ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

INFLUENCE OF PLASTICITY AND FINES CONTENT ON CYCLIC BEHAVIOUR OF SAND

M.Sc. THESIS

Özge AKIN

Department of Civil Engineering

Soil Mechanics and Geotechnical Engineering Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

PLASTİSİTE VE İNCE DANE ORANININ KUMLU ZEMİNLERİN DİNAMİK DAVRANIŞINA ETKİSİ

YÜKSEK LİSANS TEZİ

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Özge AKIN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 501101310 successfully defended the thesis entitled **"INFLUENCE OF PLASTICITY AND FINES CONTENT ON CYCLIC BEHAVIOUR OF SAND"**, which he/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 : **22 December 2013**
Date of Defense : **04 April 2014**

To my family,

FOREWORD

First and foremost, I would like to express my gratitude and thanks to my supervisors. I am extremely grateful to Ece Bayat for her guidance, patience and continuous support. Also I am deeply thankful to Murat Monkul his help, advices and encouraging attitude. I would like to thank jury members Aykut Şenol, Ayşen Lav and Ayşe Edinçliler for taking time to read this thesis. The last but the most, there is no word to state how grateful I am to my family beside love.

April 2014 Özge AKIN

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ABBREVIATIONS

CH	: High Plastic Clay
CRR	: Cyclic Resistance Ratio
CSR	: Cyclic Stress Ratio
CSS	: Cyclic Simple Shear
CTX	: Cyclic Triaxial
e_{max}	: Maximum Void Ratio
e_{min}	: Minimum Void Ratio
FC	: Fines Content
LL	: Liquid Limit
NoC	: Number of Cycle to Initial Liquefaction
PI	: Plasticity Index
Dr	: Relative Density
Gs	: Specific Gravity
e	: Void Ratio
τ_{cyc}	: Amplitude of Cyclic Stress
σ_v	: Normal Consolidation Stress

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INFLUENCE OF PLASTICITY AND FINES CONTENT ON CYCLIC BEHAVIOUR OF SAND

SUMMARY

Liquefaction is one of the most challenging phenomena that has being still investigated to be understood the exact mechanism. During history, it has been considered that sand containing fines has stronger cyclic resistance than pure sand samples. As a result of this, sand containing fines are commonly viewed as not liquefiable. However, especially after the earthquake in Adapazari, 1999, reseracher started to study this subject again as it was observed that silt or silty sand can liquefy.

This thesis aims to understood the effect of fines content and the plasticity on undrained behaviour of sandy soils. To clarify the effect of fines content, soil specimen are prepared at different fine contents, which are 5% and 10% respectively. To examine the effect of plasticity, non-plastic silt and clay samples, which have different PI values, are added to clean sand and at least five CDSS tests are performed on each of them.

In this study, 120 Cyclic Direct Simple Shear tests are performed. In order to choose the method to be used in the preparation of specimen, the previous literature that discusses the sample preparation method had been examined. Six main commonly used methods are chosen form the sample preparation method literature are: "Wet Pluviation", "Staged Wet Pluviation", "Dry Pluviation and Flushing Water" and "Dry Pluviation and Flushing Water with CO_2 and Water". These methods are compared based on their degree of saturation values, fines content, homogeneity, repeatability and test duration.

Once the sample preparation method had chosen, four different soil mixtures that have different plasticity values, are compared to each other in terms of their cyclic response under constant volume condition. To see the cyclic behaviour of soil more precisely, all test groups are performed at three CSR values. All tests are discussed in terms of many different parameters including fines content, plasticity, void ratio, relative density and CSR.

Based on this laboratory study, especially based on the pore pressure generation curves it can be said that, the fines content (FC) causes a decrease in liquefaction resistance of clean sand at each FC amount. Additionally, Non-plastic Silt and High Plastic Clay are compared to each other but not a clear evidence of the effect of plasticity on liquefaction resistance can be found. Further investigations about this subject is needed.

PLASTİSİTE VE İNCE DANE ORANININ KUMLU ZEMİNLERİN DİNAMİK DAVRANIŞINA ETKİSİ

ÖZET

Kum zeminlerin deprem gibi dinamik yükler altında sıvılaşması geoteknik mühendisliğinin önemli problemlerinden biri olarak kabul edilmektedir. Tarih boyunca, içerisinde ince dane barındıran kum zeminlerin sıvılaşma direncinin saf kuma göre daha yüksek olduğu düşünülmüş ve bu anlamda ince dane içeren kumlar üzerinde çok fazla çalışma yürütülmemişse de özellikle 1999 Adapazarı depreminde silt ve siltli kum olarak sınıflandırılabilecek zeminlerin önemli oranlarda sıvılaşma göstermesi geoteknik mühendislerini bu konuda üzerinde tekrar çalışmaya itmiştir.

Bu tez çalışması kapsamında da ince daneli kum zeminlerin içerisindeki ince danelerin oranından ve bulundurduğu dane tipinin plastisitesinden nasıl etkilendiği anlaşılmaya çalışılmıştır. Bu minvalde, plastik olmayan silt, düşük plastisiteli Kaolinit ve yüksek plastisiteli başka bir kil %5 ve %10 oranlarında temiz kumun içerisinde katılmış ve farklı zemin tiplerinin dinamik davranışındaki değişim gözlemlenmeye çalışılmıştır.

Yürütülen proje kapsamında, tüm dinamik testler Yeditepe Üniversitesi bünyesinde bulunan GeoComp marka bir tam otomatik Tekrarlı Basit Kesme deney düzeneği ile gerçekleştirilmiştir. Farklı türlerde testler yapmaya imkan veren düzenek Dinamik Üç Eksenli Test ile karşılaştırıldığında daha küçük boyutlu bir numune ile çalışılabilmesi ve daha üniform dalga üretebilmesi gibi avantajlara sahiptir. Bu çalışma kapsamında bahsi geçen düzenek ile "Sabit Hacim Testi" yapılmıştır. Sabit Hacim Testi deney süresince numunenin boyu ve çapı sabit tutularak yapılan bir testtir ve bu durum deney esnasında numune üzerindeki düşey basıncın değişimi ile ayarlanmaktadır. Literatüre bakıldığında Sabit Hacim Testinin numunenin doygun olmadan da kullanılabildiği bir test olduğu görülmüştür. Ancak, yapılan testler sonucunda bu durumun kilin su ile reaksiyona giren yapısından dolayı killi numuneler için geçerli olmayacağı fark edilmiştir. Bu nedenle, bu tez çalışması kapsamında kullanılan deney aletinin orijinal düzeneğinin sıvılaşma çalışması için önemli kabul edilen suya doygun numune hazırlamaya elverişli hale getirilmiştir.

Ek olarak, literatürde sıkça kullanılan numune hazırlama yöntemleri tek tek araştırılmış ve tümbyöntemler sırasıyla, doygunluk derecesi, içerdiği ince dane oranı, homojenliği, tekrarlanabilirliği ve numune hazırlama süresi gibi beş farklı parametre açısından karşılaştırılmıştır. Bunun yanısıra, ilk defa bu çalışmada kullanılan ve "Tabakalı Islak Yağmurlama" adı verilen başka bir yöntem geliştirilmiştir. Bahsedilen ana yöntemler, "Islak Yağmurlama", "Tabakalı Islak Yağmurlama", "Kuru Numuneden H_2O Geçirme" ve "Kuru Numuneden CO_2 and H_2O Geçirme" olarak sıralanabilir. Bunlara ek olarak, "Kil Bulamaç" ve "Piknometre Yardımıyla Dökme" gibi farklı türde numune hazırlama yöntemleri de denenmiş ancak çeşitli sebeplerden bu yöntemlerle başarıya ulaşılamamıştır. Elde edilen sonuçlara göre "Kuru Numuneden CO_2 and H_2O Geçirme" yönteminin istenilen numuneyi elde etmede en başarılı metot olduğuna

karar verilmiştir. Bahsedilen yöntem %98 civarında doygunluk yüzdesi ile en yüksek doygunluğu veren yöntem olmuştur. Bununla birlikte %9,9 gibi oldukça yüksek bir oranda ince dane muhteva ederek bu çalışmanın ikinci önemli parametresi olan ince dane oranında da yeterli düzeye erişmiştir. Bahsi geçen tüm yöntemler homojenlik açısından da karşılaştırılmıştır. Bu çalışmada homojenlik, herhangi bir yöntemle hazırlanan numunenin yatay ve düşey yönde iki eşit parçaya ayrılması ve her bir parçanın ayrı ayrı ıslak elek analizine tabi tutulması ile belirlenmiştir ve yapılan deneyler sonucunda yöntemler arasında bir üstünlük bulunamamıştır. Son olarak tüm bu metotlar test süresi ve tekrarlanabilirlik açısından karşılaştırılmıştır. Deneylerin tekrarlanabilirliği standart sapma yardımı ile belirlenmiştir ve kuru numune temelli yöntemlerin ıslak yağmurlama bazlı yöntemlere göre daha tekrarlanabilir sonuçlar verdiği gözlemlenmiştir. Tüm bu parametreler açısından bakıldığında, "Kuru Numuneden CO_2 and H_2O Geçirme" yönteminin en başarılı yntem olduğuna karar verilmiş ve tüm sıvılaşma deneyleri bu yöntemle hazırlanan numuneler üzerinde gerçekleştirilmiştir.

Numune hazırlama yöntemi seçildikten sonra, 110 farklı Tekrarlı Basit Kesme deneyi plastik olmayan silt, yüksek plastisiteli ve düşük plastisiteli kil içeren kum numuneler üzerinde plastisitelerdeki dört farklı zemin numunesi üzerinde uygulanmış ve dinamik davranışın etkisini daha iyi görebilmek için her bir zemin grubu 0.12, 0.1 ve 0.08 CSR değerlerinde test edilmiştir. Elde edilen sonuçlar, ince dane oranı, plastisite, boşluk oranı, rölatif sıkılık, CSR gibi parametreler açısından karşılaştırılmış ve her bir parametrenin dinamik davranışa olan etkisi anlaşılmaya çalışılmıştır. Tüm bu testler için frekans değeri 0,1 Hz. alınmıştır.

Yapılan testler ekseninde görülmüştür ki, CSR değerinin artması zemin numunesinin tipinden bağımsız olmak üzere numunenin sıvılaşmaya başladığı dalganın sayısında düşüşe neden olmaktadır. Başka bir deyişle, yüksek CSR değerlerinde zemin daha kolay sıvılaşmaktadır. Literatür ile karşılaştırıldığında bu durum beklenen bir sonuçtur.

Kum zemin içine katılan ince danenin, özellikle boşluk suyu basıncının gelişimi baz alınarak bakıldığında kum zeminin sıvılaşmasına ciddi oranda katkı sağladığı görülmüştür. Başka bir deyişle, bütün ince dane tipleri kumun sıvılaşma direncini hem %5 hem de %10 ince dane oranı için düşürmektedir. Ancak farklı CSR değerlerinde zemin tiplerinin sıvılaşma direncilerinin sırlaması ve sıvılaşmaya karşı en güçlü muhavemeti gösteren zemin tipi farklı olabilmektedir.

Ek olarak, bütün zemin tipleri plastisitenin etkisini anlamak için de birbirleriyle karşılaştırılmıştır. Literatürde plastisitenin etkisi konusunda birbiriyle çelişen ifadeler bulunmaktadır. 1960'lı yılların başlarında yalnızca kil zeminler ile çalışan araştırmacılar yüksek plastisiteli killerin sıvılaşmadığını söylemişlerdir. Zamanla gelişen teknoloji ile plastisitenin etkisinin her ince dane oranında aynı olmadığını ve tümden bir artış ya da azalışın söz konusu olmadığı söylenmiştir. Bu kapsamda çeşitli araştırmacılar hem çeşitli kriterler geliştirmişler hem de plastisite etkisinin farklılaştığı noktayı belirlemeye çalışmışlardır. Bu bağlamda likit limit ve plastisite indisine dayanan çeşitli kriterler geliştirilmeye çalışılmışsa da günümüzde halen daha bu konu netleştirilememiştir. Bu çalışma kapsamında da farklı plastisiteli killer kumun içerisine katılmış ve böylece plastisitenin etkisine bakılmaya çalışılmıştır. Bu tez çalışmasında düşük plastisiteli kil olarak plastisite değeri 11 olan Kaolinit ile 45 olan yüksek plastisiteli başka bir kil kullanılmıştır. Ek olarak numune içine plastik olmayan silt katılarak var olması beklenen etki bu açıdan da yorumlanmaya çalışılmıştır.

