ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

UNDRAINED DYNAMIC RESPONSE OF FULLY AND PARTIALLY SATURATED SANDS THROUGH DYNAMIC SIMPLE SHEAR TEST DEVICE WITH CONFINED PRESSURE

M.Sc. THESIS

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Department of Civil Engineering

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TAM DOYGUN VE KISMİ DOYGUN KUMLARIN HÜCRE BASINÇLI DİNAMİK BASİT KESME DENEYLERİ İLE DRENAJSIZ DİNAMİK DAVRANIŞI

YÜKSEK LİSANS TEZİ

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EYLÜL 2017

Derya Burcu GÜLEN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 501151306, successfully defended the thesis entitled "UNDRAINED DYNAMIC RESPONSE OF FULLY AND PARTIALLY SATURATED SANDS THROUGH DYNAMIC SIMPLE SHEAR TEST DEVICE WITH CONFINED PRESSURE", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 06.09.2017
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To my lovely family,

FOREWORD

This thesis was written during my Master of Science education at Istanbul Technical University in the dates between September 2015 and September 2017. This research was conducted as a part of the TUBITAK (The Scientific and Technological Research Council of Turkey) Project under grant no 213M367 and project title of "Dynamic Response of Sands Mitigated by IPS (Induced Partial Saturation) under New and Existing Structures".

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ABBREVIATIONS

CSR **:** Cyclic Stress Ratio
CSSLB **:** Cyclic Simple Shear Liquefaction Box
DA **:** Double Amplitude
DSS-C **:** Dynamic Simple Shear Test Device with Confining Pressure
FSS **:** Fully Saturated Sands
IPS **:** Induced Partial Saturation
PSS **:** Partially Saturated Sands

SYMBOLS

B	: B-value
d	: Depth
$\mathbf{D_r}$	: Relative density
$\mathbf{E_r}$	: Skeleton rebound modulus
$\mathbf{K_{aw}}$	: Bulk modulus of air-water mixture
$\mathbf{K_w}$	: Bulk modulus of water
N	: Number of cycles
n	: Porosity
$\mathbf{N_L}$	: Number of cycles required to liquefaction
$\mathbf{N_{max}}$	: Maximum number of cycles
$\mathbf{P_0}$	: Atmospheric pressure
$\mathbf{r_u}$	: Excess pore water pressure ratio
$\mathbf{r_{u,max}}$	: Maximum excess pore water pressure ratio
S	: Degree of saturation
$\mathbf{u_0}$	: Pore water pressure
V	: Volume of soil
$\mathbf{V_p}$	: P-wave velocity
W	: Weight of soil
$\Delta\varepsilon_{vd}$	: Change in volumetric strain in drained condition
Δu	: Excess pore water pressure
τ	: Shear stress
γ	: Shear strain
σ	: Total vertical stress
σ'_v	: Effective vertical stress
σ_d	: Deviator stress

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UNDRAINED DYNAMIC RESPONSE OF FULLY AND PARTIALLY SATURATED SANDS THROUGH DYNAMIC SIMPLE SHEAR TEST DEVICE WITH CONFINED PRESSURE

SUMMARY

Liquefaction induced seismic hazard is still a major problem in geotechnical engineering. Sand boils, liquefaction induced settlements and bearing capacity failures create damages for both human life and structures. At this concern, various liquefaction mitigation techniques have been improved. Altering the fully saturated condition in loose sands to partial saturated is one of the recent liquefaction mitigation techniques that is being developed. Partial saturation is induced by air entrapment inside the voids. In this method, liquefaction resistance of loose fully saturated specimens can be increased by decreasing degree of saturation of the specimen. This study aims to investigate undrained dynamic response of fully and partially saturated sand specimens.

VJ Tech brand dynamic simple shear with confining pressure (DSS-C) testing system was used in this research to simulate field conditions in the laboratory. The testing system was established in Geotechnical Earthquake Engineering Laboratory of Civil Engineering Faculty in Istanbul Technical University. Initially, the working mechanism of DSS-C testing system was studied comprehensively. Clisp Studio software program was used to perform the tests. The test setups include; saturation, isotropic consolidation and undrained cyclic loading liquefaction tests.

The best specimen preparation methods were examined for both fully and partially saturated sand specimens by using an unconfined membrane. Dry pluviation, wet pluviation and moist undercompaction methods were performed for fully saturated sand specimen preparation. Moist undercompaction method was chosen as the most suitable technique for this research to get loose, undeformed and fully saturated sand specimens for undrained dynamic loading tests. Secondly, partially saturation was achieved by generation of gas bubbles inside the voids. Gas bubbles were created by using sodium percarbonate powder. The partially saturated sand specimen preparation methods were examined in two sections, which were preparing sand-chemical mixture and preparing water-chemical mixture. The best specimen preparation method was chosen as preparing water-chemical mixture and wet pluviation of dry sand into this mixture to get loose and undeformed partially saturated sand specimens at various degrees of saturation.

Several undrained cyclic loading strain controlled tests were performed on fully and partially saturated sand specimens. During the test program, change in effective vertical stress and excess pore pressure generation with time and shear stress-shear strain behavior of the fully and partially saturated specimens were determined. Excess pore pressure generation in fully and partially saturated sand specimens were compared under different shear strain levels at 15, 50 and 100 number of cycles. Furthermore, the effect of effective vertical stress, degree of saturation and back pressure on excess pore pressure generation in partially saturated sand specimens were investigated.

The results demonstrated that the liquefaction resistance of partially saturated sand specimens increases by decreasing degree of saturation, decreasing back pressure and increasing effective vertical stress. Although the excess pore pressure generations are lower in partially saturated sand specimens compared to fully saturated specimens, it was observed that eventually the excess pore pressure ratio (r_u) reaches to 1.0 in partially saturated sand specimens, contrary to the published results in large sand specimens tested, where r_u stabilizes at maximum values less than 1.0. This difference in small specimen tests can be attributed to the escape of oxygen bubbles from the short samples, resulting in increasing degree of saturation as cycling continues. Therefore, the behavior in small specimen tests should be only examined for low number of cycles.

This research was funded by TUBITAK (The Scientific and Technological Research Council of Turkey) under the grant No: 213M367 and project title of "Dynamic Response of Sands Mitigated by IPS (Induced Partial Saturation) under New and Existing Structures". The research results were used to improve the project goals. Additionally, this study will give a contribution to next literature researches to determine the undrained dynamic response of fully and partially saturated sands through dynamic simple shear tests with confining pressure also to improve Induced Partial Saturation (IPS) method as a liquefaction mitigation technique against liquefiable soils.

TAM DOYGUN VE KISMİ DOYGUN KUMLARIN HÜCRE BASINÇLI DİNAMİK BASİT KESME DENEYLERİ İLE DRENAJSIZ DİNAMİK DAVRANIŞI

ÖZET

Deprem yükleri altında tam doygun ve gevşek kum zeminlerde görülen aşırı boşluk suyu basıncı artışına sıvılaşma denir. Zeminde oluşan aşırı boşluk suyu basıncı artışı düşey efektif gerilmenin azalmasına neden olmaktadır. Serbest saha koşullarında, aşırı boşluk suyu basıncındaki artış, örtü yükü düşey efektif gerilmesine eşit olduğu durumda zeminde sıvılaşma olayı meydana gelmektedir. Deprem anında gerçekleşen sıvılaşma olayı serbest saha zemininde oturma ve yapı altında taşıma gücü kaybına ve oturmaya neden olmaktadır. Sıvılaşma sonucu dayanımını kaybeden zemin çeşitli yapısal hasarlara ve can kaybına yol açmaktadır. Son 60 yıldır doygun gevşek kumların sıvılaşma davranışı literatürde çalışılmaktadır ve çeşitli sıvılaşmayı önleyici yöntemler geliştirilmektedir. Bu çalışmalar sırasında kumlu zeminlerin doygunluk derecesindeki az bir miktar azalışın dahi zeminin sıvılaşmaya karşı dayanımını artırdığı gözlemlenmiştir. Buna bağlı olarak kısmi doygun kumların sıvılaşma davranışı üzerine çalışmalar hız kazanmıştır ve kısmi doygunluk, sıvılaşma problemine karşı bir zemin iyileştirme yöntemi olarak geliştirilmeye başlanmıştır.

Ancak hala literatürde serbest saha koşullarında kısmi doygun kumların yüksek efektif gerilmeler altındaki drenajsız dinamik davranışı, boşluk suyu basıncındaki değişimlerin bu davranışa etkisi, sıvılaşma direncinin derinliğe bağlı olarak doygunluk derecesiyle değişimi araştırma konusudur.

Son yıllarda geliştirilen Kısmi Doygunluğa İndirgeme (IPS) yöntemi sıvılaşmayı engelleyici zemin iyileştirme yöntemlerinden bir tanesidir. Bu yöntemde zemin içerisinde hava kabarcıkları oluşturularak kısmi doygunluk sağlanmaktadır. Kısmi Doygunluğa İndirgeme yöntemi sıvılaşmaya karşı geliştirilen diğer zemin iyileştirme yöntemlerine kıyasla daha ekonomiktir ve hem yeni hem de mevcut binalar altında uygulanmaya elverişlidir.

Tez çalışması kapsamında öncelikle, VJ Tech marka Hücre Basınçlı Dinamik Basit Kesme Test Sistemi'nin alımı gerçekleştirilmiş ve İTÜ İnşaat Mühendisliği, Geoteknik Deprem Mühendisliği Laboratuvarına sistemin kurulumu yapılmıştır. Deney düzeneğinin çalışma mekanizması öğrenilmiştir. Hücre Basınçlı Dinamik Basit Kesme Test Sistemi; dinamik basit kesme makinesi, dinamik servo kontrol ünitesi, hücre basıncı ve ters basınç kontrol makineleri, hava basınç kompresörü, hava ve su basıncını dengeleyen silindir, vakum makinesi ve su tankından oluşmaktadır. Deneyler için Clisp Studio yazılım programı kullanılmıştır. Clisp Studio programı kullanılarak çeşitli koşullar altında doygunluk, konsolidasyon, statik yükleme, tekrarlı yükleme ve sıvılaşma deneyleri yapılabilmektedir.

Deneylere başlamadan önce, çeşitli tam doygun ve kısmi doygun kum numune hazırlama yöntemleri çalışılmıştır. Deformasyonsuz ve gevşek numune elde edilmesi

sıvılaşma deneyleri için önem taşımaktadır. Numuneler plastik membran içinde hazırlanmıştır. Tam doygun numune hazırlama yöntemleri olarak; kuru yağmurlama, ıslak yağmurlama ve yarı doygunlukta sıkıştırma yöntemleri incelenmiştir. Öncelikle, kuru yağmurlama yöntemi denenmiştir. Bu yöntemde kuru kum numunesi huni yardımıyla sabit bir yükseklikten numune kalıbının içine dökülmüştür. Ancak kuru yağmurlama tekniği ile yüksek sıkılıkta numuneler elde edilmiştir. Diğer yöntem olarak ıslak yağmurlama tekniği denenmiştir. Bu yöntemde kuru kum numunesi belirli bir miktar suyun içerisine huni yardımıyla sabit bir yükseklikten dökülmüştür. Ancak numune kalıbı çıkartıldığında ıslak numunenin kolayca deformasyona uğradığı ve yüksek sıkılıkta numune elde edildiği gözlemlenmiştir. Her iki yöntemde de deformasyonsuz ve gevşek numune elde edilememiştir. Bu nedenle tam doygun numune hazırlama yöntemi olarak tercih edilmemişlerdir. Son yöntem olarak yarı doygunlukta sıkıştırma yöntemi incelenmiştir. Bu yöntemde, yaklaşık %50 doygunluk derecesi elde edilecek şekilde kum ve su karıştırılmıştır. Daha sonra bu karışım tabakalar halinde sıkıştırılarak numune kalıbına yerleştirilmiştir. Bu yöntem kullanılarak sıkıştırma miktarının ayarlanmasıyla istenilen sıkılıkta, deformasyonsuz numune hazırlanabilmektedir. Bu nedenle, tam doygun kum numune hazırlama yöntemi olarak yarı doygunlukta sıkıştırma yöntemi en uygun yöntem seçilmiştir ve tam doygunluk, numuneye ters basınç uygulanarak elde edilmiştir.

Kısmi doygun kum numune hazırlama yöntemi ise iki farklı aşamada incelenmiştir. Kısmi doygunluk derecesi, zeminin içerisindeki boşluklarda hava (gaz) kabarcığı oluşturularak elde edilmiştir. Hava (gaz) kabarcıkları, sodyum perkarbonatın suyla tepkimeye girmesi sonucu oluşmuştur. Bu tepkime sonucunda çevreye zararlı her hangi bir yan ürün oluşmamaktadır. İlk yöntem olarak, kuru kum ve sodyum perkarbonat belli oranlarda karıştırılıp suyun içerisine yağmurlama tekniği ile dökülmüştür. Ancak, bu yöntemde tepkime sonunda farklı büyüklüklerde, homojen olmayan hava kabarcığı dağılımı gözlemlenmiştir. Kısmi doygunlukta, numune içerisinde homojen dağılımlı hava kabarcığı oluşumu istendiği için bu yöntem tercih edilmemiştir. İkinci yöntem olarak, öncelikle sodyum perkarbonatlı su çözeltisi hazırlanmıştır. Daha sonra, hazırlanan bu çözelti içerisine kuru kum numunesi yağmurlama tekniği ile dökülmüştür. Tepkime sonucunda homojen dağılımlı hava kabarcıklarının oluştuğu gözlemlenmiştir. Hava kabarcıklarının oluşumuyla yükselen su seviyesi zamana bağlı olarak ölçülmüş ve doygunluk derecesindeki değişimler hesaplanmıştır. Numune hazırlama sürecinde tepkimenin tamamlanması için bir gün beklenilmiştir. Kimyasal ve kuru kum miktarları arasında bir oran elde edilmiş olup bu farklı oranlara göre hazırlanan numunelerin doygunluk dereceleri ölçülmüştür. Ölçümler sonucunda doygunluk derecesinin kimyasal ve kum miktarı arasındaki orana bağlı olarak değişimini gösteren bir grafik elde edilmiştir. Bu oranlara göre de çeşitli doygunluk derecelerinde numuneler hazırlanmış olup istenilen doygunluk derecesinin ayarlanması ters basınç ile numune içerisine alınan su miktarına göre hesaplanmıştır.

Uygun numune hazırlama yöntemleri belirlendikten sonra, tam doygun ve kısmi doygun kumlar üzerinde sırasıyla; B değeri kontrolü ve doygunluk deneyleri, izotropik basınçlar altında konsolidasyon deneyi ve drenajsız koşulda tekrarlı yüklemeler altında kayma deformasyonu kontrollü sıvılaşma deneyleri yapılmıştır. Öncelikle, tam doygun numuneler üzerinde hücre basınçlı dinamik basit kesme deneyleri yapılmıştır. Farklı düşey efektif gerilmeler ve birim kayma deformasyonları altında gerçekleştirilen tam doygun numuneler üzerindeki deneyler, aynı koşullarda gerçekleştirilecek kısmi doygun numuneler üzerindeki deneylerle karşılaştırılmak için yapılmıştır. Tam doygun numuneler üzerindeki deneylerde, sabit birim kayma deformasyonu ve rölatif sıkılıkta, düşey efektif gerilmenin artması sonucu sıvılaşma için gerekli çevrim sayısında artış gözlemlenmiştir. Sabit rölatif sıkılık ve düşey efektif gerilme altında ise birim kayma deformasyonu arttıkça sıvılaşma için gerekli çevrim sayısında azalış gözlemlenmiştir. Ancak her koşulda da gerekli çevrim sayısı sağlandığı sürece tam doygun numunelerde sıvılaşma meydana gelmiştir.

Kısmi doygun numunelerdeki deney sonuçlarına göre, yeterli çevrim sayısı sağlandığında düşük doygunluk derecelerinde dahi maksimum aşırı boşluk suyu basıncı oranı ($r_{u,max}$) 1.0'a ulaşmıştır. Bu bulgu, büyük boyutlu numuneler üzerindeki sarsma tablası ve santrifüj deneylerinde (model deneylerinde) elde edilen maksimum aşırı boşluk suyu basıncı oranı $r_{u,max}<1.0$ bulgusu ile ters düşmektedir. Model deneyleri sonuçlarının tersine, çevrim sayısı arttıkça aşırı boşluk suyu basıncı oranında (r_u) artış gözlemlenmiş, bu değer $r_u<1.0$ değerlerinde sabitlenmemiş ve 1.0'a yaklaşmıştır. Bunun sebebi olarak, küçük numune deneylerinde çevrim sayısı arttıkça, numune boşluklarındaki hava (gaz) kabarcıklarının kaçtığı ve numunenin kolaylıkla doygun hale geldiği düşünülmektedir. Büyük numunelerde hava yüzeyden ilk 5-10 santimetredeki boşluklardan ancak kaçabilmekte, daha derindeki boşluklardaki hava (gaz) hapsolmaktadır.

Kısmi doygun numuneler üzerindeki deneylerde, birim kayma deformasyonu, doygunluk derecesi, düşey efektif gerilme ve boşluk suyu basıncının (ters basınç) aşırı boşluk suyu basıncı artışına etkisi incelenmiştir. Birim kayma deformasyonundaki artış, sıvılaşma için gerekli çevrim sayısını (N_L) düşürmüştür. Doygunluk derecesindeki azalmalar ise sıvılaşma için gerekli çevrim sayısını (N_L) artırmıştır. Aynı şekilde, düşey efektif gerilmelerdeki artış sonucunda N_L artırmıştır. Sabit boşluk suyu basıncı altında, farklı düşey efektif gerilmelerin aşırı boşluk suyu basıncı artışına etkisi incelendiğinde, düşey efektif gerilmeler arttıkça sabit çevrim sayısında, r_u değerinin azaldığı gözlemlenmiştir. Son olarak da boşluk suyu basıncının r_u oluşumuna etkisi incelenmiştir. Sabit düşey efektif gerilme, birim kayma deformasyonu ve doygunluk derecesi altında, boşluk suyu basıncı arttıkça kısmi doygun zeminin sıvılaşmaya karşı direnci azalmıştır. Deneyler sonucunda, boşluk suyu basıncı ve düşey efektif gerilmelerdeki artışın aşırı boşluk suyu basıncı artışına birbirlerine göre ters oranda etkidiği gözlemlenmiştir. Bu nedenle, analizlerin belli bir derinlikte numunenin sahip olduğu düşey efektif gerilme ve o derinlikteki gerçek boşluk suyu basıncı altında incelenmesi kararlaştırılmıştır. Sabit doygunluk derecesinde ve birim kayma deformasyonunda, boşluk suyu basıncı ve düşey efektif gerilme aynı miktarda arttıkça kısmi doygun numunenin sıvılaşmaya karşı direncinin arttığı gözlemlenmiştir. Bu sonuçlara göre, doygunluk derecesinin r_u oluşumuna etkisi aynı derinlikteki efektif gerilme ve boşluk suyu basıncında karşılaştırılmıştır.

Analiz sonuçlarına göre, sabit 100 kPa boşluk suyu basıncı ve düşey efektif gerilme altında; 15., 50. ve 100. çevrim sayılarında, tam doygunluk ve farklı kısmi doygunluk derecelerinde oluşan aşırı boşluk suyu basıncı oranlarının (r_u) birim kayma deformasyonu ile değişimini gösteren bir parametrik çalışma yapılmıştır.

Bu tez çalışması sonucunda, tam doygun ve kısmi doygun kumların farklı değişken parametreler altında drenajsız dinamik davranışı Hücre Basınçlı Dinamik Basit Kesme deneyleri ile belirlenmiştir. Sonuç olarak; doygunluk derecesindeki azalışın, birim kayma deformasyonundaki azalışın, eşit miktardaki düşey efektif gerilme ve boşluk suyu basıncındaki artışın, gevşek kum zeminlerin sıvılaşmaya karşı dayanımını artırdığı belirlenmiştir. Tez çalışması, "Deprem Anında Sıvılaşmayı Engellemek Amacıyla Önerilen Kısmi Doyguna İndirgeme (IPS) Yöntemiyle İyileştirilmiş Zeminlerinin Mevcut veya Yeni Yapılar Altında Dinamik Davranışı" başlıklı, 213M367 numaralı TÜBİTAK Projesi kapsamında gerçekleştirilmiştir ve araştırma sonuçları projenin geliştirilmesinde kullanılmıştır. Aynı zamanda bu çalışma, tam doygun ve kısmi doygun kumların drenajsız dinamik davranışının hücre basınçlı dinamik basit kesme deneyleri ile belirlenmesi ve Kısmi Doygunluğa İndirgeme yönteminin sıvılaşmaya karşı bir zemin iyileştirme yöntemi olarak geliştirilmesi için gelecek literatür çalışmalarına katkı sağlayacaktır.

1. INTRODUCTION

This section includes the purpose of the thesis; literature reviews about the recent studies related to liquefaction tests on fully and partially saturated sands, liquefaction mitigation techniques and finally the hypothesis of the research.

1.1 Purpose of Thesis

Liquefaction is one of the major problems in geotechnical earthquake engineering discipline. During 2011 Tohoku, 1999 Adapazari, 1999 Duzce and 1995 Kobe Earthquakes, liquefaction induced hazards caused lots of damages in structures and in the built environment such as sand boils, settlement and bearing capacity failures. In recent years, the researches about the liquefaction behavior of sandy soils and liquefaction mitigation techniques are improved rapidly. However, there are still unsolved problems related to liquefaction behavior of soils under structures and their improvement techniques. Most of the liquefaction mitigation techniques are applicable for only new structures. Liquefaction mitigation of soils under the existing structures is an important problem to be solved. At this concern, Induced Partial Saturation (IPS) technique was developed by Yegian et al. (2007) as a new liquefaction mitigation technique by decreasing degree of saturation of soils with creating air entrapment inside the voids. The liquefaction behavior of partially saturated sands was examined by Eseller-Bayat (2009) in shaking table tests. Eseller-Bayat (2009) performed partially saturated liquefaction tests under small effective vertical stresses.

In this study, the undrained cyclic loading liquefaction tests were performed under high effective vertical stresses in Dynamic Simple Shear with Confining Pressure (DSS-C) testing device. In the scope of the research, fully and partially saturated sand samples were tested in undrained cyclic loading conditions to analyze their liquefaction behavior under high effective vertical stresses. The main purpose of the research is improving Induced Partial Saturation (IPS) technique by analysis of effective vertical stress, degree of saturation, back pressure, shear strain and coupled effect of effective vertical stress and back pressure effects on partially saturated loose sands.

The second chapter includes information about experimental setup for Dynamic Simple Shear Test Device with Confining Pressure (DSS-C). The tests performed in the study were presented in this section such as saturation, consolidation and liquefaction test setups.

In the third chapter, fully and partially saturated tests in DSS-C were presented. The fully and partially saturated specimen preparation methods were explained in detail. Typical tests were shown in this section.

In the fourth chapter, DSS-C tests analysis results were presented. The effect of shear strain, degree of saturation, effective vertical stress and back pressure on excess pore pressure generation in partially saturated sands were examined. In addition, overall results about the excess pore pressure generation in fully and partially saturated sands were presented in this section. Finally, conclusion and recommendations were discussed in the last section, Chapter 5.

1.2 Literature Review

Extensive research exists about liquefaction phenomena of loose and fully saturated sandy soils in the literature. Liquefaction occurs as a shear strength loss during cyclic loading while excess pore water pressure is developed in fully saturated loose sands. Liquefaction criteria in free field is defined as the excess pore pressure ratio equals to 1.0 (r_u=1), when the increase in excess pore water pressure generation (Δu) equals to the initial effective vertical stress (σ'_v). Formulation of the excess pore pressure ratio (r_u) was shown in equation 1.1.

$$r_u = \frac{\Delta u}{\sigma'_{v0}} \tag{1.1}$$

In 1976, Finn et al. developed an equation (1.2), which gives the relation between excess pore pressure in undrained condition and the change in volumetric strain in drained condition.

$$\Delta u = \frac{\Delta \varepsilon_{vd}}{\frac{1}{E} + \frac{n}{K_w}} \tag{1.2}$$

The excess pore pressure generation in partially saturated sands can be estimated by replacing bulk modulus of air-water mixture (K_{aw}) into the bulk modulus of water (K_w) in equation 1.2. Since the bulk modulus of air-water mixture is less than the bulk modulus of water, it is estimated, as the excess pore pressure generation in partially saturated sands will be less than the excess pore pressure generation in fully saturated sands. Koning (1963) developed an equation (1.3) which is mostly used in the calculation of air-water mixture bulk modulus.

$$K_{aw} = \frac{K_w u_w}{S u_w + (1-S) K_w} \tag{1.3}$$

In a cyclic loading such as earthquake load, an instantaneous undrained conditions occurs, water inside the voids does not dissipate and excess pore water pressure increases by number of cycles. Since, the total water pressure increases compared to initial conditions, effective vertical stress decreases during liquefaction. Liquefaction occurs when the initial effective vertical stress equals to excess pore water pressure. The undrained cyclic loading and consolidation stress conditions are shown in the Figure 1.1.

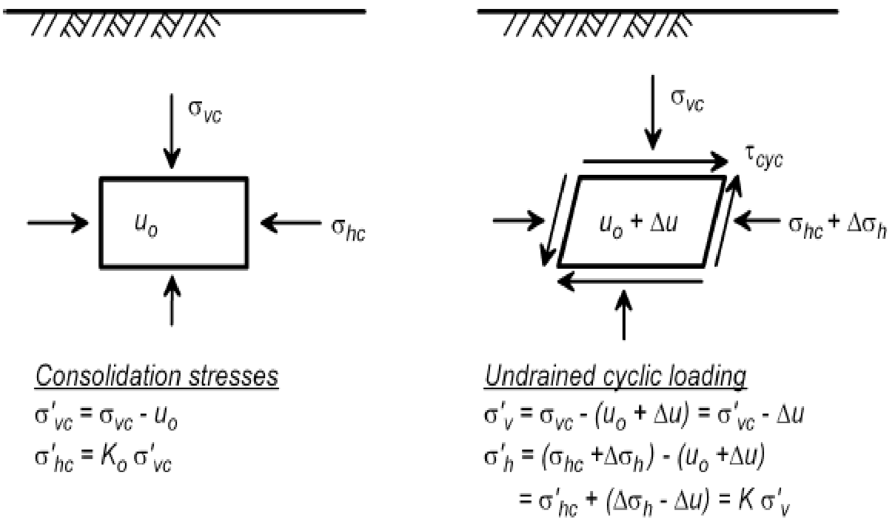


Figure 1.1 : Comparison of consolidation stresses and undrained cyclic loading conditions (Kramer, 1996).

The potential risk of existing structures on liquefiable soils is still an important issue to concern because of the destruction of cities and loss of life. Liquefaction induced failures caused huge damages in 1995 Kobe, 1999 Adapazari and 2011 Tohoku Earthquakes. Sand boils, liquefaction induced settlement and bearing capacity failures damaged many residential areas, roads and infrastructure systems.

The massive liquefaction and settlement damages in a port area in 1995 Kobe Earthquake is shown in Figure 1.2.

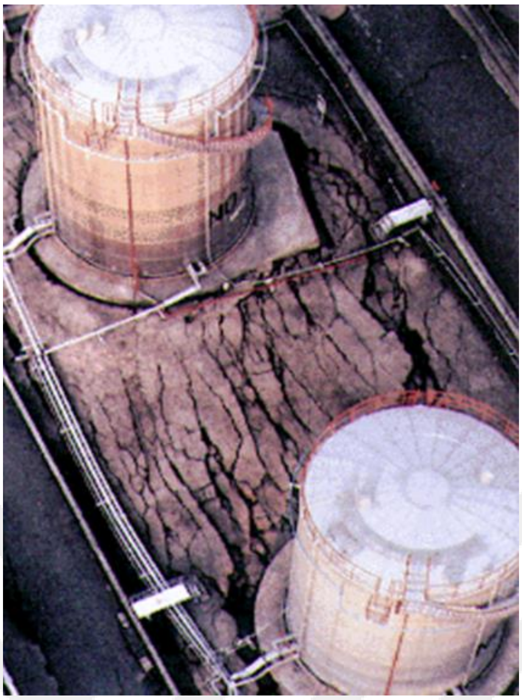


Figure 1.2 : Tanks in the port area. The ground shows signs of massive liquefaction and settlement. The tanks appear to be on pile-supported foundations (The January 17, 1995 Kobe Earthquake an EQE Summary Report).

Figure 1.3 shows a parking area which covered by a large scale sand ejection due to liquefaction phenomena occurred in 1995 Kobe Earthquake.

