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변형률 제어 반복직접단순전단시험에서 세립분이 모래-실트 혼합토의 간극수압에 미치는 영향

Effect of Non-Plastic Fines Content on the Pore Pressure Generation of Sand-Silt Mixture Under Strain-Controlled CDSS Test

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/ ABSTRACT /

Understanding the behavior of soil under cyclic loading conditions is essential for assessing its response to seismic events and potential liquefaction. This study investigates the effect of non-plastic fines content (FC) on excess pore pressure generation in medium-density sand-silt mixtures subjected to strain-controlled cyclic direct simple shear (CDSS) tests. The investigation is conducted by analyzing excess pore pressure (EPP) ratios and the number of cycles to liquefaction (Ncyc-liq) under varying shear strain levels and FC values. The study uses Jumunjin sand and silica silt with FC values ranging from 0% to 40% and shear strain levels of 0.1%, 0.2%, 0.5%, and 1.0%. The findings indicate that the EPP ratio increases rapidly during loading cycles, with higher shear strain levels generating more EPP and requiring fewer cycles to reach liquefaction. At 1.0% and 0.5% shear strain levels, FC has a limited effect on Ncyc-liq. However, at a lower shear strain level of 0.2%, increasing FC from 0 to 10% reduces Ncyc-liq from 42 to 27, and as FC increases further, Ncyc-liq also increases. In summary, this study provides valuable insights into the behavior of soil under cyclic loading conditions. It highlights the significance of shear strain levels and FC values in excess pore pressure generation and liquefaction susceptibility.

Key words: Excess pore pressure ratio, Non-plastic fines content, Strain-controlled cyclic simple shear test, Cyclic shear strain

1. Introduction

Studying soil behavior under cyclic loading conditions is particularly important in geotechnical engineering, especially in areas susceptible to seismic activity. Dynamics acting on soil during seismic events can lead to phenomena such as liquefaction, in which soil temporarily loses its strength and behaves like a liquid [1], leading to ground instability and potentially causing catastrophic consequences for infrastructure and communities.

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The influence of non-plastic fine content (FC) on the liquefaction resistance of sandy soils is a complex topic, involving both field observations and laboratory studies. The literature review highlights the conflicting evidence surrounding the effect of fines on sand-silt liquefaction. These findings can be classified into four main distinct patterns: 1) an initial decrease in liquefaction resistance, followed by a relative increase with higher FC values ([2-5]); 2) liquefaction resistance decreases continuously as FC increases ([6-8]); 3) liquefaction resistance increases as FC increases ([9, 10]); and 4) initially rises before eventually declining with further increments in FC ([11, 12]). These distinct findings emphasize the complexity of the relationship between FC and liquefaction resistance, highlighting the need for an in-depth understanding of this important geotechnical factor.

It is noteworthy that many previous investigations predominantly employed cyclic stress-controlled testing, with fewer exploring the effects of FC through strain-controlled testing. Continuing the study by Silver and Seed [13], Dobry et al. [14, 15]extended the exploration of excess pore pressure (EPP) response within saturated sands, particularly under the conditions of strain-controlled, undrained loading. The findings from these investigations collectively reveal that the initiation of EPP generation typically occurs at shear strains exceeding 0.01%. Beyond this threshold, excess pore pressure ratios (EPPR, where EPPR = the ratio between EPP and the effective confining pressure) increase notably, with shear strains in the range of 0.3 - 1% capable of inducing EPPR exceeding 100%. An attractive aspect of these results is the consistency across different soil types, different relative densities, distinct preparation techniques, and various confinement pressures. Despite such differences, the data consistently aligned within a relatively narrow range, underscoring the reliability of these findings.