Buna rağmen, elde edilen sonuçlara göre, özellikle plastik olmayan Silt ve Yüksek Plastisiteli Kilin dinamik davranışları karşılaştırılmış ve plastisitenin etkisine dair net bir sonuç bulunamamıştır. Düşük PLastisiteli kilin yapısından kaynaklanan özel bir problemi olduğu düşünülmüş ve deney verileri Silt ve Yüksek plastisiteli kil açısından karşılaştırılmakla yetinilmiştir. Bu konu hakkında gelecek çalışmalara ihtiyaç vardır.

1. INTRODUCTION

During the past 50 years, although geotechnical engineers studied about the liquefaction not only in field but also in laboratory, there is still confusion about the liquefaction phenomena of sands containing fine grained materials. The effect of soil type, fines content amount and the plasticity are also the subjects which are still needed to be investigated to achieve a better understanding about the cyclic behaviour of sandy soils.

The aim of this study is to investigate the effect of plasticity and fines content on cyclic behaviour of sandy soils. Although there is an extensive literature examining the effects of amount and plasticity of fines, there is still no clear consensus among researchers. Chapter 2 presents the summary of the literature and discusses the confusion.

In order to choose the method to be used in the preparation of specimen, the previous literature that discusses the sample preparation method for direct simple shear testing had been examined. Six methods were used in this study are: "Wet Pluviation", "Staged Wet Pluviation", "Dry Pluviation and Flushing Water" and "Dry Pluviation and Flushing Water with CO_2 and Water". These methods were compared based on the degree of saturation values obtained in the specimens, fines content achieved, homogeneity, repeatability and test duration. In Chapter 3, the advantages and disadvantages of each method were discussed and the best method to achieve fully saturated and homogeneous specimens at desired fines content regarding the suitability for liquefaction analysis was chosen.

In order to investigate the effect of fines content on the liquefaction resistance, soil specimens were prepared at 5% and 10%. To understand the effect of plasticity, non-plastic silt and clay samples, which have different PI values, were added to clean sand and at least five CDSS tests were performed on each of them. To see the cyclic behaviour of soil more precisely, all test groups were performed at three CSR values, which were 0.12, 0.1 and 0.08, respectively. Four different soil mixtures were compared to each other in terms of their cyclic response under constant volume condition. The effect of plasticity and fines content was analysed using the stress-strain graphs. Moreover, 120 tests were performed and the results were discussed based on fines content, plasticity, void ratio, relative density and Cyclic Stress Ratio(CSR). Chapter 4 presents the results of these experiments.

2. LITERATURE REVIEW

2.1 Introduction

Soil liquefaction describes a phenomenon whereby a saturated or partially saturated soil substantially loses strength and stiffness in response to an applied stress, usually earthquake shaking or other sudden change in stress condition, causing it to behave like a liquid. In soil mechanics the term "liquefied" was first used by Hazen (1920) in reference to the 1918 failure of the Calaveras Dam in California. [8] He described the mechanism of flow liquefaction of the embankment dam as follows:

If the pressure of the water in the pores is great enough to carry all the load, it will have the effect of holding the particles apart and of producing a condition that is practically equivalent to that of quicksand... the initial movement of some part of the material might result in accumulating pressure, first on one point, and then on another, successively, as the early points of concentration were liquefied.

Liquefaction potential assessment requires the determination of two values: (1) the loading the deposit will be subjected to as a result of earthquake; and (2) the resistance of the soil to liquefaction. In the widely used liquefaction assessment procedure initially outlined by Seed and Idriss (1971) [9], and later improved by Seed (1979) [10], Seed et al. (1983, 1984) [11] [12], these two quantities are the cyclic stress ratio (CSR) and cyclic resistance ratio (CRRM=7.5). The CSR is the ratio of the shear stress generated by the earthquake to the vertical effective stress at the desired depth. The CRRM=7.5 is the ratio of the cyclic resistance to liquefaction to vertical effective stress. Liquefaction at a given depth is expected to occur when CSR>CRRM=7.5 at that depth (Carraro et al. (2006) [13]).

Previous studies were examined in order to determine the effects of fines and plasticity of sandy soils. With the help of this literature review, it is seen that although the effects of plasticity and fines content on liquefaction potential of sandy soils have been investigated by several researchers, there is still confusion about this subject. A brief review of these different results are summarized in Table.

2.2 The Effects of Non-Plastic Fines Content

Many researchers have reported that the cyclic resistance of a sandy soil increases with increasing silt content. Chang and Yeh (1982) [14] indicated that, with increasing silt content, cyclic resistance increased significantly after a small initial drop. Likewise, Dezfulian (1982) [15] found that cyclic resistance increases with increasing silt content.

Several investigators have found that cyclic resistance decreases with increasing silt content. Shen (1977) [16], Tronsco and Verdugo (1985) [17], and Vaid (1994) [18] have found a decrease in cyclic resistance for samples which were prepared at a constant gross void ratio or a constant dry density. The decreases in cyclic resistance were marked, decreasing as much as 60 percent from their clean sand values for an increase in silt content of 30 percent Vaid (1994) [18].

In addition to these findings, many researchers have reported that the cyclic resistance of a sandy soil first decreased as the fines content increased and then it increased. Koester (1994) [19] and Law and Ling (1992) [20] said that the cyclic resistance of the soil decreased as silt content increased, but it is true only for a limiting silt content value.

Koester (1994) [19] reported that a decrease in cyclic resistance to less than one-quarter of the clean sand cyclic resistance at a silt content of 20 percent, followed by an increase in cyclic resistance to 32 percent of the clean sand value at a silt content of 60 percent.

Polito and Martin (2001) [1] have found that the liquefaction resistance of silty sands is more dependent on the relative density of sand-silt mixtures than other terms. The variation in cyclic resistance with silt content for yatesville sand specimens prepared by moist tamping adjust to 30% relative density is given in Figure 2.1.

Based on the majority of the available studies, Carraro and Bandini (2003) [13] concluded that (i) the increase of non plastic fines increases the liquefaction resistance

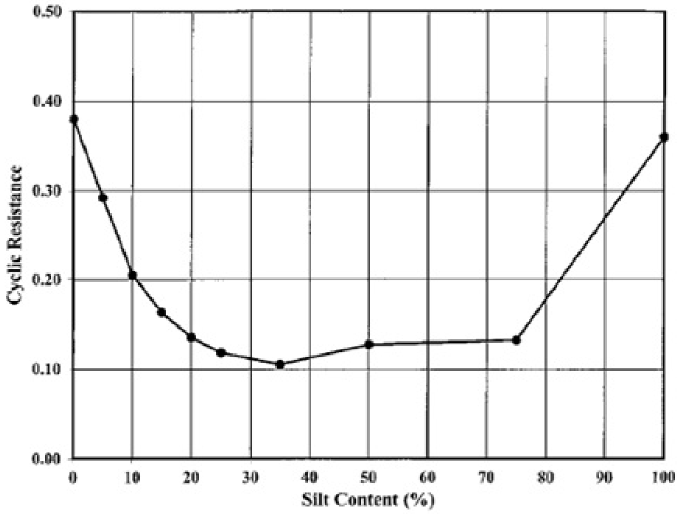


Figure 2.1: Cyclic resistance of monterey sand at constant void ratio with variation in silt content, Polito and Martin (2001) [1]

of silty sand if the relative density is used as the basis for comparison, and (ii) at the same void ratio, increase of non plastic fines results in lower liquefaction resistance.

Wang and Wang (2010) [2] show that increasing fines content amount of non-plastic silt in sand specimen lead to first an increase in cyclic strength and then causes a decrease. Figure 2.2 shows the variation in relative density with fines content.

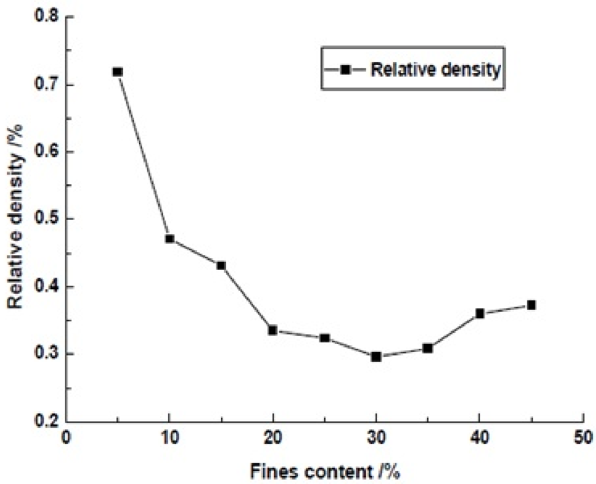


Figure 2.2: Variation in relative density with fines content, Wang and Wang (2010) [2]

In addition to these findings, Monkul and Yamamuro (2011) [21] showed that the influence of fines content may be significantly affected by the nature of the fines, and the resulting undrained response of a sand can be vastly different (e.g., complete liquefaction versus completely stable) for the same stress conditions, depending on the silt gradation.

2.3 The Effects of Plastic Fines Content and Plasticity

For many years, the effect of plasticity on liquefaction potential of sands have been investigated at different fines content. Finn (1982) proved that soils are liquefiable if the PI<10 and the clay content <10 percent. Seed et al. (1983) [11] said that clayey soil will not liquefy if its clay content greater than 20 percent or a water content less than 90 percent of liquid limit. Ishihara and Koseki (1989) [22] reported that there was no clear correlation between clay content and liquefaction resistance, but they said that the liquefaction resistance increased as increasing plasticity index. Also, Yasuda et al. (1994) [23] said that plasticity index has positive effect on liquefaction resistance.

Koester (1994) [19] provided evidence that would appear to indicate that soil plasticity is not a controlling factor in liquefaction resistance in soils with plastic fines. He found that while at a given void ratio, fine type and plasticity play a minor role in liquefaction resistance, they exert far less influence than the percentage of fines in the soil.

Polito (1999) [24] found that increasing plasticity decreases cyclic strength when liquid limit lower than 17%. He also said that there is a little correlation between fines content of a sand and its cyclic resistance. Figure 2.3 represents the variation in cyclic resistance with liquid limit for specimens prepared to a constant soil specific relative density.

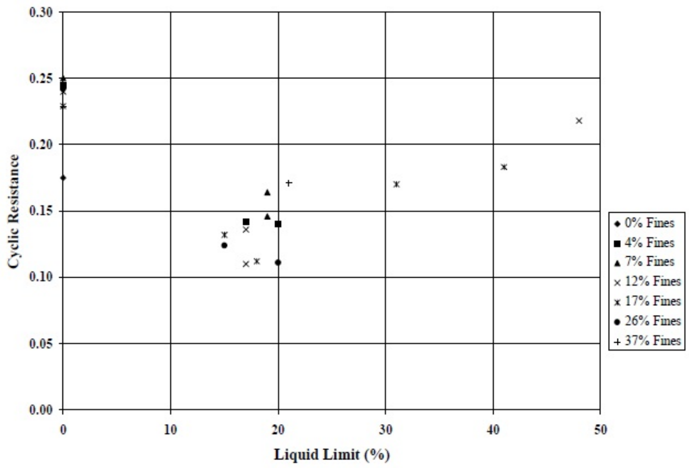


Figure 2.3: Variation in cyclic resistance with liquid limit for specimens prepared to a constant soil specific relative density, Polito and Martin (2001) [1]

In addition to this, Polito (1999) [24] mentioned that no clear correlation may be drawn regarding the effect of clay content on liquefaction resistance of clayey sand.

Yasuda et al. (1994) [23] stated that cyclic strength increases slightly as clay percentage increases. Besides, he concluded that the cyclic strength increases as PI increases.

Bouferra and Shahrour (2004) [3] also showed that from cyclic triaxial tests using a sand containing up to 15% clay, the liquefaction resistance decreased as the clay content increased. Influence of fines content on resistance to liquefaction of sand-clay mixture is shown in Figure 2.4.