Figure 1.3 : Parking lot on reclaimed land near Ashiya. Sand covering the lot is evidence of large-scale liquefaction and sand ejection (The January 17, 1995 Kobe Earthquake an EQE Summary Report).

In 2011 Tohoku Earthquake; many roads, infrastructure systems, manholes and pipelines were damaged due to liquefaction. One of the case of liquefaction induced buckling and settling of roads in 2011, Tohoku Earthquake was shown in Figure 1.4. Excess pore pressure generation and large settlement damages can be easily seen in the figure below.

Figure 1.4 : Liquefaction in Urayasu city, outside Tokyo, created an uneven buckling and settling of roads and the surface (Toshifumi Kitamura/AFP/Getty Images).

The extensive liquefaction mitigation techniques are improved and used in the field to reduce the concluding hazards. Recent methods can be classified in the several main topics, which are using drainage and dissipating the excess pore water pressure, ground improvement for loose soils, using retaining structures to prevent the horizontal flow of the soil and using chemical treatments to improve the soil strength. Seed et al. (2003) classified liquefaction mitigation methods in six general categories. The first category contains the mitigation techniques related to excavation of liquefiable soils and compaction of new fills. The second part summarizes the several in-situ ground densification techniques related to compaction with vibratory probes, compaction piles and dynamic consolidation by using heavy tamping. Other types of ground treatments includes various draining and grouting systems such as permeation grouting, jet ground, deep mixing. The berms, dikes, sea walls and other retaining structures can be classified as fourth category to prevent the large lateral spreading caused by liquefaction. In the last categories, deep foundations and reinforced shallow foundations can be used as mitigation techniques against liquefaction. However, these techniques are quite expensive and they have some limitations to apply them for existing structures. Table 1.1 contains the general techniques of liquefaction mitigation.

Table 1.1 : General methods for soil liquefaction mitigation (Seed et al., 2003).

General Category	Mitigation Methods	Notes
Excavation and/or compaction	Excavation and disposal of liquefiable soils, Excavation and recompaction, Compaction (for new fill)	
In-situ ground densification	Compaction with vibratory probes (e.g.: Vibroflotation, Terraprobe), Dynamic consolidation (Heavy tamping), Compaction piles, Deep densification by blasting, Compaction grouting	-Can be coupled with installation of gravel columns -Can also provide reinforcement
Selected other types of ground treatment	Permeation grouting, Jet grouting, Deep mixing, Drains (Gravel drains, Sand drains, Prefabricated strip drains), Surcharge pre-loading, Structural fills	Many drain installation processes also provide in-situ densification.
Berms, dikes, sea walls and other edge containment structures/systems	Structures and/or earth structures built to provide edge containment and thus to prevent large lateral spreading	
Deep foundations	Piles (installed by driving or vibration), Piles (installed by drilling or excavation)	Can also provide ground densification
Reinforced shallow foundations	Grade beams, Reinforced mat, Well reinforced and/or post tensioned mat, Rigid raft	

1.2.1 Literature on the effect of degree of saturation on liquefaction resistance in fully saturated sands

In these literature researches, liquefaction resistance of fully saturated sands was examined by using cyclic triaxial, cyclic torsional shear and torsional simple shear testing devices. Degree of saturation, B-value, relative density, cyclic stress ratio were used as variable input parameters. Table 1.2 summarizes the researches based on the effect of degree of saturation on liquefaction strength of fully saturated sands.

Table 1.2 : Researches based on the liquefaction resistance of fully saturated sands.

Reference	Experimental Setup	Specimen Preparation Method	Variable Input Parameter	Evaluation of Liquefaction Resistance
Sherif et al. (1977)	Torsional simple shear	By circulation of deaired water with back pressure 0.25<B<1.0	S, B-value	B-value↓: N_L↑ S↓: Cyclic strength↑
Chaney (1978)	Cyclic Triaxial Test	By flushing with deaired water and using back pressure 0.67<B<1.0 D_r=53%, 93%	D_r, S, B-value, σ_{3c}, P_a, N	B-value↓: N_L↑ S↓: Δu↓ S↓, P_a↓: K_{aw}↓ S↓: Cyclic strength↑ @ constant N, S↑: Δu↑
Yoshimi et al. (1989)	Cyclic torsional shear tests	Air pluviation and saturation by using CO_2 gas without applying back pressure 70<S< 100 0.0<B<0.96 D_r=60%	S, B-value, CSR	B-value↓: N to DA=5%↑ S↓: Liquefaction resistance↑
Xia and Hu (1991)	Cyclic triaxial tests	Saturation by back pressure 0.7<B<1.0	S, B-value, P_0	B-value↓ or S↓: Liquefaction resistance↑ Back pressure↓: Liquefaction resistance↓
Tsukamoto et al. (2002)	Cyclic triaxial test	Air pluviation 0.0<B<1.0	V_p, D_r, B-value	B-value↓: V_p↓ B-value↓: CSR @ N_L↑ @ constant B-value, D_r↑: CSR@ N_L ↑ V_p is constant, D_r↑: CSR @ N_L ↑
	B: B-value CSR: cyclic stress ratio DA: double amplitude shear strain	D_r: relative density K_{aw}: air-water mixture bulk modulus N: number of cycles	N_L: number of cycles required to liquefaction P_0: atmospheric pressure P_a: axial load	S:degree of saturation Δu: excess pore water pressure V_p: P wave velocity

Several specimen preparation methods were used to get fully saturated samples such as air pluviation, circulation of deaired water by applying back pressure and saturation by using CO_2 gas without applying back pressure. Researches aimed to investigate the liquefaction response of fully saturated sands. However, it was observed when the specimen could not be fully saturated enough; the overestimated liquefaction resistance was achieved. Even small decrements in the degree of saturation increases the resistance against the liquefaction potential of the samples.

Sherif et al. (1977) investigated the effects of saturation degree on soil liquefaction in torsional simple shear device. A general relationship was formed between B-value and initial degree of saturation to determine the liquefaction resistance of soil as a function of initial degree of saturation. Soil specimen was prepared in a hollow cylinder which has 102 mm at the outside and 51 mm at the inside diameter also 25 mm at the outside and 13 mm at the inside height. In the test procedure, equal amount of vertical stress, outside and inside horizontal stresses were applied to the soil specimen and the sinusoidal shear stress was subjected from the top of the specimen. Partially saturated specimens were prepared by circulating varied amount of deaired water into the specimen with back pressure. Figure 1.5 shows the relation between the pore pressure rises by changing B values.

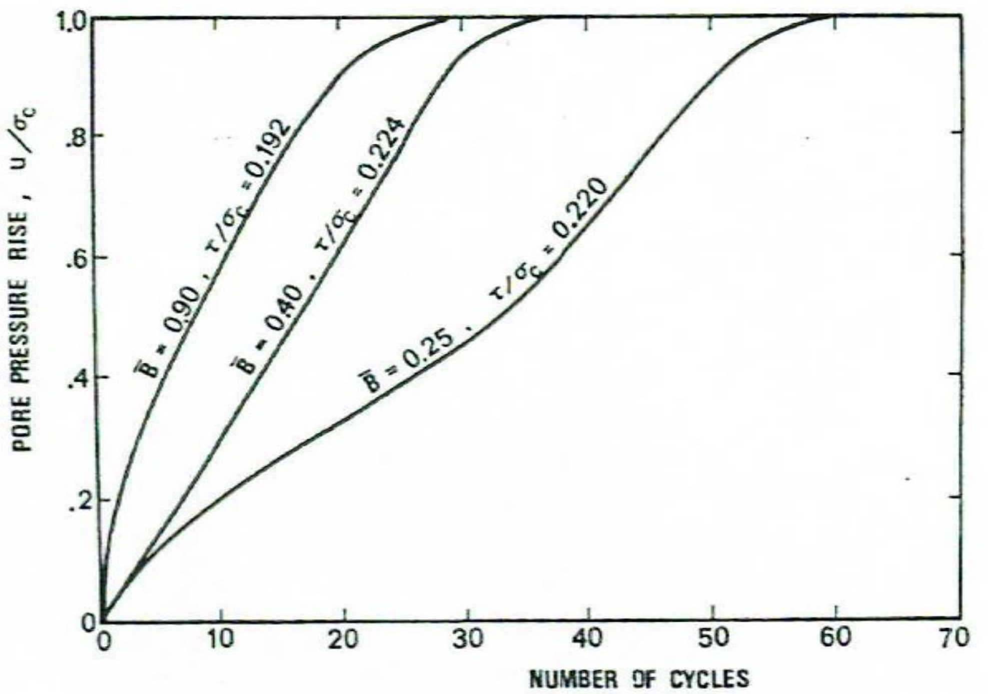


Figure 1.5 : Typical liquefaction data for low B and high B values (Sherif et al., 1977).

Figure 1.6 shows the liquefaction potential as a function of initial degree of saturation. According to the results, soil specimens liquefy even decreasing B values. However, the number of cycles required to liquefaction increases with decreasing degree of saturation.

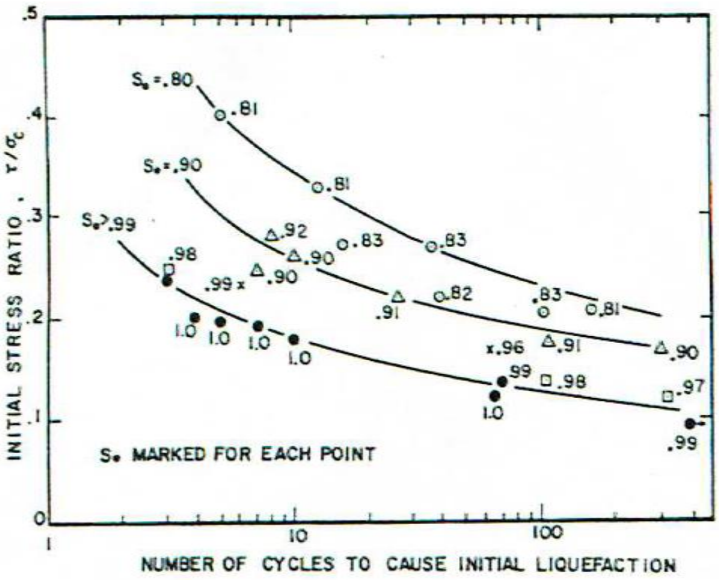


Figure 1.6 : Liquefaction potential as function of initial degree of saturation (Sherif et al., 1977).

Chaney (1978) investigated the saturation effects on the cyclic strength of sands in cyclic triaxial test device by performing stress-controlled tests. Specimens were tested at 53% and 93% relative densities and at the range from 0.67 to 1.00 B-values. Different degrees of saturation were achieved by using varying amount of deaired water and applying back pressure. Test results present that cyclic strength of the soil, which is the number of cycles required to reach 5% double amplitude axial strain at a specific cyclic stress ratio, increases by decreasing degree of saturation. Chaney stated that reducing B-value from 1.0 to 0.9 raises the number of cycles required to liquefaction as 1.7 times for dense sand and 16 times for loose sand. Additionally, cyclic strength was affected significantly by decreasing degree of saturation at low cyclic stress ratio, which is less than or equal to 0.3, compared to high cyclic stress ratio such as 0.45.

Yoshimi et al. (1989) performed cyclic torsional shear tests on hollow cylindrical specimen to investigate the liquefaction behavior of partially saturated sands. They analyzed the effect of degree of saturation on undrained cyclic shear strength of partially saturated sands. They used 100 mm in outside diameter, 60 mm in inside diameter and 100 mm in height sand specimens prepared by dry pluviation of Toyoura sand at 60 % relative density. In their research, fully saturated samples were prepared by using CO_2 gas with 2.5 kgf/cm^2 back pressures. Partial saturation was gained by applying varying amounts of CO_2 gas without back pressures. Specimens were consolidated isotropically under 1.0 kgf/cm^2. In the shear stress-controlled liquefaction test, cyclic torsional loading was applied with sinusoidal waves under undrained conditions at 0.1 Hz frequency. The typical liquefaction test result of Yoshimi et al. (1989) in fully saturated sand specimens was presented in Figure 1.7.

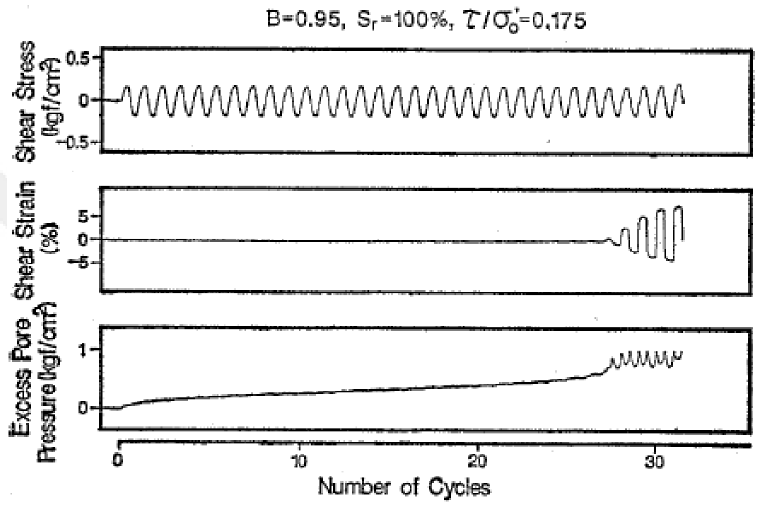


Figure 1.7 : Time histories of pore pressure and shear strain during liquefaction test for saturated specimen (Yoshimi et al., 1989).

The typical liquefaction test result of Yoshimi et al. (1989) in partially saturated sand specimens was presented in Figure 1.8.

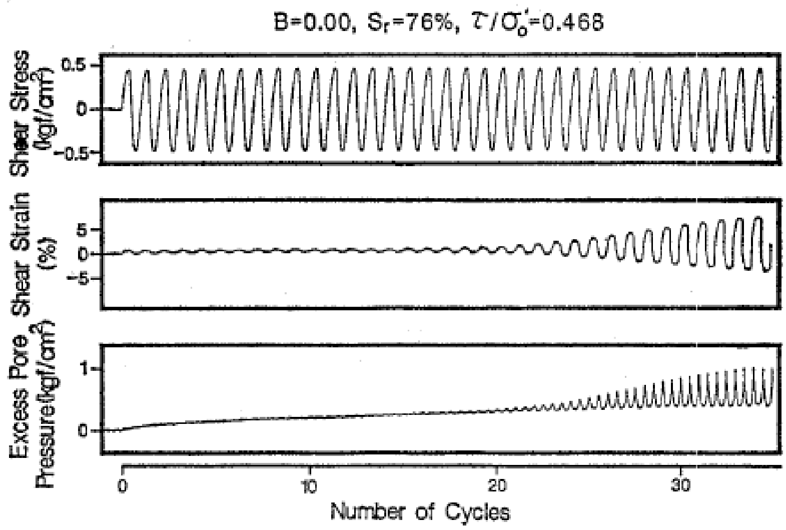


Figure 1.8 : Time histories of pore pressure and shear strain during liquefaction test for partially saturated specimen (Yoshimi et al., 1989).

The effect of degree of saturation on liquefaction characteristics of sand was demonstrated in Figure 1.9 (Yoshimi et al., 1989).

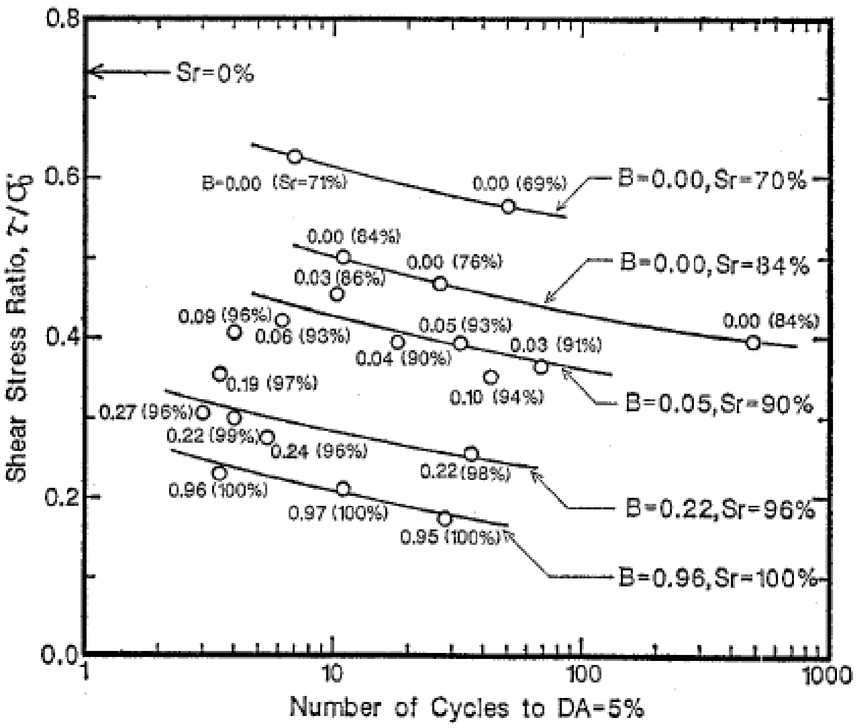


Figure 1.9 : Effects of degree of saturation on liquefaction characteristics of sand (Yoshimi et al., 1989).

According to Yoshimi et al. (1989), following results were found from undrained cyclic shear tests on sand at 60% relative density and degree of saturation between 70% to 100%: 1) Liquefaction resistance of partially saturated sand at 70% degree of saturation was three times higher compared to one of fully saturated specimens. 2) Liquefaction resistance of partially saturated sands increase by decrease in B-value. Nearly zero B-value was necessary to gain an important increase in liquefaction resistance. 3) Denser partially saturated sand specimen demonstrates higher undrained cyclic shear strength and less deformation behavior.

In 1991, Xia and Hu investigated the saturation and back pressure effect on the sand liquefaction resistance. They performed cyclic triaxial tests on the sand specimens with varying degree of saturation and back pressures. Specimens were prepared in three layers inside a latex membrane with dimensions of 50 mm in diameter and 120 mm in height and 60% relative density was gained by compacting of each layer. The different degrees of saturation were achieved by penetrating water into the specimen at varying time and applying vacuum pressure. After specimen preparation process, all specimens were consolidated under 98.1 kPa effective stress. Then, stress controlled cyclic loading liquefaction tests were performed. The liquefaction resistance behavior of tested specimens with changing number of cycles were demonstrated in Figure 1.10 at different degrees of saturation (Xia and Hu, 1991).

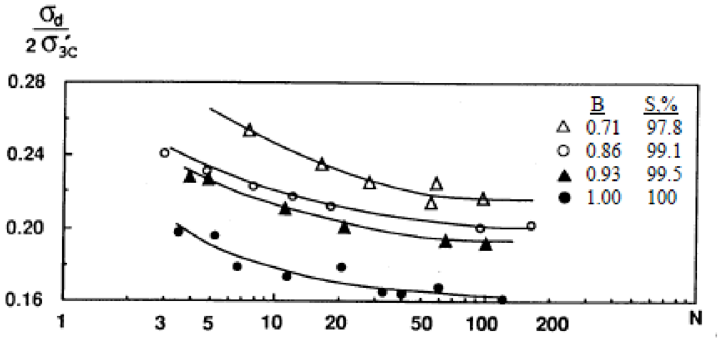


Figure 1.10 : Effect of degree of saturation (Xia and Hu, 1991).

The effect of back pressure on liquefaction resistance was presented in Figure 1.11. Xia and Hu (1991) stated that the liquefaction resistance increases linearly with decreasing degree of saturation and increasing back pressure.

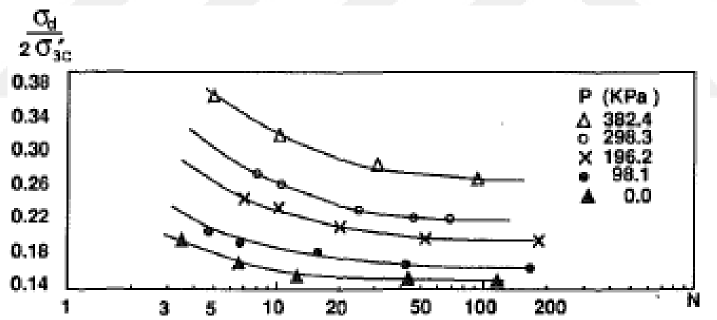


Figure 1.11 : Effect of back pressure (Xia and Hu, 1991).

Another research is about liquefaction resistance of partially saturated sand was examined by Tsukamoto et al. (2002) by considering longitudinal and shear wave velocities. Tsukamoto et al. manufactured a cyclic triaxial test device to measure both P and S wave velocities and to perform stress-controlled cyclic triaxial tests on the same specimen. They used poorly graded clean fine Toyoura sand with no fines. Sand specimens were prepared by air pluviation method with dimensions of 60 mm in diameter and 120 mm in height at the range of 30 to 70% relative density. The specimens were consolidated isotropically and B-value was measured. The saturation tests were performed under 200-400 kPa back pressure with the range of B-value as 0 to 0.5. Then, P and S wave velocities were measured. After wave velocity measurements, stress controlled cyclic triaxial tests were performed under undrained conditions at designated cyclic stress ratio $\sigma_d/(2\sigma'_o)$ with sinusoidal cycles at 0.1 Hz frequency until deformation of 5% double amplitude axial strain. The results of Tsukamoto et al. (2002) were shown in Figure 1.12 in terms of relation between number of cycles and cyclic stress ratio.

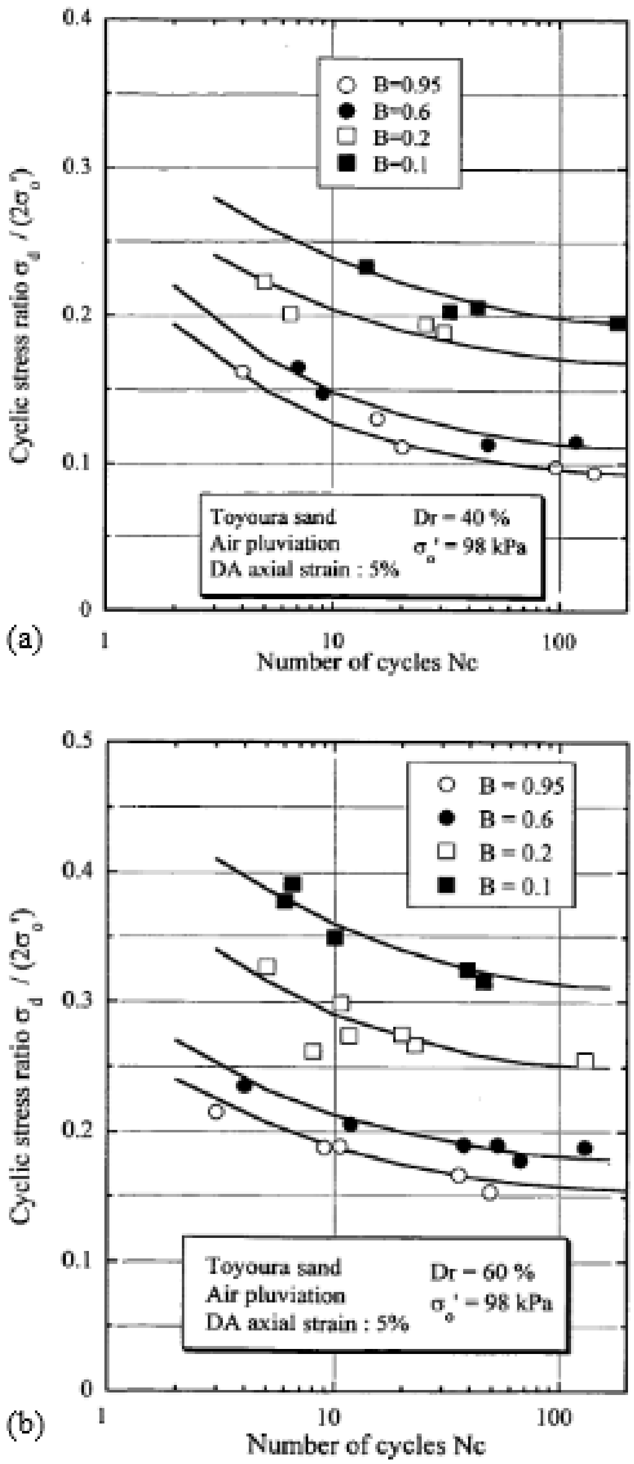


Figure 1.12 : Cyclic stress ratio versus number of cycles causing 5% DA axial strain (a)D_r=40%, (b)D_r=60% (Tsukamoto et al., 2002).

Cyclic strength versus B-value and P wave velocity relations were shown in Figure 1.13 (Tsukamoto et al., 2002).

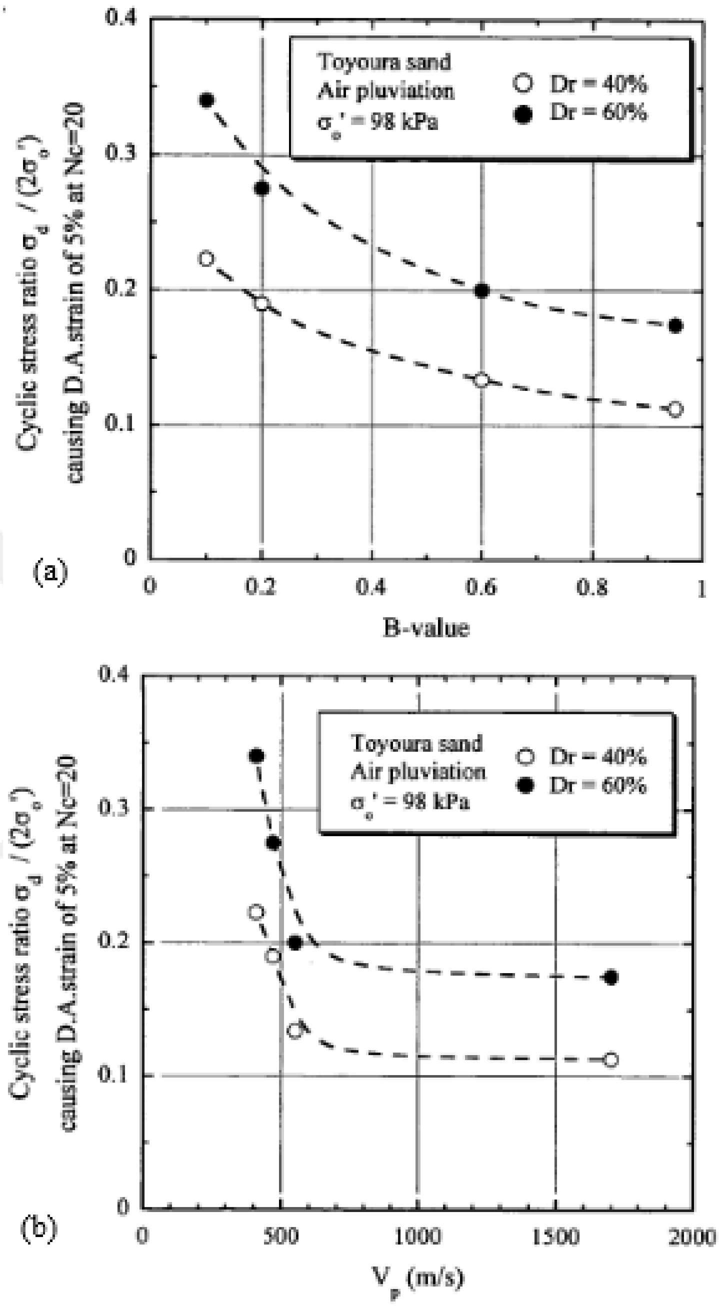


Figure 1.13 : (a)Cyclic strength versus B-value, (b)Cyclic strength versus P-wave velocity V_p (Tsukamoto et al., 2002).

According to their conclusions, liquefaction resistance of sands increases by decreasing degree of saturation and the degree of saturation can be demonstrated with both saturation ratio S_r or B-value. In addition, this study shows that P-wave velocity can be used as an indicator for degree of saturation. Tsukamoto et al. (2002) stated that the cyclic strength at zero B-value with 90% degree of saturation is greater twice as much as than the liquefaction resistance while B-value is 0.95.

1.2.2 Literature on the partial saturation method as a liquefaction mitigation technique

In recent researches, partial saturation method has been improved as a new liquefaction mitigation technique. There are extensive researches about the liquefaction resistance of partially saturated sands. As mentioned in the previous literature reviews about the effect of degree of saturation on the liquefaction resistance of fully saturated sands, even small decrements in the degree of saturation increases the liquefaction resistance of loose liquefiable sands. There are several cyclic triaxial, undrained triaxial compression and extension, shaking table and centrifuge tests performed on the partially saturated sands. The purpose of these researches is to investigate the liquefaction resistance of partially saturated sands in the free field and under foundation conditions. The liquefaction resistance was examined according to the cyclic stress ratio, maximum excess pore pressure generations and maximum number of cycles. Partially saturated sand specimens were prepared by using various methods such as moist undercompaction and passing deaired water into the specimen, air injection, air pluviation and changing the ground water level, applying different back pressure, wet pluviation with chemical powder and creating gas bubbles inside the voids. Degree of saturation, B-value, relative density, atmospheric pressure, surcharge load, shear strain, maximum acceleration and width of desaturation zone were used as variable input parameters in the tests.