Furthermore, Hazirbaba and Rathje [16]comprehensively explored the EPP generation properties in sand and non-plastic silty sand (Monterey #0/30 sand and Sil-Co-Sil 52 nonplastic silt mixtures). The study included multiple cyclic direct simple shear (CDSS) tests and strain-controlled cyclic triaxial (CTX) tests, maintaining constant relative density, sand-skeleton void ratio, and overall void ratio. Considering different FC values, the conclusion indicated a trend of decreasing EPP with increasing FC, up to FC of 20%. Derakhshandi et al. [17] investigated the effect of plastic fine (kaolinite – PI = 15, LL = 42) on EPP generation in saturated sand through a strain-controlled CTX test. The findings showed that samples containing up to 20% plastic FC produced higher EPP than clean sand samples. Interestingly, when the FC reaches 30%, the EPP of the mixture drops below that of the clean sand sample.

Recent studies have shown contradictions in the influence of FC on EPP generation. Besides, most previous studies on this issue were conducted through CTX experiments [14],[15],[17]. Meanwhile, the CDSS experiment has many advantages including: (1) best representing the in situ seismic condition, (2) soil element under plane-strain condition, and (3) allowing principal stresses rotation [18, 19]. Therefore, a comprehensive study of this issue under cyclic simple shear conditions is needed. To understand the effect of FC on the EPP generation, a series of strain-controlled CDSS tests were conducted in this study. The Jumunjin sand was mixed with silica silt with varying FC values of 0%, 10%, 20 %, 30%, and 40%, where FC = the percentage of silt particles in the total dry weight of the sample. By evaluating the response of the samples under cyclic loading, the effects of FC on the EPP generation of sand-silt mixtures were investigated.

2. Materials and Testing Program

2.1 Materials Properties

Jumunjin sand (S – Fig. 1(a)) has a grain size ranging from 0.3 to 0.85 mm (Fig. 2). It exhibits a uniformity coefficient (Cu) of 1.52, a

(a) Jumunjin Sand (b) Silica Silt

Fig. 1. Image of material used in this study: (a) Jumunjin Sand, and (b) Silica Silt

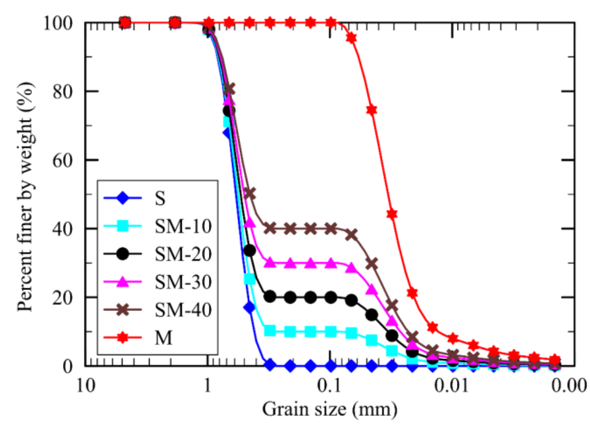


Fig. 2. The Particle Size Distribution Curves of Testing Materials

Table 1. Material properties of Jumunjin sand (S) and silica silt (M)

Type	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	G_s
Jumunjun sand (S)	0.415	0.508	0.631	1.52	0.98	2.65
Silica silt (M)	0.022	0.042	0.063	2.91	1.28	2.60

Note: C_u – coefficient of uniformity; C_c – coefficient of curvature; and G_s – specific gravity.

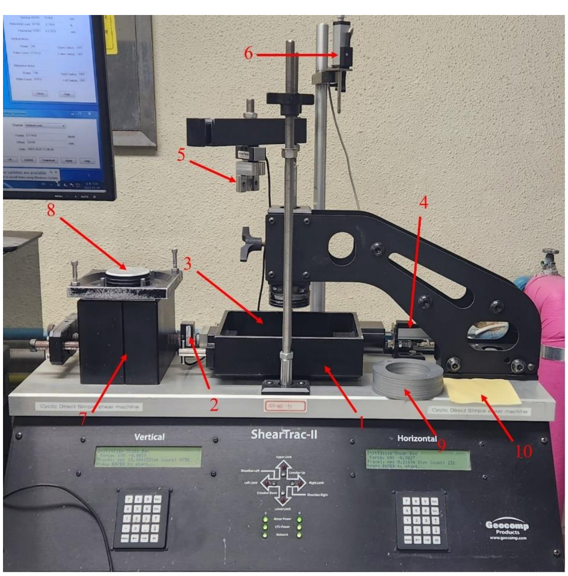
Table 2. Properties of the sand-silt mixture