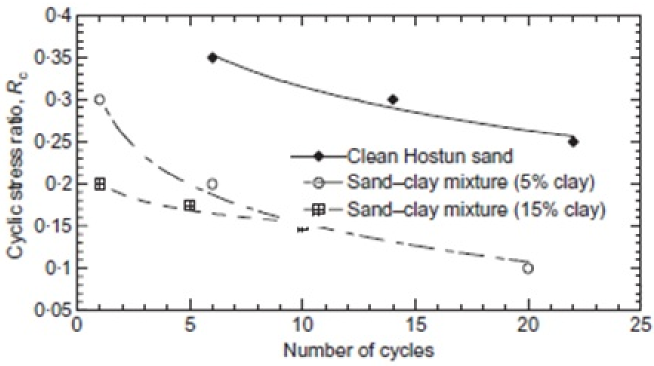


Figure 2.4: Influence of fines content on resistance to liquefaction of sand-clay mixture, Bouferra and Shahrour (2004) [3]

Gratchev et al. (2006) [25] concluded that cyclic behaviour of clayey sand specimen depends on the PI value of sample. He found that low plastic clay causes a rapid liquefaction if its PI values lower than 4. Liquefaction resistance increases when medium plastic clayey sand, which have a PI value between 5 and 14, is added to sand specimen. And he said that liquefaction can not be observed if clayey sand has higher PI value than 14. His findings also indicated that bentonite-sand mixture did not liquefy, and it has remarkably higher liquefaction resistance than Kaolinite and Illite-sand mixtures. Hence, he said that the boundary between liquefiable and nonliquefiable artifial mixtures is drawn at PI=15.

Ghahremani and Ghalandarzadeh (2006) [4] found that the cyclic strength increases as plasticity increases. Also, at a constant void ratio, he indicated that increasing plastic fines amount up to 30% decreases the cyclic strength. Additionally, he found that the pore pressure generation rate for soils with higher clay contents is faster at the beginning of the cyclic loading. The effect of fines content on liquefaction resistance of sand-kaolinite mixtures for constant values of void ratio is given in Figure 2.5.

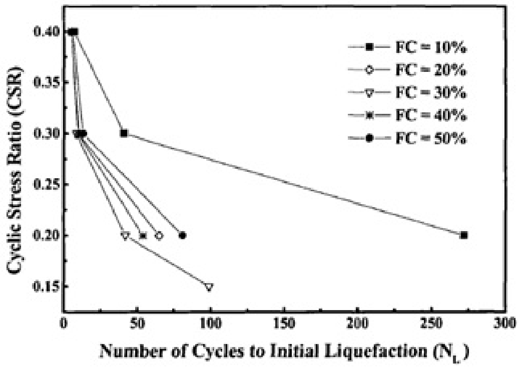


Figure 2.5: Effect of fines content on liquefaction resistance of sand-kaolinite mixtures for constant values of void ratio, Ghahremani and Ghalandarzadeh (2006) [4]

Chang and Hong (2008) [7] concluded that 5-10-15% clay content results are similar each other, but 35% is significantly different than other samples.

Tsai et al. (2010) [26] indicated that cyclic strength decreases as CSR value increases independently from the soil type.

More recently, Park and Kim (2013) [5] concluded that when small amount (10%) of plastic fines is included in sand matrix, the liquefaction resistance of sandy soils appears to be dependent on the plasticity of the fines. As the plasticity of 10% fines increased, the liquefaction resistance of medium or dense specimens decreased, but that of the loose specimen decreased slightly. The behaviour of sandy soils at dense states was significantly influenced by the plasticity or particle size of fines within the sand matrix. Liquefaction resistance curves for different relative densities is shown in Figure 2.6.

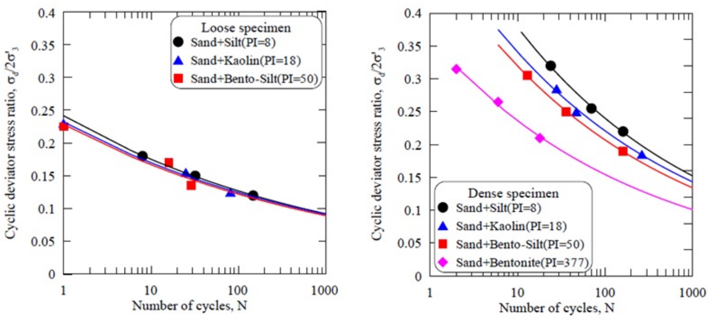


Figure 2.6: Liquefaction resistance curves for different relative densities, Park and Kim (2013) [5]

Table 2.1. presents summary on key findings of the recent literature that analyse the cyclic behaviour of sand containing fines. There are other studies that are investigating the effect of plasticity on pure clay samples. But this thesis focuses only on cyclic behaviour of sand containing fines. Hence literature review does not consider those studies.

Considering this confusion faced in literature, it can be said that the effect of non-plastic silt and plastic fines content on cyclic behaviour of sandy soils have to be investigated with more studies.

Table 2.1: Literature Review.

Reference	Soil Type	FC Type	PI	FC Range (%)	Test Type	Comparison Basis	Cyclic Strength
[5]	Sand	• **Silt** • **Kaolinite** • **Bentonite+Silt** • **Bentonite**	• **Silt**(8) • **Kaolinite**(18) • **Bentonite+Silt**(50) • **Bentonite**(377)	10	Cyclic Triaxial	• regardless of the plasticity, increasing Dr • Increasing PI	• Increases • Decreases (for medium-dense samples)
[26]	Fine Sand	• **Silt**(Non-plastic) • **Clay**	• **Clay**(21)	15-60	Cyclic Triaxial	• Increasing CSR, irrespective soil type	• Decreases
[2]	Fine Sand	• **Silt**	• Non-plastic	5-45	Cyclic Triaxial	• Increasing FC	• First increase, then decrease
[27]	Fine Sand	• **Silt**	• Non-plastic	0-100	Cyclic Triaxial	-	-
[7]	Silica Sand	• **Kaolinitic Clayey Silt**	• **Kaolinitic Clay**(19)	0-35	Cyclic Simple Shear	-	-
[25]	Silica Sand	• **Na-Bentonite** • **Kaolinite** • **Illite**	• **Kaolinite**(21) • **Illite**(35) • **Bentonite**(272)	15	Ring Shear	• PI<4 • 5<PI<4 • PI>14	• Rapid Liquefaction • Increases • No liquefaction
[4]	Sand	• **Kaolinite** • **Bentonite**	• **Kaolinite**(19) • **Bentonite**(48)	10-50	Cyclic Triaxial	• Increasing PI • Increasing FC amount up to 30%	• Increases • Decreases
[3]	Sand	• **Kaolinitic Clay**	• Clay+Sand Mixture(3)	0-20	Cyclic Triaxial	• Increasing FC (in the range 0-15%)	• Decreases
[24]	• **Yatesville Sand** • **Monterey Sand**	• **Silt** • **Kaolinite** • **Bentonite**	• Kaolinite(31) • Bentonite(343)	4-37	Cyclic Triaxial	• Increasing LL(<17) • Increasing LL(>17) • Increasing PI	• Decreases • Increases • Increases

3. EXPERIMENTAL SETUP AND SPECIMEN PREPARATION

Understanding the behaviour of soils under dynamic conditions requires many different type of laboratory tests that simulate the in-situ conditions proximately as much as possible. There are two popular tests which are widely used in experimental research: Cyclic Triaxial Test (CTX) and Cyclic Simple Shear Test (CSS). Not only The Cyclic Simple Shear Test device but also The Cyclic Triaxial Test device can be used to investigate various practical geotechnical engineering problems like liquefaction, embankment design or cyclic behaviour of soils. Single test is not enough to understand the complexity of soils; but the combination of these methods could be very informative.

At laboratory conditions, generally one of these test types is chosen to examine the dynamic behaviour of sandy soils. When compared to Cyclic Triaxial, it can be said that CSS has two common advantages. First, the shearing direction is similar to that of a vertically incident S-waves propagating on site (Duncan and Dunlop, 1969) [28]. Second, the diameter and height of CSS test specimen is much less than CTX specimen and it allows researchers to prepare a soil sample without disturbing the specimen too much.

In addition to these advantages, many researchers showed that the saturation of specimen is not necessary for a constant-volume simple shear test (Duncan and Dunlop, 1969) [28]. This thesis finds that in order to understand the liquefaction potential of sandy and silty soils, the saturation is unnecessary, but this result is not true for clayey soils because of its special properties against water. The details of these findings will be explained in Chapter 3.2.

3.1 Cyclic Simple Shear Test

3.1.1 Device types

In the literature review, it is seen that there are several direct simple shear device types which are used in experimental studies. But actually two of them are widely used in research studies: The Norwegian and Swedish Geotechnical Institute type (NGI/SGI-type) and the Cambridge University type. In both cases, the soil specimen is confined laterally such that shear deformations are allowed while the horizontal specimen length is constant. This is accomplished by hinged metallic walls in the Cambridge device and a cylindrical wire-reinforced rubber membrane in the NGI-device (Dyvik et al. 1987) [29]. The sketch of these common apparatus types are given in Figure 3.1. The difference between SGI-type and NGI-type is the way of reinforcement of rubber membrane; if it is reinforced by metal rings it is called as SGI-type, otherwise it is called as NGI-type. However, nowadays the distinction between these two types disappeared, and all the test types are called as NGI-type.

The standart DSS test device, which is also used in this study, is developed firstly by Bjerrum and Landva in 1966 at The Norwegian Geotechnical Institute.

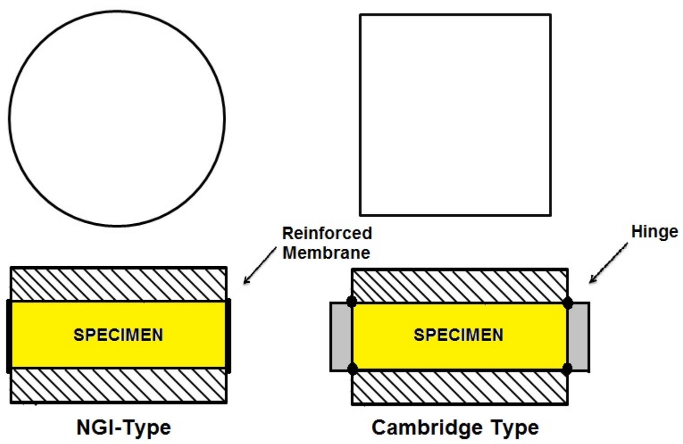


Figure 3.1: Sketch of different Simple Shear Test apparatus

3.1.2 Geo-Comp device

The CSS test apparatus used in this study is a Geocomp ShearTrac II-DSS system located in the Soil Mechanics Laboratory of Yeditepe University, Istanbul (See Figure 3.2).

Figure 3.2: ShearTrac II, the Cyclic Simple Shear Test apparatus

The device allows load-controlled **Constant-Volume** Cyclic Simple Shear test with a load frequency up to 1 Hz on a consolidated soil specimen, as well as the conventional displacement-controlled slow monotonic loading (i.e., DSS) tests (Zehtab, 2010) [6]. In constant volume direct simple shear testing, it is assumed that the change in applied vertical stress as the specimen height maintained constant during shear is equal to excess pore pressure which would have been measured in a truly undrained test with constant total vertical stress (Dyvik et al. 1987) [29]. The simplified sketch of test device is given in Figure 3.3.

The experiment has two main phases: Consolidation phase and Cyclic phase. Its working principle is based on to maintain the volume of soil specimen during test. It occurs by changing vertical stress acts on specimen. With this method, the height and diameter remains constant but the vertical effective stress changes. When vertical effective stress is zero, it means that the soil is liquefied.

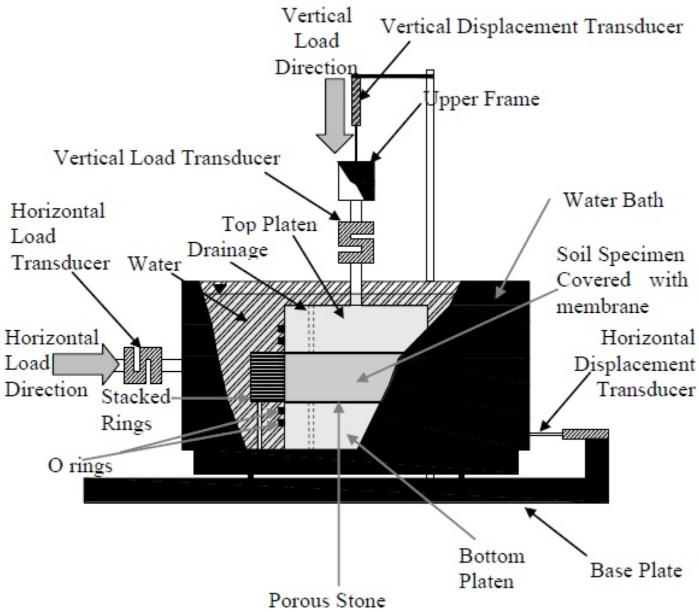


Figure 3.3: Simlified sketch of Cyclic Simple Shear Setup [6].