The evaluation of liquefaction resistance of literature reviews about the partial saturation method as liquefaction mitigation technique in the free field condition can be summarized as follows: 1) While, the degree of saturation is decreasing the cyclic stress ratio (CSR) increases at the constant number of cycles required to liquefaction. 2) While, the degree of saturation is decreasing, the relative density is increasing or the cyclic shear strain is decreasing, the maximum excess pore pressure ratio decreases or the maximum number of cycle increases. Additionally, the liquefaction response of partially saturated sands under the foundation is still a discussible issue. At this point, the load of the foundation and the degree of saturation have important effects on the excess pore pressure generation. Under the foundation, the excess pore pressure ratio decreases by decreasing degree of saturation and by increasing surcharge load. Table 1.3 summarizes the recent studies related to the partial saturation method as a liquefaction mitigation technique.

Table 1.3 : Researches based on the partial saturation method as a liquefaction mitigation technique.

Reference	Experimental Setup	Specimen Preparation Method	Variable Input Parameters	Evaluation of Liquefaction Resistance
Okamura and Soga (2006)	Cyclic triaxial test	PS: Moist undercompaction and passing deaired water into the specimen 70%<S<100% D_r=40%	D_r, S, σ'_c, P_0	@ constant S, σ'_c↑:CSR↑ S↓: CSR @ N_L ↑ ε^*_v↓: Liquefaction resistance ratio↓
Okamura and Teraoka (2006)	Shaking Table Test	PS: Air injection 98%<S<100%	D_r, S, P_a, a_{max}, width of desaturation zone	*Free Field:* P_a↓: N_L↑ @constant ε_v, a_{max}↓: N_L↑ S↓: r_u @constant N ↓ *Under foundation:* S↓: r_u @constant N ↓
Takemura et al. (2009)	Centrifuge test	PS: Air pluviation and by lowering and increasing ground water table under 50g centrifugal acceleration	S, p_f	S↓: r_u ↓ @constant N S↓: N_{max} ↑ @constant $r_{u,max}$
Kamata et al. (2009)	Undrained triaxial compression and extension tests	PS: Wet tamping, air pluviation methods and saturation with back pressure B-value=0.12, 0.64, 0.95 D_r=20%, 40%, 60 %	B-value, S, D_r, q	D_r ↑: undrained shear strength ratio ↑ B↑: undrained shear strength ratio ↓
Eseller-Bayat et al. (2013)	Cyclic simple shear liquefaction box (CSSLB), (1D) shaking table	PS: Wet pluviation with chemical powder 40%<S<100%	S, D_r, γ	S<90%: $r_{u,max}$<1.0 S↓or D_r↑, or γ↓: $r_{u,max}$↓ S↓or D_r↑, or γ↓: N_{max}↑
Marasini and Okamura (2015)	Centrifuge test	PS: Air injection	S, D_r, d, q	*Free Field:* S↓: N_L ↑ *Under Foundation:* *S*↓*:* r_u↓
Nababan (2015)	Laminar Box on shaking table	PS: Wet pluviation with the use of a chemical powder	S, γ, d, a_{max},	S↓: Δu↓
Zeybek and Madabhushi (2016)	Centrifuge test	PS: Air injection	S, d, q	*Under Foundation:* *S*↓ q↑*:* r_u↓ d↑ q↓: $r_{u,max}$↑
a_{max}: max. acceleration γ: shear strain ε_v: volumetric strain B: B-value	CSR: cyclic stress ratio d: depth DA: double amplitude shear strain	D_r: relative density K_{aw}: air-water mixture bulk modulus N: number of cycles N_L: number of cycles required to liquefaction	P_0: atm. pressure P_a: axial load q: surcharge load	r_u: excess pore pressure ratio S:degree of saturation Δu: excess pore water pressure V_p: P wave velocity

Okamura and Soga (2006) explained that initial confining pressure and initial pore pressure have also effects on the liquefaction resistance of partially saturated sands. Specimens were prepared at 5% water content and at 40% relative density by tamping in a mold with 50 mm in diameter and 100 mm in height. Then, 98 kPa back pressure was applied and the amount of water was measured for an hour. The volume of air was calculated by using Boyle’s law with the help of volume of water entered into the specimen. After specimen preparation, undrained cyclic triaxial test was performed at 0.01 Hz under applied initial effective stress and back pressure. Okamura and Soga (2006) examined the effect of initial effective confining pressure on the relationships between cyclic stress ratio and number of cycles as seen in Figure 1.14.

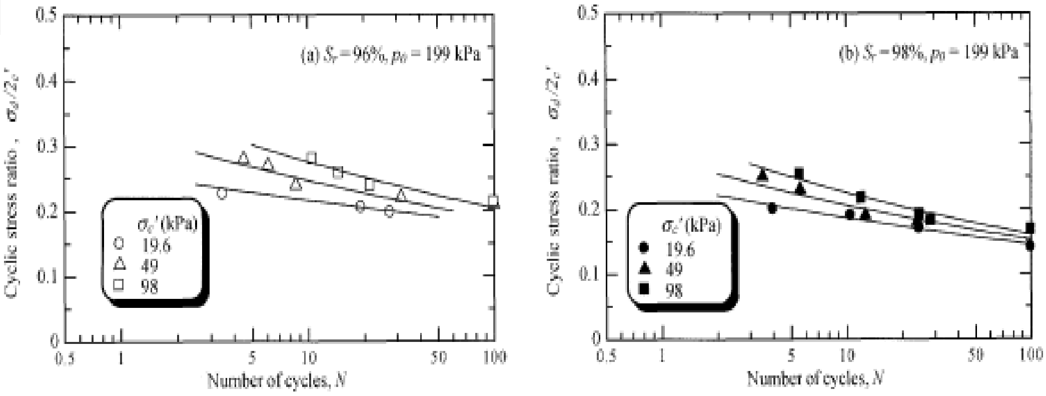


Figure 1.14 : Effect of initial effective confining pressure on the relationships between cyclic stress ratio and number of cycles (Okamura and Soga, 2006).

The effect of initial pore pressure on the relationships between cyclic stress ratio and number of cycles were shown in Figure 1.15. Okamura and Soga (2006) emphasized that liquefaction resistance of partially saturated sands increases while the initial confining stress increases and the initial pore pressure decreases.

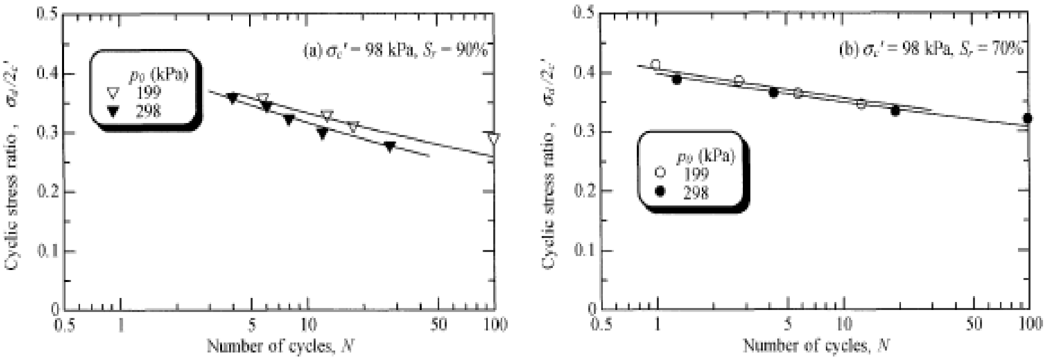


Figure 1.15 : Effect of initial pore pressure on the relationships between cyclic stress ratio and number of cycles (Okamura and Soga, 2006).

Additionally, Okamura and Soga (2006) stated that the cyclic stress ratio increases significantly as twice as while the degree of saturation decreases from 100% to 90%. However, the degree of saturation under 90% increases the liquefaction resistance, which required cyclic stress ratio to deform double amplitude axial strain as 5% at 20 cycles at a slow rate.

Okamura and Teraoka (2006) performed several 1 g shaking table tests to examine the performance of desaturation method as a liquefaction mitigation technique both in the free field and under structure conditions. Specimens were prepared in a box with 90 cm in length, 30 cm in width and 60 cm in height. Desaturation was achieved by using a 5 mm diameter pipe to inject gas bubbles into the specimen. Desaturated specimens were subjected to various atmospheric pressures and the model was shaken at 0.17g, 0.33g and 0.40g peak accelerations at 5 Hz frequency. Figure 1.16 shows the experimental setup (Okamura and Teraoka, 2006).

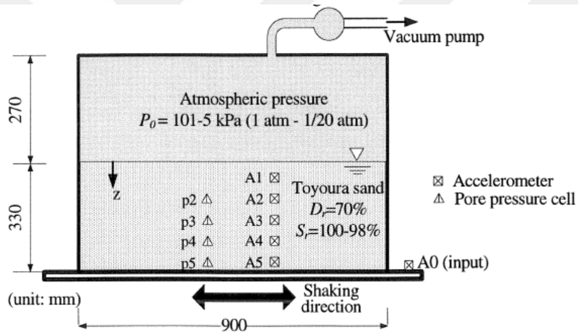


Figure 1.16 : Schematic of model (Okamura and Teraoka, 2006).

Figure 1.17 shows the excess pore pressure generation on saturated and desaturated models in the free field condition at 101 kPa atmospheric pressure (Okamura and Teraoka, 2006).

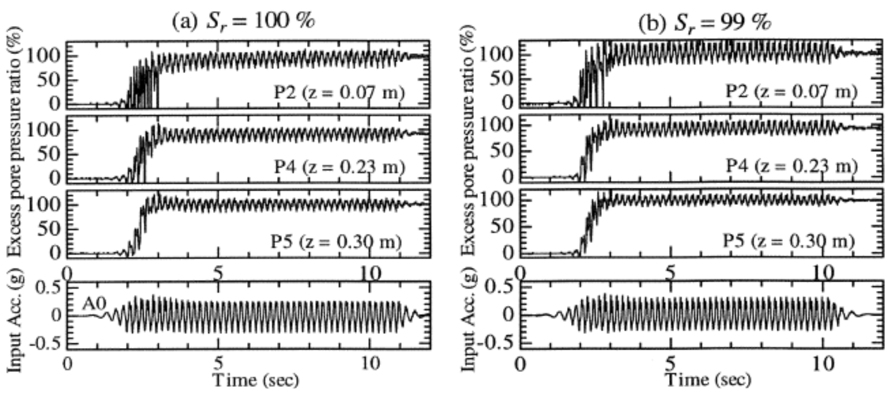


Figure 1.17 : Excess pore pressure responses of saturated and desaturated models under atmospheric pressure of 101 kPa (A_{max}=0.33g) (Okamura and Teraoka, 2006).

Figure 1.18 shows the effect of atmospheric pressure on the excess pore pressure generation on desaturated models. Okamura and Teraoka (2006) stated that tests at free field condition with lower vacuum pressures increase the number of cycles required to liquefaction.

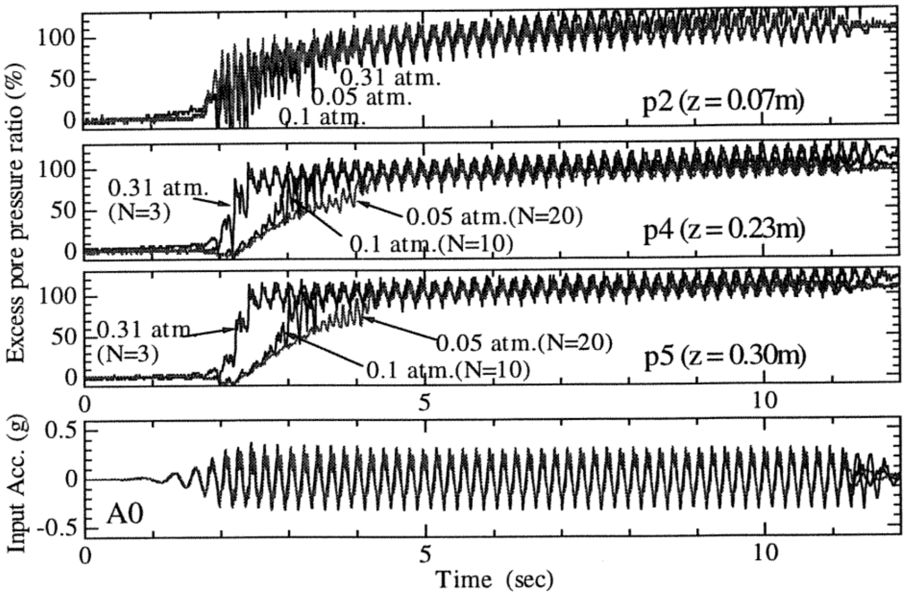


Figure 1.18 : Excess pore pressure responses of desaturated models (S_r=99%) at different atmospheric pressure (A_{max}=0.33g) (Okamura and Teraoka, 2006).

In 2009, Takemura et al. investigated the dynamic behavior of partially saturated sand under centrifuge tests at 50g centrifugal acceleration. The partial saturation of specimen was measured by time domain reflectometer and pore pressure transducers. Then, shaking tests were performed for partially saturated sand under a model of structure. Specimens were prepared at 60% relative density with silica sand and coarse sand material by using air pluviation method in a shear box with 440 mm in width, 150 mm in breadth and 310 mm in height. The specimen was saturated with deaired water and a mass of 2.5 kg foundation model was placed onto the specimen surface with the dimensions of 80 mm x 150 mm in area and 80 mm in height. Partial saturation was achieved by draining and recovering the water. Then, the centrifuge tests were performed with horizontal sinusoidal waves at 100 Hz frequency for 0.2 seconds. According to Takemura et al., centrifuge test is applicable to get partially saturation by decreasing and increasing water level. Desaturation process is suitable to apply for both free field and under structure conditions. As a results of the test, settlements under footing was smaller on the partially saturated sand compared to the fully saturated conditions.

Kamata et al. (2009) conducted another research related to undrained shear strength of partially saturated sand. They performed undrained triaxial compression and extension tests on Toyoura sand. Loose sand specimens at D_r=20% were prepared by wet tamping method and specimens with D_r=40% and D_r=60% were prepared by air pluviation. After specimen preparation process, 98 kPa effective confining pressure was applied for isotropic consolidation and the samples were saturated with applying back pressure until required B-value is achieved. Then, undrained triaxial compression and extension tests were applied with constant mean principal stress as $p = (\sigma_a+2\sigma_h)/3$ where σ_a represents the axial stress and σ_h represents the horizontal stress. As a result, Kamata et al. (2009) stated that gas bubbles inside the voids of partially saturated sands change the compressibility of the air-water mixture and affect the pore pressure generation during undrained loading.

Eseller (2004) and Yegian et al. (2007) improved a new method, which is Induced Partial Saturation (IPS) as liquefaction mitigation technique. IPS technique is improved to decrease the degree of saturation by creating entrapped gas in the voids of the soil. Gas in the voids decreases the potential of excess pore water pressure increment during liquefaction. The recent liquefaction mitigation methods are generally applicable for new structures and they are quite expensive methods. However, IPS method can be applied for both new and existing structures and it presents economical solutions. Figure 1.19 shows concept of IPS method by using entrapped gas/air (Eseller-Bayat, 2009).

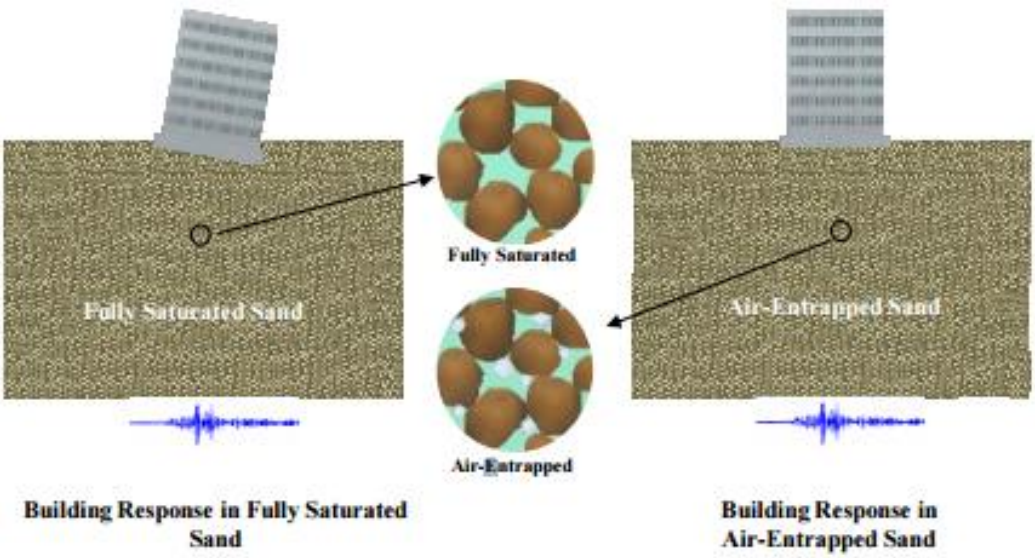


Figure 1.19 : Concept of liquefaction mitigation using entrapped gas/air (Eseller-Bayat, 2009).

Figure 1.20 shows the distribution of water and gas bubbles in the voids of partially saturated sand (Eseller-Bayat, 2009).

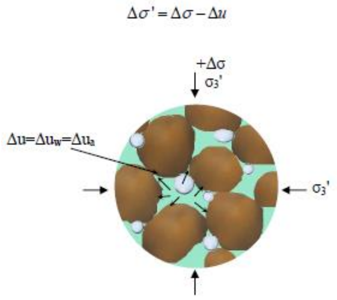


Figure 1.20 : Partially saturated sand element: sand particles, water and air bubbles in the voids (Eseller-Bayat, 2009).

Eseller-Bayat et al. (2013) performed shaking table tests on partially saturated sands and examined the degree of saturation effect on the liquefaction resistance. They could perform tests under small effective vertical stresses. Figure 1.21 demonstrates the typical cyclic simple shear strain tests performed on partially saturated sand specimens and the generation of excess pore pressure ratio by varying degree of saturation (Eseller-Bayat et al., 2013).

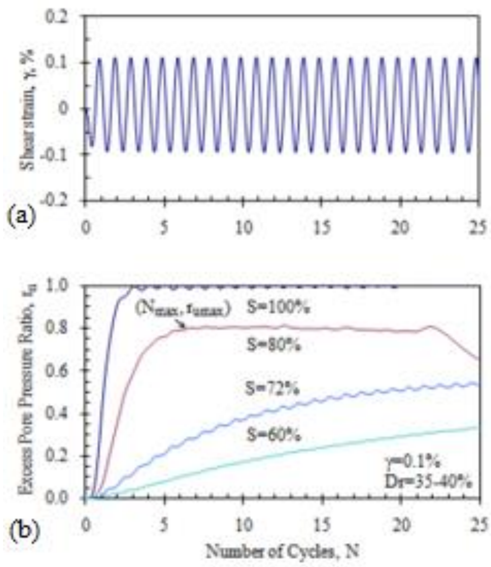


Figure 1.21 : (a)Typical cyclic simple shear strain history applied on partially saturated sand specimens, (b)Comparison of excess pore pressure ratio (r_u) for different degrees of saturation (γ=0.1%, σ'_v=2.5 kPa) (Eseller-Bayat et al., 2013).

Eseller-Bayat et al. (2013) investigated the liquefaction resistance of partially saturated sands in a cyclic simple shear liquefaction box (CSSLB) on the shaking table. CSSLB was manufactured as dimensions of 19 x 30 cm in inside plan and 49 cm in height. The box has two fixed and two rotating side walls, which connected to the bottom plate of CSSLB. The side view of the box and the experimental setup was shown in Figure 1.22 (Eseller-Bayat et al., 2013).

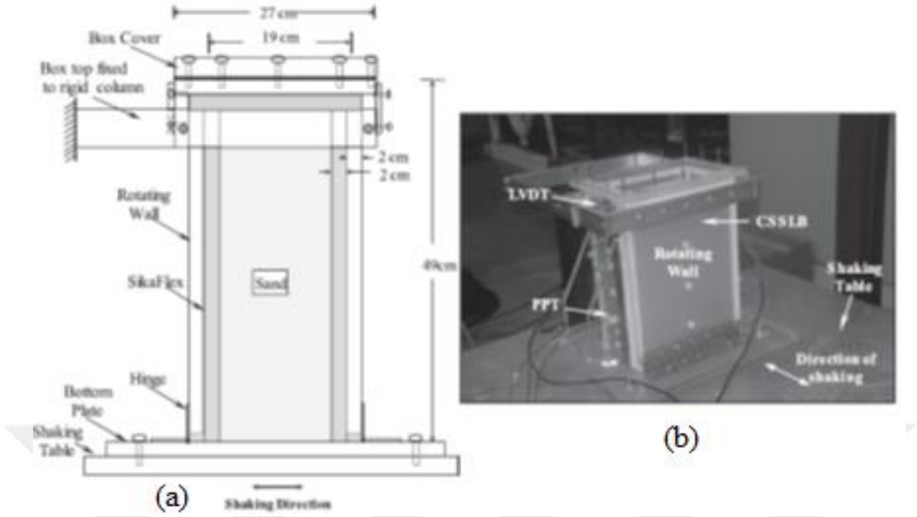


Figure 1.22 : (a)Side view of CSSLB. (b)Experimental setup (Eseller-Bayat et al., 2013).

Bender elements and bender disks were used in addition to pore pressure and displacement transducers to observe the uniformity of the prepared specimens. Sodium perborate monohydrate chemical powder (Efferdent) was used for generation of gas bubbles inside the voids to reduce the degree of saturation of the sand specimen and wet pluviation method was applied to prepare partially saturated specimens by mixing chemical powder and Ottawa sand. Uniformly distribution of oxygen bubbles was monitored by using a high-resolution digital camera. The digital image of partially saturated sand specimen was demonstrated in Figure 1.23 (Eseller-Bayat et al., 2013).

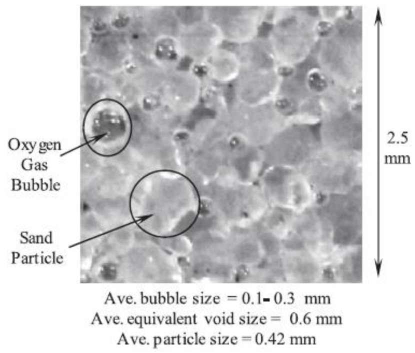


Figure 1.23 : Partially saturated sand specimen prepared through wet pluviation with Efferdent–dry sand mix (S=80% from phase relations, S=77% from the digital image) (Eseller-Bayat et al., 2013).

Several shaking table tests were performed on partially saturated sands at D_r=20-67% and 40%<S<90% under γ=0.01-0.2% and in a frequency range of 4-10 Hz at low effective vertical stress such as σ'_v=2.5 kPa. Test results show that excess pore pressure ratio reduces with reducing degree of saturation, decreasing shear strain and increasing relative density. Eseller-Bayat et al. emphasized that $r_{u,max}$ generation does not reach to initial liquefaction criteria in partially saturated sand specimens. Therefore, $r_{u,max}$ and N_{max} can be determined clearly by reducing degree of saturation in large size specimen shaking table tests.

Eseller-Bayat et al. (2013) developed an empirical model, which named as RuPSS to examine the liquefaction response of partially saturated sands by using the experimental results gained from cyclic simple shear strain tests in CSSLB. Experiments were performed in a range of relative density D_r=20-67% and degrees of saturation from 40% to 90% under γ=0.01-0.2% cyclic shear strain. However, small effective vertical stresses such as σ'_v=2.5 kPa could be applied during tests. The purpose of the empirical model was to investigate excess pore pressure ratio (r_u) generated under dynamic loading in partially saturated sands. RuPSS model includes two main sections, which are related to calculate $r_{u,max}$ and r_u generations. Maximum excess pore pressure ratio was represented as a function of degree of saturation, relative density and cyclic shear strain in equation 1.4. Relation in between r_u and $r_{u,max}$ was demonstrated in equation 1.5 as a function of the ratio of equivalent number of cycles (N_γ) occurred during an earthquake to maximum number of cycles (N_{max}) which generated the maximum excess pore pressure ratio. Finally, excess pore pressure ratio in partially saturated sands was achieved as a combination of f_1 and f_2 functions in equation 1.6.

$$r_{u,max} = f_1(S, D_r, \gamma) \tag{1.4}$$

$$\frac{r_u}{r_{u,max}} = f_2\left(\frac{N_\gamma}{N_{max}}\right) \tag{1.5}$$

$$r_u = f_1 \times f_2 = f(S, D_r, \gamma, \sigma'_v, M) \tag{1.6}$$

Eseller-Bayat et al. (2013) stated that the degree of saturation has a main effect on $r_{u,max}$ generation in partially saturated sands compared to the effect of relative density and cyclic shear strain according to test results. Thus, $r_{u,max}$ generation was modelled mainly based on degree of saturation. The effect of degree of saturation on $r_{u,max}$

generation was examined under different shear strain levels and relative densities. Excess pore pressure ratio can be calculated as a normalization of ($r_u/r_{u,max}$) to number of cycles (N/N_{max}) in equation 1.7 (when $N_\gamma/N_{max} \leq 1$) and 1.8 (when $N_\gamma/N_{max} > 1$).

$$\frac{r_u}{r_{u,\max}} = f_2\left(\frac{N_\gamma}{N_{\max}}\right) = \left\{ \frac{sin\left[\left(\frac{N_\gamma}{N_{max}} - 0.5\right) \times \pi\right] + 1}{2} \right\}^{\theta} \tag{1.7}$$

$$\frac{r_u}{r_{u,max}} = 1 \tag{1.8}$$

Figure 1.24 shows the comparisons of maximum excess pore pressure ratio obtained from laboratory data and model predictions (Eseller-Bayat et al., 2013). It is observed that the RuPSS model is successful to simulate the experimental results.

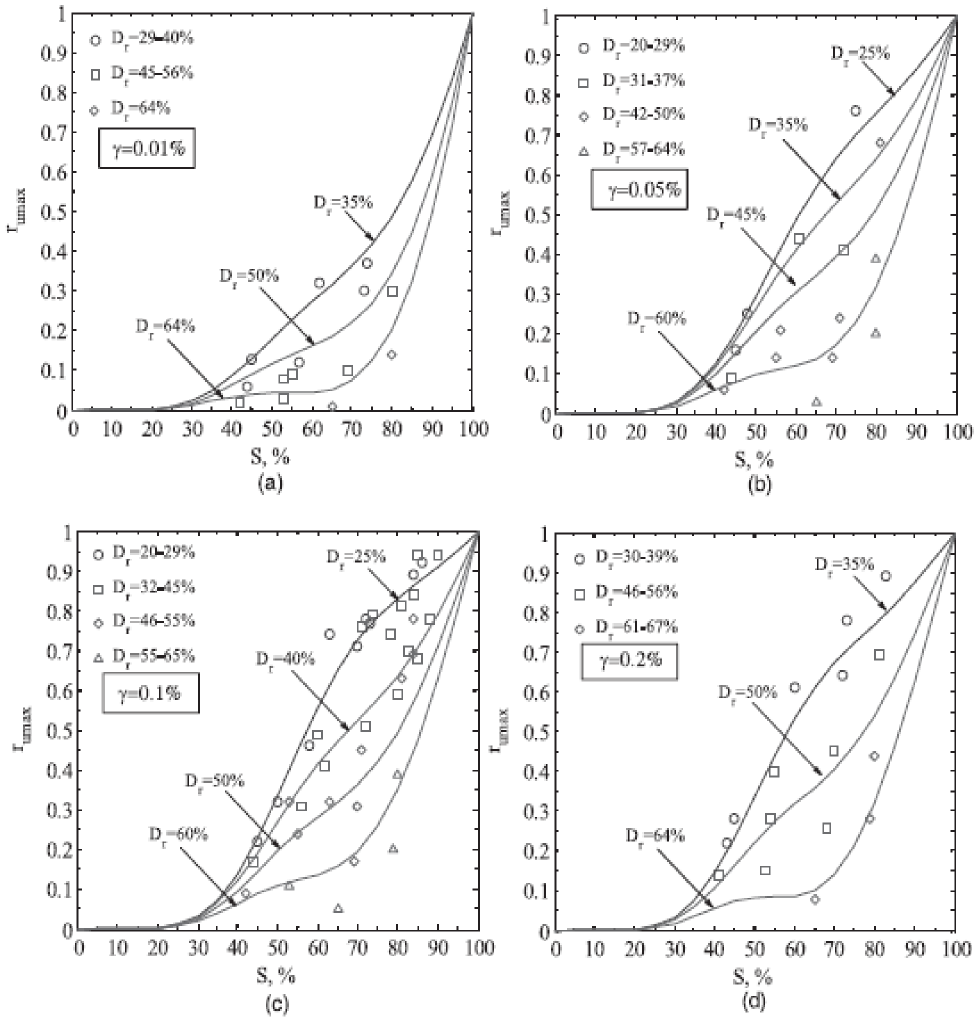


Figure 1.24 : Comparisons of $r_{u,max}$ from laboratory data and model predictions. (Eseller-Bayat et al., 2013).