IDs	FC(%)	γ_{max} (g/cm^3)	γ_{min} (g/cm^3)	G_s	e_{max}	e_{min}
S	0	1.622	1.369	2.648	0.897	0.601
US-10	10	1.783	1.432	2.643	0.810	0.454
US-20	20	1.842	1.466	2.638	0.766	0.405
US-30	30	1.905	1.481	2.633	0.744	0.356
US-40	40	1.883	1.461	2.629	0.765	0.369
M	100	1.545	1.101	2.600	1.317	0.650

coefficient of curvature (Cc) of 0.98, and a specific gravity (Gs) of 2.65 (Table 1). The non-plastic fine particles sieved # 200 from silica sand were used and called silica silt (M − Fig. 1(b)). The material properties of the sand-silt mixture are noted in Table 2.

2.2 Testing Program and Liquefaction Criteria

The testing program was carried out using the CDSS system, which is manufactured by Geocomp Corporation [20] and depicted in Fig. 3. The CDSS samples, originally 25 mm in height and 63.5 mm in diameter, were crafted using the dry deposition technique alongside a trial-and-error approach. This methodology, widely recognized and employed, is commonly used for investigating the cyclic behavior and liquefaction resistance of sand and sandy soil [21-24]. When preparing dry sand samples, the soil specimen must undergo lateral confinement within Teflon stacked aluminum rings to effectively prevent any lateral movement of the soil sample. This confinement ensures that the soil element undergoes consolidation in K0 conditions [25, 26], with an initial vertical effective stress (σ'_{v0}) of 100 kPa applied. Herein, the specimen height was adjusted to exceed 25 mm by approximately 0.5 mm, targeting a reconsolidated relative density of 70%. The reconsolidated relative density was determined by calculating the ratio of the dry sand's mass to the specimen volume after consolidation. Hazirbaba and Rathje [16] and Derakhshandi et al. [17] demonstrated that EPP generation is not significantly influenced by relative density under strain-controlled CDSS tests.



1. Shear box
2. Horizontal load cell
3. Soil sample place
4. Horizontal displacement
5. Vertical load cell
6. Vertical displacement
7. Motor control cyclic loading
8. Sample Base
9. Set of 30 stack rings
10. Membrane

Fig. 3. The ShearTrac-II Cyclic DSS load frame

Following consolidation, a series of undrained strain-controlled CDSS tests were carried out at a constant loading frequency of 0.1 Hz to ensure the little effect of loading frequency on the testing results [20],[24],[27]. A wide uniform shear strain level (γ = 0.1, 0.2, 0.5, 1%) was applied to replicate the real earthquake loading conditions in the field. Throughout the cyclic phase, a constant volume control condition is implemented to mimic the undrained state. In this testing method, the vertical load is automatically adjusted to keep the specimen's volume constant. The EPP generated during the cyclic shear phase corresponds to the alteration in vertical effective stress [28-30]. The liquefaction criteria were defined as the EPPR of about 95% [16, 17]. The testing programs are listed in Table 2.

3. Results and Discussion

3.1 Test Results

Table 3 presents the results of the undrained strain controlled CDSS test, which outlines the values of FC, shear strain levels, and EPPR after 1, 2, 5, 10, and 50 loading strain cycles, as well as the number of uniform strain cycles required to achieve liquefaction.

