxial-compression tests have been used for more than 40 years. Therefore, it is insufficient to simply perform inference through liquefaction evaluation in the field with SPT results.

Table 2 is the result of calculating the void ratio according to the particle size distribution and relative density of sand.

As a result of comparing and analyzing the results of this study with previous studies, the experimental results of



(a) Relationship between deviato stress (q) and Axial strain

(c) Relationship between deviator stress(q) and Initial effective stress(p)

(c) Relationship between excess pore pressure ratio and number of cycles

Fig. 11 Elemental level calibration : comparison between simulations and experimental results

the repeated triaxial-compression test conducted in this study can be confirmed as a similar trend to previous studies. This means that the reliability of the laboratory experiment is very accurate, and through this study, it is possible to check the distributed results of previous studies using the repeated triaxial-compression test at once.

The detailed liquefaction evaluation method applies to laboratory experiments, but the question of reliability has been raised because undisturbed sample is impossible to collect sand samples and there are no laboratory repeated test regulations in Korea. However, through the experimental results of this study, the results of the liquefaction characteristics of the domestic weathered sand in Korea were reestablished, and the following numerical analysis was additionally performed to compensate for the limitations of such existing studies.

In the case of repeated triaxial compression tests, the reliability of the experimental results is problematic due to the limitations of the equipment, which is a period of 0.1Hz and a low confining pressure of 100 kPa. In order to overcome these limitations, the dynamic behavior characteristics of sand during liquefaction were reviewed by additionally inputting frequencies and high confining pressure in various frequencies through numerical analysis.

5. Numerical analysis for liquefaction evaluation

5.1 Interpretation conditions

5.1.1 Liquefaction analysis model

For the liquefaction analysis, a review was conducted using FLAC (ver.7.0). The PM4sand model was employed as the analysis model. FLAC is an analysis program that utilizes the finite difference method and is typically used for dynamic analysis.

The PM4Sand model used in this study can simulate the stress-strain behavior at the time of reaching liquefaction and after liquefaction. The PM4Sand model is a user-defined model proposed by Boulanger and Ziotopoulou (2018) and is applied to FLAC programs in the form of Dynamic Link Library (DLL). In order to properly simulate liquefaction behavior, this model was developed by comparing analysis results with laboratory experiments and earthquake occurrences.

Table 3 The value of the properties according to the distribution of the sand

Parameter	Value		
	D_r, 40%	D_r, 55%	D_r, 70%
G_s	2.631	2.631	2.631
γ_{dmax}	0.577	1.588	1.588
γ_{dmin}	1.359	1.359	1.359
e_{max}	0.711	0.711	0.711
e_{min}	0.470	0.470	0.470
γ_d	1.440	1.48	1.51
$E(kPa)$	14,000	24,000	40,000
ν	0.2	0.3	0.4
e	0.615	0.578	0.542

This model consists of a nonlinear behavior, a shear strength model, and a pore pressure increase model. The basic input parameters of the PM4Sand model have $\hbar_{po}$, E, K, c, ϕ, D_r etc., as shown in Table 3, and most of the variables are proposed to be estimated through relative density(D_r). In this study, the value of the input variable was changed and applied according to the relative density.

Fig. 11 shows the comparison of laboratory experiments and numerical analysis performed by the LEAP Test (2017) by applying the PM4Sand model.

5.1.2 Input parameters

The input parameters used for the analysis was basically fixed with 8 parameters, and the remaining 6 physical properties were derived through laboratory experiments except for the E(kPa) value, which is the elastic modulus, and the ν value, which is the Poisson ratio. The E(kPa) and ν values were used by reference in previous studies (Kim 2018).

Table 3 shows the input parameters used in the analysis.

5.1.3 Boundary conditions

Modelling during liquefaction evaluation is applied as part of the LEAP Test (Liquefaction Experiments Analysis Project) (Bruce *et al.* 2020). The LEAP-2017 project is a comparison of research results on centrifugal model experiments and liquefaction by various academic

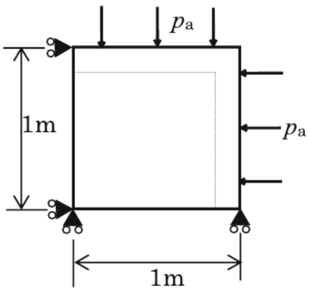


Fig.12 Numerical model for liquefaction analysis

institutions and geotechnical engineering companies from around the world, and studies on liquefaction have been conducted most appropriately so far.

