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DSS-C CİHAZINDA KISMİ DOYGUNA İNDİRGEME YÖNTEMİ (KDİ) İLE İYİLEŞTİRİLMİŞ KUM NUMUNELERDE GERİLME KONTROLLÜ DİNAMİK DENEYLER

DYNAMIC STRESS-CONTROLLED TESTS ON SPECIMENS PREPARED BY INDUCED PARTIAL SATURATION (IPS) IN DSS-C DEVİCE

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ÖZET

Kısmi Doyguna İndirgeme (KDİ) sıvılaşma problemi bulunan zeminlerde pratik ve ekonomik bir şekilde uygulaması geliştirilmekte olan yeni bir zemin iyileştirme yöntemidir. Sahada uygulandığında, bu yöntem ile iyileştirilmiş zeminlerin sıvılaşmaya karşı dayanıklılığının belirlenmesi gerekmektedir. Bu çalışmada suya doygun ve kısmi doygun kum numunelerde Hücre Basınçlı Dinamik Basit Kesme (DSS-C) Cihazında gerilme kontrollü dinamik deneyler gerçekleştirilmiştir. Çalışma sonuçları kısmi doyguna indirgeme yönteminin önemli ölçüde aşırı boşluk suyu basınçlarını azalttığını ve sıvılaşma başlangıcını geciktirdiğini göstermiştir. Çevrimsel dayanım eğrileri belirli kısmi doygunluk seviyelerinde elde edilmiştir ve sunulmuştur. Bu çalışmanın sonuçları saha uygulamalarında KDİ ile iyileştirilmiş zeminlerde sıvılaşma dayanımını tahmin etmek için yapılacak olan gelecek çalışmalara katkı sağlamaktadır.
Anahtar Kelimeler: *Kısmi Doyguna İndirgeme (KDİ), laboratuvar deneyleri, sıvılaşma, zemin iyileştirme yöntemleri*

ABSTRACT

Induced Partial Saturation (IPS) is a new mitigation technique developed to be practically and economically applied in the field where liquefaction is a potential problem. When applied in the field, the resistance of mitigated soil by IPS needs to be determined. In this study, dynamic stress-controlled tests were performed on fully and partially saturated sand specimens in a Dynamic Simple Shear Test Device with Confining Pressure (DSS-C). The results demonstrated that the induced partial saturation effectively reduced the excess pore water pressures generated and retarded the initial liquefaction. The cyclic resistance curves were obtained and demonstrated for certain partial saturation levels. The results of the study contribute to future research for estimating the liquefaction resistance of sands mitigated by IPS for practical applications.
Keywords: *Induced Partial Saturation (IPS), laboratory testing, liquefaction, soil mitigation*

1. INTRODUCTION

Soil liquefaction due to dynamic loading emerged as a significant concern in geotechnical earthquake engineering following the occurrence of two notable earthquakes: the Alaska earthquake (Mw=9.2) and the Niigata earthquake (M_w=7.6) in 1964. The phenomenon of liquefaction has been observed in saturated sands,

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silty sands, and silts during the majority of previous moderate to large earthquakes, including the recent Kahramanmaras EQ sequences: Pazarcık M_w = 7.7 AFAD, 2023 or M_w = 7.8 according to USGS, 2023 and Elbistan M_w=7.6 AFAD, 2023 or M_w =7.5 according to USGS, 2023. Over the subsequent years, various methods for mitigating soil liquefaction were developed although many of these methods primarily focused on addressing liquefaction in free field sites. Laboratory experiments and field observations have indicated that the degree of saturation is a significant parameter that affects soil behavior in terms of liquefaction.

Yegian et al. (2007) introduced the Induced Partial Saturation (IPS) method which can be applied to fields with existing structures as a means to remediation of soil liquefaction. This method involves entrapping air bubbles within the soil voids. The implementation of the IPS method results in a reduction in the degree of saturation, consequently leading to an improvement in the liquefaction resistance (Eseller-Bayat et al., 2013; Eseller-Bayat and Gulen, 2020).