Typical CDSS testing results are shown in Fig. 4. Jumunjin sand

Table 3. Undrained Strain-controlled CDSS test result in case of medium-dense sand after consolidation

ID	FC (%)	γ (%)	Excess Pore Pressure Ratio after N_{cyc} cycles					$N_{cyc-liq}$
			1	2	5	10	50	
SM	0	0.1	15.1	18.7	27.5	34.4	56.3	-
		0.2	26.4	32.1	46.7	62.0	≈100	42
		0.5	39.2	55.0	75.4	94.9	≈100	11
		1.0	72.2	92.2	≈100	≈100	≈100	3
SM-10	10	0.1	18.8	22.3	22.9	33.7	57.4	-
		0.2	28.3	35.3	45.8	62.0	≈100	27
		0.5	50.4	63.6	85.6	98.6	≈100	9
		1.0	67.2	92.6	≈100	≈100	-	3
SM-20	20	0.1	16.2	16.4	22.8	29.9	49.3	-
		0.2	24.3	30.8	47.3	65.9	≈100	36
		0.5	47.6	64.2	85.7	96.7	97.1	10
		1.0	66.2	96.0	≈100	≈100	-	2
SM-30	30	0.1	18.1	23.4	30.2	37.5	53.4	-
		0.2	23.0	32.5	44.8	57.1	96.7	43
		0.5	47.8	66.2	88.3	99.6	≈100	8
		1.0	72.8	91.6	98.5	≈100	-	3
SM-40	40	0.1	18.4	13.9	27.3	29.7	33.8	-
		0.2	23.5	29.6	40.1	51.7	86.7	67
		0.5	40.7	56.7	81.8	96.8	≈100	10
		1.0	72.2	96.6	≈100	≈100	-	2

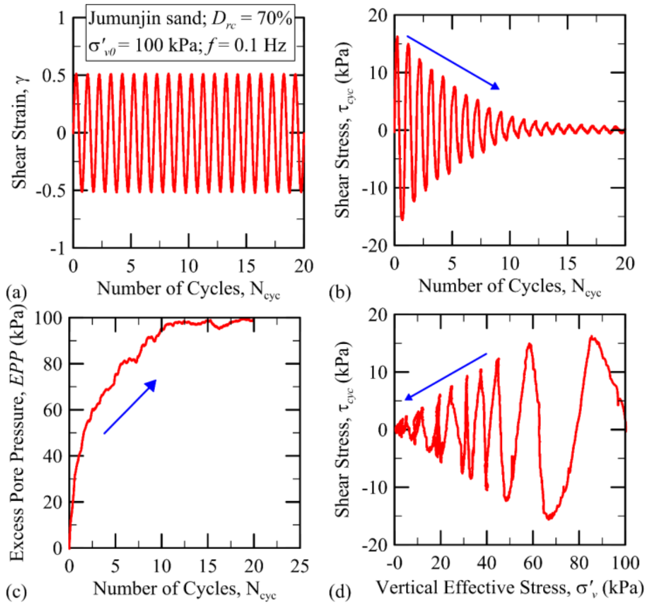


Fig. 4. The Undrained strain-controlled test result of medium-dense density Jumunjin sand

sample is subjected to a constant γ of 0.5 (Fig. 4(a)) until causing liquefaction. The induced shear stress rapidly decreases with a few cycles from high shear stress (τ_{cyc} = 16.23 kPa at 1st cycle) until little enough at liquefaction state (τ_{cyc} = 1.8 kPa at 11th cycle) in Fig. 4(b). In Fig. 4(c), the EPP is generated with a smooth accumulated form until the EPPR of about 100%.

3.2 Excess Pore Pressure Generation in Clean Sand

The EPP generation characteristics are analyzed through the pore pressure history curves, in which the EPPR is plotted versus N_{cyc} for a wide range of γ levels of 0.1%, 0.2%, and 0.5% in Fig. 5. The EPPR increased rapidly during 11 cycles to reach the liquefaction at the applied shear strain of 0.5%. Moreover, the EPPR increased significantly during the first 5 loading cycles for the shear strain level of 0.2% and continued to increase at a slower rate with further loading cycles. At the lowest shear strains of 0.1%, the EPP generated slowly along with the loading cycles. The EPPR rose to 100% at the liquefaction state after 11, 42, and 180 cycles at shear strain levels of 0.5%, 0.2%, and 0.1%, respectively. In general, greater shear strain levels generate more EPP for the same number of loading cycles, while fewer loading cycles are required to cause liquefaction.