In general, numerical analysis modelling is performed in the same way as the laboratory experiment standard, but during liquefaction evaluation, the 1m×1m grid is regarded as an element, and the physical properties of the sample are entered, and the liquefaction resistance strength is analyzed.

Fig. 12 shows the boundary conditions of modelling during liquefaction analysis. In this study, loading and unloading of loads were repeatedly applied under the conditions of the laboratory experiment, fixed the bottom as in the same conditions, and isotropic pressure was applied with σ_3 and σ_1. Here, the load means the deviator stress.

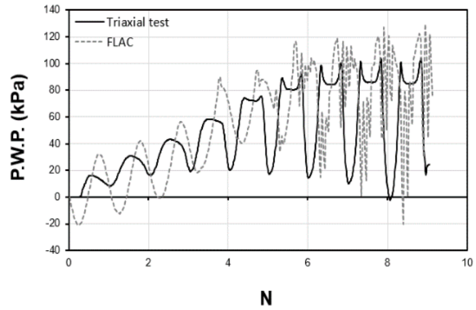
5.2 Analytical verification of laboratory experiments

In this study, to analytically verify the reliability of the results of the liquefaction resistance strength derived through the repeated triaxial compression test, an analytical verification was conducted on the change in axial strain and pore pressure according to the number of repetitions. In repeated triaxial compression tests, conditions for frequency domain and confining pressure conditions cannot be changed, so they cannot be simulated in the same way as actual earthquakes and ground conditions.

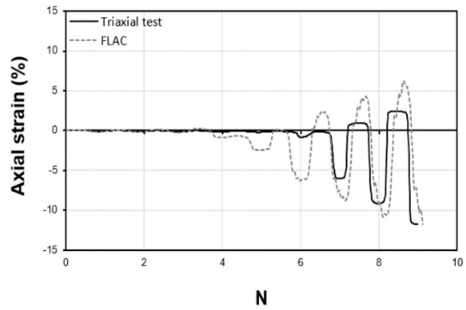
In order to compensate for these shortcomings, the analysis was performed by changing the frequency domain and confining pressure conditions in numerical analysis. The input parameter used in the analysis conditions was also changed and applied according to the relative density.

Fig. 13 shows a comparison of the results by verifying the results derived through laboratory experiments in the program. Fig. 13(a) shows the increase in pore water pressure according to the number of repetitions, and it can be seen that excessive pore water pressure was generated at the same time as the liquefaction occurred in Fig. 13(b). The relationship between stress-strain and stress-path can be confirmed through Figs. 13(c) and 13(d), and as the excess pore pressure increases, the strain increases in Fig. 13(c).

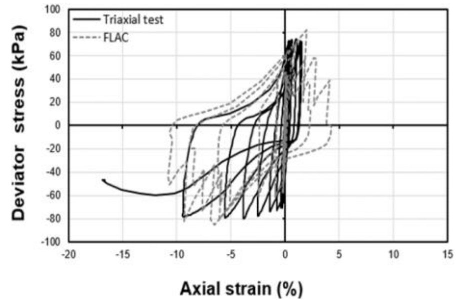
As a result of the verification, the analysis value was measured 2-4% larger than the experimental value in the graph of the number of repetitions and the axial strain, but the timing of liquefaction is calculated as the positive amplitude strain. As shown in 13(b), the CRR values are very close from both expermients and numerical analyses.