In the study, the researchers utilized a dynamic simple shear test device with confining pressure (DSS-C) to examine the liquefaction behavior of sand treated with the IPS method in the laboratory. The objective of the study was to generate liquefaction resistance curves for varying levels of degree of saturation and relative density. Additionally, pore pressure generation curves were presented to compare the generation of excess pore water in terms of the degree of saturation, relative density and cyclic stress ratio (CSR).

2. METHOD

In the geotechnical engineering dynamic laboratory at Istanbul Technical University (ITU), stress-controlled undrained dynamic simple shear tests were conducted by a Dynamic Simple Shear Test Device with Confining Pressure (DSS-C). The purpose of these tests was to investigate the effectiveness of liquefaction remediation through the implementation of the induced partial saturation method.

Stress-controlled undrained DSS-C tests were conducted using clean Sile sand (AFS 40-45). Prior to initiating the dynamic testing program, the soil index properties were determined. The soil index properties given in Table 1 were necessary to calculate the initial degree of saturation and relative density. Partially saturated samples were prepared using the induced partial saturation (IPS) method. In this method, the sodium percarbonate chemical is utilized, which reacts with water and generates air bubbles within the sample. This process aids in achieving partial saturation by reducing the degree of saturation and creating air bubbles within the specimen. Gulen and Eseller-Bayat (2017) suggested that the wet pluviation method is the most convenient method for partially saturated samples to be able to obtain uniformly distributed air bubbles in the soil. Therefore, the wet pluviation method was utilized as a sample preparation technique for both fully and partially saturated samples.

Table 1 Soil index properties of Sile sand (AFS 40-45).

Soil Index	Sile Sand
Soil Type	SP
γ_s (g/cm^3)	2.65
e_{max}	0.89
e_{min}	0.57

The water supplied to the sample during the saturation step and the water expelled from the sample during the consolidation stage were measured using H-APC. For monitoring changes in the vertical direction, an LVDT attached to a bracket mounted on the vertical arm was utilized. However, it should be noted that directly measuring the change in sample diameter is not possible in this testing setup. To address the challenge of directly measuring the change in sample diameter, Deniz (2021) adopted an alternative approach. High-quality digital photographs were taken from outside the confining cell at various test stages, including during the saturation phase, immediately after the saturation phase, and at the end of the consolidation phase. These photographs were then utilized to determine the reduction in diameter throughout the test. By using the captured photographs and other available resources, the researcher was able to calculate the final degree of saturation and relative density of the tested samples.

Stress-controlled undrained cyclic simple shear tests consist of saturation, consolidation, and liquefaction stages. Each stage is set up and controlled by the clip studio software. The saturation stage including B check and cell pressure ramp (CPR) phases is needed to attain the target degree of saturation for fully saturated samples. Before the liquefaction stage, samples were consolidated, and a medium of a certain depth was created. Tests within the scope of this research were performed under isotropic consolidation conditions. Under the vertical effective stress of σ_v' = 100 kPa, both fully saturated and partially saturated samples were subjected to the consolidation process. The liquefaction stage is the final stage of DSS-C testing. The DSS-C testing system enables the execution of both strain-controlled and stress-controlled cyclic simple shear tests. For the tests conducted in the context of this research, stress-controlled undrained cyclic loading conditions were used. The cyclic loading was applied using a uniform sinusoidal waveform. In the literature, two criteria are commonly used to identify the initiation of liquefaction: the double amplitude (DA) strain criterion and the excess pore water pressure ratio criterion (where initial liquefaction begins at r_u=1). According to ASTM D:8296-19 (Standard Test Method for Consolidated Undrained Cyclic Direct Simple Shear Test under Constant Volume with Load Control or Displacement Control) testing system is required to maintain uniform cycle loading throughout the test until either the sample fails or a double amplitude shear strain of 10% is reached. In general, for stress-controlled tests, a reduction in cyclic load at large strains should not exceed 5% of the initial loads. However, it is important to note that the ASTM D8296-19 standard provides an exception for testing related to liquefaction. In liquefaction testing, higher reductions in cyclic load are considered acceptable. In the tests conducted for this research, the investigation of liquefaction was based on the excess pore water pressure ratio criterion, and the shear strains at r_u=1 were noted, see Table 2. A loading frequency of 1Hz suggested by ASTM D:5311/D5311M (Standard Test Methods for Load Controlled Cyclic Triaxial Strength of Soil) was utilized in the tests.