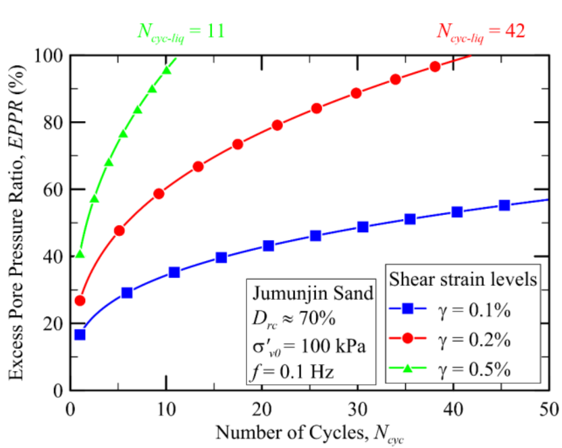


Fig. 5. The EPPR versus Ncyc for various shear strain levels of 0.1, 0.2, and 0.5% of medium-dense density on Jumunjin sand

3.3 Excess Pore Pressure Generation in sand-silt Mixture and Effect of Non-Plastic Fine Content

Fig. 6 illustrates the generation of EPP with the number of loading cycles for various shear strain levels of 0.1, 0.2, 0.5%, and 1.0% on sand-silt mixture with various FCs of 0%, 10%, 20%, 30%, and 40%.

In general, the medium-dense sand-silt samples exhibited gradual increases in EPP with the number of loading cycles, and the magnitude of EPP was found to be dependent on the level of shear strain applied, regardless of FC. In particular, as shown in Fig. 6, at a shear strain of 0.1% and FC = 10%, the EPP in medium-dense sand-silt samples exhibited a gradual increase from approximately 18% after the first loading cycle to 33% after 10 loading cycles, and to 57% after 50 loading cycles. In samples subjected to a shear strain of 0.2%, the EPPR rose from 28% after the first loading cycle to 96% after 33 cycles. The higher pore pressure ratios were observed in the samples subjected to the larger applied shear strain of 0.5%, and 1.0%. Specifically, the EPPR was approximately 50% after the first loading cycle in case shear strain of 0.5% and increased progressively with the number of loading cycles until a maximum of 96% was reached at N_{cyc} = 9. After the first loading cycle, the EPPR in the case of a shear strain

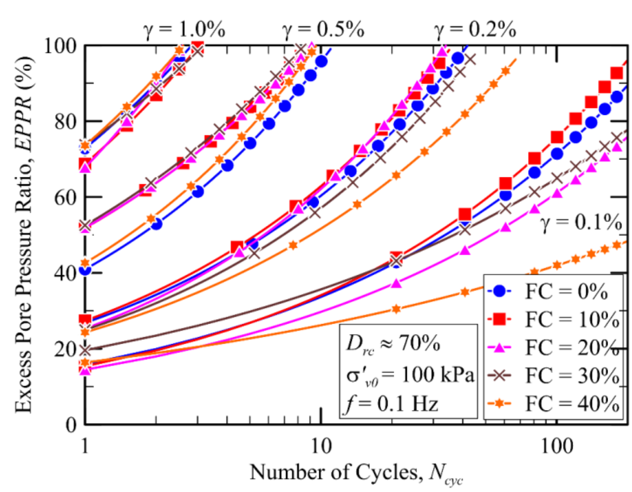


Fig. 6. The EPPR versus N for various shear strain levels of 0.1, 0.2, 0.5%, and 1.0% of sand-silt mixture with various FCs of 0%, 10%, 20%, 30%, and 40%

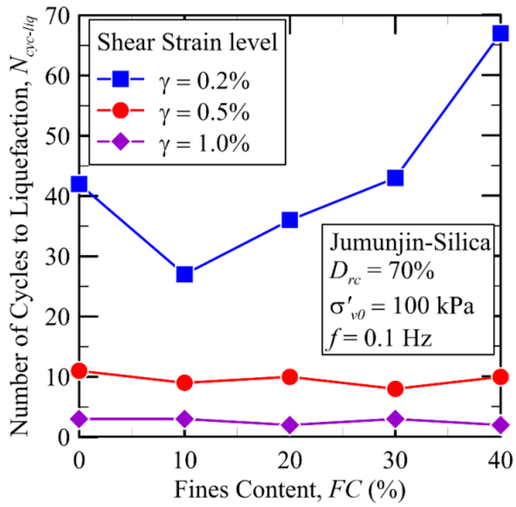


Fig. 7. N_{cyc} Effect of FC on the N_{cyc} under strain-controlled test with various shear strain levels