Marasini and Okamura (2015) studied the liquefaction response of partially saturated soils in centrifuge tests to investigate the liquefaction-induced settlements under light structures. Partially saturation at S=85% and S=87% were achieved by using air injection method. The foundations of light weight structures were modelled with 10 kPa and 35 kPa base contact pressures in 1/50 scale under 50g centrifugal acceleration. The experimental results were compared with a numerical model by using Coupled Analysis of Liquefaction (LIQCA-2D) program in terms of excess pore pressure ratio, volumetric strain distributions and settlements. In free field condition, the number of cycles necessary to liquefaction increases by desaturation. Under the light and heavy load foundations, maximum excess pore pressure ratio decreases by decreasing degree of saturation and by increasing depth. The decrease in excess pore pressure generation is significant at the center compared to the edges of the structure. Additionally, settlement amount is lower in partially saturated specimen than fully saturated specimen.

Nababan (2015) studied the development of Induced Partial Saturation (IPS) method and its application in large size laboratory specimens and in the field. Partially saturated specimens were prepared by using sodium percarbonate chemical powder. Gas bubbles were generated as a product of sodium percarbonate-water chemical reaction. Specimens were tested in a large laminar box on the shaking table and the test results confirmed that excess pore pressure generation decreases with decreasing degree of saturation.

As a recent research, Zeybek and Madabhushi (2016) performed centrifuge tests to analyze the liquefaction resistance of air injected partially saturated sands under shallow foundation with different bearing pressures. Experiments were performed at 70g centrifugal acceleration. Dry pluviation method was used to prepare a liquefiable sand specimen at 40% relative density and 240 mm in height. The saturation was applied by using hydroxypropyl methylcellulose with a viscosity 70 times that of water. The specimen was vacuumed at 90 kPa pressure and then flushed with CO_2 as three times. Partially saturated specimens were prepared by using varying mass and volume relations. The testing model simulates 16.8 m depth in the prototype. Air bubbles were injected into the saturated specimen by using a rubber air curtain hose such as 0.5 mm in diameter and 5 mm in length. After specimen preparation process, a shallow foundation model, 3.5 m in width and 1.75 m in height, was made by using different materials to simulate the foundation of heavy and light structures with bearing pressures of 135 kPa and 50 kPa at 65g respectively. Excess pore pressure generation in fully and partially saturated specimens under the shallow foundation of both heavy and light structures were shown in Figure 1.25 (Zeybek and Madabhushi, 2016).

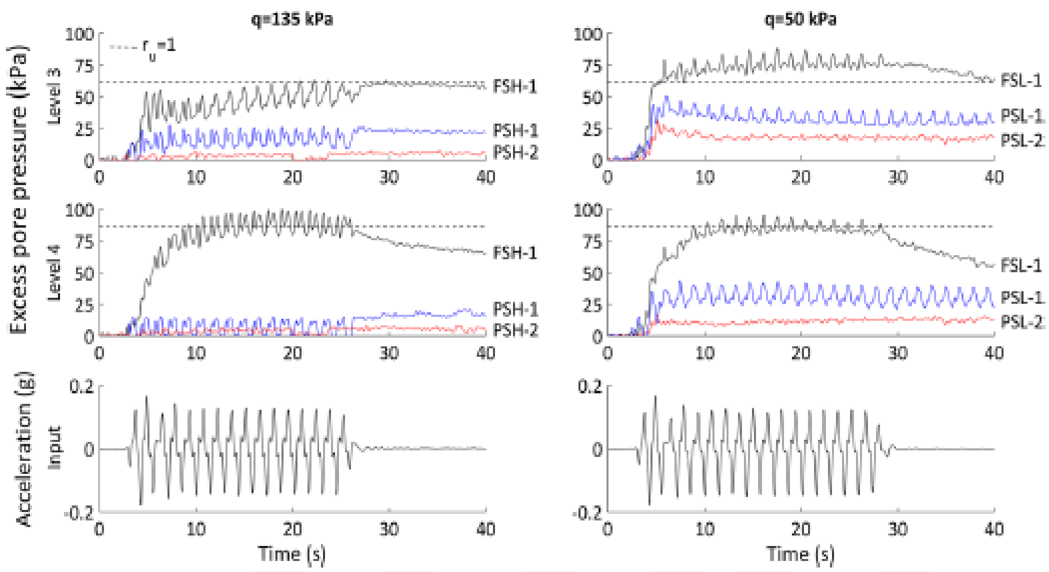


Figure 1.25 : Excess pore pressure–time histories measured beneath the shallow foundation (Zeybek and Madabhushi, 2016).

According to test results, excess pore pressure generation decreases by decreasing degree of saturation under light and heavy structures. It was observed that the decrease in excess pore pressure generation is significant under heavy structure compared to light structure. Excess pore pressure generation does not reach to liquefaction criteria (r_u=1.0). Thus, it is possible to determine $r_{u,max}$ and N_{max} in large size specimen centrifuge test.

1.2.3 Literature on researches performed by using dynamic simple shear testing device

There are many experimental researches performed in dynamic simple shear testing device related to determination of dynamic behavior of soils.

In 1987, Yıldırım examined the dynamic behavior of clays under different cyclic loadings by using stress-controlled dynamic simple shear test device. Undisturbed clay samples taken from Halic area in Istanbul were used in the tests. The shear stress-shear strain behavior of clay samples and the effect of loading frequency on that behavior were investigated under cyclic loading conditions. In addition, cyclic shear strength of clay samples were determined under undrained cyclic loading conditions. Before static loading and during static loading, the effect of different shear stress amplitudes and number of cycles on the static strength of the samples were investigated and mathematically modelled.

In 1991, Kara studied the dynamic behavior of normally consolidated clays under cyclic loading conditions. The clay samples were prepared at high water contents and consolidated. Tests were performed in dynamic simple shear and dynamic triaxial devices. Changes in shear stress-shear strain relation and cyclic strength of the samples were observed by time. The test stopping conditions were determined according to stabilization of pore water pressure for tests performed at low frequency loading and for other tests, the stopping condition were chosen according to $\pm$10% shear strain deformations. The test results show that the pore water pressure and shear deformations increase and cyclic strength of samples decrease by increasing number of cycles and shear stresses at low frequencies.

Hazirbaba (2005) examined the pore pressure generation behavior of clean sands and silty sands by using GCTS cyclic direct simple shear tests under strain-controlled conditions. The various specimen preparation techniques such as dry pluviation, water sedimentation, moist undercompaction and slurry deposition were used in the research. Specimens were prepared inside a wire reinforced membrane. The effect of relative density on pore water pressure generation was examined in clean sands. In addition, the effect of experimental setup was investigated by comparing the excess pore water pressure generation gained from tests performed in cyclic triaxial and cyclic direct simple shear devices. Additionally, the effect of non-plastic fines on excess pore water pressure generation was measured by changing fine content and void ratio relations.

Kayalı (2008) investigated the shear strength properties of undisturbed clay samples under cyclic loading conditions in cyclic simple shear testing device. Stress controlled and two-way sinusoidal wave loading were performed for all tests. Three different cyclic loading stages were applied to the specimen. In the first two stages, pore water pressure was dissipated by drainage and at the last stage; static shear load was applied to the specimen at undrained condition. The effect of pore water pressure, shear strain and consolidation settlement on the cyclic stress ratio were determined. The undrained shear strength of undisturbed clay samples change by cyclic loading. As a result, post-cyclic undrained shear strength increased when cyclic stress ratio was greater than 0.34 and under this level, the post-cyclic undrained static strength decreased.

Wichtmann et al. (2013) performed undrained cyclic triaxial and direct simple shear (DSS) tests on high quality undisturbed samples which taken from Norwegian clay at different depths. Different shear stress amplitudes, frequencies and various specimen geometries were used in the tests. According to test results, changes in the undrained cyclic strength and changes in pore water pressure by average shear stress were determined. Wichtmann et al. stated that the undrained cyclic strength, which changes significantly with frequency, is higher for samples taken from the shallow depths.

Fonseca et al. (2015) performed stress-controlled cyclic direct simple shear tests to determine the effect of stress densification in liquefaction resistance. In the specimen preparation procedure, moist tamping method was used with a water content of 5% and the specimens have dimensions of 72 mm in diameter and 38 mm in height. Soil specimens were prepared at both saturated and dry conditions inside a rubber membrane which surrounded by Teflon rings that give an anisotropic confinement to the specimen when the vertical confining stress affected. In the test procedure, the initial static shear stresses were not applied to the specimen and the constant volume conditions were used during tests. In addition, several initial vertical confining stresses such as 100 kPa, 300 kPa and 500 kPa were applied to the specimen. According to test results, at the same relative densities, cyclic resistance ratio (CRR) is high under higher confining stresses and by increasing number of cycles, CRR decreases.

1.3 Hypothesis

As stated before the purpose of this thesis is to investigate the undrained behavior of the partially saturated sands under cyclic loading and to determine the effect of degree of saturation, shear strain, initial effective stress and back pressure on the excess pore water pressure generation. Under this goal, it is expected to observe excess pore water pressure generations will be less than those of fully saturated sands and the excess pore water pressure generations will be less in lower shear strain levels, and at higher effective stresses. The excess pore water pressure generations is expected to increase as the back pressure increases since the gas bubbles in the voids would get smaller in volume and the compressibility of the pore fluid would reduce. Therefore as the effective stress increases (which means the depth increases in the field), excess pore water pressure ratio (r_u) would reduce, however as the depth increases, the back pressure should increase, which results in higher r_u. The test results will be examined in detail in order to observe the couple effect of effective stress and the back pressure. In addition, Eseller-Bayat (2009) performed shaking table tests to investigate the seismic response of partially saturated sands and improved an empirical model (2013). However, Eseller-Bayat et al. (2013) could study under small effective stresses in shaking table test device. This research will also be helpful to improve that empirical model by the effect of high effective vertical stresses on the undrained dynamic response of partially saturated sands.

2. EXPERIMENTAL SETUP FOR DYNAMIC SIMPLE SHEAR TESTS

In this section, the dynamic simple shear test device with confining pressure was introduced and the system components were explained. The testing procedure of Clisp Studio software program was explained. The information about testing procedure of saturation, consolidation and liquefaction setups were clarified in detail.

2.1 Dynamic Simple Shear (DSS) with Confining Pressure Testing System

VJ Tech dynamic simple shear testing device with confining pressure was used in this study. At the beginning, the working mechanism and installation steps of the testing system were studied in detail. The testing system in Istanbul Technical University is shown in Figure 2.1. The testing system consists of main DSS-C apparatus, dynamic servo controller unit (DSC), pneumatic automatic pressure controller (APC), hydraulic automatic pressure controller, air compressor, air-water cylinder, vacuum machine and de-aired water tank. Clisp Studio program was used to perform tests in the order of saturation, consolidation and liquefaction.

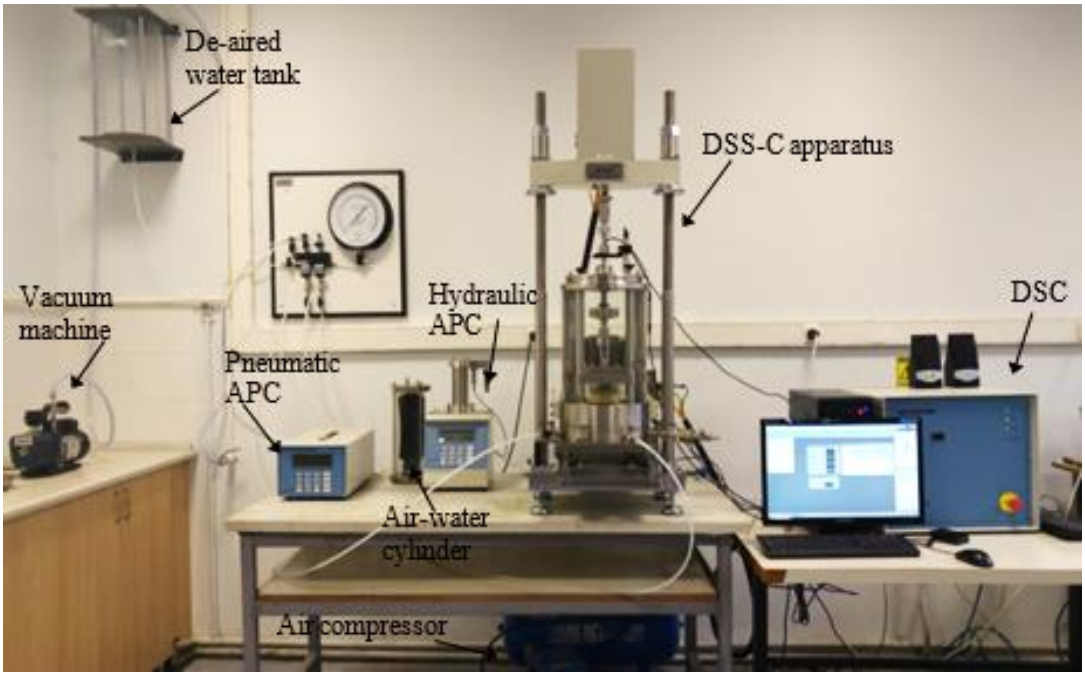


Figure 2.1 : VJ Tech Dynamic Simple Shear Test Device with Confining Pressure.

2.2 Testing Procedure

Tests were performed by using Clisp Studio software program. Testing procedure includes saturation, consolidation and liquefaction setups. Saturation setup starts with B check and continues with cell pressure ramp. Consolidation test is run under isotropic conditions. Liquefaction test is performed under undrained cyclic loading conditions.

2.2.1 Saturation setup

At the beginning of saturation test, B check is performed to learn the initial saturation condition of tested sample. Then, cell and back pressures are increased to saturate the sample. After the saturation of the sample, another B check test is run to measure the final saturation condition. B value is the ratio of change in pore water pressure to change in cell pressure. If B value is equal to or greater than 0.95, the sample can be accepted as fully saturated. If the sample is saturated enough, other tests can be performed in the fully saturated testing procedure. However, in partially saturated conditions, the important point is to measure the change in water volume during saturation. According to initial degree of saturation of the prepared specimen, final degree of saturation can be calculated by measuring the amount of water volume entered into the specimen during cell pressure ramp. Figure 2.2 shows typical saturation test setup performed on fully saturated specimens.

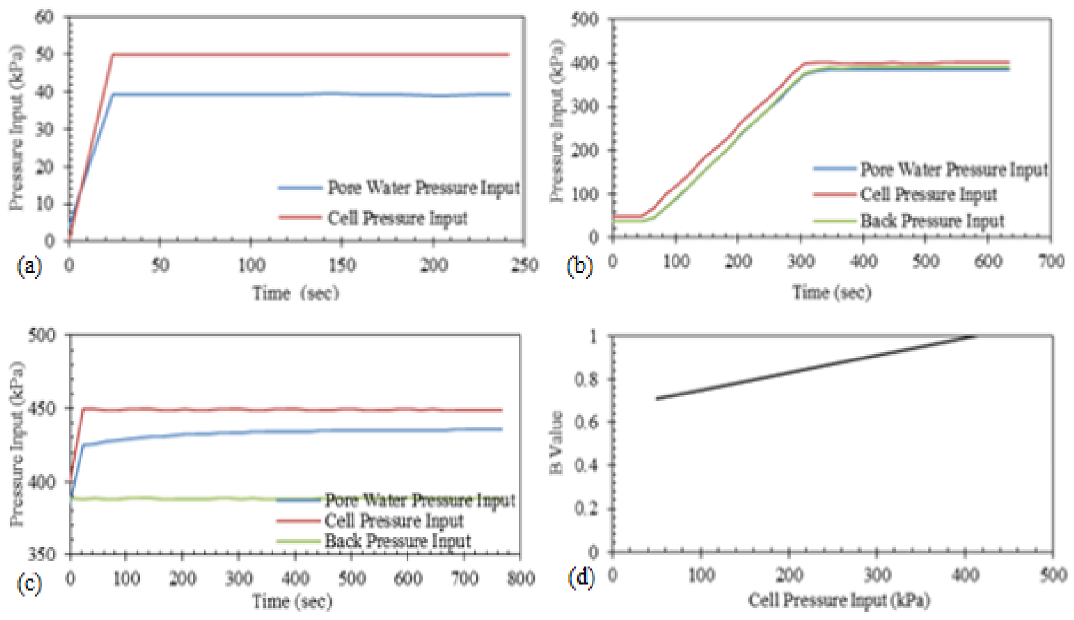


Figure 2.2 : (a)B check at 50 kPa. (b)Cell pressure ramps until 400 kPa. (c)B check at 450 kPa. (d)B value change by cell pressure.

2.2.2 Consolidation setup

The fully and partially saturated samples were tested under different effective vertical stresses such as 50, 75,100 and 150 kPa. Before isotropic consolidation test start, a certain time was waited to stabilize the pore water pressure change. In fully saturated specimen tests, at least 300 kPa back pressure was applied for dissipation of gas inside the voids. However, in partially saturated specimen tests, the change in back pressure affects the liquefaction resistance of the sand. Thus, different minimum back pressures were used according to different effective vertical stresses. The effect of back pressure and effective vertical stress on the liquefaction resistance was shown in DSS test analysis results section. The consolidation test is run until the dissipation of pore water pressure stabilized. Figure 2.3 shows the consolidation test running on a partially saturated sand specimen where $\sigma'_v=u_0=150$ kPa, S=87% and $D_r=30\%$.

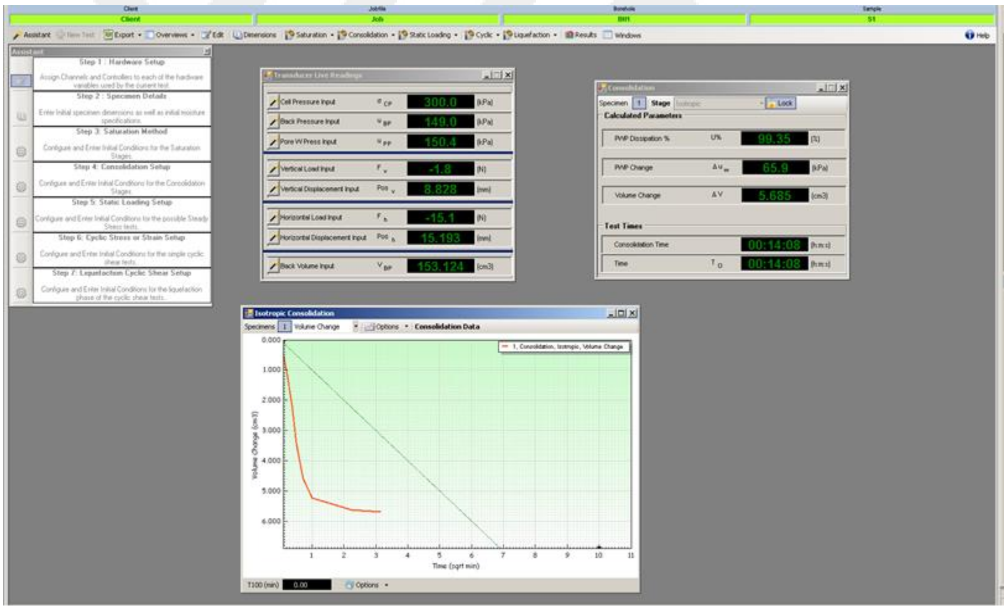


Figure 2.3 : The consolidation test running on a partially saturated sand specimen where $\sigma'_v=u_0=150$ kPa, S=87% and $D_r=30\%$.

2.2.3 Liquefaction setup

Strain controlled undrained cyclic loading liquefaction tests were performed in this study. Sinusoidal wave form was used in the cyclic loading liquefaction tests. A certain amount of deformation is given for stain-controlled test. Excess pore water pressure ratio and number of cycle relations were investigated for both fully and partially saturated specimens.

Tests were performed under 0.1, 0.2, 0.3 and 0.4% shear strains. Sinusoidal waveform was used during liquefaction test. Tests were run until the excess pore water pressure ratio stabilized. Figure 2.4 shows the liquefaction test performed on a fully saturated sand specimen where σ'_v=100 kPa, γ=0.4% and D_r=35%.

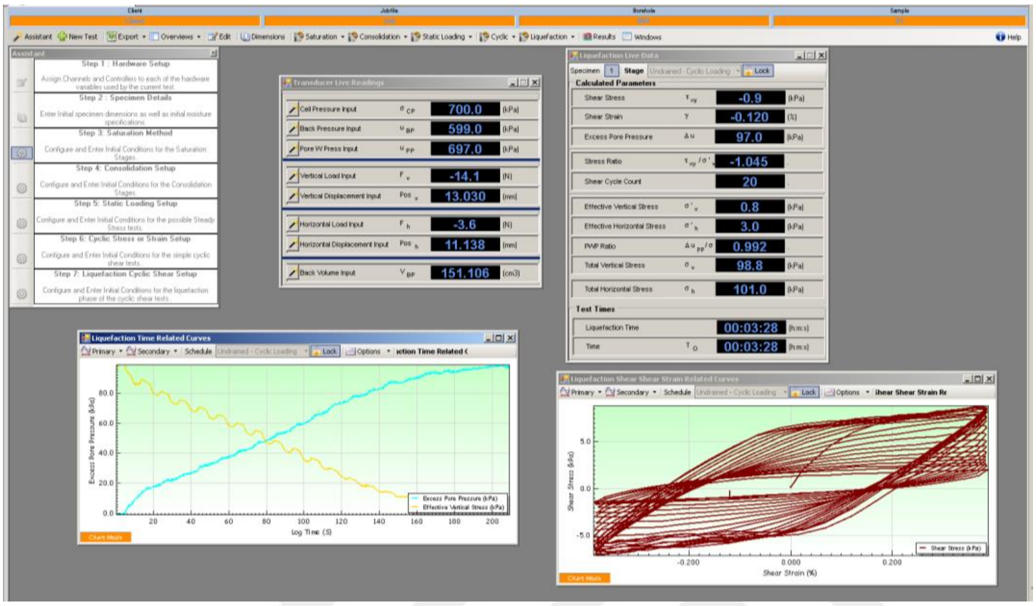


Figure 2.4 : The liquefaction test performed on a fully saturated sand specimen where σ'_v=100 kPa, γ=0.4% and D_r=35%.

Figure 2.5 shows a liquefaction test performed on a partially saturated sand specimen for 76% degree of saturation and 34% relative density where 50 kPa effective vertical stress and back pressure were applied under 0.2% shear strain.

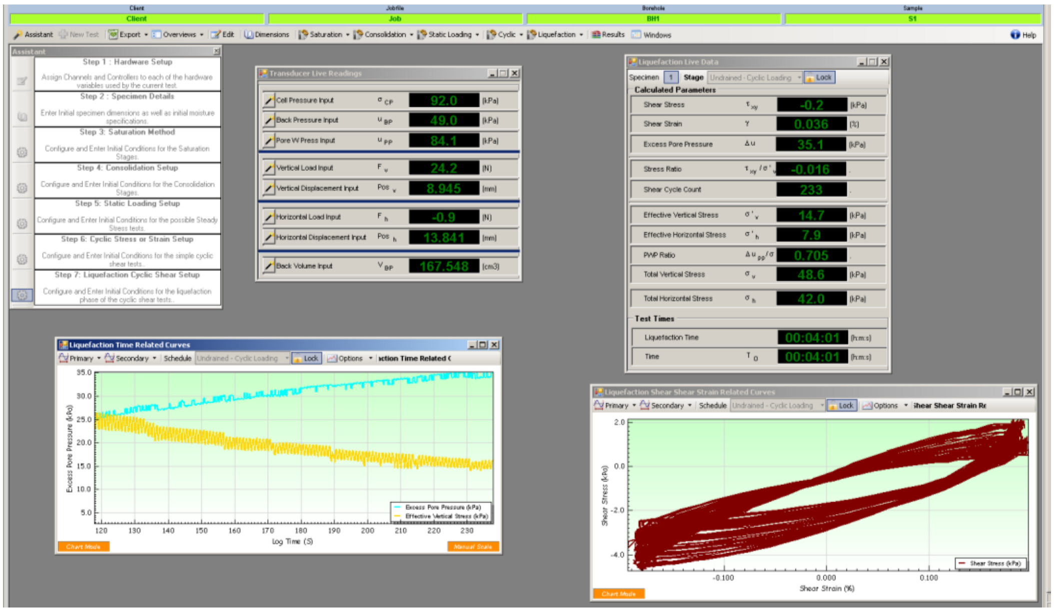


Figure 2.5 : The liquefaction test performed on a partially saturated sand specimen where σ'_v=u_0=50 kPa, γ=0.2%, S=76% and D_r=34%.

3. DSS TESTS ON FULLY AND PARTIALLY SATURATED SPECIMENS

In this section, firstly properties of soil tested in this study will be explained. Then, the general specimen preparation steps in DSS device will be presented. Later on, fully saturated specimen preparation methods will be examined in three subsections, which are dry pluviation, wet pluviation and moist undercompaction methods. Typical fully saturated specimen test results will also be shown in this section. After that, partially saturated specimen preparation methods will be explained in two subsections such as firstly mixing sand and chemical secondly mixing water and chemical. Then typical partially saturated test results will be presented. Finally, the remark points and the problems faced during specimen preparation of fully and partially saturated sands will be discussed at the end of this section.

3.1 Properties of Soil Tested

Ottawa sand was used by Eseller-Bayat (2009) in her studies with partially saturated sand specimens on shaking table testing system. In the scope of this project, her test results were examined in dynamic simple shear test device under high effective vertical stresses and different back pressures. Thus, tested soil was chosen as similar properties with Ottawa sand. Sile sand (AFS 40-45) was used in this project, which was brought from Celiktas Sand Company in Istanbul. The properties of Ottawa and Sile sands were listed in Table 3.1.

Table 3.1 : Properties of Ottawa and Sile sands.

Properties of Sand	Ottawa Sand	Sile Sand
D_{60}	0.4	0.35
D_{30}	0.32	0.28
D_{10}	0.2	0.22
C_u	2	1.59
C_c	1.28	1.02
Soil Type	SP	SP
γ_s (g/cm^3)	2.65	2.65
e_{max}	0.80	0.89
e_{min}	0.50	0.57

Sieve analysis of Ottawa and Sile sand samples were compared in Figure 3.1. According to the sieve analysis results, grain distributions of Ottawa sand and Sile sand are similar.

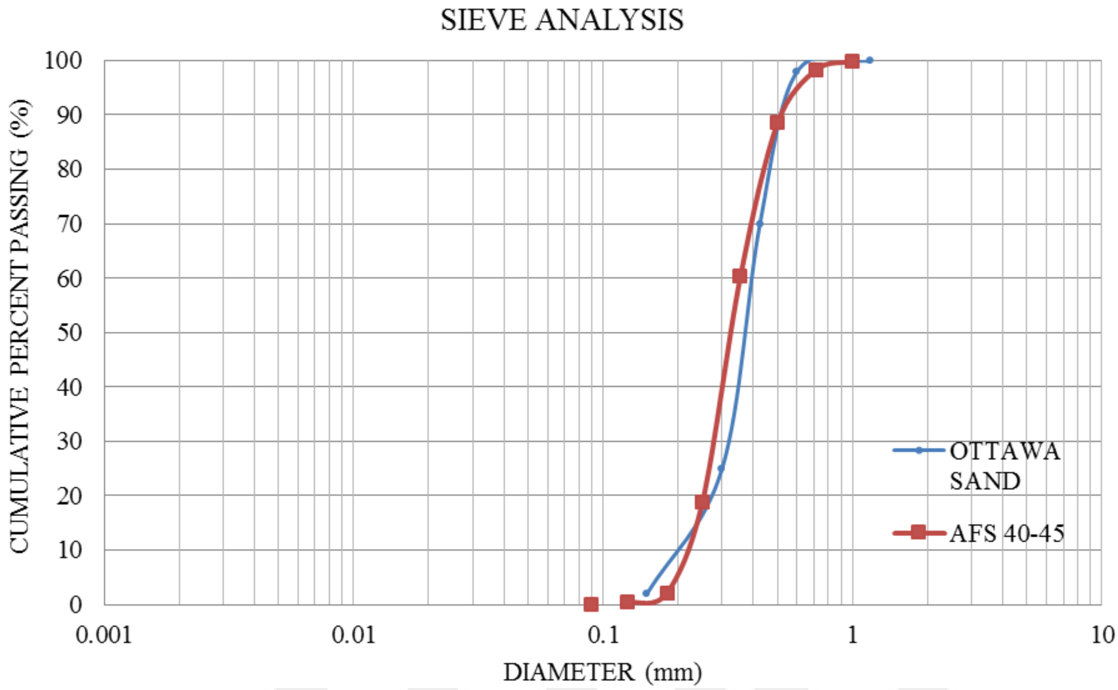


Figure 3.1 : Sieve analysis of Ottawa and Sile sands.