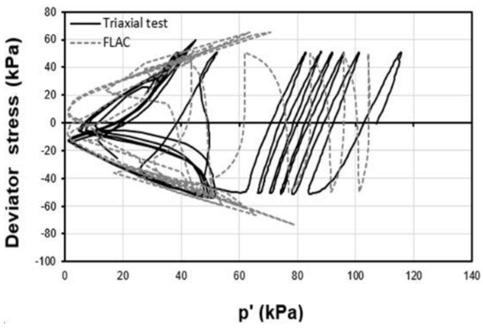
(a) N - P.W.P



(b) N - Axial strain



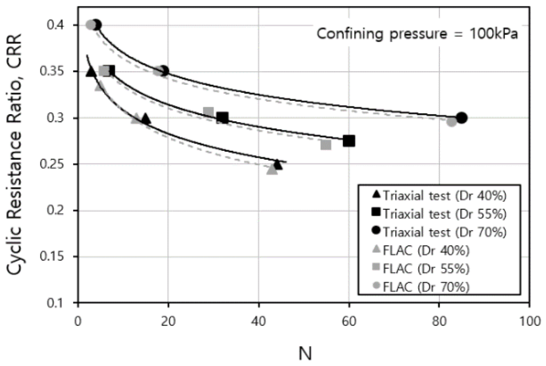
(c) Axial strain – Deviator stress



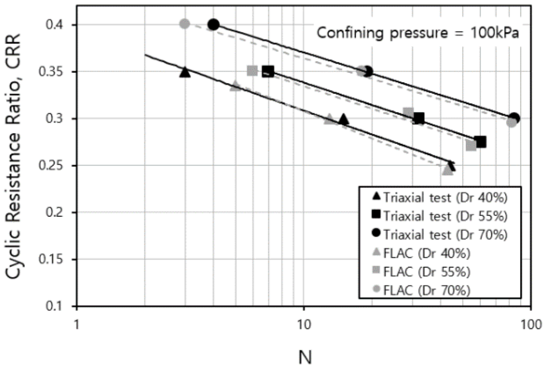
(d) Deviator stress – P'

Fig. 13 Comparison of numerical analysis with laboratory experiment

Fig. 14 is a comparison of the liquefaction evaluation results of indoor experiments as a result of numerical analysis. Compared to laboratory experiments, the number of repetitions at the 5% strain point, which is the time of liquefaction, occurred 1-2 times earlier under low input load and 6-8 times under high input load, but the difference was determined to be small. It is judged that the influence of the input load is greater than the difference in the number of repetitions.

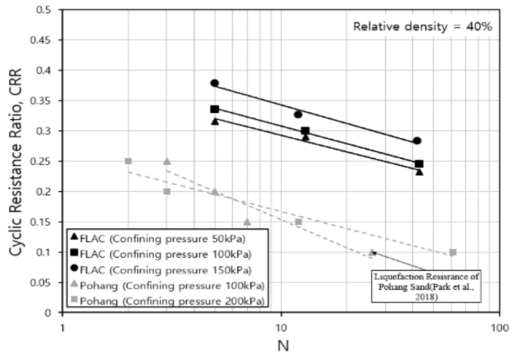


(a) Curve graph

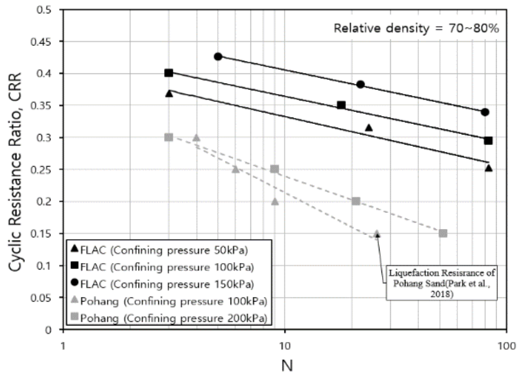


(b) Log graph

Fig. 14 Cyclic resistance stress ratio of laboratory experiment and numerical analysis



(a) Loose sand



(b) Dense sand

Fig. 15 Cyclic resistance stress ratio according to confining pressure

5.3 Repeated resistance stress ratio according to confining pressure conditions

In order to confirm the liquefaction resistance strength according to the increase in the confining pressure, the results of the previous studies and this study experiment were compared and analyzed according to the degree of loose and dense relative density.

Park *et al.* (2018) conducted a repeated triaxial-compression test using sand (SP under the unified classification method) in Pohang, where liquefaction occurred due to the earthquake. As a result of the experiment, under loose relative density conditions, the CRR value increased by 15% or more as the confining pressure increased by 100 kPa. In this study, as the confining pressure increased by 100 kPa from 50 kPa to 150 kPa, the CRR value increased by nearly 20%.