3.1.2.1 Consolidation phase

After the sample preparation, the constant-volume test starts with consolidation phase. By increasing the vertical load, the sample is consolidated to the target value step by step. In this study, all specimens are consolidated under 50 kPa.

3.1.2.2 Cyclic shearing phase

After the consolidation phase, constant-volume cyclic shearing of specimen begins. A horizontal load acts on specimen just like a sinusoidal waveform. The frequency of cyclic load, f, is 0.1 Hz.

3.2 Specimen Preparation

Cyclic Simple Shear Test is a laboratory experiment that allows to investigate the behaviour of soils under static and dynamic conditions. In spite of its user friendly set-up for undisturbed specimens, especially for sandy specimens, there are lots of challenges to prepare a reconstitute specimen in laboratory.

3.2.1 Literature review

Today, Cyclic Simple Shear Test equipment can be found rarely in universities. On the other hand, considering the improvements in technology and some advantages of Cyclic Simple Shear Test, it can be expected that Cyclic Simple Shear will be used widely in recent future. But, its specimen preparation mould is not useful to prepare a homogeneous and saturated clayey or silty sand specimen at laboratory conditions. To understand the preparation of clayey sand, other studies are checked. However, as it can be seen in the literature review, there is not a comprehensive study about silty or clayey sand specimen preparation methods for CSS test. The summary of this literature is presented in Table 3.1 and 3.2.

In this study, some specimen preparation methods that are commonly used for Cyclic Triaxial Test are performed and also a new technique called as "Staged Wet Pluviation" is developed. In light of these experiments, the original specimen preparation mould of Cyclic Simple Shear Test device is modified.

Six specimen preparation methods named as "Wet Pluviation", "Staged Wet Pluviation", "Dry Pluviation and Flushing Water" and "Dry Pluviation and Flushing Water with CO_2 and Water" were performed and discussed. These methods are compared based on their degree of saturation values, fines content, homogeneity, repeatability and time duration. This chapter explains the challenges of each method and then proposes solutions for each of them.

Table 3.1: Literature Review about Sample Preparation.

Reference	Sample	Test Technique	Sample Preparation	Saturation
[30]	Fraser River Sand	• Stress-controlled simple shear • Steel-wire reinforced membrane • Constant-Volume Test • Frequency=0.1 Hz.	• Air-pluviation • All samples were pluviated at the loosest possible state • For denser samples: Low-energy and High-frequency vertical vibrations were applied	The degree of saturation is not applicable in dry-pluviated sands (technically zero), nor is there a concern in simple shear due to the enforcement volume conditions.
[31]	Non-plastic Sandy Silt	• Cyclic Direct Simple Shear • Constant-Volume condition • Steel-wire reinforced rubber membrane • Consolidated to effective vertical stress varying from 100 to 400 kPa • Frequency=0.1 Hz.	• Oven-dired tailings mixed with water • Thin-necked beaker with a nozzle on its tip to limit the flow rate • Slurries pluviated through water • The nozzle kept submerged and within 1 cm. of the surface during pluviation	Saturation of samples, that are prepared with this method, is controlled with B-value check in triaxial
[32]	Silica Sand	• Constant-volume condition • Frequency=0.02 Hz.	• Water-sedimentation method • Consolidated under a vertical effective stress of 100 kPa	Constant volume test can be performed on either dry or saturated sands maintaining, in both cases, drained conditions.Finn (1985) showed that the mechanical behaviour is not affected by whether the soil is saturated or dry.
[33]	• Nevada Sand • Silty Sand • 5 Low to High Plastic Clays	• Strain-controlled Test	• Sand: Dry and Wet Compaction • Silty Sand and Clay: Wet Compaction	Fine samples are saturated with wet compaction

Table 3.2: Literature Review about Sample Preparation (continue).

Reference	Sample	Test Technique	Sample Preparation	Saturation
[34]	• Santa Monica Sand • Antelope Valley Sand • 3 Different Clay Samples	• Double Specimen Direct Simple Shear (DSDSS)	• Constant-volume condition	All soils were tested under the constant-volume conditions, the sand in dry state and the clays fully saturated.
[22]	Fuji River Sand	• Cyclic Simple Shear Test	• Sand saturated with de-aired water was then poured into the mold and sedimented under water • Sedimentation applied with a small hammer	Saturation controlled with B-value exceeding 0.95
[35]	Sand	• Constant volume condition • Frequency=0.2 Hz.	• Not only saturated but also dry samples are prepared	No practical differences were found between saturated and dry samples; the results from the both kinds of samples seemed identical.

3.2.2 Characteristics of soils tested

Although this thesis includes both clayey and silty sand, the results presented in this chapter will be based on clayey sand. Clean Sile Sand 20/55 was used as the base parameter and Kaolinite type clay was used as the fines.

Tests are performed on Clean Sile Sand containing Kaolinite of about 10%. The Clean Sile Sand 20/55 is yellow in color with a specific gravity 2.65, maximum void ratio 0.87, and minimum void ratio of 0.48. The Clean Sile Sand 20/55 is classified as poorly graded sand (SP) in Unified Soil Classification System (USCS). The grain size distribution all soil samples with 10% FC are shown in Figure 3.4.

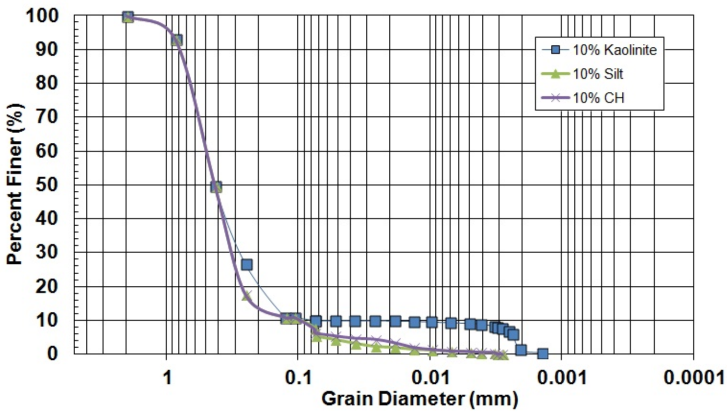


Figure 3.4: Grain Size Distribution of 10% Kaolinite, 10% Silt and 10% CH specimens

The Kaolinite is white in color and has a specific gravity of 2.58, liquid limit (LL) of 48%, and plasticity index (PI) of 11%. The USCS classification of the Kaolinite is Low Plastic Silt (ML).

Table 3.3: Plasticity and Specific Gravity of Fines.

Soil	Kaolinite	CH	Silt
Liquid Limit (%)	48	72	-
Plastic Limit(%)	37	27	-
Plasticity Index	11	45	Non-plastic
Specific Gravity (Gs)	2.58	2.71	2.65

Although other fine types that was used in liquefaction analysis was not used in this section, the characteristics of all soil types are mentioned here.

The High Plastic Clay (CH)is grey in color and has a specific gravity of 2.71, liquid limit (LL) of 72%, and plasticity index (PI) of 45%. The USCS classification of the CH is High Plastic Clay (CH).

Table 3.4: Maximum and Mininmum Void Ratio Values for Each Soil Specimen.

Soil	emax	emin
Clean Sand	0.78	0.48
5% Kaolinite	1.0	0.48
10% Kaolinite	1.19	0.48
5% Silt	0.84	0.45
10% Silt	0.82	0.43
5% CH	0.87	0.46
10% CH	0.88	0.46

The Silt is brown in color and has a specific gravity of 2.70. It is a non-plastic material.

The Plasticity and Specific Gravity of Fines are given in Table 3.3 and the emax-emin values for each soil mixture tested in this study are shown in Table 3.4.

3.2.3 Specimen preparation methods

In this study, sand specimens with clay content 10% were prepared in six different methods and all specimens are compared each other based on their degree of saturation values, fines content, homogeneity, repeatability and time duration. The computation of each comparison parameter are discussed and interpreted in this chapter.

The Degree of Saturation: As this thesis mainly interested in liquefaction strength of sand specimens with different type and amount of fines, the degree of saturation is the main parameter of interest in this study.

On the other hand, the original Cyclic Simple Shear Test specimen preparation mould does not allow to determine the degree of saturation directly. Therefore, the degree of saturation amounts of specimens are calculated mathematically.

The Amount of Fines Content: After each test, the reconstituted clayey sand specimens were sieved to determine the amount of fines content. The particles that are passing through No. 200 sieve (mesh opening 0.075 mm) were collected and oven-dried. After this, the amount of collected Kaolinite are weighted.

Homogeneity: To determine the homogeneity, every specimen is divided into four main parts. As it is seen in the Figure 3.5, every part of specimen is sieved from

No. 200 sieve and the amount of fines content is calculated. Hence, the vertical and horizontal distribution of fines can be analysed.

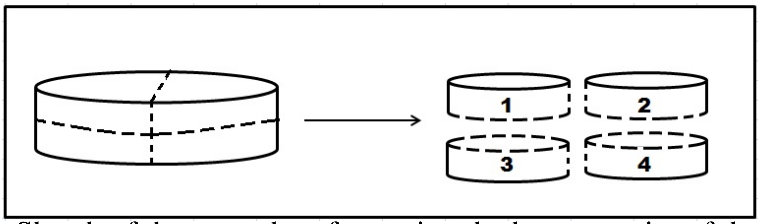


Figure 3.5: Sketch of the procedure for testing the homogeneity of the specimens

Repeatability: For each specimen preparation method, at least three experiment were performed and the repeatability of the methods is determined using the standard deviation of the experiment results.

Time Duration: The time duration is determined with the help of a timekeeper.

3.2.3.1 Wet pluviation

In this study, firstly, one of the most widely used specimen preparation methods, "Wet Pluviation" is performed to achieve a desired specimen for liquefaction tests. In this method, Clean Sile Sand 20/55 containing Kaolinite amount of 10% is mixed with the help of a spatula during approximately 10 minutes until visually homogeneous specimen is achieved. Then the mixture is pluviated at a height of 3 cm. into specimen preparation mould which is filled with de-aired water. As shown in Figure 3.6, because Kaolinite stays in suspension, the soil is pluviated into water slowly.

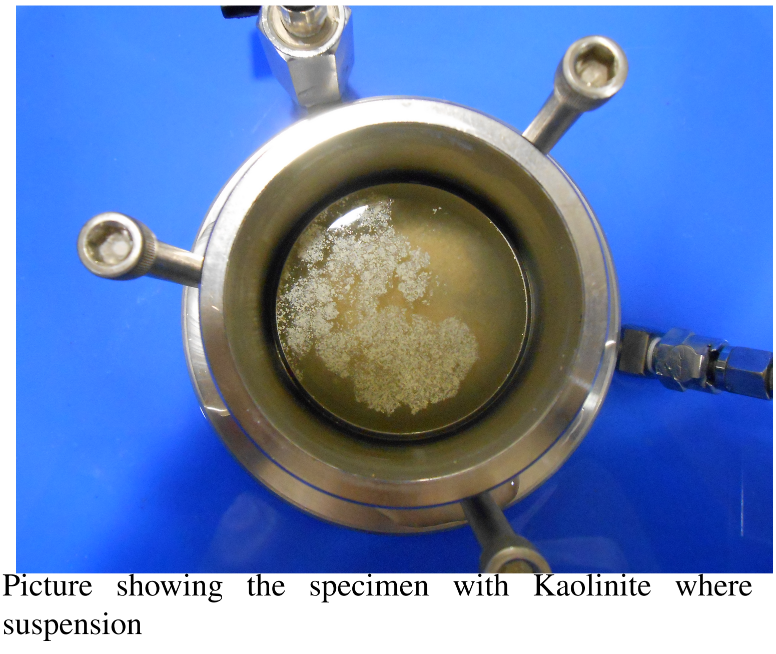


Figure 3.6: Picture showing the specimen with Kaolinite where Kaolinite in suspension

In this method, experiment should be performed very slowly to achieve a homogeneous specimen at desired fines content.

3.2.3.2 Staged wet pluviation

Staged Wet Pluviation is a new specimen preparation technique developed in this study. It is quiet similar to "Wet Pluviation" method with only one exception. In this method, the mould is filled with de-aired water gradually and the sand-clay mixture is poured into mould. The mixture is pluviated into mould slowly, so the amount of Kaolinite that stays in suspension is reduced. The sketch of this new technique is given in Figure 3.7.