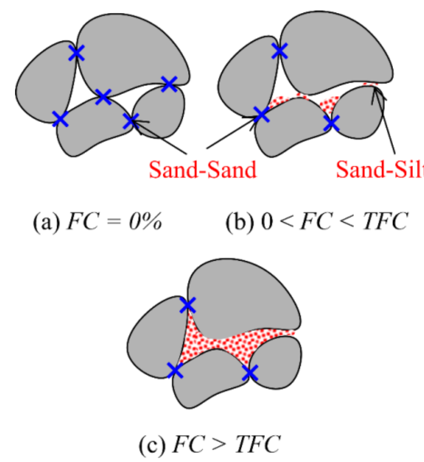


Fig. 8. Theoretical Sand-silt mixture grain framework

of 1.0% was estimated to be about 67%, and it rapidly increased until liquefaction was observed after only three loading cycles. The same trend can be found in the case of FC of 20, 30, and 40%.

Moreover, the generation of EPP also depends on the FC value as shown in Fig. 6. Specifically, when the shear strain level is 1.0%, the influence of FC on EPP generation is quite small and can be ignored. When the shear strain is 0.5%, the EPP generated for clean sand is smaller than that for sand-silt mixtures, regardless of the value of FC. When the shear strain level is 0.2%, the EPP generated for FC values of 10% and 20% are larger than those for clean sand. It is valuable to note that the EPP generation for FC values of 10% and 20% is remarkably similar. The pore pressure is smaller for FC = 30% and falls below that for clean sand. The EPP is smallest for FC = 40%. The difference in EPPR is relatively small for small values of N_{cyc} and increases as N_{cyc} increases with changes in FC. This is more pronounced for samples with a shear strain of 0.1%. In this case, when N_{cyc} is small, the difference in EPPR is not significant. As N_{cyc} increases, the difference in EPPR becomes more pronounced, with the EPPR of the sample with FC = 10% being larger than that of clean sand, followed by FC values of 20% and 30%. Similarly, for a shear strain of 0.2%, the EPPR for FC = 40% with a shear strain of 0.1% is significantly smaller and falls below that for other sand-silt mixtures.

The effect of FC on the number of uniform strain cycles required to reach liquefaction ($N_{cyc\text{-}liq}$) can be found in Fig. 7. As previously stated, the liquefaction criteria was defined as EPPR of approximately 95%. For a shear strain level of 0.2%, the value of $N_{cyc\text{-}liq}$ is 67 for FC = 40%, which has the highest $N_{cyc\text{-}liq}$. However, it decreases to 43, 36, 27, and 42 for FC = 30%, 20%, 10%, and clean sand, respectively. The effect of FC on $N_{cyc\text{-}liq}$ is insignificant at a shear strain level of 0.5%, as $N_{cyc\text{-}liq}$ remains relatively constant at around 10 when FC is varied from 0 to 40%. Similarly, at a shear strain level of 1.0%, $N_{cyc\text{-}liq}$ is 3 for nearly all FC values, indicating little to no effect.

It can be stated that at shear strain levels of 1.0% and 0.5%, $N_{cyc\text{-}liq}$ hardly changes or changes little as FC increases from 0 to 40%. However, at a lower shear strain level (γ = 0.2%), the influence of FC on $N_{cyc\text{-}liq}$ is more apparent. At a small strain level, the liquefaction resistance of sand-silt mixture initially decreased with an increase in FC; however, beyond a threshold FC (TFC), in this case at 10%, the further increments in FC lead to an enhancement in the liquefaction resistance. This observation aligns with previous studies in the literature review [2-5],[31-34].