Under dense relative density conditions, in previous studies (Park 2018), the CRR value increased by nearly 10% as the confining pressure increased by 100 kPa, and in this study, the CRR value increased by nearly 20% as the confining pressure increased from 50 kPa to 150 kPa.

It can be seen that as the confining pressure increases, the rigidity of the ground also increases, and the liquefaction resistance strength increases.

Figs. 15(a) and 15(b) show the cyclic stress ratio according to the confining pressure condition according to the loose relative density and the dense relative density.

5.4 Cyclic resistance stress ratio according to frequency domain

In general, the frequency of liquefaction evaluation is low because when liquefaction occurs during an earthquake, the seismic wave changes from a short period wave (15-20 Hz) to a long period wave (less than 5 Hz). This is because after the earthquake, the loose sand ground acts as a damping at the same time as liquefaction occurs, and the amplitude and frequency decrease.

Fig. 16 shows the change in frequency at the time of liquefaction.

Figs. 17(a) and 17(b) show the cyclic resistance stress ratio according to the frequency domain according to the same relative density and confining pressure conditions.

In order to confirm the liquefaction resistance strength according to the frequency domain, the results of the previous study and the experiment in this study were compared and analyzed under the same relative density and the same confining pressure conditions.

Yoon (2019) changed the frequency of Jumunjin standard sand and conducted a repeated triaxial-compression test. As a result of the experiment, even if the frequency increased to 0.1 to 0.5 Hz under the same confining pressure (100 kPa) condition, the liquefaction resistance strength was not significantly affected.

Ishigaki *et al.* (2010) also analyzed clay samples according to the frequency domain. As a result of the experiment, the CRR values increased at 0.001 and 0.01 Hz,

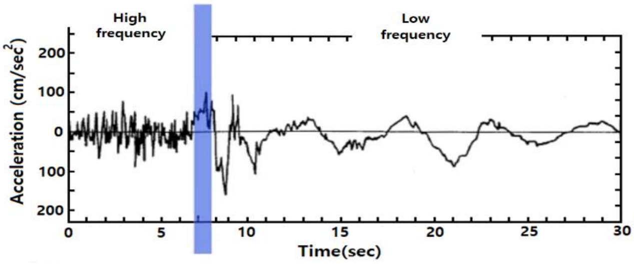
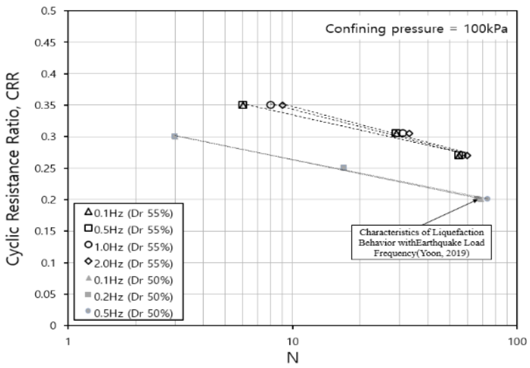
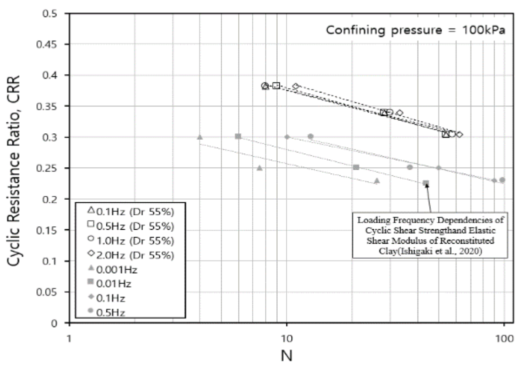


Fig. 16 Frequency change after liquefaction



(a) Dr 50-55%



(b) Confining pressure 100 kPa

Fig. 17 Cyclic resistance stress ratio by frequency area

but the difference in liquidation resistance strength was insignificant even though the frequency was increased at 0.1 and 0.5 Hz as shown in this study.

This is because the liquefaction resistance strength does not increase significantly between 0.1 and 2.0 Hz even if the frequency increases, and the amplitude and frequency decrease as the loose sand ground acts as a damping at the same time as the liquefaction occurs.