DSS-C tests were performed on the different degrees of saturation (S) and relative densities (D_r) by using a range of cyclic stress ratios (CSR). The used parameters and the results of the tests are listed in Table 2. In the scope of this study, samples with degrees of saturation at a range of 70-80% were tested. The samples with higher degrees of saturation were tested and reported by Deniz (2021).

Table 2. Stress-controlled undrained cyclic simple shear tests on fully and partially saturated sand samples.

Soil Index	S (%)	D_r (%)	CSR	N_L @ $r_{u,1}$	γ (%) @ $r_{u,1}$
PS-1	78	47	0.35	22	5.33
PS-2	77	59	0.35	34	7.29
PS-3	72	40	0.29	52	5.52
PS-4	79	40	0.25	72	4.51
PS-5	83	54	0.25	109	3.79
PS-6	77	56	0.27	64	5.24
PS-7	80	19	0.28	33	4.97
PS-8	77	37	0.31	21	4.91
PS-9	72	20	0.25	56	3.57
PS-10	78	41	0.23	123	4.04
PS-11	80	41	0.27	38	5.53
PS-12	77	44	0.27	49	3.75
FS-1	100	52	0.18	11	3.8
FS-2	100	42	0.15	35	3.23

3. RESULTS AND DISCUSSION

CSR, the degree of saturation and relative density were changed for different experiments in order to evaluate the effect of those on the soil. The degree of saturation and relative density couldn’t be estimated precisely because the volume of the specimen changed during the experiments. Therefore, the degree of saturation and relative density were calculated after the consolidation. While the estimated saturation degrees at the beginning of the test and the degrees of saturation calculated after the consolidation are close, an increase is observed in the relative densities due to the volume change. It should be noted that all experiments should be performed by the same researcher, as sample preparation and measurement are highly dependent on the operator.

The effect of CSR and relative density on liquefaction can be observed in Figure 1. Figure 1 presents the liquefaction resistance curves for samples with different relative density ranges and at S=75%. It can be revealed that similar to the fully saturated sample tests, the liquefaction resistance curve shifts up as the relative density increases. When fully and partially saturated samples are compared, it is apparent that the degree of saturation affects the initiation of the liquefaction. The number of cycles to reach liquefaction (N_L), relative density and CSR values for the samples FS-1 and FS-2 are N_L=11, D_r=52%, CSR=0.18 and N_L=35, D_r=42%, CSR=0.15, respectively. The number of cycles to reach liquefaction in the same relative density range for partially saturated samples varies from 21 to 109 depending on the CSR. In light of this information, it is obvious that the degree of saturation plays an essential role in the initiation of liquefaction.

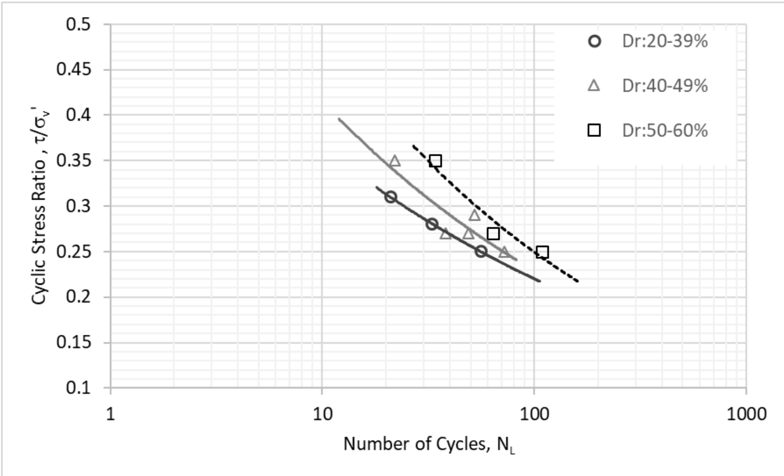

Figure 1. Liquefaction resistance curves for partially saturated sand samples (S=75%) D_r=30%, D_r=45%, D_r=55%.