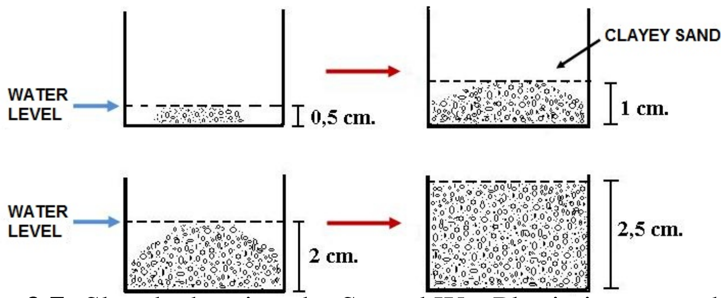


Figure 3.7: Sketch showing the Staged Wet Pluviation procedure

3.2.3.3 Dry pluviation and flushing with H_2O

In this method, homogeneous sand-clay mixture is obtained utilizing from a spatula and then the mixture is poured into mould.

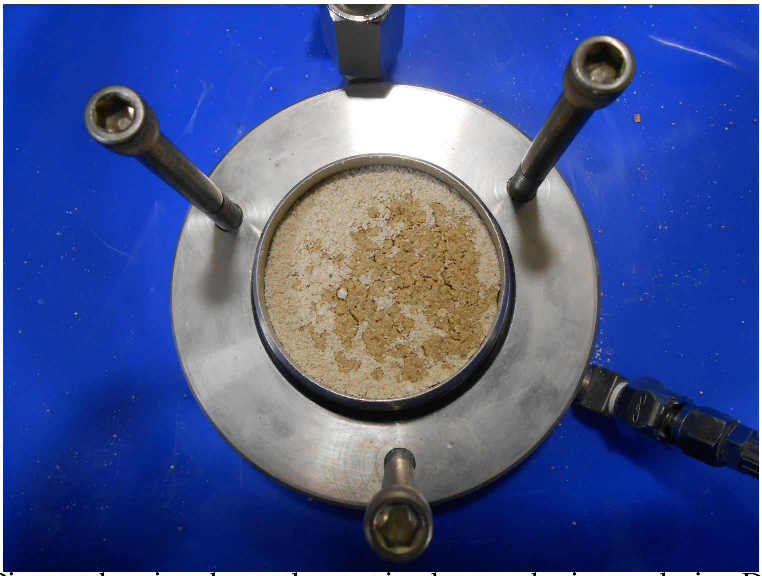


Figure 3.8: Picture showing the settlement in clay-sand mixture during Dry Pluviation and Flushing with H_2O procedure

After the mould is filled with soil mixture, the top of specimen is levelled with the help of a coping saw, and the excess soil mixture is poured into a cup. Then, de-aired water is got through from bottom to top of specimen. The settlement of clay-sand mixture can be seen in Figure 3.8.

3.2.3.4 Dry pluviation and flushing with CO_2 and H_2O

Lastly, after employing several methods, "Dry Pluviation and Flushing with CO_2 and H_2O" is performed to achieve a desired specimen. This technique is quite similar to the method described in Section 3.2.2.3.

Figure 3.9: Clayey sand specimen prepared by Dry Pluviation and Flushing with CO_2 and H_2O procedure

The mixture prepared with the help of a spatula is pluviated into mould with a spoon and the surface is levelled with a coping saw. In this technique, approximately 20 minutes CO_2 is got through from bottom to top of specimen firstly. Then, the de-aired water is got through into specimen in similar to the previous technique "Dry Pluviation and Flushing with H_2O". The specimen is prepared with this method can be seen in Figure 3.9.

3.2.3.5 Other methods

Literature documents some other saturated and homogeneous sand-clay mixture preparation methods which are discussed in this section. However, the results shows that none of these methods are successful enough.

Clay Slurry

One of the most useful sample preparation methods for sand containing fines is air pluviation into a slurry (Khalili and Wijewickreme, 2008) [36]. In this method, slurry is prepared into a mould and then sand base sample is pluviated into the mould. This method is tried with different slurries which includes different amount of Kaolinite. One representative slurry is presented in Figure 3.10.

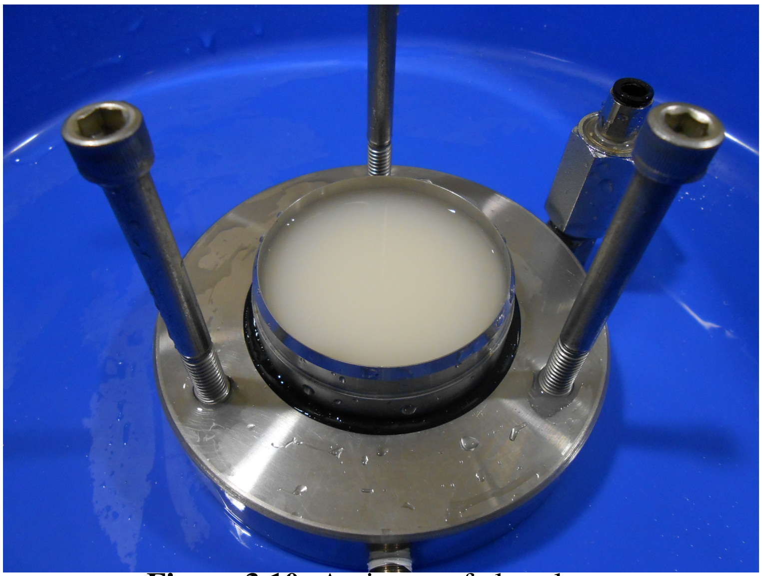


Figure 3.10: A picture of clay slurry

In this method, clean sand is pluviated into a clay slurry. This technique is used because it is assumed that while sand particles are deposited into mould, some amount of clay particles in slurry are also deposited into mould with sand. Thus, a relatively homogeneous clay-sand mixture can be prepared. Nevertheless, with several experiments, it is observed that clay particles are washed away from the specimen preparation mould. So, the amount of fines content in slurry reduced while experiment was being performed. After several tests were performed, it is seen that specimens cannot be prepared at desired fines content. To solve this problem, the amount of Kaolinite in slurry is increased but a homogeneous and saturated specimen at desired fines content still cannot be achieved.

Water Pluviation

Water pluviation with a spoon or pycnometer is another useful technique to prepare a saturated specimen documented in the literature. (James et al, 2011) [31] utilized from this method to achieve a saturated specimen to be used in their cyclic simple shear tests. They described this method in detail and proved the degree of saturation with a B-value check in triaxial test device.

3.2.4 Discussion

In this section, methods presented in previous sections are discussed and compared to each other based on their advantages and disadvantages.

3.2.4.1 Degree of saturation

Degree of saturation is the most important parameter in this study. Figure 3.11 presents the maximum and minimum degree of saturation test results together with their standard deviations.

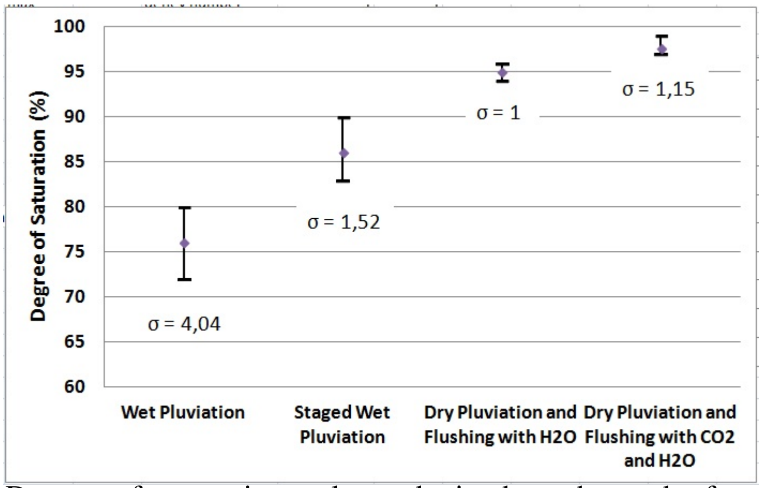


Figure 3.11: Degree of saturation values obtained at the end of each specimen preparation technique

The average degree of saturation is 75% in Wet Pluviation whereas it is recorded as 86% in Staged Wet Pluviation. Although Dry Pluviation and Flushing with H_2O method helps to get a better saturation degree, the highest degree is obtained with Dry Pluviation and Flushing with CO_2 and H_2O method (98%).

These results suggest that specimen that is prepared using Dry Pluviation provides better results compared to the specimen prepared using Wet Pluviation.

3.2.4.2 Fines content

As it is mentioned in previous sections, Kaolinite stays in suspension. This physical property of Kaolinite makes it difficult to prepare a homogeneous specimen without loosing fines content. So that, Figure 3.12 presents the test results that compares the amount of fines content.

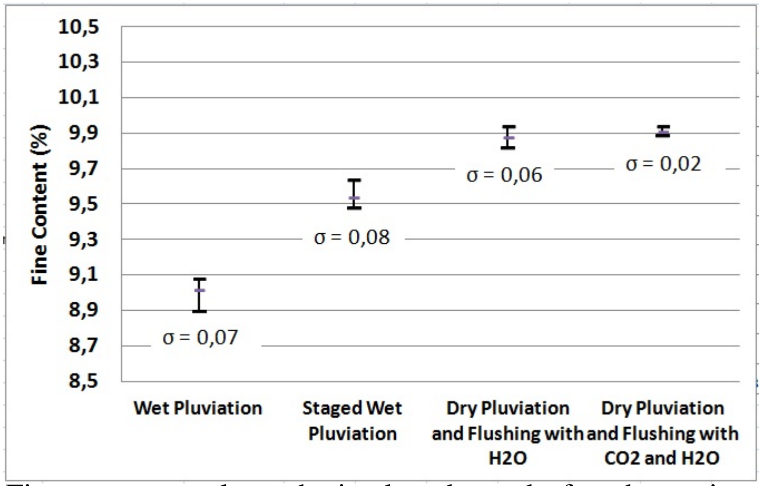


Figure 3.12: Fines content values obtained at the end of each specimen preparation technique

3.2.4.3 Homogeneity

Homogeneity is one of the most important parameters that is taken into consideration in this study. Although the amount of fines content of soil mixture gives an idea about the soil structure, homogeneity can be completely a different problem. Homogeneity term is used to represent the quality of being uniform throughout the soil mixture. To understand the uniformity of soil mixture, the soil sample is divided into four parts and the amount of fines content in each of them is computed. Results that are obtained from experiments are presented in Table 3.5.

Test results shows that the upper parts of specimens have more fines content slightly. However, the small difference between the upper and lower parts that ranges between 0.1-0.5% suggests that the specimens are homogeneous enough.

Table 3.5: Method Comparison based on Homogeneity.

Method		**FC Amount at different parts(%)**		
		#1	**#2**	**#3**
Wet Pluviation	**1**	9.1	9.2	9.1
	2	8.9	9.0	8.8
	3	9.0	9.1	9.0
	4	8.7	9.1	9.0
	Avg	9.1	9.1	8.9
		#1	**#2**	**#3**
Staged Wet Pluviation	**1**	9.7	9.8	9.5
	2	9.5	9.4	9.5
	3	9.4	9.6	9.9
	4	9.2	9.6	9.5
	Avg	9.4	9.6	8.6
		#1	**#2**	**#3**
Dry Pluviation and Flushing with H_2O	**1**	9.8	9.9	9.7
	2	9.7	9.8	9.5
	3	9.4	9.7	9.4
	4	9.2	9.5	9.5
	Avg	9.5	9.7	9.5
		#1	**#2**	**#3**
Dry Pluviation and Flushing with CO_2 and H_2O	**1**	9.7	9.8	9.8
	2	8.6	9.7	9.7
	3	9.4	9.3	9.7
	4	9.4	9.5	9.5
	Avg	9.5	9.6	9.7

3.2.4.4 Repeatability and test duration

Repeatability is another important parameter of this study. The repeatability of specimen is calculated using the standard deviations of the experiments performed with a specified method. Test results are showed in Table 3.6.

Table 3.6: Comparison of Specimen Preparation Techniques in terms of Repeatability.

Method	Degree of Saturation	Fines Content
Wet Pluviation	σ=4.04	σ=0.007
Staged Wet Pluviation	σ=1.52	σ=0.008
Dry Pluviation and Flushing with H_2O	σ=1	σ=0.006
Dry Pluviation and Flushing with CO_2 and H_2O	σ=1.15	σ=0.002

Table 3.7: Comparison of Specimen Preparation Techniques in terms of Test Duration.

Method	Test Duration
Wet Pluviation	120
Staged Wet Pluviation	90
Dry Pluviation and Flushing with H_2O	60
Dry Pluviation and Flushing with CO_2 and H_2O	75

Test results indicate that Dry Pluviation Methods gives the most repeatable results. Also, Staged Wet Pluviation gives better results than Wet Pluviation.