6. Conclusions

In this study, an attempted has been done to supplement the limitations of the liquefaction resistance strength according to the particle size distribution and fine grain content of sand and to verify the reliability of laboratory experiments. For this purpose, analytical verification was performed through FLAC V.7.0, a ground response analysis program. In addition, to analyze the liquefaction resistance strength of the sand ground according to the depth of the ground and the loading speed of deviator stress, the limit of the equipment, the confining pressure condition and frequency range were changed through numerical analysis

- As a result of analyzing the liquefaction resistance strength according to the particle size distribution of sand, the liquefaction resistance strength of sand (SW) with good particle size distribution increased by more than 23 to 60% as the relative density increased by 40-70%. In this study, this was judged as the difference due to the particle size distribution of the two types of sand. However, when compared with previous studies, the resistance strength to liquefaction was confirmed to be quite high in the case of SP close to SW. Rather than simply evaluating the liquefaction evaluation of sand limited to the good and poor degree of particle size distribution, all the physical properties of the soil according to the particle size distribution of sand should be considered.
- Analytical verification using the program under the same confining pressure showed that the number of repetitions at the 5% strain point, which is the time of liquefaction, occurred 1 to 2 times earlier than laboratory experiments and 6 to 8 times earlier than in high input loads. However, as a result of comparing the liquefaction resistance intensity value at 10 repetitions, it was determined that the difference was small. It can be determined that the influence of the input load and the confining pressure has a greater influence on the time of liquefaction occurrence.
- As a result of analyzing the liquefaction resistance strength according to the confining pressure condition, it was confirmed that the liquefaction resistance strength increased when the confining pressure was 150 kPa compared to the confining pressure of 100 kPa at the same relative density. However, in the relatively low relative density of 40%, there was no significant difference even if the confining pressure was reduced to 50 kPa. It may be determined that the liquefaction resistance strength does not decrease below a certain limit even when the confining pressure is significantly reduced at a low relative density. In addition, it was confirmed that the liquefaction resistance strength increased as the relative density increased under the same confining pressure conditions, which is believed to have increased as the depth of the ground increased due to the rigidity of the ground due to confining pressure.
- According to the analysis of liquefaction resistance strength according to frequency range, the number of repetitions was the same or very small up to 0.5 Hz, but from 1.0 Hz, the number of repetitions increased more than 5 times for low deviator stress and 20 times for high deviator stress. In addition, in dense ground with a relative density of 70%, the number of repetitions decreased due to an increase in frequency compared to loose ground with a relative density of 40%. This means that even if the loading speed increases, the liquefaction resistance strength increases according to the relative density and confining pressure of the ground. In general, a repeated load cycle of 0.1-1.0 Hz, which is the existing regulation, is not much different from the laboratory experiment results, but it can be judged that the standard for the repeated load cycle needs

to be corrected in Korea as high frequency earthquakes are frequently taking place.

References

Ahn, J.G., Baek, W.H., Choi, J.S. and Kwak, D.Y. (2018), "Investigation of Pohang earthquake liquefaction using 1D effective stress site response analysis", *J. Korean Geotech. Soc.*, **34**(8), 37-49. https://doi.org/10.7843/kgs.2018.34.8.37.

Amanta, A.S. and Dasaka, S.M. (2021), "Air injection method as a liquefaction countermeasure for saturated granular soils", *Transport. Geotech.*, **30**, 100622. https://doi.org/10.1016/j.trgeo.2021.100622.

Ardeshiri-Lajimi, S., Yazdani, M. and Assadi-Langroudi, A. (2016), "A Study on the liquefaction risk in seismic design of foundations", *Geomech. Eng.*, **16**(6), 805-820. https://doi.org/10.12989/gae.2016.11.6.805.

Beak, W.H., Choi, J.S. and An, J.G. (2018), "Liquefaction hazard map based on in Pohang under based on earthquake scenarios", *J. Earthq. Eng. Soc. Korea*, **22**(3), 219-224. https://doi.org/10.5000/eesk.2018.22.3.219.

Boulanger, R,W. and Ziotopoulou, K. (2018), "A sand plasticity model for earthquake engineering applications", Univercity of California.

Bruce, L.K., Majid, T,M. and Mourad, Z. (2020), "Model tests and numerical simulations of liquefaction and lateral spreading", Springer open. https://doi.org/10.1007/978-3-030-22818-7.