3.2 Specimen Preparation for DSS Device with Confining Pressure

The main purpose of specimen preparation for fully saturated and partially saturated liquefaction tests in DSS-C device is to prepare loose, uniform and undeformed samples. The steps of general specimen preparation in DSS-C device are explained in this section.

As a first step, the saturated porous stones and papers are placed into the top and bottom specimen plates. Grease oil is put on around the base plate. The membrane with two O rings is stretched around the bottom specimen pedestal.

Secondly, the split mold with O rings is put over the specimen pedestal and the membrane is stretched onto the mold. The saturated pore and back pressure pipes are connected to the base plate and top cap. Specimens are prepared inside the testing apparatus. The height of the sample is measured both before the top cap is placed and after the mold is removed. After the top cap placed onto the specimen, the initial measured height decreased and the sample deformed in both horizontal and vertical axis. Thus, the relative density of the specimen increases compared at the beginning.

It was noticed that the reason of the sample deformation is the higher dimensions of the split mold. It is hard to prepare loose and undeformed samples by using that split mold. Thus, Gulen and Eseller-Bayat (2017) designed a new mold 70 mm in diameter and 28 mm in height for this research according to ASTM D6528-07 Standard for specimen size requirements. In addition, they designed a 2.5 mm gap after the sample height as an intrusion of the top cap in the mold to prevent the deformation of the sample. The new mold design of Gulen and Eseller-Bayat (2017) was shown in Figure 3.2. Dimensions were written in millimeter.

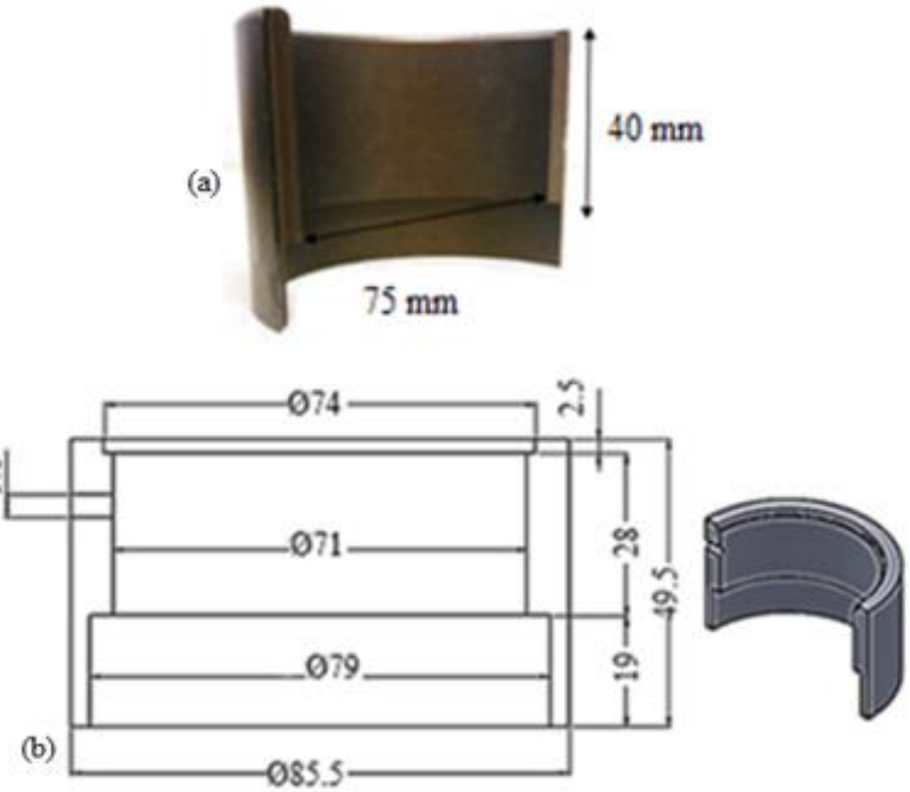


Figure 3.2 : The new mold design (a)The picture of old mold. (b)Schematic of new mold with dimensions in mm (Gulen and Eseller-Bayat, 2017).

The specimens were prepared by using the new mold for all tests. After the specimen prepared inside the mold, the upper platform is placed over the specimen top cap. At this point, it is important not to deform the specimen while connecting the screws. Then, the vertical load cell is connected to the upper platform. The necessary screwing works are done carefully. The cell of the dynamic simple shear device is placed and the cap of the cell is placed over it. Finally, the vertical and horizontal rams are connected and the cell is filled with deaired water. Dynamic servo controller and Clisp Studio connection is used for necessary electronic connections and for performing of test setups. Specimen preparation steps in DSS-C device with the new mold was demonstrated in Figure 3.3.

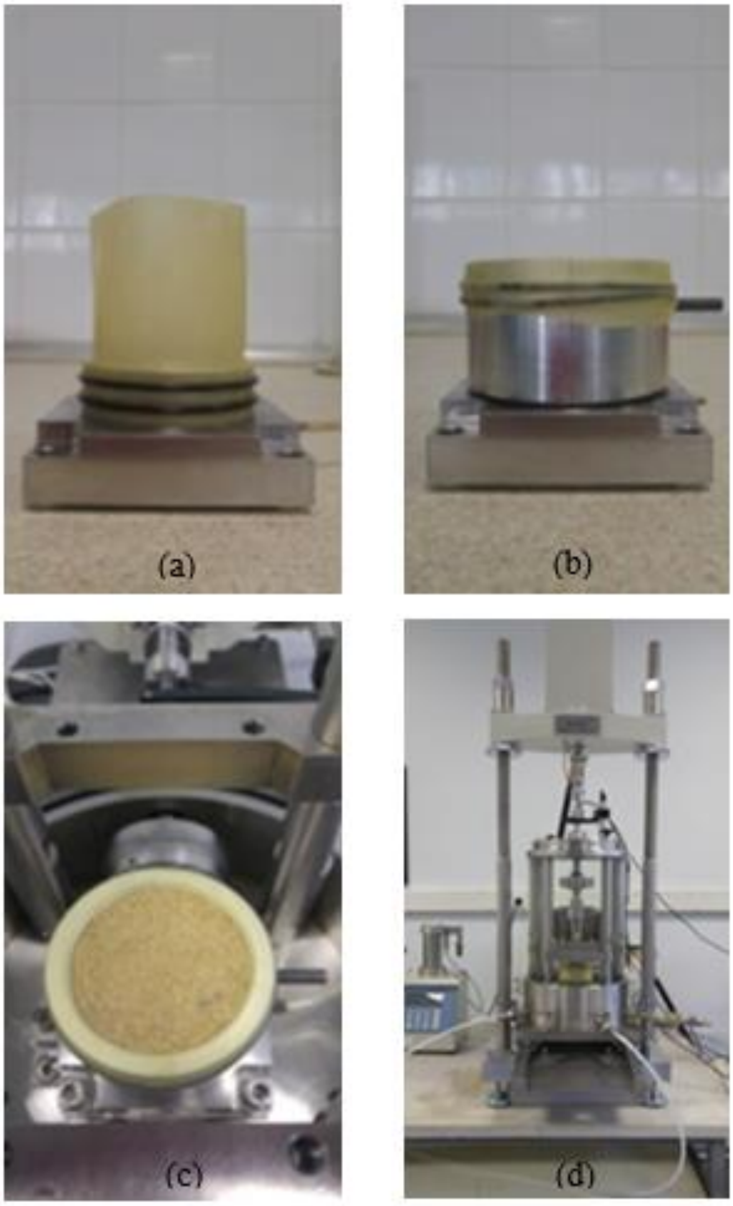


Figure 3.3 : Sample preparation. (a)Membrane and O rings in the base plate. (b)Split mold over the membrane and O rings over the mold. (c)Specimen inside the mold. (d)Specimen in place in DSS-C device under cell pressure (Gulen and Eseller-Bayat, 2017).

3.3 Fully Saturated Sand Specimen Preparation

The mostly used fully saturated specimen preparation techniques in literature are examined under three main methods, which are dry pluviation, wet pluviation and moist undercompaction. The latex membrane without confinement is used for specimen preparation for DSS-C system. On the contrary, these techniques generally were used with constrained ring or wire reinforced membrane specimen preparations. All these methods were tested and discussed in this research with their advantages and disadvantages to determine the best method for DSS-C testing system.

3.3.1 Dry pluviation method

Firstly, dry pluviation method was investigated. The predetermined amount of dry sand is poured through a funnel into the mold by raising the funnel slowly. The drop height of the sample is important to arrange the relative density of the specimen. Ishihara stated that (1996), the dropt height from funnel to the surface of specimen must be constant. Additionally, denser relative densities can be obtained by using dry pluviation method compared to other techniques. In fully saturated liquefaction tests, it is important to get loose specimens. The specimen prepared by using dry pluviation method was shown in Figure 3.4.

Figure 3.4 : (a)Dry pluviation of sand into the mold. (b)Specimen prepared by using dry pluviation method.

Dry pluviated specimens could be prepared at 80-81% relative densities. Loose relative densities could not be achieved in dry pluviation method. Since, the dry sand specimens can easily deform when the split mold is removed around the rubber membrane. Two tests were performed on dry pluviated specimens.

Firstly, saturation tests were performed. The dry sand specimens were saturated by applying back pressure into the specimen. Back pressure was increased by increasing cell pressure, with a 10 kPa effective pressure difference, until enough water entered into the specimen to get fully saturation. Cell pressure was increased up to 750 kPa during saturation process, then B check was applied at 800 kPa cell pressure**.** B values were achieved as 0.80 for both tests after saturation. Then, saturated specimens were isotropically consolidated under 50 kPa effective vertical pressure and undrained cyclic loading was performed at 0.3% shear strain amplitude. Since the high relative densities and small B values were achieved during specimen preparation and saturation processes, the dry pluviation technique was found as not a good solution to get loose as well as fully saturated specimens.

3.3.2 Wet pluviation method

Secondly, wet pluviation technique was performed in this research. Dry sand can be pluviated though a funnel (Ishihara, 1996) or though a sealed flask (Finn et al., 1971) into a predetermined amount of de-aired water inside the mold. The specimen prepared by wet pluviation was shown in Figure 3.5.

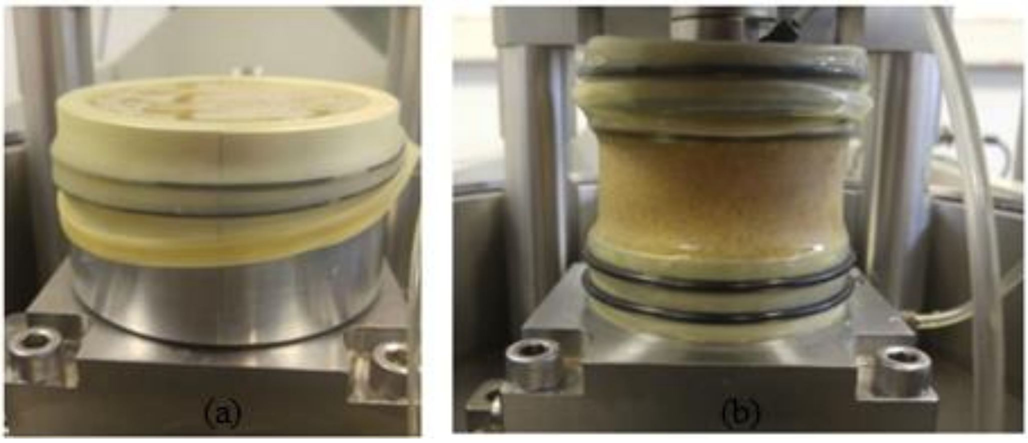


Figure 3.5 : (a)Wet pluviation of sand into the mold. (b)Specimen prepared by using wet pluviation method.

Wet pluviated specimens could be prepared at 93-100% relative densities. Very dense specimens were achieved in wet pluviation method. Because, the wet sand specimens can easily submerge when the top cap is placed over the specimen.

Two tests were performed on wet pluviated specimens. In the saturation setup, cell pressure was increased up to 400 kPa to remove air from the voids and to get fully saturated samples, then B check was applied at 450 kPa cell pressure. B values were achieved as 1.00 for both tests after saturation. In isotropic consolidation tests, 50 kPa effective vertical pressure was applied and 0.3%. shear strain was used in undrained cyclic loading liquefaction tests. Although it is easy to get fully saturated samples by using wet pluviation technique, loose specimens could not be obtained. Additionally, it is difficult to prepare loose, undeformed fully saturated samples inside an unconfined latex membrane. The sample was easily disturbed after the split mold was removed. Thus, wet pluviation method was not preferred.

3.3.3 Moist undercompaction method

The final method was used as moist undercompaction. In moist undercompaction method, a soil sample is prepared at approximately 50% degree of saturation by mixing predetermined amount of water and dry sand in a bowl uniformly (Ladd, 1978). The moist soil mixture is poured into the mold in uniformly compacted layers. A wide range of relative densities as well as loose samples can be achieved in this method by arranging the compaction of layers. The moist undercompaction method presents the best solutions for getting loose and fully saturated samples for this study. The specimen prepared by moist undercompaction method was shown in Figure 3.6.

Figure 3.6 : (a)Mixing predetermined amount of water and dry sand in a bowl. (b)Placing the sample into the mold in compacted layers. (c)Specimen prepared by using moist undercompaction method.

Moist compacted specimens could be prepared at 30-40% relative densities. Moist undercompaction method presents an advantage to prepare specimens at varying relative densities from loose to dense. In addition, it is easy to get undeformed specimens by using this method compared to dry and wet pluviation methods.

Two tests were performed on moist compacted specimens. Firstly, B check test was applied at 50 kPa as similarly done for all specimen preparation methods. Since, the specimens were not saturated enough; the back pressure was increased by increasing cell pressure with a constant 10 kPa effective pressure difference. During saturation setup, cell pressure was increased up to 400 kPa and B check was applied at 450 kPa cell pressure. B values were achieved as 0.95-0.96 at the end of the saturation process. After fully saturated specimens were achieved, isotropic consolidation test was performed under 50 kPa effective vertical pressure and the testing setup completed with undrained cyclic loading tests, which were performed at 0.3% shear strain.

The most useful fully saturated specimen preparation methods to perform liquefaction tests in DSS-C device were discussed in this section. Firstly, fully saturated specimen preparation methods were investigated in three main groups such as dry pluviation, wet pluviation and moist undercompaction. Saturation, consolidation and undrained cyclic loading tests were applied on the specimens, which were prepared by using different specimen preparation methods. The moist undercompaction method was chosen as a best technique to prepare loose, undeformed and fully saturated samples. In this study, all the undrained cyclic loading tests performed on fully saturated specimens were prepared by using moist undercompaction method.

3.4 Typical Undrained Cyclic Simple Shear Tests on Fully Saturated Sand Specimens

Typical tests on fully saturated samples were presented in this section. Firstly, the specimens were prepared by using moist undercompaction method. Then, saturation setup was performed on the specimen to get a fully saturated sample. Saturation setup starts with B-check test and continues with cell pressure ramp until achieving the fully saturation. When the B-value $\geq$ 0.95, the specimen accepted as fully saturated and isotropic consolidation test performed on the fully saturated specimen. Minimum 300 kPa back pressure was applied for fully saturated specimens in the consolidation stage to dissolve the air inside the voids. Finally, the undrained cyclic loading liquefaction setup was run. In the liquefaction setup, stain controlled and sinusoidal waveform tests were performed.

A typical output of undrained cyclic loading liquefaction test under 50 kPa effective vertical stress and 0.3% cyclic shear strain performed on a fully saturated specimen, which was prepared at 40% relative density was presented in Figure 3.7 in terms of shear strain, shear stress and excess pore pressure ratio relations by number of cycles.

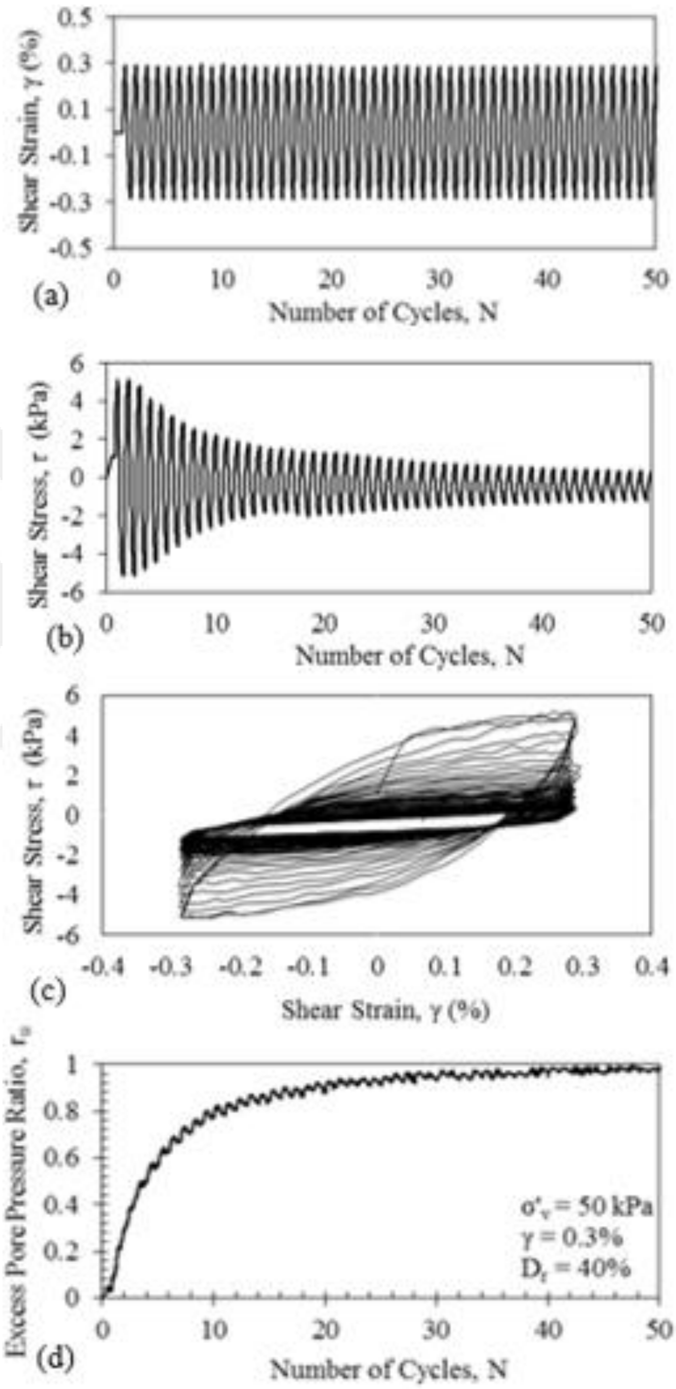


Figure 3.7 : Typical undrained cyclic loading liquefaction test results performed under 0.3%shear strain and 50 kPa effective vertical stress on fully saturated sand specimen in DSS-C (a)Shear strain vs number of cycles. (b)Shear stress vs. number of cycles. (c)Shear strain vs. shear stress. (d)Excess pore pressure ratio vs. number of cycles.

Another example of undrained cyclic loading liquefaction test under 100 kPa effective vertical stress and 0.4% cyclic shear strain performed on a fully saturated specimen, which was prepared at 35% relative density was presented in Figure 3.8 in terms of shear strain, shear stress and excess pore pressure ratio relations by number of cycles.

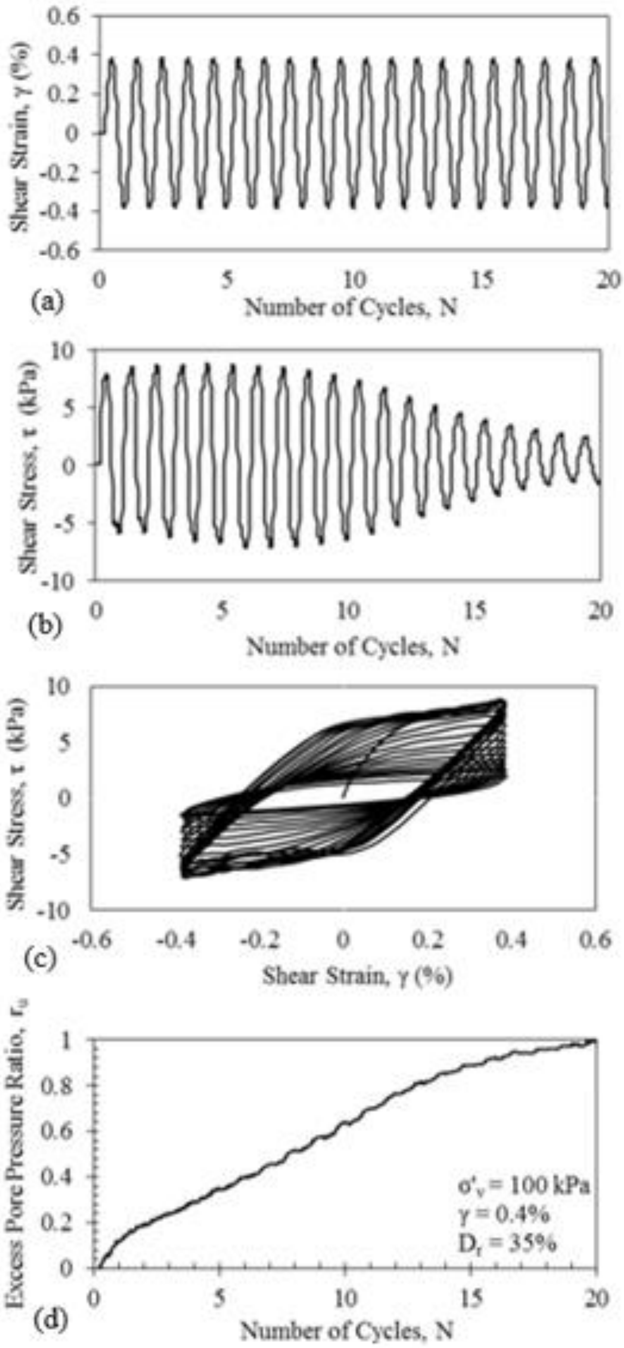


Figure 3.8 : Typical undrained cyclic loading liquefaction test results performed under 0.4% shear strain and 100 kPa effective vertical stress on fully saturated sand specimen in DSS-C. (a)Shear strain vs. number of cycles. (b)Shear stress vs. number of cycles. (c)Shear strain vs. shear stress. (d)Excess pore pressure ratio vs. number of cycles.

3.5 Partially Saturated Sand Specimen Preparation

In IPS method, partial saturation was created by air (gas) generation in the voids. Air/gas was generated by using an environmentally friendly chemical sodium percarbonate (Figure 3.9). In the partially saturated specimen preparation process, three main specimen preparation methods were considered such as dry pluviation, moist undercompaction and wet pluviation. In dry pluviation method, partially saturation can be obtained by applying various back pressures during saturation test. However, as stated in the fully saturated specimen preparation section, it was hard to get loose samples by using dry pluviation method. The other method was moist undercompaction. Low relative densities can be achieved by compacting of moist sand mixture and partially saturation can be achieved by applying back pressure into the sample. However, this method can create nonuniformly distributed voids inside the specimen. Thus, moist undercompaction method was not chosen to prepare partially saturated specimens.

In 2007, Yegian et al. developed Induced Partial Saturation (IPS) technique by generating gas bubbles inside sand specimen. Additionally, application of IPS method both in large laboratory specimens and in the field improved by Nababan (2015). Nababan prepared partially saturated specimens by using a chemical powder of sodium percarbonate in his study. Sodium percarbonate reacts with water and creates oxygen gases, which reduce the degree of saturation as mentioned by Nababan (2015), Gokyer (2015) and Kazemiroodsari (2016). Gas generation rate in the chemical reaction and the change in degree of saturation of partially saturated sands were studied by Gokyer (2015) and by Kazemiroodsari (2016) in details. The chemical reaction of sodium percarbonate with water is shown in equation 3.1 and 3.2 as follows:

$$Na_2CO_3.1.5H_2O_2 \rightarrow 2Na^{+1} + CO_3^{-2} + 1.5H_2O_2 \qquad (3.1)$$

$$1.5H_2O_2 \rightarrow 1.5H_2O + 0.75O_2 \qquad (3.2)$$

Figure 3.9 : Sodium percarbonate powder.

Finally, wet pluviation method and generation of gas bubbles inside the specimen was chosen as partially saturated specimen preparation technique. The partially saturated sample preparation was investigated in two different methods:1) Wet pluviation of the mixture of dry sand and chemical powder into predetermined amount of water2) Wet pluviation of dry sand into the mixture of predetermined amount of water and chemical powder.

3.5.1 Wet pluviation of the mixture of dry sand and chemical powder

In this procedure, dry sand and sodium percarbonate was uniformly mixed and then this mixture was rained into the predetermined amount of water. Changes in water level were measured to determine the degree of saturation. The samples were waited for one day. It was observed that big gas gaps occurred inside the soil. It was not a uniform distribution. This method is not suitable to get a uniformly distributed gas generation. The specimen prepared by wet pluviation of the mixture of dry sand and chemical was shown in Figure 3.10.

Figure 3.10 : Wet pluviation of the mixture of dry sand and chemical powder.

3.5.2 Wet pluviation of dry sand into the mixture of predetermined amount of water and chemical solution

In this procedure, predetermined amount of water and sodium percarbonate were mixed and then dry sand was rained into this solution. The sodium percarbonate-water was mixed at various concentrations from 0.10% to 1.0%. The weight of sodium percarbonate and dry sand were mixed in the ratio of R as presented in equation 3.3:

$$R = \frac{\text{Weight of sodium percarbonate (g)}}{\text{Weight of dry sand (g)}} * 100 \qquad (3.3)$$

As stated by Gulen and Eseller-Bayat (2017), partially saturated samples were prepared at different R ratios from 0.03 to 0.30. The amount of water was calculated according to the fully saturated condition. In this method, firstly water and sodium percarbonate were mixed until getting a uniform distribution. Later on, wet pluviation method was applied into this solution. The change in water level on the surface of the sample was measured hourly and was waited for 24 hours for the completion of chemical reaction. Air/gas occurred during reaction entered the voids of sand and increased the water level. Generation of gas volume was assumed as equal to the change in water level. The specimen prepared by mixing water and chemical then wet pluviation of dry sand into the mixture was shown in Figure 3.11.

Figure 3.11 : Wet pluviation of dry sand into the mixture of predetermined amount of water and chemical powder.

Specimens prepared at different concentrations where R values equal to 0.05, 0.10, 0.15, 0.20 and 0.25 were presented in Figure 3.12. the change in the water level during chemical reaction was marked on the beaker.

Figure 3.12 : Specimens prepared at various R ratios.

Generated air/gas volume reduces the degree of saturation of specimens. The change in degree of saturation by time was measured at different R ratios. Kazemiroodsari (2016) stated that relative density and volume of the sample has negligible effect on achieving a specified degree of saturation using the R ratios. Partially saturated specimens were prepared by wet pluviation of dry sand into the sodium percarbonate-water solution and the samples was kept during 1 day to complete the chemical reaction. The change in degree of saturation was calculated by measuring the rise in the water level in the specimen. The relation between the final degree of saturation and R values for 24 hours were demonstrated in Figure 3.13.