Last parameter that is considered is test duration. Table 3.7 presents time duration results. According to these findings, Wet Pluviation is the method that takes the longest time to perform whereas Dry Pluviation and Flushing with H_2O takes the shortest time to complete.

3.3 Conclusions

Liquefaction is one the most complex phenomena in geotechnical engineering. During history, many researchers showed that there is a significant difference in cyclic behaviour of saturated samples and that of dry samples. So, researchers who try to understand the liquefaction mechanism and cyclic behaviour of soils, should run their experiments with saturated samples. Therefore, in this study, samples that will be used in liquefaction investigation is tried to become saturated to achieve reliable results.

Literature review provides the most common specimen preparation methods that are used by researchers. This thesis chose some of them that are suitable to prepare saturated soil samples. Sand samples containing Kaolinite of about 10% was prepared with six different methods, and four of them which gave better results are discussed based on the following parameters: degree of saturation, fines content, homogeneity, repeatability and time duration.

The results of this thesis are as follows:

- **"Wet Pluviation"** is the worse method to achieve a saturated clayey sample. The amount of the degree of saturation is significantly lower than other samples that are prepared with different methods. Also, when Kaolinite is added into water, because of the special characteristic of Kaolinite, it stays in suspension. So that, fines content washes away and specimens prepared by Wet Pluviation has less fines content. In addition to this, based on the standard deviation of experiments' saturation degrees (4.04), it can be inferred that it is hard to achieve repeatable results with Wet Pluviation.

- **"Staged Wet Pluviation"** gives better results than Wet Pluviation based on the degree of saturation parameter. Although two methods do not differ much in terms of the preparation technique, results shows that the Staged Pluviation Method is successful than Wet Pluviation in terms of achieving fines content. Additionally, given the low standard deviations, it can be inferred that Staged Wet Pluviation Method provides reliable results.

- **"Dry Pluviation and Flushing with H_2O"** gives successful results in terms of achieving fines content, but its degree of saturation is not high enough for liquefaction analysis (S=95%). However, its repeatability is well enough to achieve reliable results.

- **"Dry Pluviation and Flushing with CO_2 and H_2O"** is successful enough to achieve samples which will be used in liquefaction studies. Not only the degree of saturation amount but also its fines content achieves the target amount. Its repeatability is also good enough to obtain reliable and repeatable results.

- In terms of homogeneity, all methods that are used in this study gives parallel results and all methods are good enough to prepare a homogeneous specimen.

- Dry Pluviation methods produce better results than Wet Pluviation methods in terms of both the degree of saturation and fines content.

- The complete specimen preparation time is much longer in Wet Pluviation methods than Dry Pluviation Methods because Kaolinite stays in suspension. It took approximately 120 minutes to prepare a specimen using Wet Pluviation Methods, whereas it took approximately 60-75 minutes in Dry Pluviation Methods. These experiments suggest that Dry Pluviation Methods are better than Wet Pluviation Methods in terms of time duration.

In this study, chooses **"Dry Pluviation and Flushing with CO_2 and H_2O"** was determined to be as the best method to prepare a saturated and homogeneous specimen at desired fines content. This method also provides reliable and repeatable results. Hence specimen is prepared using this chosen method in light of all these findings.

4. CYCLIC SIMPLE SHEAR TESTS ON SAND WITH FINES

4.1 Purpose

This section was performed to understand the effect of plasticity and fines content on cyclic behaviour of sand. For this purpose, seven different reconstituted sandy soil mixtures were prepared at laboratory and at least five CDSS test were performed on each of them. Totally, 110 CDSS tests were performed on seven different soil mixture and all test results were discussed in this section.

4.2 Experimental Program

To clarify the effect of fines content, soil specimens were prepared at different fines contents, which are 5% and 10% respectively. To understand the effect of plasticity, non-plastic silt and clay samples, which have different PI values, were added to clean sand and to check whether cyclic stress level has any influence on the response of specimens, all test groups were performed at three CSR values that is defined as follows:

CSR = τ_{cyc} / σ_v

where τ_{cyc} is the amplitude of cyclic stress, and σ_v is the normal consolidation stress.

In this thesis CSR takes values of 0.12, 0.1 and 0.08, respectively. A brief summary of the number of CSS Test were performed on each soil is given in Table 4.1.

Table 4.1: Number of CSS Tests were performed.

Soil Type	CSR=0.12	CSR=0.1	CSR=0.08
Clean Sand	6	4	5
5% Kaolinite	5	5	5
10% Kaolinite	7	8	4
5% Silt	4	5	6
10% Silt	6	5	5
5% CH	5	4	5
10% CH	5	6	5

The CSR, Void Ratio, Dr(%) and NoC of 110 testes performed are presented in Table 4.2, 4.3, 4.4, 4.5 and 4.6, 4.7 and 4.8.

Table 4.2: The CSR, Void Ratio, Dr(%) and NoC for Clean Sand.

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.658	42	4
2	0.12	0.681	34	3
3	0.12	0.689	32	2
4	0.12	0.655	43	4
5	0.12	0.663	40	4
6	0.12	0.561	74	11
7	0.1	0.671	37	9
8	0.1	0.684	33	9
9	0.1	0.708	25	6
10	0.1	0.735	16	4
11	0.08	0.659	41	29
12	0.08	0.661	41	25
13	0.08	0.729	18	21
14	0.08	0.722	21	14
15	0.08	0.691	31	23

The results are discussed considering the effects of void ratio, relative density and CSR. The representative Shear Stress vs. Shear Strain, Shear Stress vs. Cycle, Shear Strain vs. Cycle and Excess Pressure vs. Cycle graphs for each soil mixture are given in Figure 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7.

Table 4.3: The CSR, Void Ratio, Dr(%) and NoC for Kaolinite(5%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.576	81	4
2	0.12	0.609	75	3
3	0.12	0.569	83	2
4	0.12	0.565	84	4
5	0.12	0.616	74	4
6	0.1	0.593	78	8
7	0.1	0.638	69	5
8	0.1	0.634	70	4
9	0.1	0.630	71	5
10	0.1	0.610	75	9
11	0.08	0.632	71	14
12	0.08	0.658	66	7
13	0.08	0.644	68	9
14	0.08	0.625	72	13
15	0.08	0.642	69	8.5

Table 4.4: The CSR, Void Ratio, Dr(%) and NoC for Kaolinite(10%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.518	95	2
2	0.12	0.509	96	5
3	0.12	0.524	94	5
4	0.12	0.529	93	3
5	0.12	0.512	96	8
6	0.12	0.519	95	4
7	0.12	0.522	94	6
8	0.1	0.537	92	10
9	0.1	0.505	97	8
10	0.1	0.536	92	7
11	0.1	0.532	93	10
12	0.1	0.557	89	3
13	0.1	0.501	97	20
14	0.1	0.528	93	11
15	0.1	0.496	98	6
16	0.08	0.599	83	12
17	0.08	0.557	89	15.5
18	0.08	0.586	85	13
19	0.08	0.542	91	23

Table 4.5: The CSR, Void Ratio, Dr(%) and NoC for Silt(5%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.692	38	3
2	0.12	0.676	42	3
3	0.12	0.653	48	4
4	0.12	0.643	51	10
5	0.1	0.67	45	9
6	0.1	0.69	38	5
7	0.1	0.73	29	3
8	0.1	0.66	46	9
9	0.1	0.65	50	5
10	0.08	0.64	51	18
11	0.08	0.66	47	15
12	0.08	0.64	51	23
13	0.08	0.67	43	13
14	0.08	0.64	52	18
15	0.08	0.71	33	9

Table 4.6: The CSR, Void Ratio, Dr(%) and NoC for Silt(10%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.674	38	3
2	0.12	0.669	39	3
3	0.12	0.673	38	3
4	0.12	0.679	36	2
5	0.12	0.671	38	3
6	0.12	0.655	43	3
7	0.1	0.651	44	8
8	0.1	0.647	45	9
9	0.1	0.606	55	9
10	0.1	0.598	57	14
11	0.1	0.645	45	10
12	0.08	0.653	43	12
13	0.08	0.711	28	13.5
14	0.08	0.689	34	11.5
15	0.08	0.714	27	8
16	0.08	0.675	38	15

Table 4.7: The CSR, Void Ratio, Dr(%) and NoC for CH(5%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.633	58	6
2	0.12	0.686	45	4
3	0.12	0.685	45	3
4	0.12	0.697	42	3
5	0.12	0.679	46	4
6	0.1	0.720	36	6
7	0.1	0.698	42	8
8	0.1	0.665	50	13
9	0.1	0.663	50	19
10	0.08	0.677	47	23
11	0.08	0.705	40	16
12	0.08	0.673	48	45
13	0.08	0.690	44	30
14	0.08	0.712	38	13

Table 4.8: The CSR, Void Ratio, Dr(%) and NoC for CH(10%).

Test No	CSR	Void Ratio	Dr(%)	NoC
1	0.12	0.673	50	4
2	0.12	0.756	29	3
3	0.12	0.663	52	4
4	0.12	0.643	57	5
5	0.12	0.685	47	4
6	0.1	0.651	55	13
7	0.1	0.631	60	8
8	0.1	0.662	52	9
9	0.1	0.693	45	8
10	0.1	0.674	50	7
11	0.1	0.662	52	6
12	0.08	0.719	39	13
13	0.08	0.685	47	14
14	0.08	0.673	50	15.75
15	0.08	0.671	50	16
16	0.08	0.659	53	20

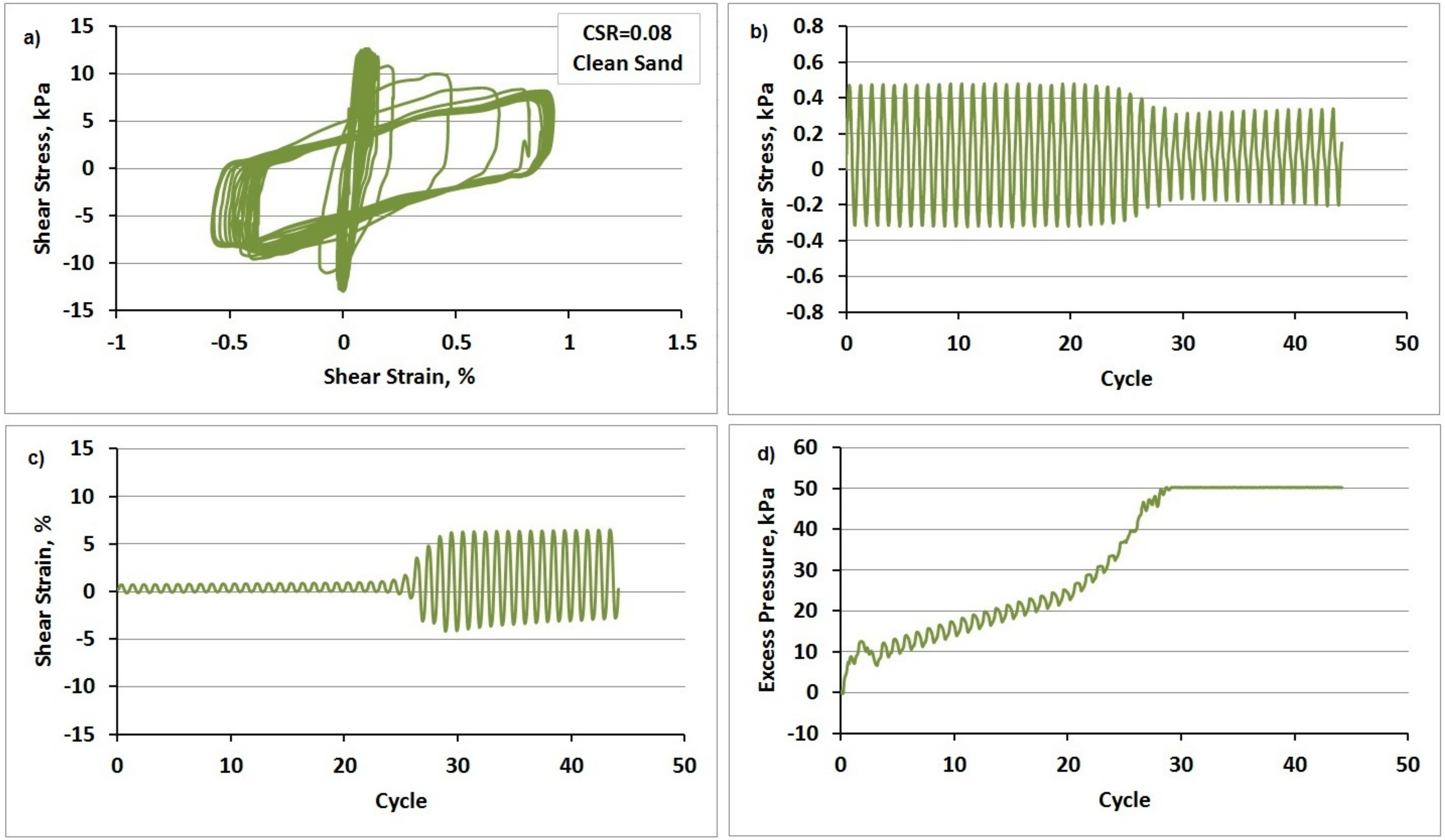


Figure 4.1: Applied shear stresses and experiment results for CSR=0.08 and clean sand, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