Choi, J.S., Jin, Y.H. and Baek, W.H. (2022), "Experimental analysis of liquefaction resistance characteristics of silica sand used in earthquake simulation tests", J. Korean Geo-Environ. Soc., **23**(5), 5-13. https://doi.org/10.14481/jkges.2022.23.5.5.

Choi, J.S., Park, I.J., Hwang, K.M. and Jang, J.B. (2018), "A study on seismic liquefaction risk map of electric power utility tunnel in South-East Korea", *Korean GEO-Environ. Soc.*, **19**(10), 13-19. https://doi.org/10.14481/jkges.2018.19.10.13.

Ha, I.S., Mun, I.J., Youn, J.W. nad Han, J.T. (2017), "Examination of applicability of liquefaction potential index to seismic vulnerability evaluation of the Korean River levees", *J. Korean GEO-Environ. Soc.*, **18**(4), 31-40. https://koreascience.kr/article/JAKO201714942384106.page.

Ha, M.K., Kang, S.G., Jang, C.Y., Yoon, H.K., Ryou, J.E. and Jung, J.W. (2023), "Evaluation of liquefaction possibility of ground based on grain size distribution and soil plasticity", *J. Korean Soc. Hazard Mitigation*, **23**(1), 191-198. https://doi.org/10.9798/KOSHAM.2023.23.1.191.

Heidari, T. and Andrus, R.D. (2010), "Mapping liquefaction potential of aged soil deposits in Mount Pleasant, South Carolina", *Eng. Geol.*, **112**(1-4), 1-12. https://doi.org/10.1016/j.enggeo.2010.02.001.

Hwang, B.Y. (2020), "Liquefaction characteristic of Pohang sand based on cyclic triaxial test", Master's Thesis, University of Science and Technology, 1-80.

Ishigaki, S., Yeon, H.S. and Kim, Y.S. (2010), "Loading frequency dependencies of cyclic shear strength and elastic shear modulus of reconstituted clay", J. Korean Soc. Agricult. Engineers, **52**(3), 73-79. https://doi.org/10.5389/KSAE.2010.52.3.073.

Kim, J.H. and Jung, D.H. (2003), "An experimental study on the liquefaction characteristics of dredged sand", *Proceedings of the* Korean Society of Civil Engineers Regular Conference, Daegu.

Kim, K.E. (2018), "3-dimensional finite element analysis for the behavior analysis of clay ground with crushed stone piles", Master's thesis, Chosun University.

Kim, S.H. (2018), "Mapping of liquefaction potential in Songdo reclamied land", J. Soc. Disaster Inform., **14**(3), 296-304. https://doi.org/10.15683/kosdi.2018.09.30.296.

Kwak, C.W. (2001), "A study on the liquefaction hazard microzonation at reclaimed ports and harbors in Korea", Master's Thesis, Yonsei University.

Lade, P.V., Yamamuro, Jerry. A. and Liggio, C.D. (2009), "Effects of fines content on void ratio, compressibility, and static liquefaction of silty sand", *Geomech. Eng.*, **1**(1), 1-15. https://doi.org/10.12989/gae.2009.1.1.001.

Lee, D.H. (2019), "A study on the relationship between the strength parameters of sand in Pohang liquefied area and cyclic resistance ratio", Master's Thesis, Busan National University.

Lee, S.H., Ham, J.T., Park, H.H. and Kim, J.H. (2022), "Comparative study on the evaluation of liquefaction resistance ratio according to the application of the Korean standard for cyclic triaxial strength test", *J. Korean Geotech. Soc.*, **38**(9), 35-44. https://doi.org/10.7843/kgs.2022.38.9.35.

Mandokhail, S.J., Park, D.H., Kim, H.S. and Park, G.C. (2016), "Cyclic simple shear test based design liquefaction resistance curve of granular soil", *J. Korean Geotech. Soc.*, **32**(6), 49-59. https://doi.org/10.7843/kgs.2016.32.6.49.

Mun, G.Y. (2018), "A study on the effect of relative density and particle size distribution on the liquefaction resistance strength of sand in Pohang liquefaction region", Master's Thesis, Busan National University.