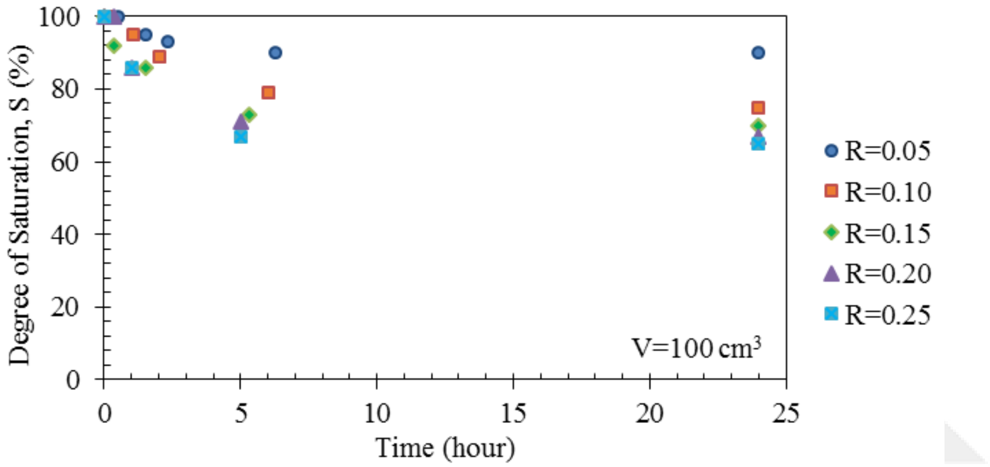


Figure 3.13 : The achieved degree of saturation with time for partially saturated samples during 24 hours for 100 cm^3 volume (Gulen and Eseller-Bayat, 2017).

The detailed change in degree of saturation by R ratios was observed in the first 8 hours and it was shown in Figure 3.14.

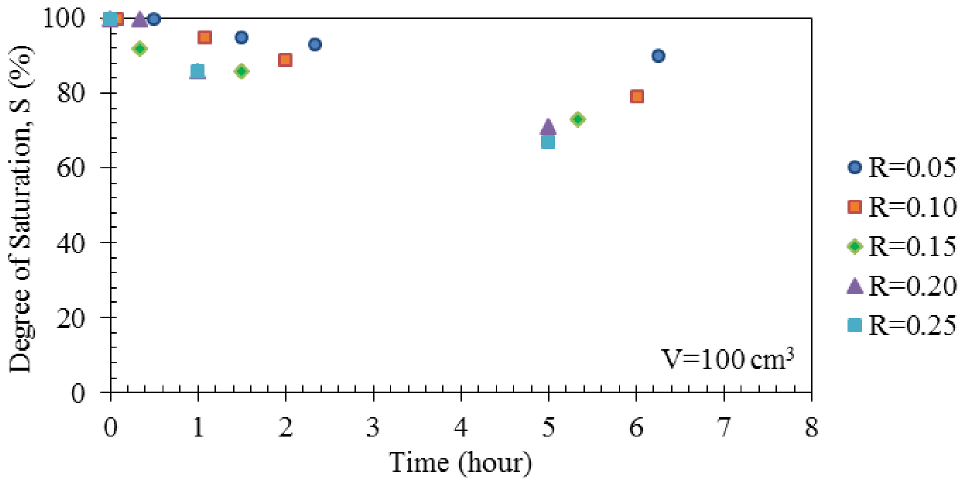


Figure 3.14 : The achieved degree of saturation with time for partially saturated samples during 8 hours for 100 cm^3 volume.

Correlation between degree of saturation and R values were presented in Figure 3.15 (Gulen and Eseller-Bayat, 2017). According to the correlation, the final degree of saturation decreases by increasing R values.

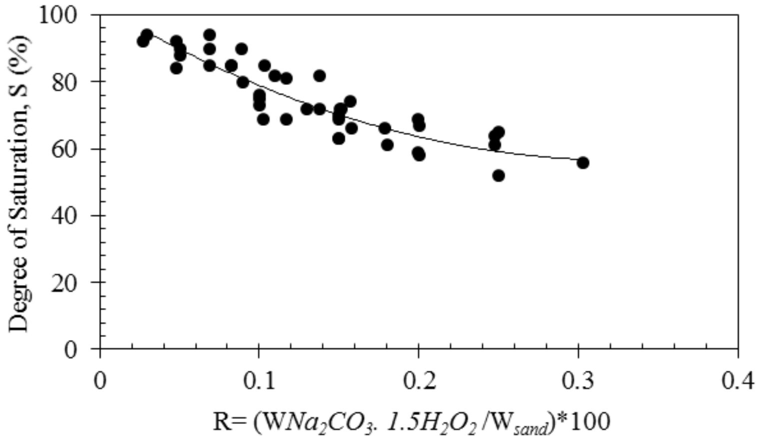


Figure 3.15 : Correlation between achieved degree of saturation and R values (Gulen and Eseller-Bayat, 2017).

When the degree of saturation decreased nearly 50%, undeformed and uniformly distributed samples can be prepared inside the membrane. The partial saturation can be achieved by applying back pressure into the sample during saturation test setup. This process was used to prevent the bulging of the sample when the split mold is removed. The final degree of saturation can be measured by calculating the amount of water entered into the soil. It is not applicable to prepare undisturbed partially saturated samples without applying back pressure. The partially saturated specimen prepared by using water-chemical mixture was shown in Figure 3.16.

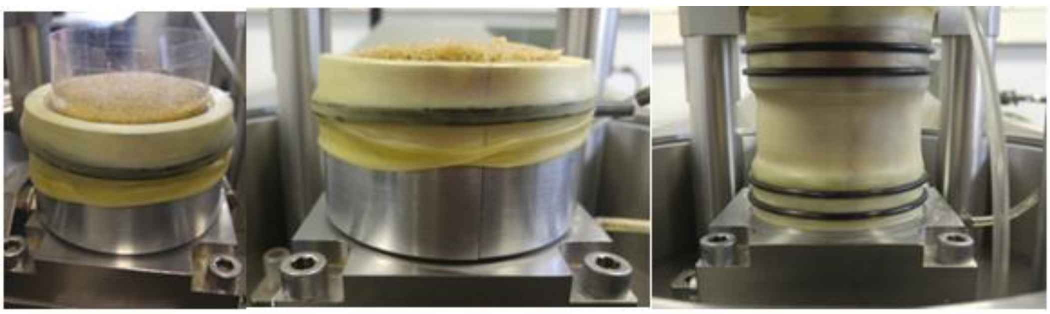


Figure 3.16 : Partially saturated specimen prepared by mixing water and chemical powder.

As a conclusion, partially saturated specimen preparation methods were examined in two parts, which are preparing sand-chemical mixture or preparing water-chemical mixture. The most suitable method for uniformly distributed gas generation in partially saturated sands was chosen as firstly, mixing water and chemical solution then wet pluviation of dry sand into this solution. Sodium percarbonate was used to generate gas bubbles in the voids of the soil. At the end of the chemical reaction, degree of saturation could go down to nearly 50% and it increased during the application of back pressure during saturation process. In this study, all the partially saturated specimens were prepared by using chemical-water mixture method and different degrees of saturation were achieved by changing the amount of chemical and applying various back pressures into the specimen.

3.6 Typical Undrained Cyclic Simple Shear Tests on Partially Saturated Sand Specimens

Typical tests on partially saturated samples were presented in this section. Firstly, the specimens were prepared by wet pluviation of dry sand into the sodium percarbonate-water mixture. Partially saturated specimens were kept during a day for completion of chemical reaction. After one day, the induced degree of saturation was calculated by using the correlation between final degree of saturation and R ratios.

Then, saturation setup was performed on the specimen to arrange the final degree of saturation of partially saturated sample by considering the change in water volume inside the specimen.

When the target degree of saturation was achieved, the isotropic consolidation test was performed on the partially saturated specimen. At this point, it is important to consider the back pressure amount. Because, the back pressure has a significant effect on the excess pore pressure generation in partially saturated sands compared fully saturated sands. The amount of back pressure was selected according to the simulation of field conditions. The effect of back pressure on the excess pore pressure generation in partially saturated sands will be explained in the next chapter in detail. The consolidation stage was completed when the change in water volume was constant and the dissipation of pore water pressure was stabilized.

Finally, the undrained cyclic loading liquefaction setup was run on the partially saturated specimen. In the liquefaction setup, stain-controlled and sinusoidal waveform tests were performed. The liquefaction stage was continued until the excess pore pressure generation stabilized. However, the maximum excess pore pressure ratio could not be determined on these tests as seen in large size specimen tests like shaking table and centrifuge tests. A typical outputs of undrained cyclic loading liquefaction test under 100 kPa effective vertical stress, 100 kPa back pressure and 0.4% cyclic shear strain performed on a partially saturated specimen which was prepared at 36% relative density was presented in Figure 3.17 in terms of shear strain, shear stress and excess pore pressure ratio relations by number of cycles.

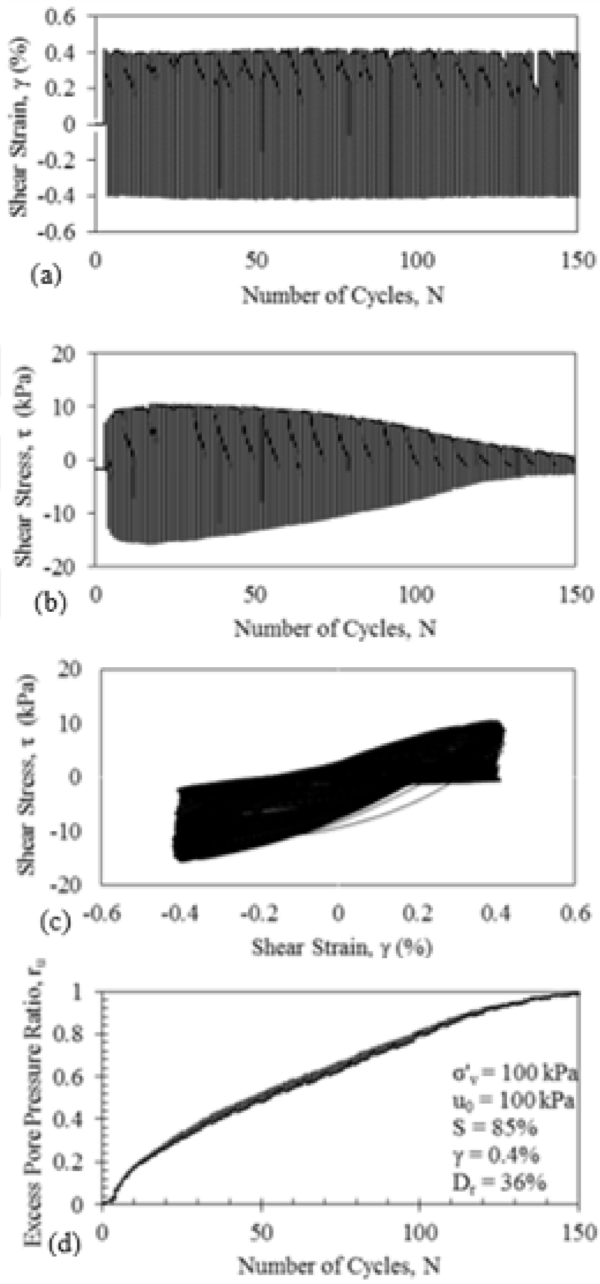


Figure 3.17 : Typical undrained cyclic loading liquefaction test results performed under 0.4% shear strain and 100 kPa effective vertical stress on partially saturated sand specimen in DSS-C. (a)Shear strain vs. number of cycles, (b)Shear stress vs. number of cycles. (c)Shear strain vs. shear stress.(d)Excess pore pressure ratio vs. number of cycles.

As seen in excess pore pressure ratio vs. number of cycles graph (Figure 3.17), partially saturated sand specimen at S=85% and D_r=36%, r_u reaches to 1.0 at 150 cycles under 100 kPa effective vertical stress, 100 kPa back pressure and 0.4% cyclic shear strain. However, in large specimen laboratory tests such as in shaking table and centrifuge test results, it was seen, as excess pore pressure ratio does not reach to 1.0 for partially saturated sands. As stated by Eseller-Bayat et al. (2013) in shaking table tests on partially saturated sand specimen, excess pore pressure ratio decreases by decreasing degree of saturation such as at 80% degree of saturation under σ'_v=2.5 kPa, γ=0.1% and D_r=35-40%, r_u generation stabilized at 0.8. The reason why the r_u generation continued increasing in small sample tests was attributed to the saturation of the small specimen while cycling continues. As number of cycles increase, the gas in the voids of the shallow specimen finds a way to escape and the degree of saturation of the specimen increases. In the large sand specimen as in the shaking table and centrifuge tests, the gas can only escape from the top 5-10 cm of the specimen and the gas at the deeper levels of the specimen remain entrapped (Eseller-Bayat, 2009).

In the undrained cyclic loading tests peformed on fully saturated specimens under σ'_v=100 kPa, γ=0.4% and D_r=35%, r_u reaches to 1.0 at 20 cycles. However, the tests performed on the partially saturated sand samples, r_u reaches to 0.27 at 20 cycles. Even though the partially saturated samples get saturated under very high number of cycles, the behavior can be observed or investigated for low number of cycles (N<50). An equivalent number of cycles for an earthquake is not more than 50 anyhow (Seed et al., 1975). Comparison on liquefaction behavior of fully and partially saturated specimens will be discussed in the next chapter in details.

4. DYNAMIC SIMPLE SHEAR TESTS ANALYSIS RESULTS

4.1 Undrained Cyclic Simple Shear Tests on Fully Saturated Sand Samples

Undrained cyclic simple shear tests performed on fully saturated sand specimens was presented in Table 4.1. Fully saturated sand specimens were prepared at the range from 25% to 40% relative densities by using moist undercompaction method.

Table 4.1 : Undrained cyclic simple shear tests on fully saturated sand samples.

Test no	S (%)	B value	D_r (%)	σ'_v (kPa)	γ (%)	r_u@ N=10	r_u @ N=15	r_u @ N=50	r_u @ N=100	N_L	r_u@ N_L
1	100	1.00	33	50	0.2	0.48	0.6	0.78	0.83	140	0.86
2	100	0.80	33	50	0.2	0.58	0.67	0.84	0.88	100	0.88
3	100	0.92	37	50	0.1	0.39	0.51	0.91	1.00	67	1.00
4	100	0.95	40	50	0.3	0.78	0.86	0.97	1.00	30	0.95
5	99	0.92	41	50	0.4	1.00	1.00	1.00	1.00	6	1.00
6	100	0.95	35	100	0.2	0.22	0.29	0.53	0.77	200	0.94
7	100	0.85	36	100	0.1	0.18	0.23	0.41	0.6	200	0.96
8	100	0.89	37	100	0.1	0.17	0.23	0.41	0.63	200	1.00
9	99	0.93	25	100	0.4	0.54	0.75	0.92	0.92	30	0.92
10	99	0.95	35	100	0.4	0.61	0.89	1.00	1.00	20	1.00

Excess pore pressure ratio (r_u) and shear strain relations at 10 cycles were demonstrated in Figure 4.1 by comparing DSS-C results with cyclic triaxial test results by Dobry (1985).

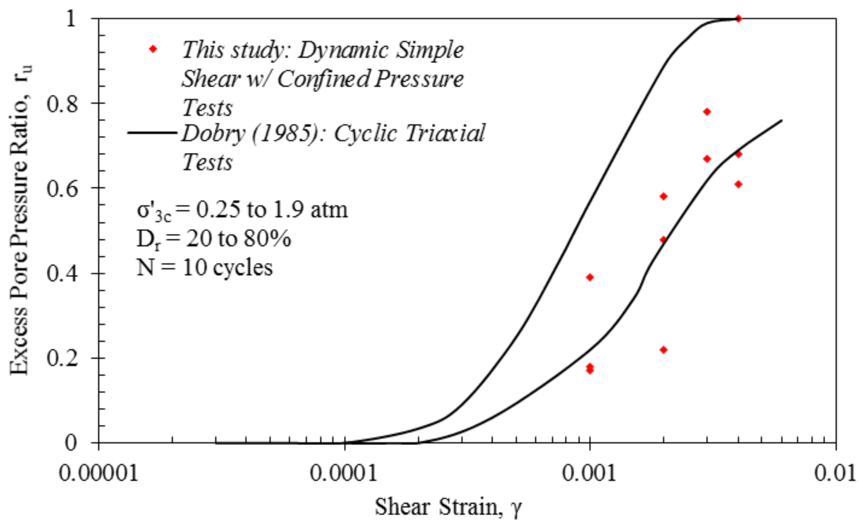


Figure 4.1 : Comparison of undrained cyclic simple shear test results on fully saturated sand samples in DSS-C and Cyclic Triaxial testing devices.

According to undrained cyclic simple shear test results performed on fully saturated sand specimens in DSS-C and Cyclic Triaxial testing devices, it is observed that results of this study present compatible outputs with research by Dobry (1985). In this study, several undrained cyclic simple shear tests were performed on fully saturated sand specimens for comparison of the results with partially saturated specimens. Firstly, the effect of effective vertical stress on excess pore pressure generation in fully saturated specimens was investigated. Undrained cyclic loading liquefaction tests performed on fully saturated specimens under 50 kPa and 100 kPa effective vertical stresses at 0.1% and 0.4% shear strain amplitudes as presented in Figure 4.2.

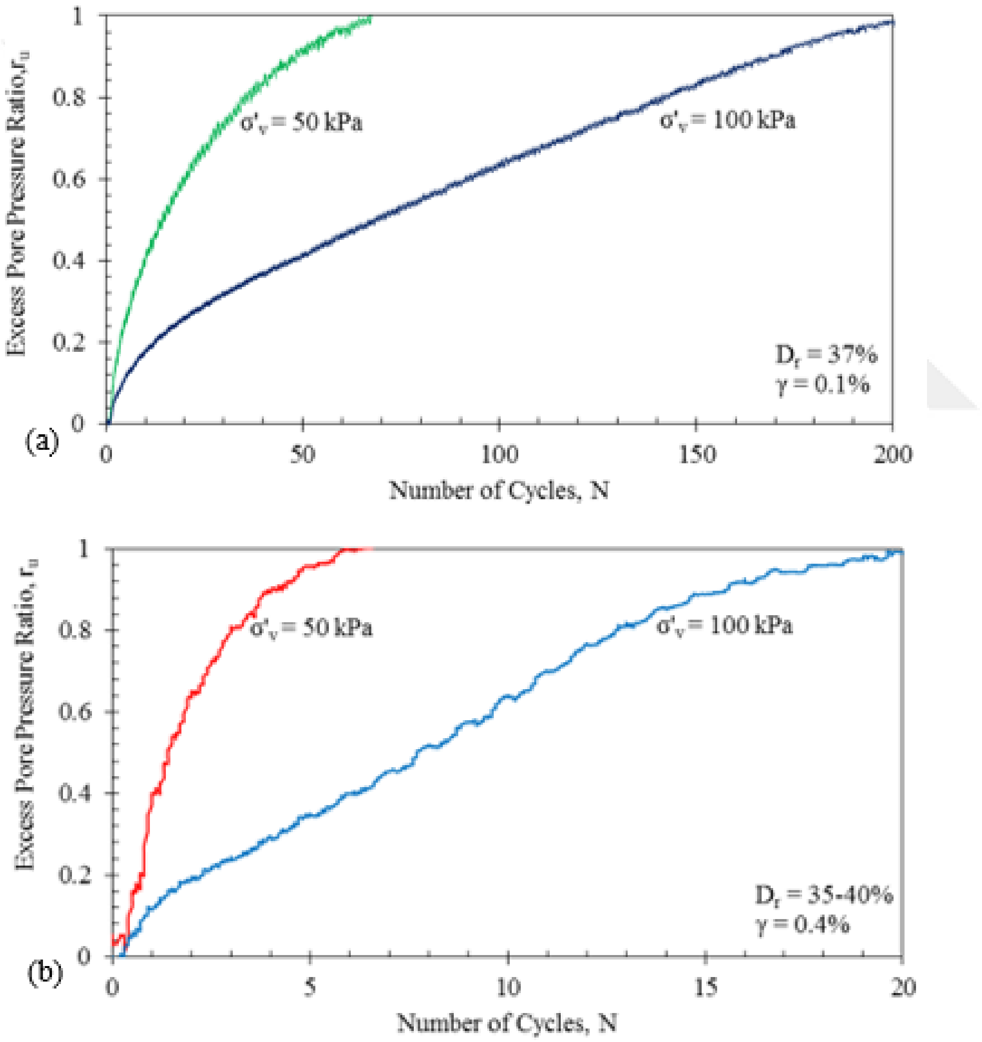


Figure 4.2 : Undrained cyclic simple shear tests on fully saturated sand samples under σ'_v=50 kPa and σ'_v=100 kPa: (a)γ=0.1%. (b)γ=0.4%.

According to test results, the increase in vertical effective stress increases the number of cycles required to liquefy of the specimen. The test performed on fully saturated specimen under σ'_v=100 kPa at γ=0.1% reached to liquefaction criteria (r_u=1) at 200 cycles while the specimen tested under σ'_v=50 kPa at γ=0.1% liquefied approximately at 70 cycles. As the effective vertical stress increases the number of cycles required to liquefaction (N_L) increases.

The effect of shear strain on excess pore pressure generation was examined under 50 kPa and 100 kPa effective vertical stresses on fully saturated samples at 35%-40% relative densities. The liquefaction behavior of specimens tested under σ'_v=50 kPa at 0.1%, 0.3% and 0.4% shear strains and also specimens tested under σ'_v=100 kPa at 0.1%, 0.2% and 0.4% shear strains were presented in Figure 4.3 (a) and (b) respectively.

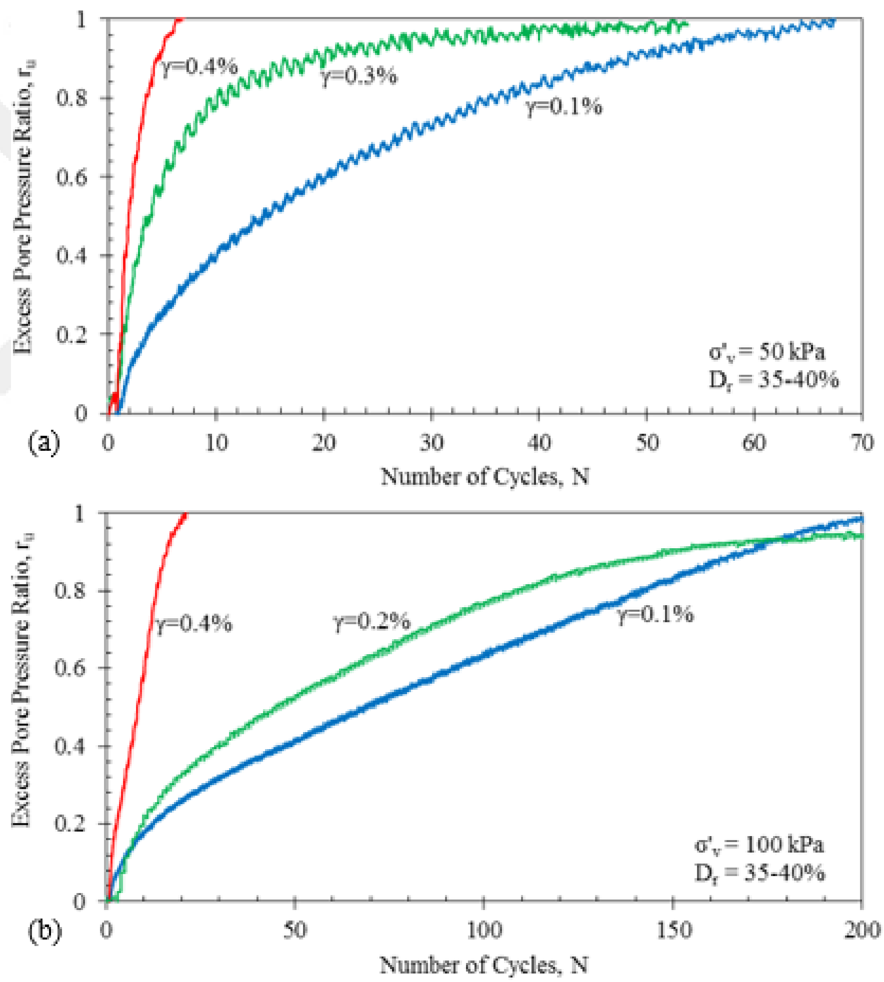


Figure 4.3 : Undrained cyclic simple shear tests on fully saturated sand samples at different shear strains: (a)σ'_v=50 kPa. (b)σ'_v=100 kPa.

It was observed that shear strain has a significant effect on the liquefaction resistance. As the shear strain increases the number of cycles required to liquefaction decreases. As a result, at all shear strain levels from 0.1% to 0.4% under 50 kPa and

100 kPa effective vertical stresses; excess pore pressure ratio reaches to nearly 1.0 and only N_L increases by increasing effective vertical stress and decreasing shear strain.

4.2 Undrained Cyclic Simple Shear Tests on Partially Saturated Sand Samples

Partially saturated specimens were prepared by wet pluviation of dry sand into water and sodium percarbonate mixture. The total of 35 undrained cyclic simples shear tests on partially saturated sand samples at different degrees of saturation, shear strain amplitudes, initial effective vertical stresses and back pressures were presented in Table 4.2. Generation of excess pore pressure ratio on partially saturated sands were examined at 15, 50 and 100 number of cycles.

Table 4.2 : Undrained cyclic simple shear tests on partially saturated sand samples.

Test No	S (%)	Dr (%)	σ'_v (kPa)	U (kPa)	γ (%)	r_u @ N=15	r_u @ N=50	r_u @ N=100
1	87	33	50	100	0.2	0.23	0.46	0.71
2	87	33	50	100	0.2	0.3	0.64	0.89
3	86	35	50	50	0.2	0.13	0.22	0.3
4	86	35	50	50	0.2	0.16	0.27	0.41
5	85	32	50	50	0.2	0.15	0.32	0.47
6	85	33	50	100	0.2	0.3	0.6	0.82
7	85	34	50	150	0.2	0.36	0.7	0.82
8	85	40	50	50	0.2	0.13	0.23	0.28
9	85	43	50	100	0.4	0.49	0.99	1.00
10	76	34	50	50	0.2	0.16	0.3	0.46
11	70	21	50	50	0.2	0.18	0.32	0.46
12	70	32	50	100	0.2	0.23	0.52	0.76
13	40	57	50	100	0.2	0.21	0.43	0.7
14	36	30	50	100	0.2	0.23	0.45	0.65
15	68	30	75	100	0.2	0.13	0.23	0.34
16	67	39	75	100	0.4	0.37	0.78	0.93
17	87	33	100	100	0.2	0.1	0.2	0.32
18	85	30	100	150	0.2	0.19	0.39	0.59
19	85	33	100	150	0.2	0.1	0.17	0.21
20	85	34	100	100	0.2	0.12	0.2	0.28
21	85	36	100	100	0.4	0.23	0.48	0.81
22	84	25	100	50	0.2	0.06	0.11	0.17
23	73	30	100	100	0.1	0.06	0.1	0.12
24	71	43	100	50	0.25	0.06	0.09	0.12
25	70	32	100	100	0.2	0.09	0.19	0.26
26	70	40	100	100	0.35	0.19	0.4	0.67
27	50	55	100	100	0.2	0.08	0.12	0.15
28	36	32	100	100	0.2	0.07	0.12	0.2
29	89	43	150	100	0.2	0.06	0.09	0.12
30	87	30	150	150	0.2	0.08	0.17	0.23
31	87	33	150	100	0.2	0.05	0.08	0.11
32	85	33	150	100	0.2	0.03	0.06	0.1
33	85	33	150	150	0.2	0.04	0.08	0.14
34	83	34	150	50	0.25	0.02	0.04	0.05
35	75	26	150	150	0.2	0.06	0.11	0.16

4.3 Discussion on Undrained Cyclic Simple Shear Test Results of Partially Saturated Sand Samples

Excess pore pressure generation in partially saturated specimens were investigated according to the effect of shear strain, degree of saturation, effective vertical stress and back pressure changes. Specimens were prepared at the range of loose to medium dense relative densities. The purpose of the undrained cyclic simple shear tests was to determine the maximum excess pore pressure ratio ($r_{u,max}$) and maximum number of cycles (N_{max}) for partially saturated sand specimens under high effective vertical stresses and to improve the empirical model of Eseller-Bayat et al. (2013) in terms of effective vertical stresses.

The other goal was to measure the settlement amount occurred in partially saturated specimens after undrained cyclic loading liquefaction test. Eseller-Bayat et al. (2013) stated that $r_{u,max}$ does not reach to 1.0 for partially saturated sand specimens in shaking table tests by decreasing degree of saturation. However, in dynamic simple shear with confining pressure testing system with a small size specimen, it was observed that $r_{u,max}$ always reaches to nearly 1.0 at higher number of cycles for different degrees of saturation, effective vertical stresses, back pressures and shear strains. It was assumed that r_u generation reaches close to 1.0 because of increase in degree of saturation by the increase in number of cycles. It is considered that the specimen is turning to fully saturated by increasing number of cycles.