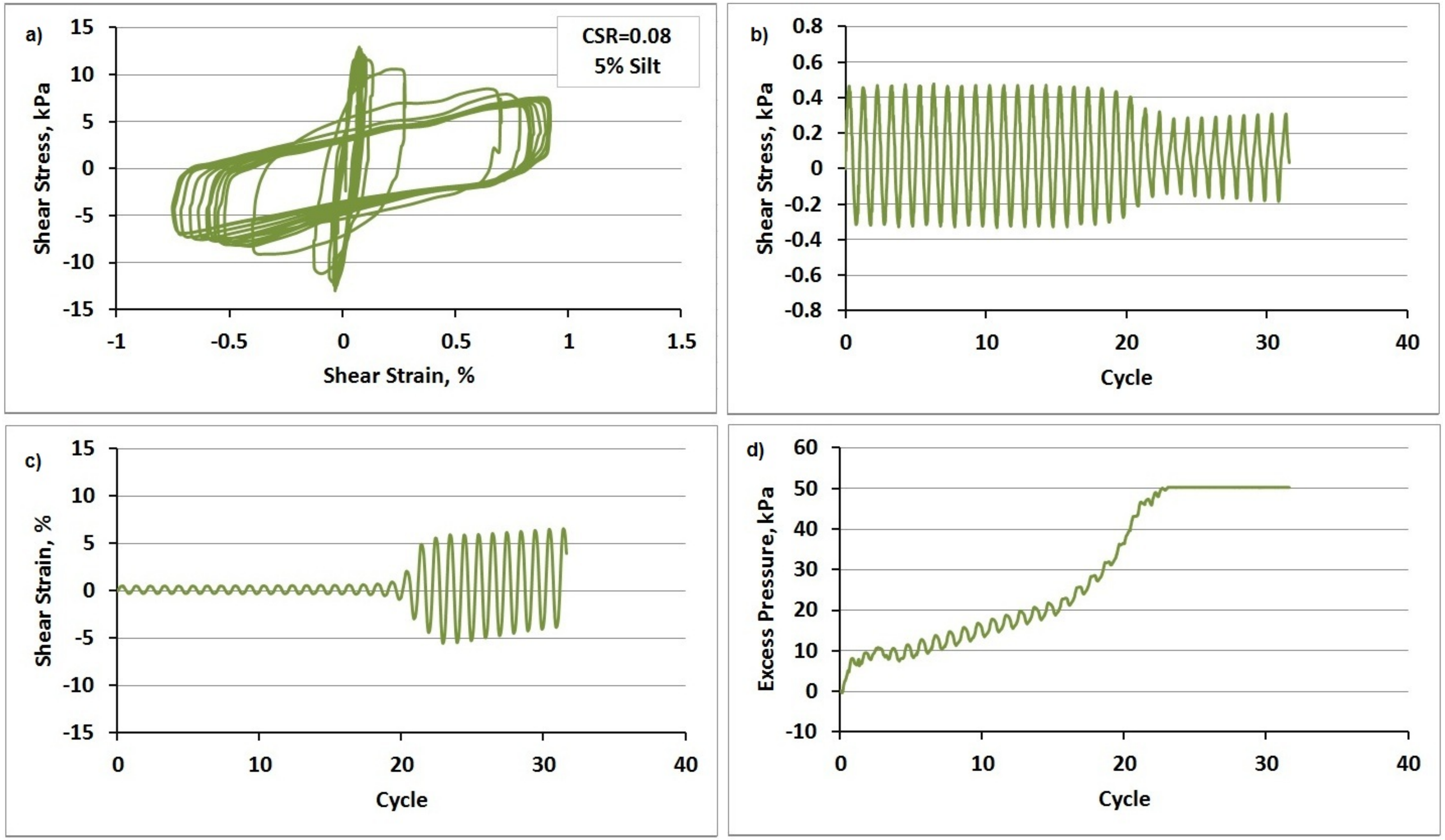


Figure 4.2: Applied shear stresses and experiment results for CSR=0.08 and 5% Silt, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

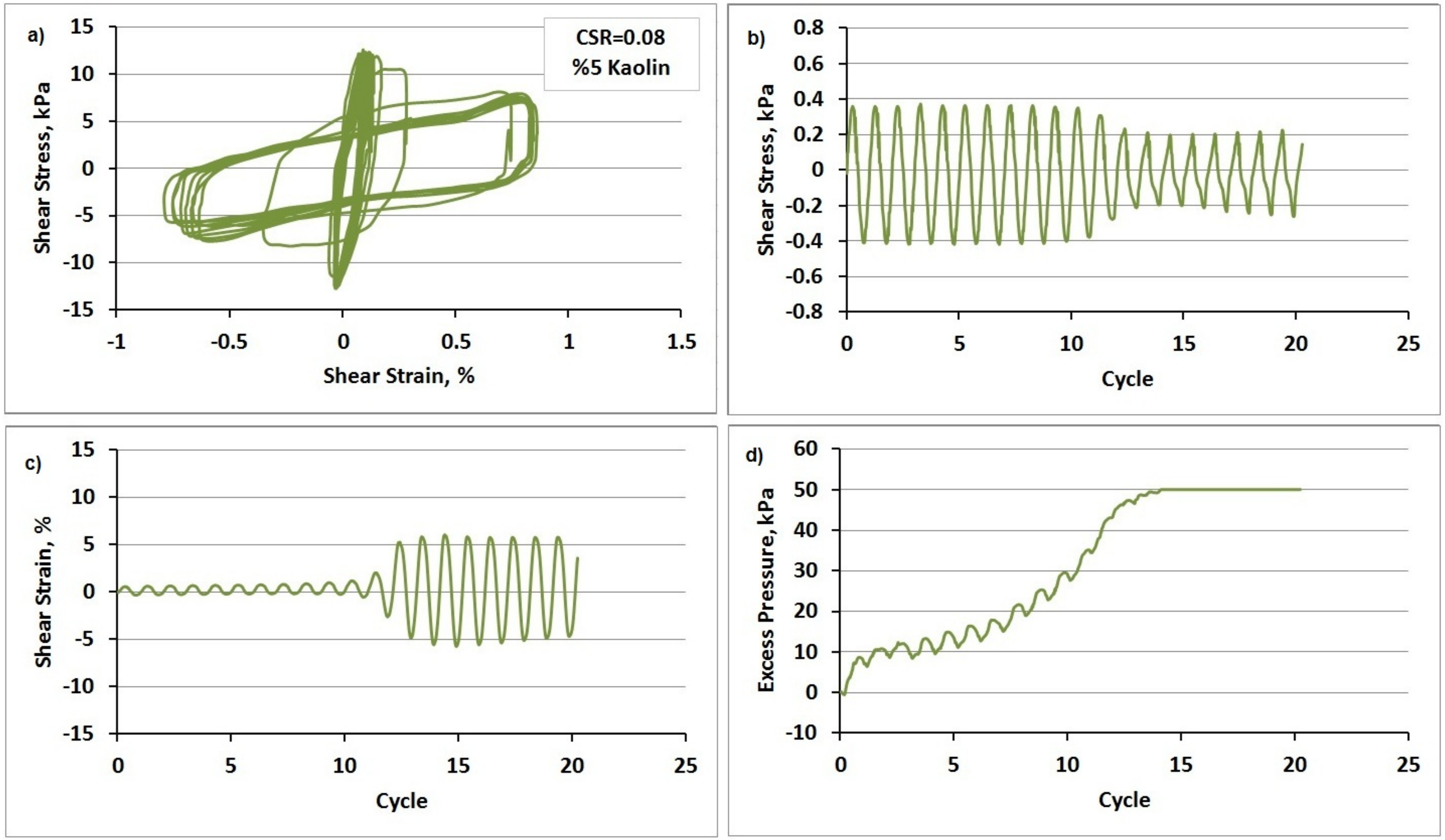


Figure 4.3: Applied shear stresses and experiment results for CSR=0.08 and 5% Kaolinite, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

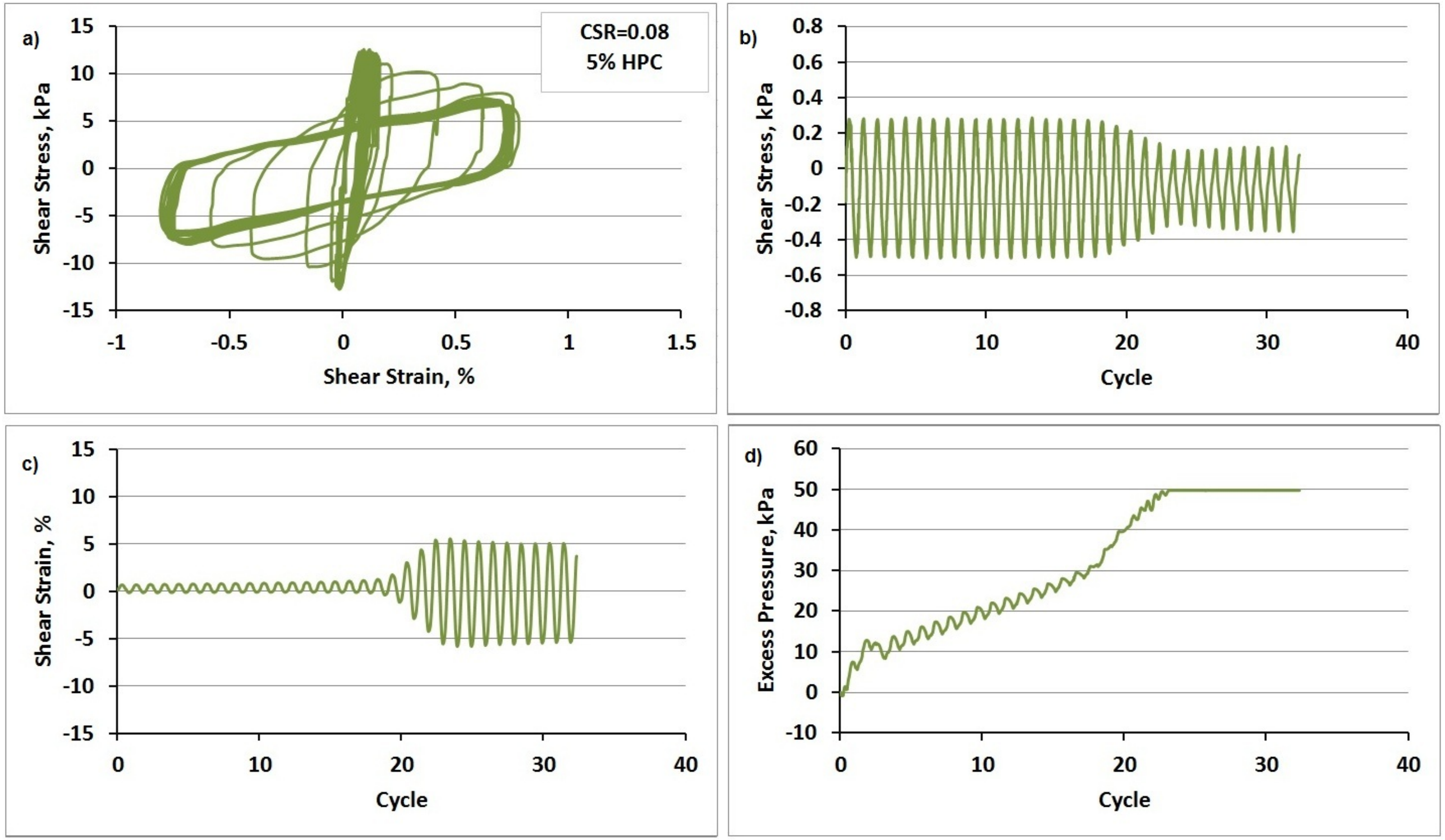


Figure 4.4: Applied shear stresses and experiment results for CSR=0.08 and 5% CH, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