Na, G.H., Ahn, D.H. and Kim, S.H. (2022), "Case study on soil liquefaction effects in Pohang using GPR scanning", J. the Korean Soc. Hazard Mitigation, **22**(4), 119-126. https://doi.org/10.9798/KOSHAM.2022.22.4.119.

Park, J.H. (2020), "A study on characteristic of liquefaction resistance of Busan's coastal sand", Master's Thesis, Busan National University.

Park, S.S., Nong, Z., Choi, S.G. and Mun, H.D. (2018), "Liquefaction resistance of Pohang sand", *J. Korean Geotech. Soc.*, **34**(9), 5-17. https://doi.org/10.7843/kgs.2018.34.9.5..

Park, T.H. and Ha, I.S. (2023), "A basic study on relative liquefaction failure risk assessment of domestic small to medium-sized earthfill dams", *J. Earthq. Eng. Soc. Korea*, **27**(3), 147-155. https://doi.org/10.5000/EESK.2023.27.3.147.

Rahman, M.Z., Siddiqua, S. and Kamal, A.M. (2015), "Liquefaction hazard mapping by liquefaction potential index for Dhaka City, Bangladesh", *Eng. Geol.*, **188**, 137-147. https://doi.org/10.1016/j.enggeo.2015.01.012.

Seed, H.B. (1967), "Earthquake resistant design of earth dams", *Can. Geotech. J.*, **4**(1), 1-27. https://doi.org/10.1139/t67-001.

Seed, H.B. (1979), "Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes", J. Geotech. Eng. Division, **105**(2), 201-255. https://doi.org/10.1061/ajgeb6.0000768.

Seed, H.B. and Idriss, I.M. (1971), "Simplified procedure for evaluating soil liquefaction potential", *J. Soil Mech. Found. Division*, **93**(9), 1249-1273. https://doi.org/10.1061/jsfeaq.0001662.

Seed, H.B. and Lee, K.L. (1966), "Liquefaction of saturated sands during cyclic loading", *J. Soil Mech. Found. Division*, **92**(6), 105-134. https://doi.org/10.2208/jscej1969.1970.180_83.

Shin, Y.S., Park, I.J., Choi, J.S. and Kim, S.I. (1999), "Evaluation of liquefaction strength based on Korean earthquake magnitude", *J. Korean Geotech. Soc.*, **15**(6), 307-317. https://koreascience.kr/article/JAKO199911921749959.page.

Sonmezer, Y.B. (2019), "Investigation of the liquefaction potential of fiber-reinforced sand", Geomechanics and Engineering, **18**(5) 503-513. https://doi.org/10.12989/gae.2019.18.5.503.

Tokimatsu, K. and Yoshimi, Y. (1983), "Empirical correlation of soil liquefaction based on SPT N-value and fines content", *Soils Found.*, **23**(4), 56-74. https://doi.org/10.3208/sandf1972.23.4_56.

Valverde-Palacios, I., Vidal, F., Valverde-Espinosa, I. and Martin-Morales, M. (2014), "Simplified empirical method for predicting earthquake-induced settlements and its application to a large area in Spain", *Eng. Geol.*, **181**, 58-70. https://doi.org/10.1016/j.enggeo.2014.08.009.

Yoo, M.T., Han, J.T., Park, Y.J. and Kim, S.J. (2023), "Evaluation of reinforcement efficiency and applicability using a reinforcement method for liquefiable ground", *J. Korean Geotech. Soc.*, **39**(5), 41-50. https://doi.org/10.7843/kgs.2023.39.5.41.

Yoon, W.S. (2019), "Characteristics of liquefaction behavior with earthquake load frequency", *J. Korean Soc. Ind. Convergence*, **22**(6), 739-748. https://doi.org/10.21289/KSIC.2019.22.6.739.

Youd, T.L. and Perkins, D.M. (1987), "Mapping of liquefaction severity index", *J. Geotech. Geoenviron. Eng.*, **113**(11), 1374-1392. https://doi.org/10.1061/(asce)0733-9410(1987)113:11(1374).

Zeybek, A. and Madabhushi, S.P.G. (2017), "Influence of air injection on the liquefaction-induced deformation mechanisms beneath shallow foundations", *Soil Dyn. Earthq. Eng.*, **97**, 266-276. https://doi.org/10.1016/j.soildyn.2017.03.018.

GC