Additionally, it is worth noticing that the shear strain (γ) at r_u=1 increases essentially as CSR increases. To illustrate, for the samples with D_r=20-39%, single amplitude shear strains were obtained as 3.79%, 5.24%, and 7.29% at CSR levels of 0.25, 0.27, and 0.35, respectively. It can also be seen that when the CSR value rises, the shear strain rises. Although the liquefaction resistance increases in partially saturated sands, it was observed that the shear strains could go up to a single amplitude of 7.29% at a high CSR value of 0.35. This indicates that the tested samples experienced significant deformation under the applied loading conditions. Therefore, for mitigation purposes, the deformations are also critical parameters to consider besides the liquefaction resistance curves.

In Figure 2, the impact of different CSR levels and relative densities on the generation of excess pore water pressure ratios is presented for fully and partially saturated samples. This figure illustrates the relationship between these variables, providing insights into how the cyclic stress ratio and relative density influence the development of excess pore water pressure ratios. It is apparent that an increase in CSR causes the sample to reach the initial liquefaction state more rapidly. Samples prepared at D_r=45% and tested under vertical effective stress of 100 kPa, partially saturated samples reached r_u=1 at higher numbers of cycles under higher CSR levels when compared with fully saturated samples. Additionally, it can be seen that the relative density of the sample impacts the occurrence rate of excess pore water pressure. It is explicitly observed that as the relative density of the sample increases and the degree of saturation decreases, the time taken to reach initial liquefaction increases (Figure 2 (b)).