The assumption is based on the idea about the escaping of gas bubbles from the surface of the specimen by increasing number of cycles. Eseller-Bayat et al. (2013) conducted tests by using drainage recharge method in a 120 cm long Plexiglass tube to observe the long term stability of gas bubbles and changes of degree of saturation under hydrostatic conditions and as well as under shaking for partially saturated specimens (Eseller-Bayat, 2009). It was mentioned that escaping of gas bubbles was observed at the top 5 cm to 10 cm of 120 cm partially saturated sand specimen and it increased the degree of saturation by 2%. Since the height of the specimen in DSS-C device was small around 2.8 cm, it was assumed that small size specimen could be affected easily from the gas escapes during cyclic loading.

As a result, generation of excess pore pressure changes by number of cycles which is affected from S, σ'_v, u_0, γ and D_r. In DSS-C device, it is hard to determine the maximum excess pore pressure ratio ($r_{u,max}$) and maximum number of cycles (N_{max}) where the r_u generation stabilized in undrained cyclic simple shear tests. The effect of S, σ'_v, u_0, γ on the liquefaction resistance of partially saturated specimens will be examined in the next sections.

4.4 Comparison of Undrained Cyclic Simple Shear Tests in Fully and Partially Saturated Sand Samples

Comparison of excess pore pressure generations (r_u) in fully and partially saturated sand specimens under undrained cyclic simple shear tests were investigated in this section in terms of changes in degree of saturation, effective vertical stress and shear strain. Fully and partially saturated specimens were prepared at the range from 30% to 45% relative densities. Figure 4.4 shows the excess pore pressure generations in fully and partially saturated specimens under 100 kPa effective vertical stress, 0.2% shear strain at 30%-35% relative densities. According to the comparison in fully and partially saturated sands, the number of cycles required to liquefaction (N_L) increases by decreasing degree of saturation. This comparison is useful to investigate the general excess pore pressure generation in fully and partially saturated sands. However, a decrement in the maximum excess pore pressure ratio could not be observed by decreasing degree of saturation as seen in large specimen tests. The detailed discussion on undrained cyclic simple shear test results of partially saturated sand specimens were explained in the previous title.

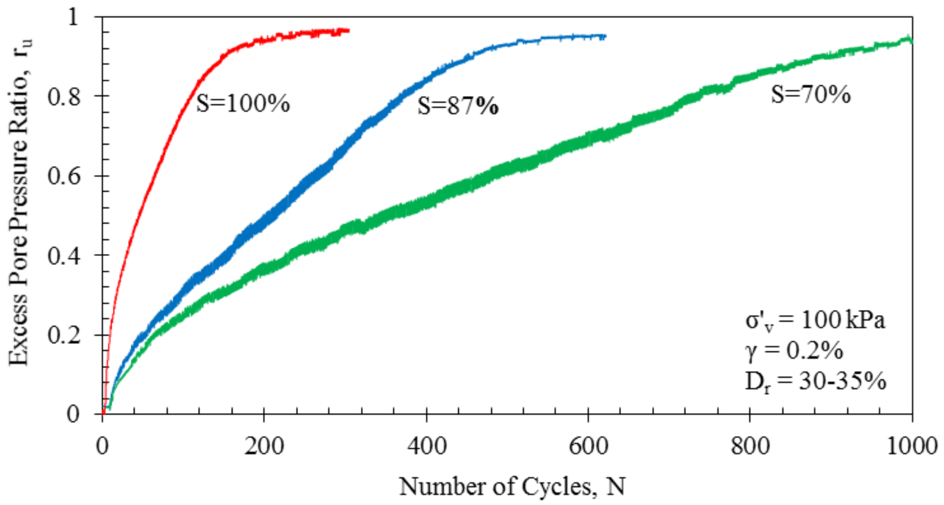
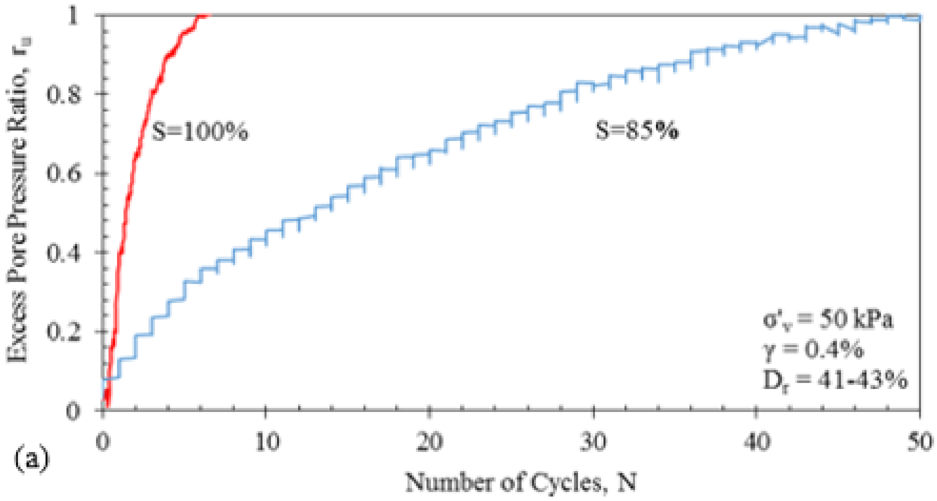


Figure 4.4 : Comparison of excess pore pressure generations (r_u) in fully and partially saturated sand specimens under undrained cyclic simple shear tests at σ'_v=100 kPa and γ=0.2%.

Figure 4.5 shows r_u generations under σ'_v=50 kPa and σ'_v=100 kPa at γ=0.4% for 100% and 85% degrees of saturation.



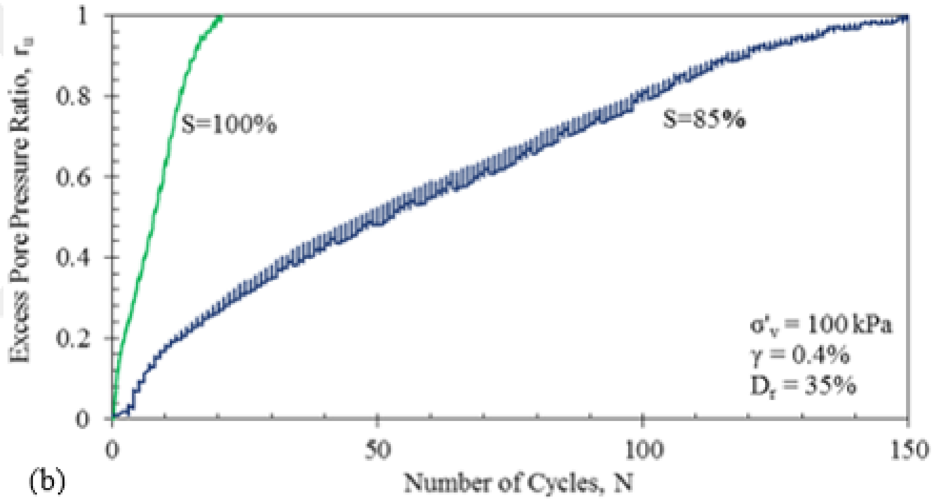


Figure 4.5 : Comparison of excess pore pressure generations (r_u) in fully and partially saturated sand specimens under undrained cyclic simple shear tests at γ=0.4%: (a)σ'_v=50 kPa. (b)σ'_v=100 kPa.

It was observed that liquefaction resistance of sands increases by decreasing degree of saturation.

4.5 Effect of Shear Strain Amplitude on Excess Pore Water Pressure Generation in Partially Saturated Sands

The effect of shear strain on undrained dynamic response of partially saturated specimens was investigated under different effective vertical stress and degree of saturation conditions at N=100 cycles. Partially saturated specimens were prepared in between 30% to 45% relative densities. In the test procedure, 0.2% and 0.4% shear strain levels were applied on partially saturated specimens at 85% and 70% degrees of saturation. Back pressure was kept constant as 100 kPa for all effective vertical stress conditions which were σ'_v=50 kPa, σ'_v=75 kPa and σ'_v=100 kPa. The comparison of excess pore pressure generation were examined at constant number of cycles such as 100. Figure 4.6 shows r_u generation at 0.2% and 0.4% shear strain levels under σ'_v=50 kPa and u_0=100 kPa at 85% degree of saturation.

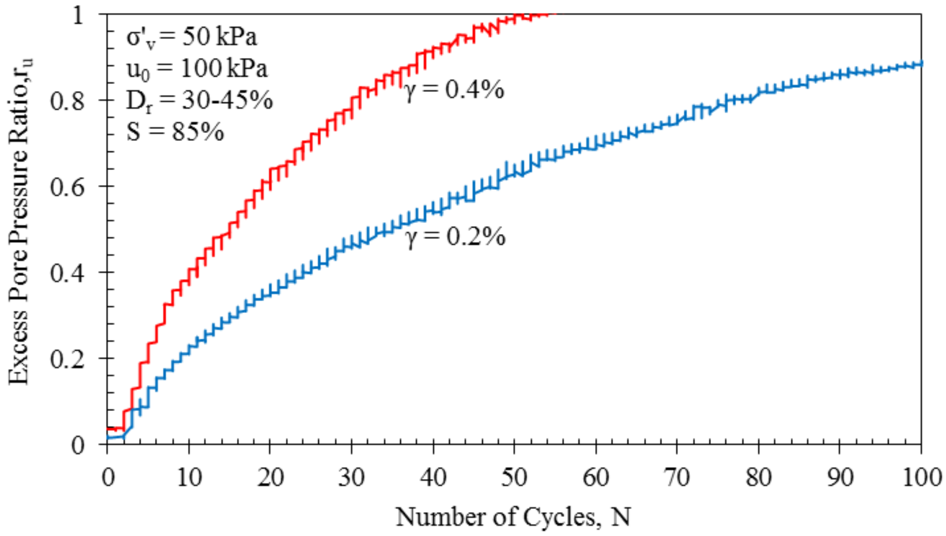


Figure 4.6 : Effect of shear strain on excess pore pressure generation in partially saturated specimens at σ'_v=50 kPa, u_0=100 kPa and S=85%.

Figure 4.7 shows r_u generation versus number of cycles while σ'_v=75 kPa and u_0=100 kPa under 70% degree of saturation.

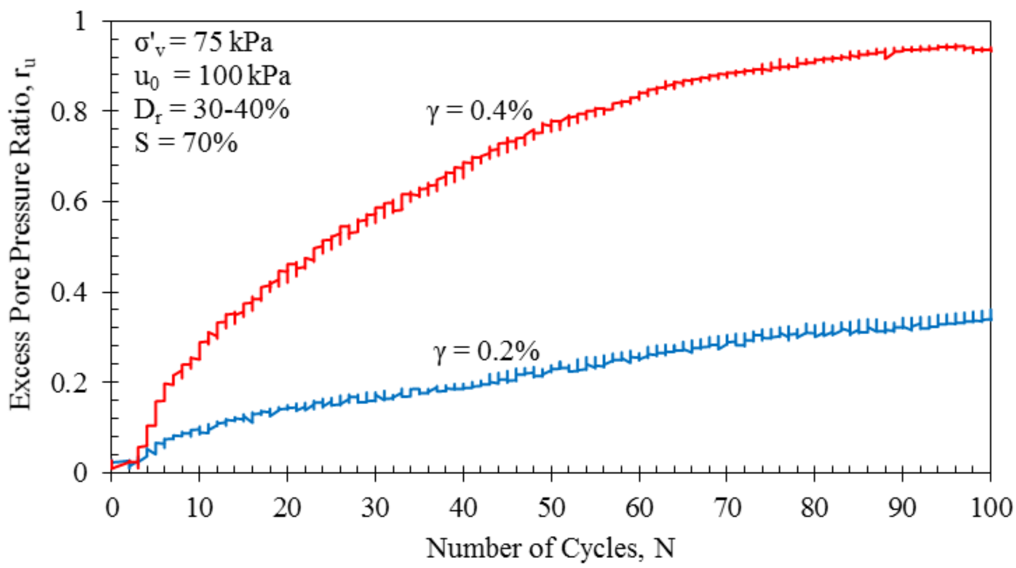


Figure 4.7 : Effect of shear strain on excess pore pressure generation in partially saturated specimens at σ'_v=75 kPa, u_0=100 kPa and S=70%.

Figure 4.8 shows effect of shear strain on r_u generation in partially saturated specimens at σ'_v=100 kPa, u_0=100 kPa and S=85%.

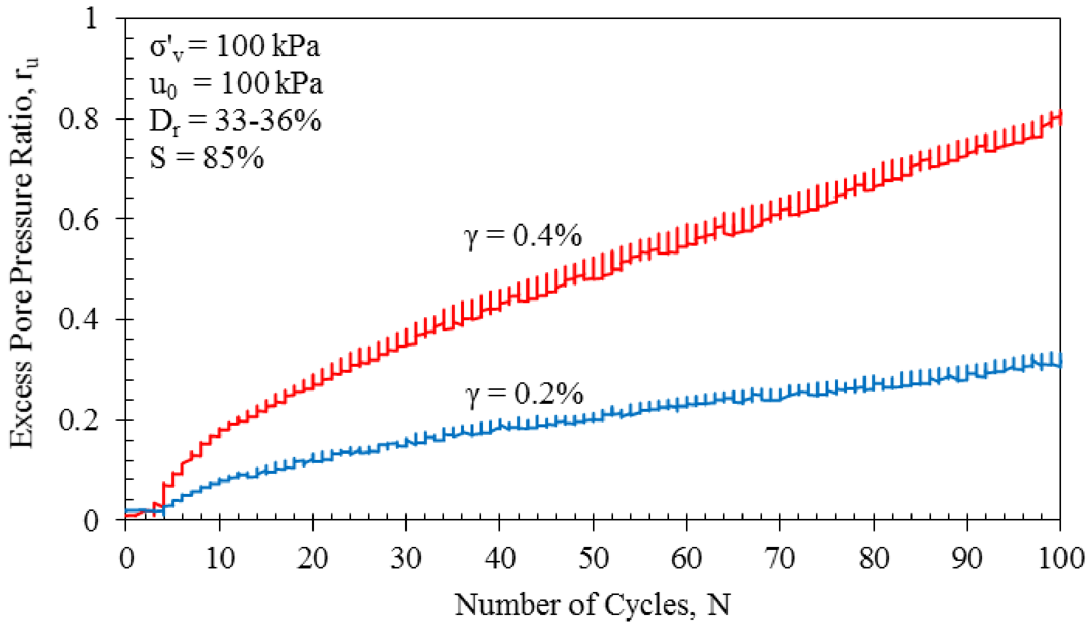


Figure 4.8 : Effect of shear strain on excess pore pressure generation in partially saturated specimens at σ'_v=100 kPa, u_0=100 kPa and S=85%.

According to test results, excess pore pressure generation increases and number of cycles required to liquefaction decreases at higher shear strain levels under the constant effective vertical stress, back pressure and degree of saturation conditions. The most critical condition occurs at the higher shear strain and lower effective vertical stress levels under constant degree of saturation and back pressure.

4.6 Effect of Degree of Saturation on Excess Pore Water Pressure Generation in Partially Saturated Sands

Effect of degree of saturation on liquefaction resistance of partially saturated sands is an important parameter of this research. Degree of saturation effect was examined under 50 kPa and 100 kPa effective vertical stresses with constant back pressures as 100 kPa at 0.2% shear strain deformation. Two main degrees of saturation was tested on the specimens, which were around 87% and 70%.

Undrained cyclic loading liquefaction tests were performed until the excess pore pressure generation stabilized. In all cases, excess pore pressure generation (r_u) reached to nearly 1.0 while number of cycles required to liquefaction increased by decreasing degree of saturation.

Figure 4.9 shows the effect of degree of saturation on excess pore pressure generation in partially saturated specimens at u_0=100 kPa and γ=0.2% under σ'_v=50 kPa and σ'_v=100 kPa respectively. The excess pore pressure generation was shown for 200 number of cycles.

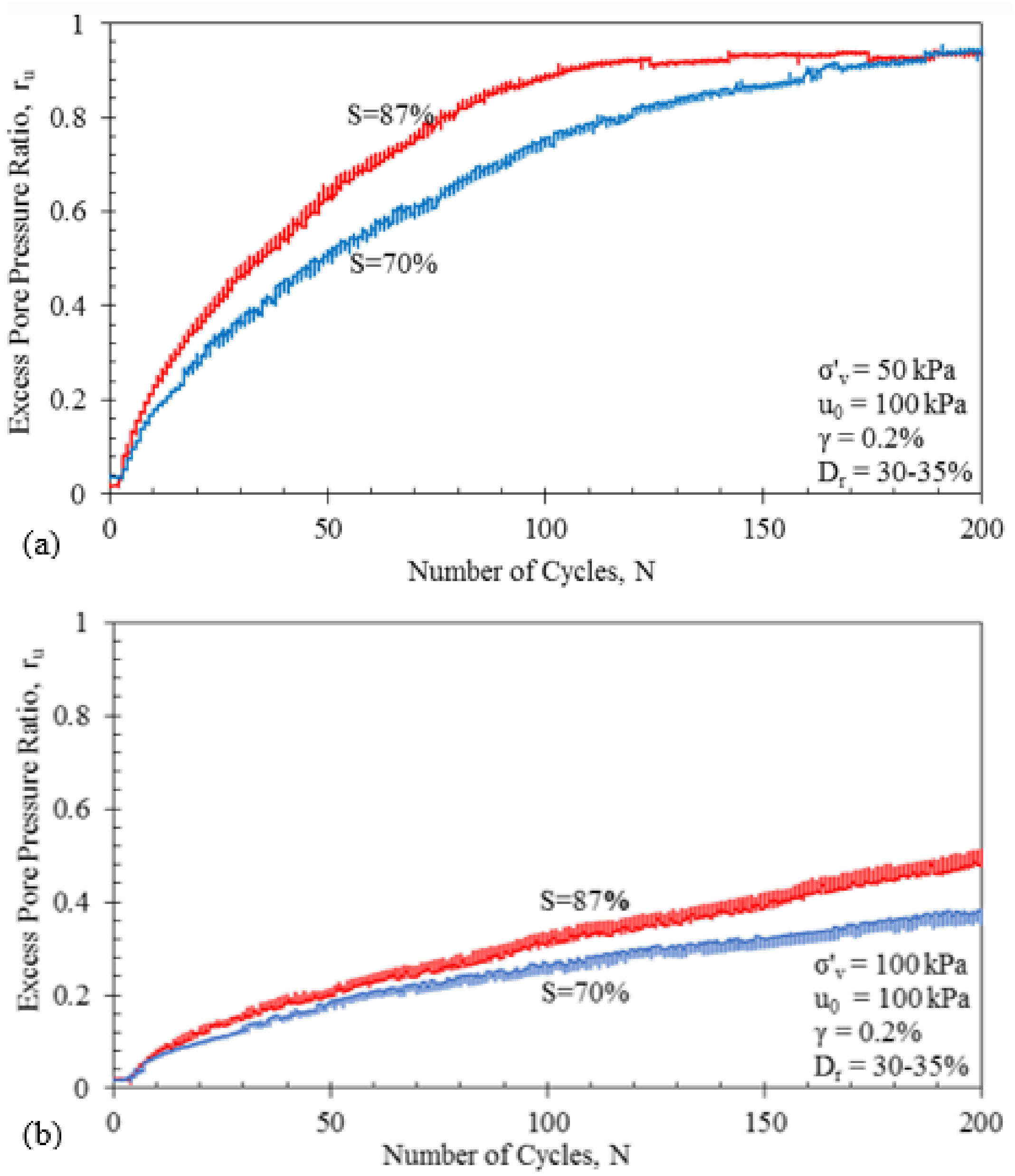


Figure 4.9 : Effect of degree of saturation on excess pore pressure generation in partially saturated specimens at u_0=100 kPa and γ=0.2%: (a)σ'_v=50 kPa. (b)σ'_v=100 kPa.

As stated before, in large size specimen testing systems such as shaking table and centrifuge tests decreasing degree of saturation has a major effect on $r_{u,max}$ generation. As stated by Zeybek and Madabhushi (2017) also by Eseller-Bayat et al. (2013) maximum excess pore pressure ratio does not reach to liquefaction criteria by decreasing degree of saturation. According to the results, the highest degree of saturation such as 87% also presents significant liquefaction resistance under 50 kPa and 100 kPa effective vertical stresses at 0.2% shear strain. However, it is not possible to observe the maximum excess pore pressure ratio ($r_{u,max}$) and maximum number of cycles (N_{max}) by decreasing degree of saturation. This difference in small specimen tests can be attributed to the escape of gas/oxygen bubbles from the top of the small samples, resulting in increasing degree of saturation as cycling continues. Therefore, the behavior in small specimen tests should be only examined for low number of cycles.

4.7 Effect of Effective Vertical Stress on Excess Pore Water Pressure Generation in Partially Saturated Sands

The effect of effective vertical stress on undrained dynamic response of partially saturated specimens was investigated under different degree of saturation levels such as 85%-87% and 68%-70%. In the test procedure, 50 kPa, 75 kPa, 100 kPa and 150 kPa effective confining stresses were applied with 100 kPa constant back pressure at 0.2% shear strain.

Under the constant back pressures, effective vertical stress has an important impact on the liquefaction resistance of partially saturated sands. Excess pore pressure generation decreases by increasing effective vertical stress. The undrained cyclic loading liquefaction tests were performed until the excess pore pressure stabilized. However, by increasing number of cycles the excess pore pressure ratio increases.

At constant number of cycles, the effect of effective vertical stress can be observed clearly. The liquefaction resistance of partially saturated sands under 150 kPa effective vertical stress is greater than the liquefaction strength of partially saturated sample under 50 kPa effective vertical stress.

Increase in effective vertical stress increases the liquefaction resistance of partially saturated sands by increasing number of cycles to liquefaction. When the excess pore pressure (r_u) generation was examined in detail for 100 cycles, it is clear to observe that liquefaction resistance increases from 50 kPa effective vertical stresses to 150 kPa effective vertical stresses under constant 100 kPa pore water pressure and constant shear strain amplitudes.

Figure 4.10 shows effect of effective vertical stress on the excess pore pressure (r_u) generation on partially saturated specimens (a) for 1000 and (b) for 100 number of cycles. The specimens were prepared at 85%-87% degree of saturation, 33% relative density and were tested under 50 kPa, 100 kPa and 150 kPa effective vertical stresses with constant 100 kPa pore water pressure at 0.2% shear strain.

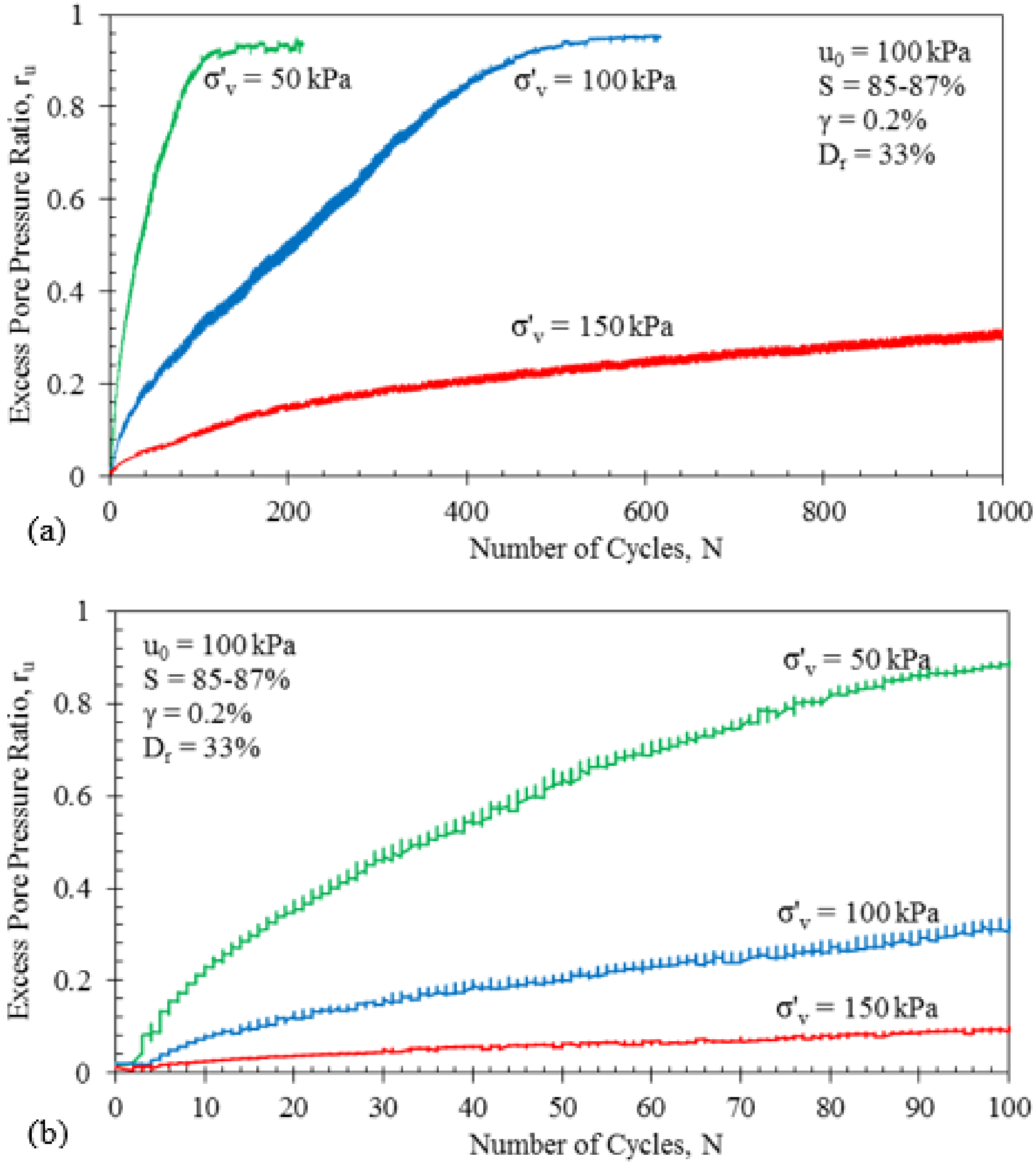


Figure 4.10 : Effect of effective vertical stress on excess pore pressure generation in partially saturated specimens at S=85-87%, u_0=100 kPa and γ=0.2%: (a)for N=1000 cycles. (b)for N=100 cycles.

The excess pore pressure (r_u) generation on partially saturated specimens which prepared at 68%-70% degree of saturation and 30%-32% relative density, tested under 50 kPa, 75 kPa and 100 kPa effective vertical stresses with constant 100 kPa pore water pressure at 0.2% shear strain amplitude were demonstrated in Figure 4.11. The section (a) shows 1000 number of cycles and (b) shows 100 number of cycles.