Fig. 8 simulates the theoretical grain framework of a sand-silt mixture. When the soil sample consists solely of coarse particles, these particles tightly bond with each other and transmit forces through sand-sand contact points (Fig. 8(a)). With the presentation of fine particles, they can interleave between the voids among the sand particles, simultaneously disrupting the connections between the sand particles, and leading to a deterioration of the original bonding. This diminishes the liquefaction resistance of the mixture. It can be stated that the addition of fine particles initially weakens the sand structure, expanding the sand void ratio and disrupting the connection of the sand grain framework (Fig. 8(b)). However, as the Fine Content (FC) reaches higher levels (higher than TFC - usually between 10% and 40%, [2-5]), these particles interlock within the sand grain framework, reducing voids, and significantly enhancing resistance against liquefaction (Fig. 8(c)).

3.4 Comparison with Previous Study

Fig. 9 provides a summary of the excess pore pressure data collected in this study, and it is compared with findings from Dobry (1985) [15], Derakhshandi et al. [17], and Hazirbaba [35] over 10 stress cycles. Dobry proposed upper and lower pore pressure curves based on data derived from diverse soil types, densities, and confining pressures.

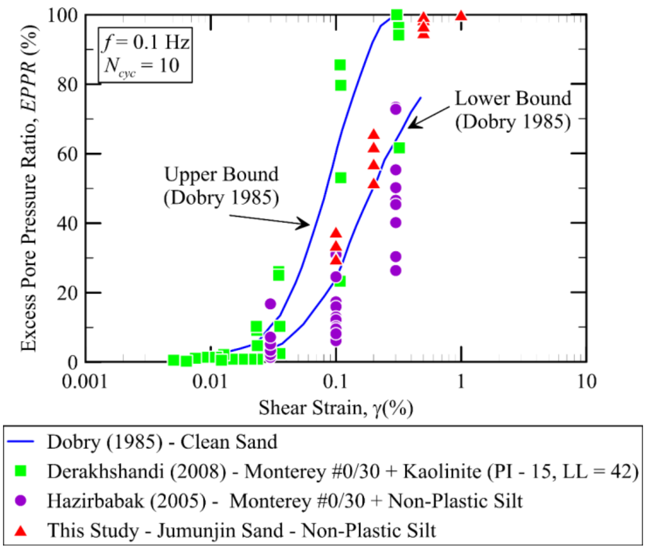


Fig. 9. EPPR after 10 cycles from this study compared with previous studies

From Fig. 8, it is evident that the results obtained by Hazirbaba [35] for the sand-non-plastic fine particle mixture fall outside the mean line established by Dobry (1985). Additionally, the experimental results by Derakhshandi et al. [17] for the sand-plastic fine particle mixture mostly align within Dobry's range, but there are still some values that deviate. Surprisingly, the experimental results obtained in this study align perfectly with Dobry's publication. This indicates the robustness and reliability of the research findings.

4. Conclusion

This study investigates the behavior of soil under cyclic loading conditions, particularly in the context of seismic events and liquefaction risks. It focuses on medium-density sand-silt mixtures and examines the influence of non-plastic fines content (FC) on excess pore pressure generation. Strain-controlled cyclic direct simple shear (CDSS) tests were employed, and the analysis included the study of excess pore pressure ratios (EPPR) and the number of cycles to liquefaction ($N_{cyc-liq}$) across varying shear strain levels and FC values. The findings demonstrate that shear strain levels play a significant role in excess pore pressure generation, with higher shear strain levels leading to more rapid EPPR generation and shorter periods required to induce liquefaction. Moreover, the influence of FC on excess pore pressure generation was found to vary depending on the shear strain level, with FC values of 10% and 20% exhibiting notably larger pore pressure generation than clean sand in specific cases. The effect of FC on the $N_{cyc-liq}$ was also investigated, revealing that the relationship between FC and $N_{cyc-liq}$ is most pronounced at lower shear strain levels. As FC increases from 0% to 10%, $N_{cyc-liq}$ decreases, and further increases in FC result in subsequent increases in $N_{cyc-liq}$.

/ 감사의 글 /

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