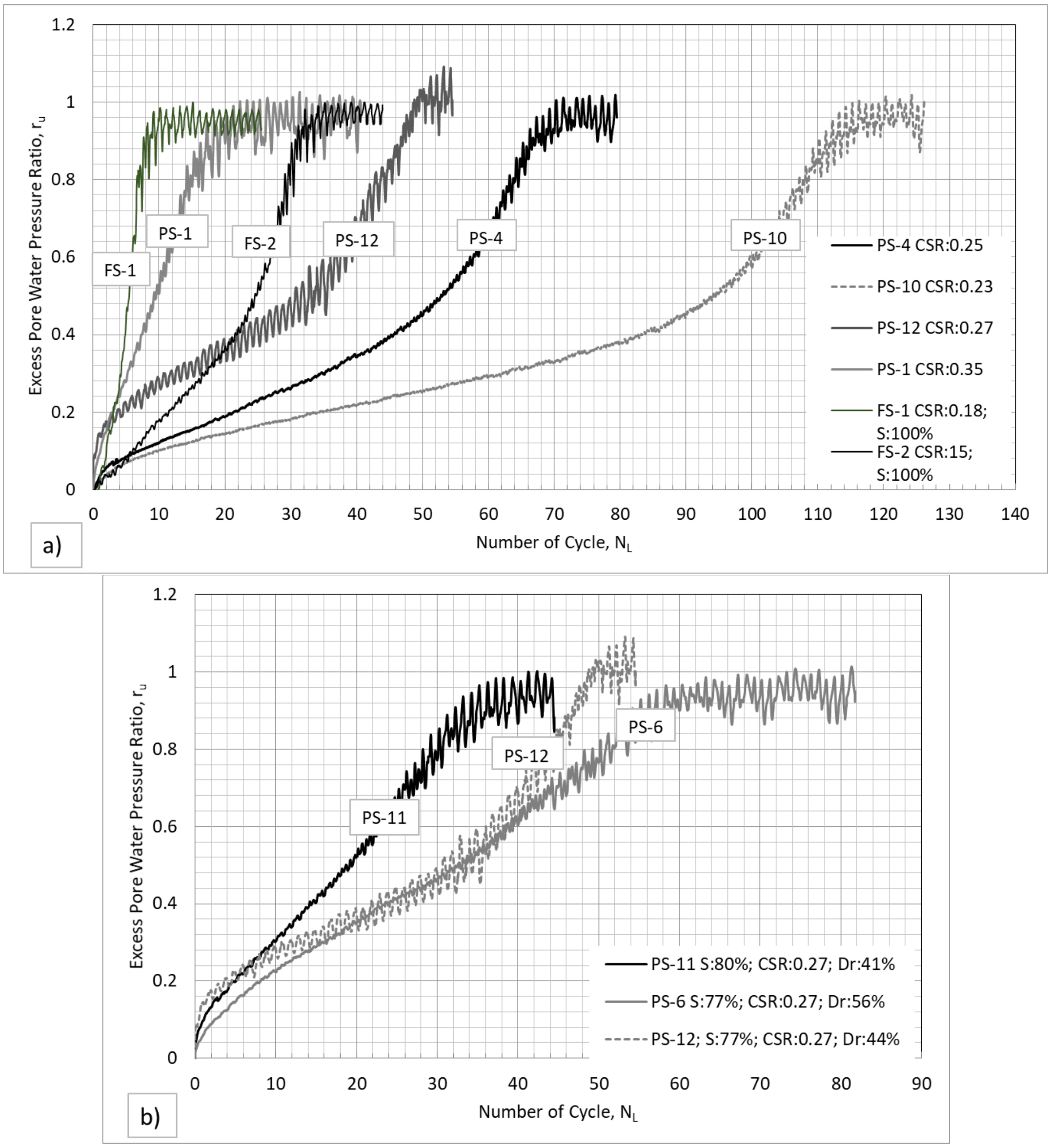

Figure 2. Stress-controlled undrained cyclic simple shear tests on partially saturated (S=78%) and fully saturated samples under σ_v'=100 kPa vertical effective stress a) effect of CSR at D_r=45%, b) effect of D_r at CSR=0.27 on excess pore water pressure ratio generation

4. CONCLUSION

This study focused on investigating the impact of partial saturation, specifically through the implementation of the IPS (Induced Partial Saturation) liquefaction mitigation technique, on the liquefaction resistance. The primary objective of the study was to obtain cyclic resistance curves and analyze the generation of pore water pressure according to the relationship between the degree of saturation and the generation of pore water pressure, which is a crucial factor in assessing the potential for liquefaction in soil. Additionally, the study presents the effect of relative density and CSR on the liquefaction response of partially saturated samples.

Sile (AFS 40-45) sand classified as poorly graded sand was used in the experimental study. Fully and partially saturated samples were prepared by the wet pluviation method. Partial saturation was achieved through the implementation of the IPS treatment method. Undrained cyclic simple shear tests were performed on samples consolidated under isotropic consolidation conditions at 100 kPa vertical effective stress. The experiments were conducted on partially saturated samples consisting of the degree of saturation 72% to 83%, relative density 19% to 59% at cyclic stress ratio values between 0.23 and 0.35. Additionally, the experiments were conducted on fully saturated samples consisting of relative densities of 42% and 52% at cyclic stress ratio values of 0.15 and 0.18. Following conclusions were made by this study.

As the relative density increases, the generation of excess pore water pressure slows down and reaches excess pore water pressure ratio, r_u=1 at a further number of cycles. Therefore, as the relative density increases, the liquefaction resistance increases in partially saturated sands.

For samples with the same degree of saturation and relative density, when the cyclic stress ratio (CSR) value rises, the sample reaches liquefaction at a lower number of cycles. High shear strains at r_u=1 are observed at higher CSR.

When partially saturated samples (S=75%) and fully saturated samples (S=100%) are compared, it is explicitly observed that decreasing the degree of saturation reduces the amount of generated excess pore water pressure at the same number of cycles. Samples having a higher degree of saturation reach initial liquefaction earlier.

The findings of this study provide valuable insights that can contribute to future research endeavors aimed at estimating the liquefaction resistance of sands treated with IPS for practical applications. By understanding the effects of IPS on liquefaction behavior and obtaining data on the cyclic resistance curves and pore water pressure generation, researchers can better assess the efficacy of IPS as a mitigation technique. This knowledge can inform the development of improved methodologies and guidelines for estimating the liquefaction resistance of sands treated with IPS in real-world scenarios. Such advancements can enhance the reliability and effectiveness of liquefaction mitigation strategies in geotechnical engineering practice.

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