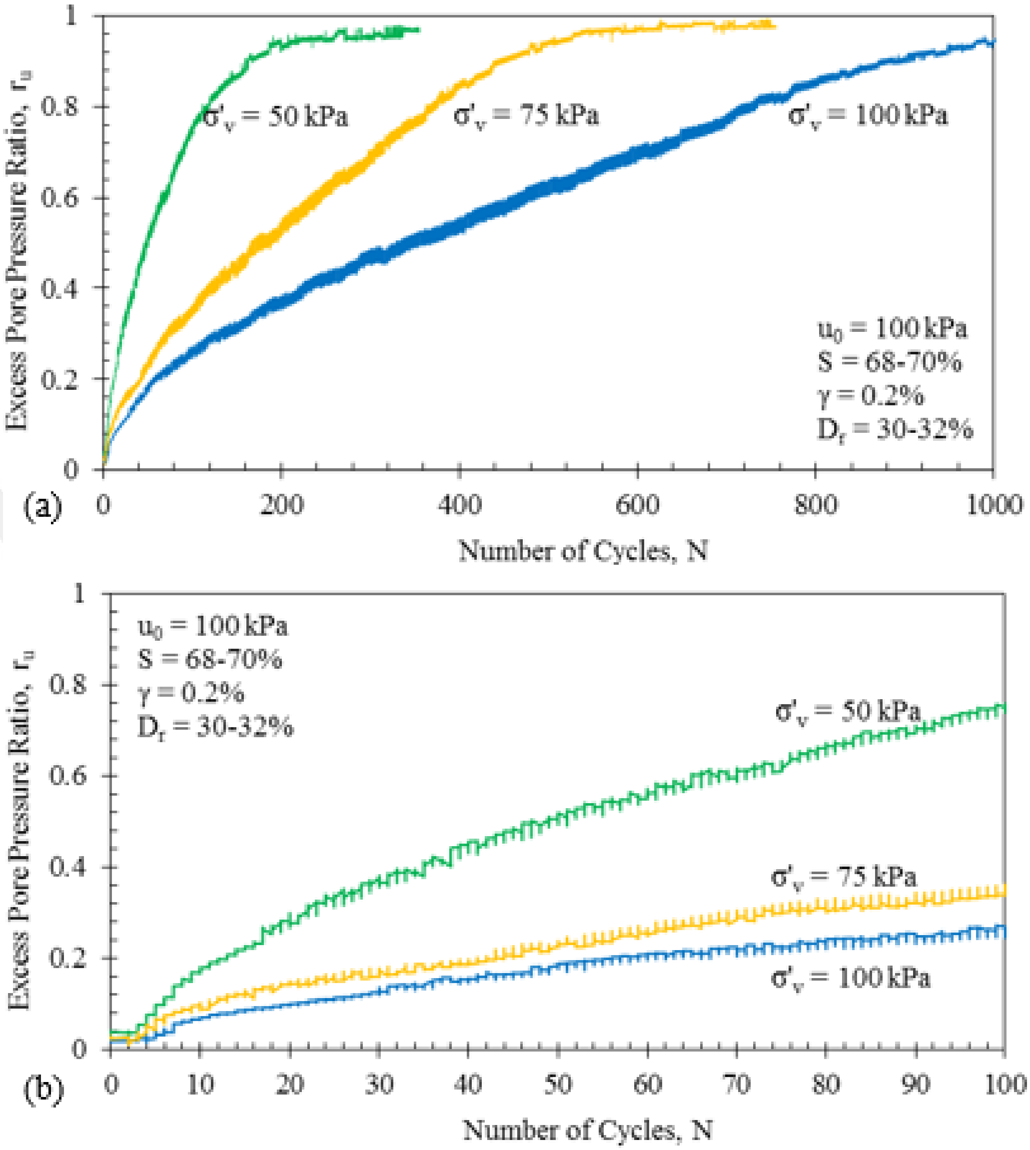


Figure 4.11 : Effect of effective vertical stress on excess pore pressure generation in partially saturated specimens at S=68-70%, u_0=100 kPa and γ=0.2%: (a)for N=1000 cycles (b)for N=100 cycles.

4.8 Effect of Back Pressure on Excess Pore Water Pressure Generation in Partially Saturated Sands

The effect of back pressure on undrained dynamic response of partially saturated specimens was examined under different degrees of saturation. In the test procedure, 50 kPa, 100 kPa and 150 kPa back pressures were applied under constant σ'_v=50 kPa, σ'_v=100 kPa and σ'_v=150 kPa at 0.2% shear strain. The effect of back pressure on r_u

generation in 85%-87% partially saturated specimen at σ′v=50 kPa and 0.2% shear strain was demonstrated in Figure 4.12.

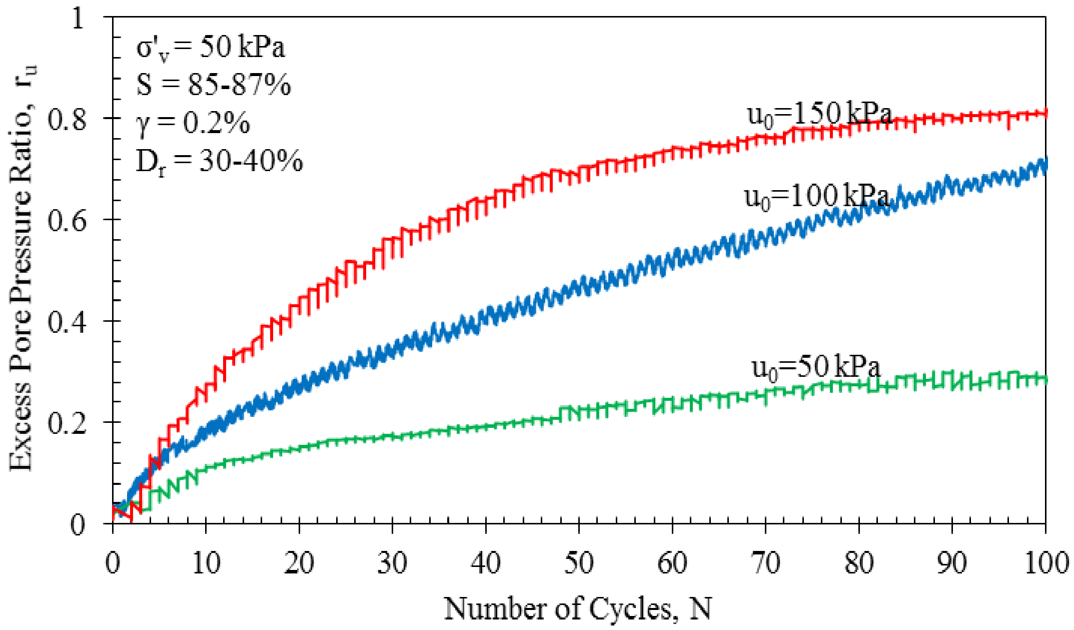


Figure 4.12 : Effect of back pressure on excess pore pressure generation in partially saturated specimens at σ′v=50 kPa, S=85-87% and γ=0.2% at N=100 cycles.

The effect of pore water pressure on the excess pore pressure generation was determined under constant effective vertical stress. The excess pore pressure ratio increases by increasing pore pressure (back pressure) on the contrary to effective vertical stress.

Back pressure has a significant effect on the r_u generation in partially saturated sands. As seen from the results, liquefaction resistance increases by decreasing back pressures. Under 50 kPa effective vertical stress, 50 kPa back pressure shows higher liquefaction resistance compared to 150 kPa back pressure. When excess pore pressure generation was observed for 100 cycles, it is easy to obtain the effect of lower back pressure on the liquefaction resistance.

The increase in excess pore water pressure generation as the back pressure increases can be attributed to the fact that under higher back pressures, the volume of gas bubbles reduces and the compressibility of the pore fluid decreases.

Since the effective vertical stress and back pressure have an opposite effect on the excess pore pressure generation in partially saturated sands, the coupled effect of back pressure and effective vertical stress should be considered.

Figure 4.13 shows r_u generation at σ′$_v$=100 kPa under various back pressures.

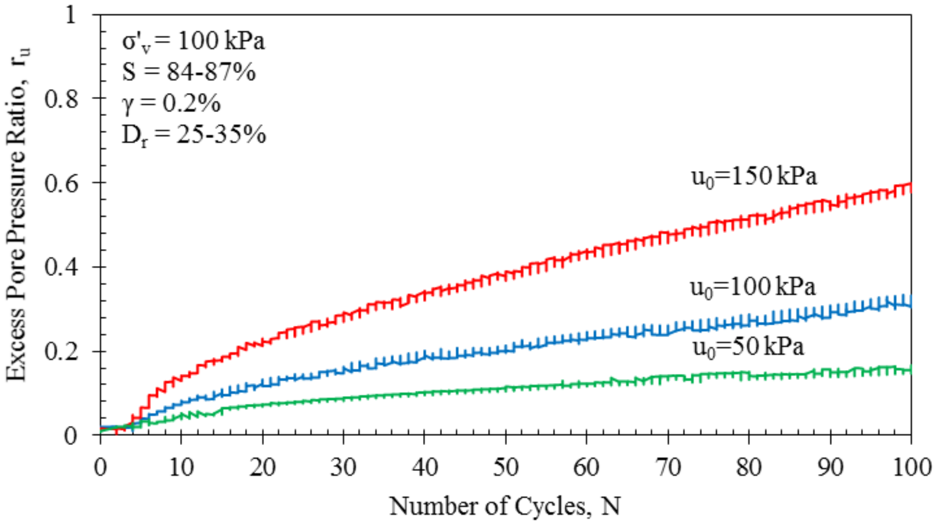


Figure 4.13 : Effect of back pressure on excess pore pressure generation in partially saturated specimens at S=84-87%, σ′$_v$=100 kPa and γ=0.2% for N=100 cycles.

Figure 4.14 presents r_u generation at σ′$_v$=150 kPa under various back pressures.

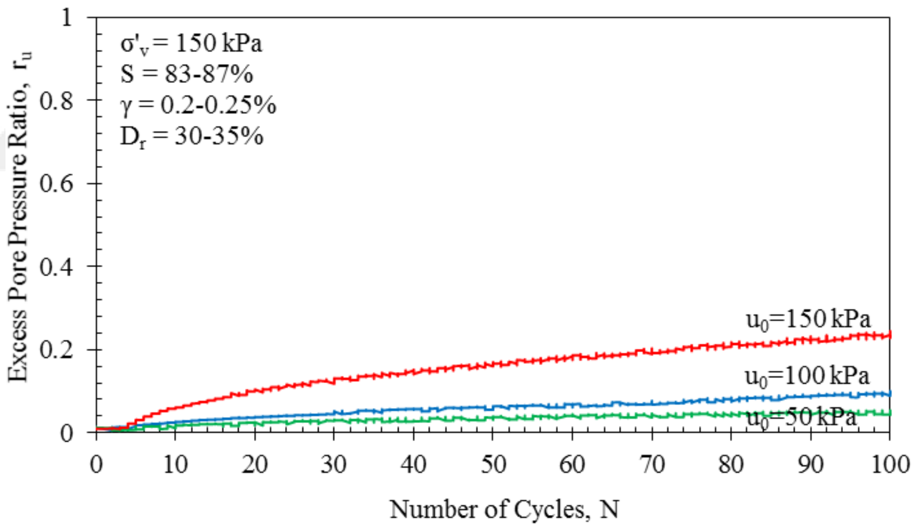


Figure 4.14 : Effect of back pressure on excess pore pressure generation in partially saturated specimens at S=83-87%, σ′$_v$=150 kPa and γ=0.2-0.25% for N=100 cycles.

Back pressure effect under higher effective vertical stresses such as for 150 kPa does not have a significant influence on the liquefaction resistance at 100 cycles. 100 kPa back pressure presents slightly decrease in r_u generation compared to 150 kPa back pressure under 150 kPa effective vertical stress. According to the assumption, the ground water table being at the surface, back pressure was considered as the pore water pressure for a specimen at 5 m, 10 m and 15 m depth from the ground surface. At the same depths, the effective stresses and the initial pore water pressures are approximately close to each other, therefore the tests were performed under σ'_v= u_0=50 kPa, σ'_v= u_0=100 kPa and σ'_v= u_0=150 kPa at 0.2% shear strain respectively. Figure 4.15 shows excess pore pressure generation in 85%-87% and 70%-75% partially saturated specimens that would be at 5, 10 and 15m under the ground surface.

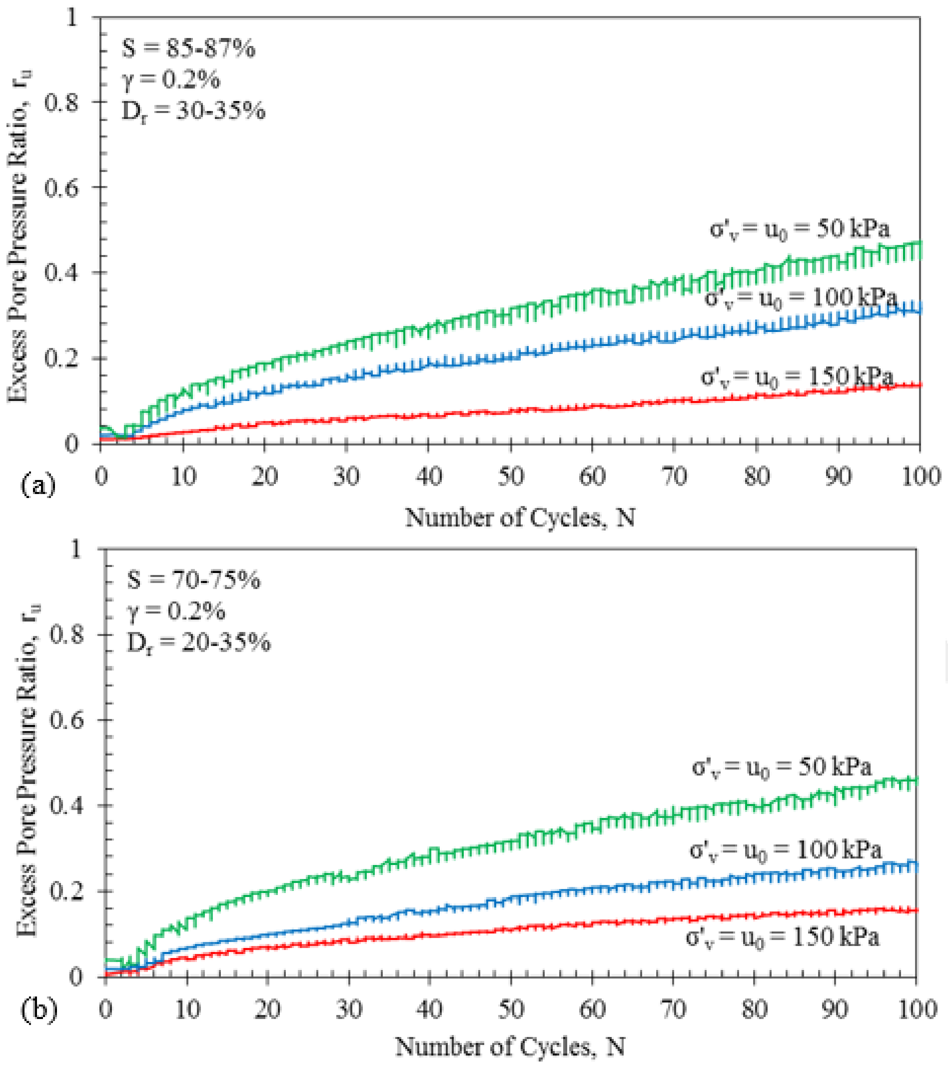


Figure 4.15 : Effect of back pressure on excess pore pressure generation in partially saturated specimens at σ'_v= u_0 =50 kPa, σ'_v= u_0 =100 kPa and σ'_v= u_0 =150 kPa and γ=0.2%: (a)S=85-87%. (b)S=70-75%.

When tests performed under the same amount of effective vertical stress and back pressures, it is clear that the highest liquefaction resistance occurs at 150 kPa and the liquefaction resistance decreases by decreasing effective confining stress and back pressures from 100 kPa to 50 kPa at 85-87% degree of saturation. In case of 70-75% degree of saturation, the effect of effective vertical stress and same amount of back pressure have a clear influence on r_u generation. The highest liquefaction resistance occurs at 150 kPa effective vertical stress and back pressure and the lowest liquefaction resistance occurs at 50 kPa pressures. According to the fact that, $\sigma'_v=u_0=50$ kPa, $\sigma'_v=u_0=100$ kPa and $\sigma'_v=u_0=150$ kPa simulate 5 m, 10 m and 15 m depth in the field. The effect of degree of saturation on r_u generation was examined under the same amount of back pressures and effective vertical stresses for 100 cycles were shown in Figure 4.16.

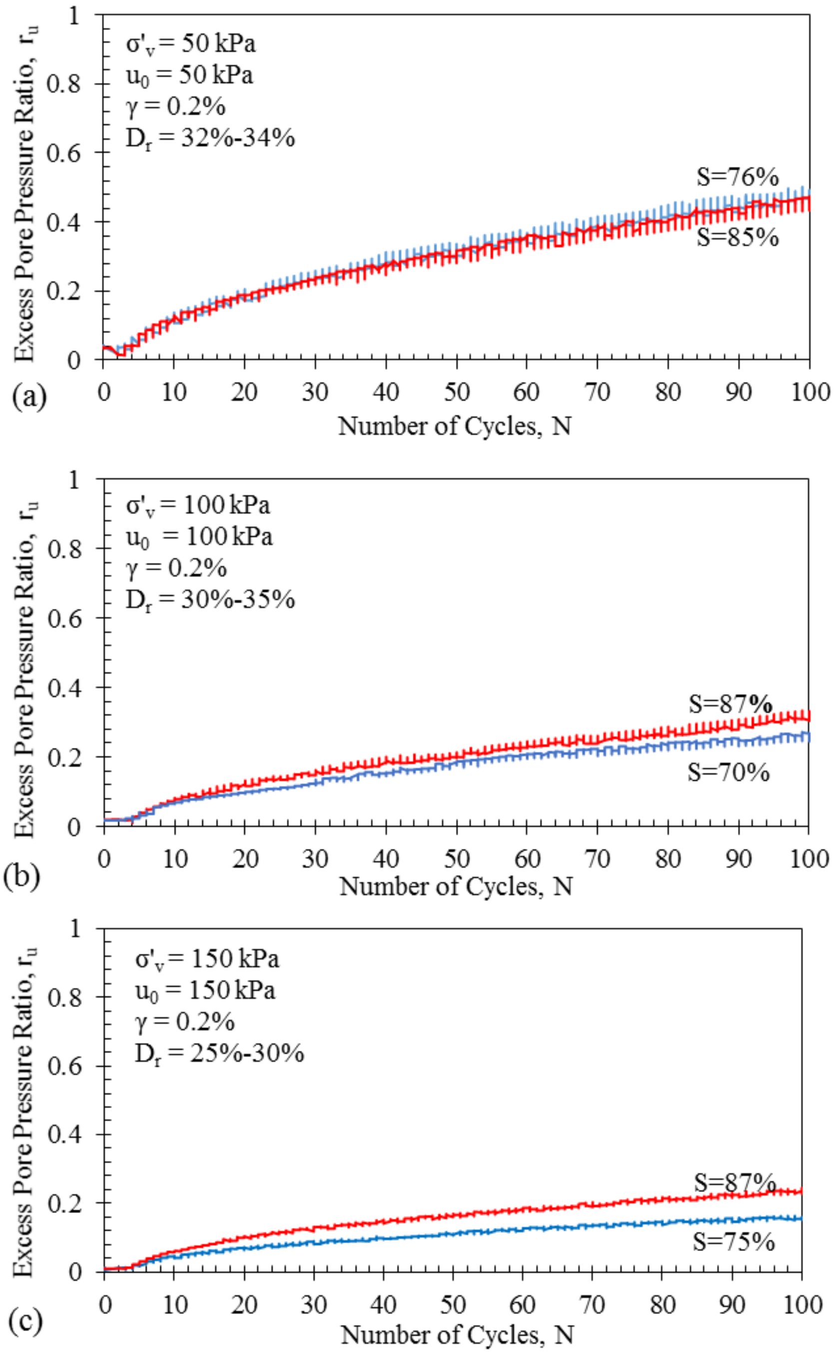


Figure 4.16 : Effect of effective vertical stress and back pressure on excess pore pressure generation in partially saturated specimens at S=70-87% and γ=0.2% for N=100 cycles: (a)$\sigma'_v = u_0$ =50 kPa. (b)$\sigma'_v = u_0$ =100 kPa. (c)$\sigma'_v = u_0$ =150 kPa.

At 50 kPa effective vertical stress and back pressure, change in degree of saturation from 85% to 76% does not affect the r_u generation significantly at 100 cycles. At 100 kPa and 150 kPa effective vertical stress and back pressure conditions, r_u generation is slightly affected by the change in degree of saturation from 87% to 70%. As a result, the lower effective vertical stress and back pressure decreases the undrained dynamic resistance of partially saturated sands compared to higher pressures. The effect of degree of saturation on the liquefaction resistance of partially saturated sand specimens becomes significant in sand samples at deeper depths.

4.9 Overall Analysis of Undrained Cyclic Simple Shear Test Results

Overall analysis of undrained cyclic simple shear tests on fully and partially saturated specimens were presented in this section. The parametric study about the undrained dynamic response of partially saturated sands were investigated according to the relation in between excess pore pressure ratio and shear strain amplitudes. In this analysis, excess pore pressure ratios at 15, 50 and 100 cycles were considered under 0.1%, 0.2%, 0.3% and 0.4% shear strain amplitudes. The undrained cyclic simple shear tests were performed on the fully saturated and partially saturated sand specimens. The all specimens were prepared at the range of 30%-40% relative density. The partially saturated specimens were prepared at the range of 85%-87% and 70%-73% degree of saturation. The effective vertical stress and the pore water pressure were kept constant at 100 kPa in the tests.

It was observed that at a specific number of cycle, excess pore pressure generation reduces with the decrease in the degree of saturation and in the shear strain, as well as the increase in effective stress and back pressure. Hence, it is clearly seen as the degree of saturation decreases liquefaction resistance increases. A significant difference between fully and partially saturated results for r_u generations was observed at 100 cycles. Additionally, Seed and Idriss (1982) stated that 15 number of cycles correspond to reference earthquake magnitude of 7.5. At this concern, the excess pore pressure ratio at 15 number of cycles generated in the partially saturated sand specimens is still less than r_u generation at 15 cycles in fully saturated sands.

The relationship between the excess pore pressure ratio and the shear strain amplitudes were examined under 100 kPa effective vertical stress and 100 kPa back pressure, which performed on fully and partially saturated specimens in a range of degrees of saturation such as 85-87% and 70-73% were presented in Figure 4.17 at 15, 50 and 100 cycles.

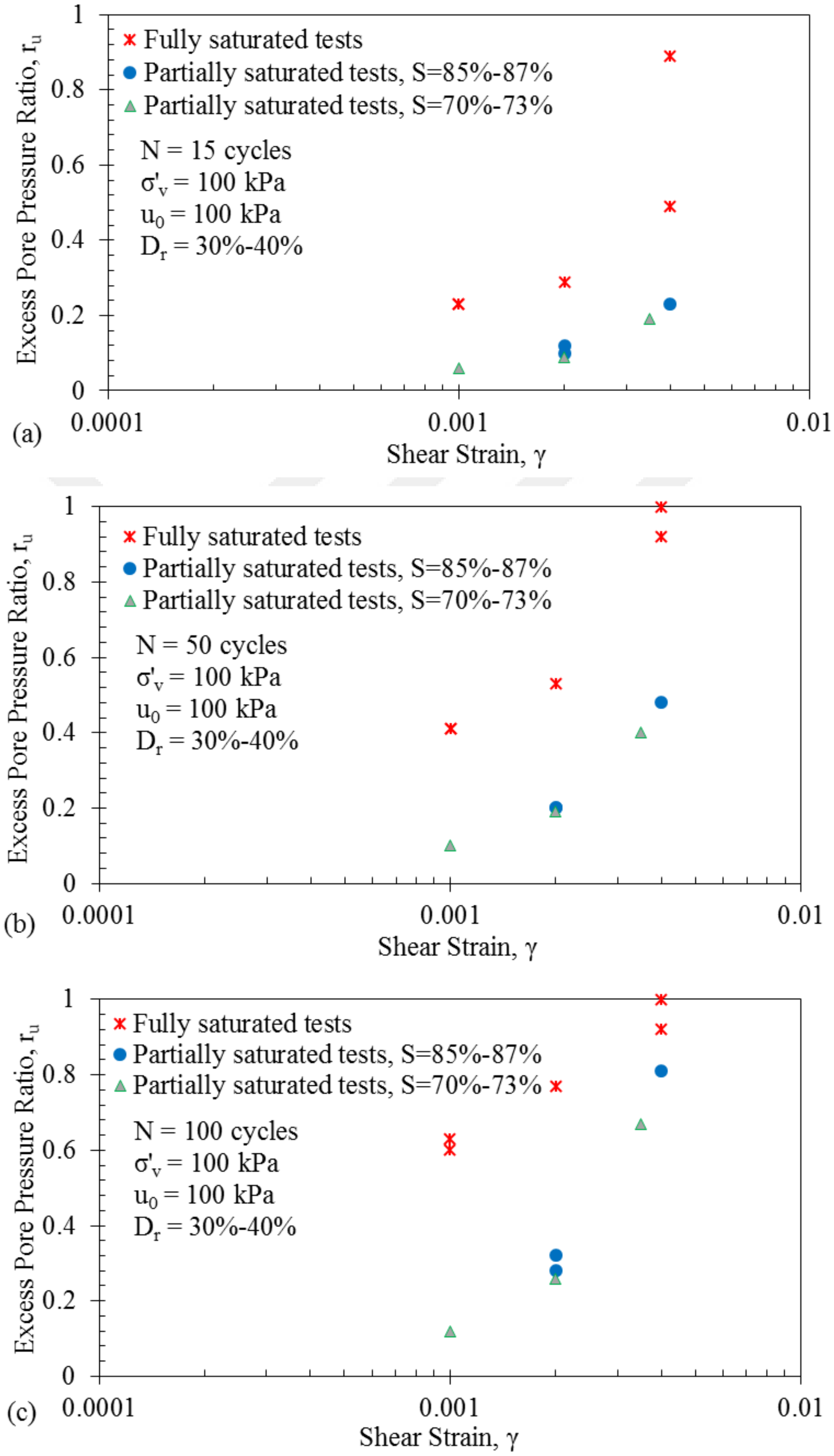


Figure 4.17 : Undrained cyclic simple shear tests on fully and partially saturated sand samples at different shear strains under σ'_v=100 kPa, u_0=100 kPa: (a)N=15 cycles. (b)N=50 cycles. (c)N=100 cycles.

5. CONCLUSIONS AND RECOMMENDATIONS

Undrained dynamic response of fully and partially saturated sands was investigated in this research. Tests were performed under undrained, cyclic loading conditions in Dynamic Simple Shear Testing Device with confining pressure. Test setup includes saturation, isotropic consolidation and undrained cyclic loading liquefaction tests.

Firstly, the best specimen preparation methods were examined for both fully and partially saturated sands by using an unconfined membrane. Dry pluviation, wet pluviation and moist undercompaction methods were performed for fully saturated specimen preparation techniques. Moist undercompaction method was chosen the most suitable technique for this research to get loose, undeformed and fully saturated specimens for liquefaction tests. Secondly, partial saturation was achieved by generation of gas bubbles inside the voids. Gas bubbles were created by using sodium percarbonate powder. The partially saturated specimen preparation was examined in two methods, which are 1) wet pluviation of the dry sand-chemical mixture into the predetermined amount of water and 2) wet pluviation of the dry sand into the water-chemical solution.

Throughout the literature, DSS-C tests on partially saturated sands were first performed in this research. The results of the liquefaction tests were examined in terms of excess pore pressure ratio generation under number of cycles of simple shear strains. Fully and partially saturated tests were compared under same effective vertical stress and shear strain conditions. In addition, the effect of degree of saturation, vertical effective stress, back pressure and shear strain were investigated on partially saturated specimens. Finally, the comparison of fully and partially saturated test results was presented at 10, 50 and 100 number of cycles.

Based on this research, the following conclusions can be drawn:

The best partially saturated specimen preparation technique for DSS-C tests was found to be wet pluviation of dry sand into the water-sodium percarbonate solution.

Loose sand specimens with desired degree of saturation could be obtained with little disturbance to the sample.

Excess pore water pressure generations in partially saturated sands were less than those in fully saturated sands. Unlike the large specimen tests where r_u never reached to 1.0 and stayed stable at a maximum r_u value ($r_{u,max}$) depending on the level of degree of saturation, excess pore water pressure ratio r_u in small sample tests reached to 1.0 under large number of cycles. This behavior was attributed to the saturation of samples due to the escape of gas/air from the shallow sand sample.

Excess pore water pressure generations in partially saturated sands reduce as the degree of saturation decreases, the effective stress increases, the back pressure decreases and the shear strain amplitude decreases.

When the cyclic simple shear tests on partially saturated sands are performed at various back pressures, unlike in fully saturated sands, the excess pore water pressure generations change based on the back pressure. The reason why the r_u generations change is due to the change in the compressibility of the pore fluid under different back pressures. Therefore, it was suggested that the tests should be performed for the representative depth of the sample in the field. The representative effective stresses and the initial pore water pressures at a specific depth in the field were applied on the specimen.

Excess pore water pressure generations in partially saturated sands reduces as the representative sample is from the deeper depths. The effect of the degree of saturation on the r_u becomes more precise at deeper levels.

The r_u values in partially saturated sands at 15^{th}, 50^{th} and 100^{th} cycles were significantly lower than the r_u values in fully saturated sands. The effect of degree of saturation in lowering ru becomes significant at 100^{th} cycle.

This research provides valuable input on the liquefaction behavior of the partially saturated sands. The first DSS-C tests on partially saturated sands in the literature were performed in this research. The outputs will have contribution on the development of partial saturation as a liquefaction mitigation measure. In addition, the findings will be used in the numerical modeling of the partially saturated sands for liquefaction behavior as future work.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Gulen D.B., Ece Eseller-Bayat E.** (2017). Specimen Preparation Techniques for Testing Fully and Partially Saturated Sands in Dynamic Simple Shear (DSS) Test Device with Confining Pressure. In: Ferrari A., Laloui L. (eds) *Advances in Laboratory Testing and Modelling of Soils and Shales (ATMSS). ATMSS 2017. Springer Series in Geomechanics and Geoengineering.* Springer, Cham.