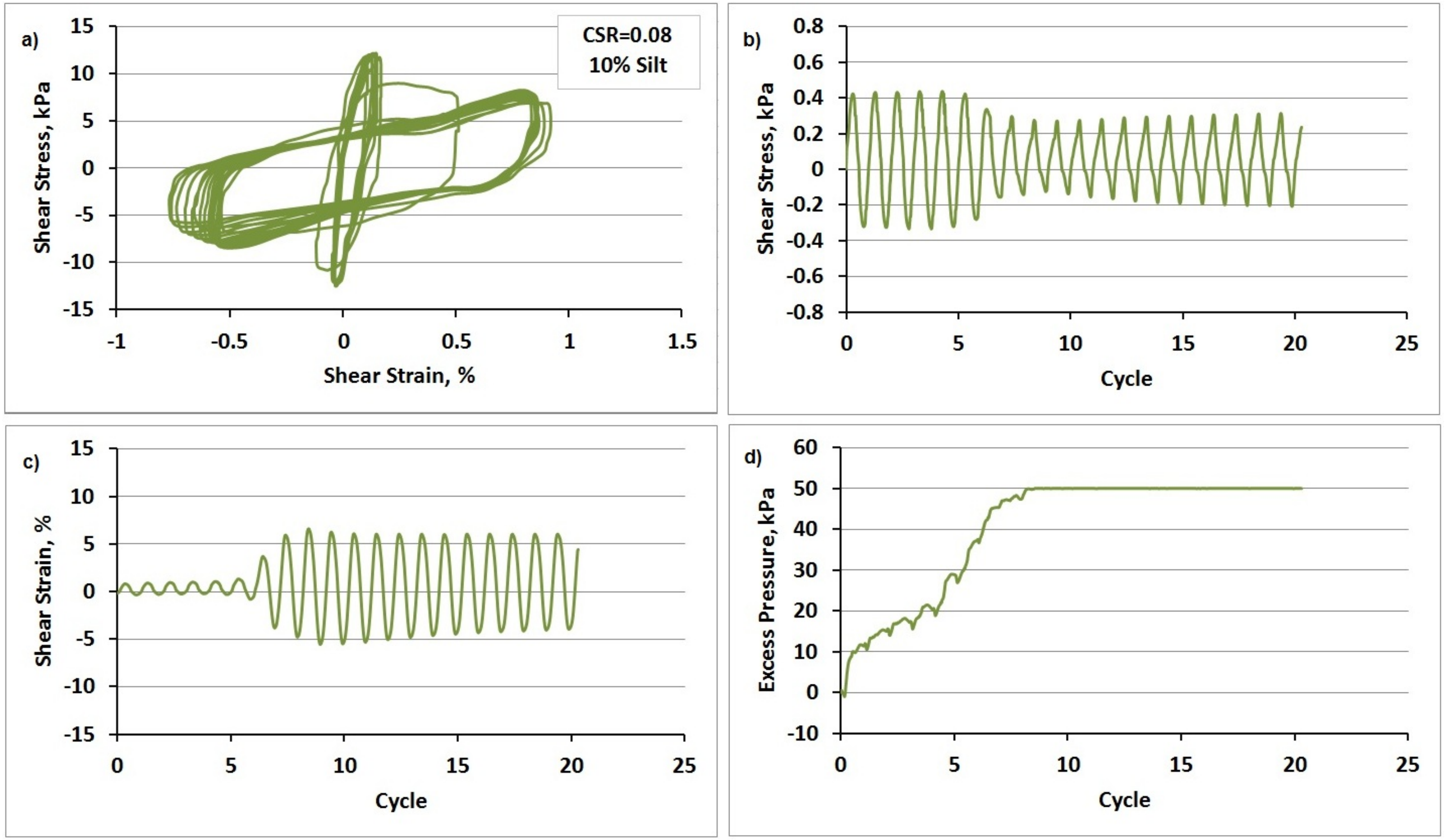


Figure 4.5: Applied shear stresses and experiment results for CSR=0.08 and 10% Silt, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

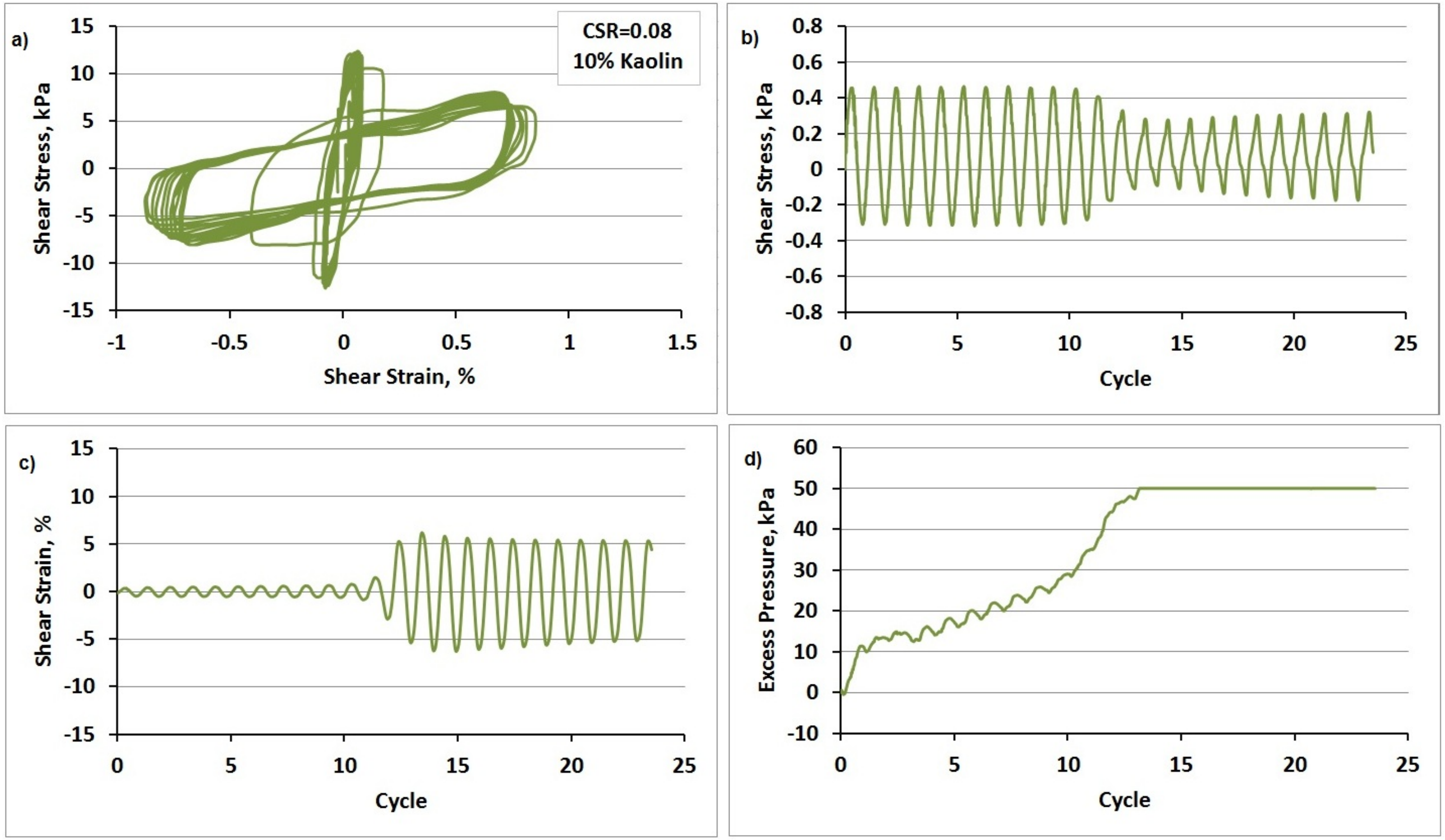


Figure 4.6: Applied shear stresses and experiment results for CSR=0.08 and 10% Kaolinite, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

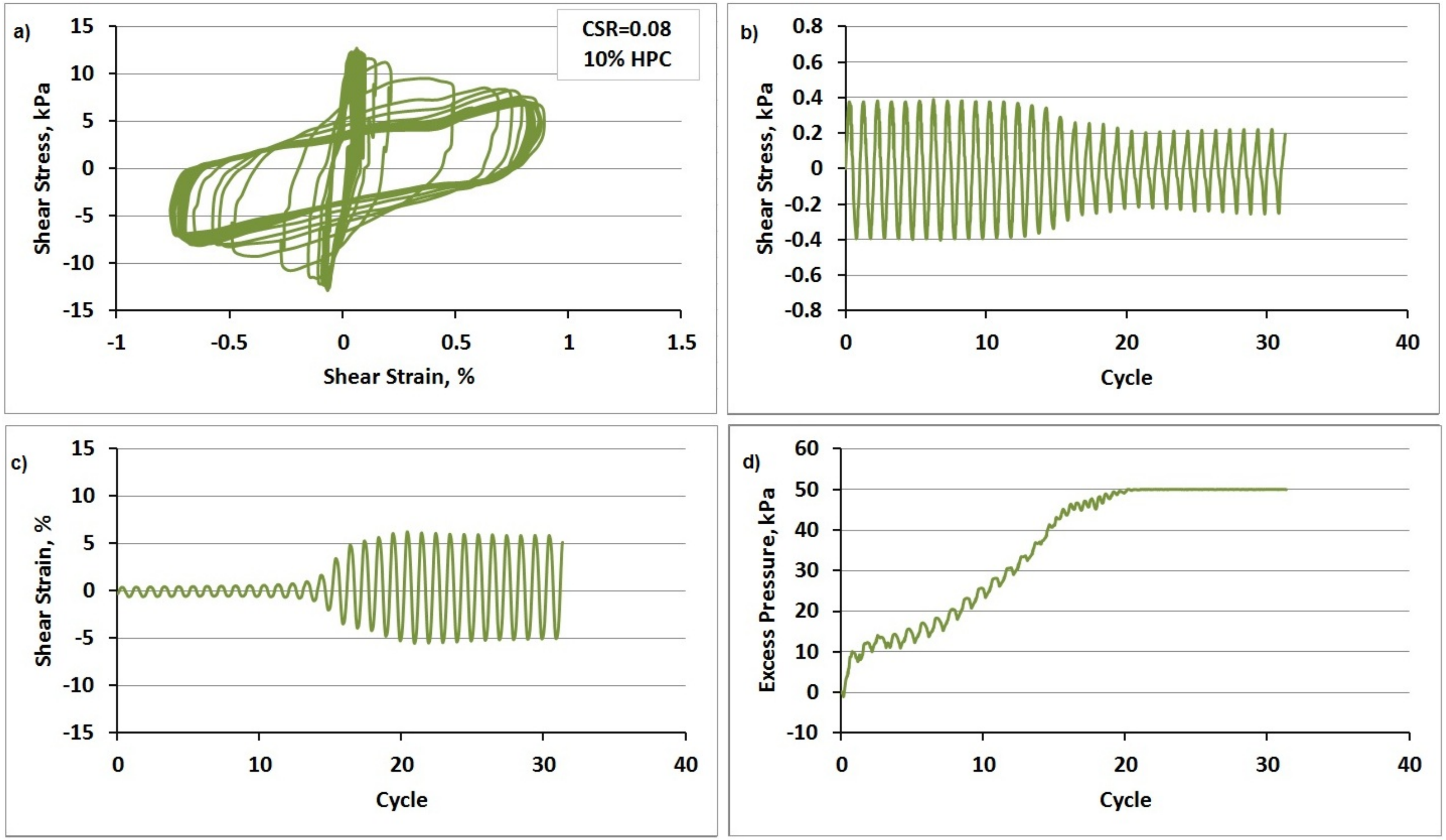


Figure 4.7: Applied shear stresses and experiment results for CSR=0.08 and 10% CH, a) Shear Stress vs. Shear Strain, b) Shear Stress vs. NoC, c) Shear Strain vs. NoC and d) Excess Pressure vs. NoC graphs

4.3 Experimental Results

This section presents results on experiments with seven different reconstitute specimens.

Relative density (Dr) and void ratio (e) are major parameters that affects the liquefaction resistance of sandy soils. In this section, 110 CSS test results are given and all of them are interpreted based on void ratio and relative density.

As known from the literature, liquefaction strength of clean sand increases as the specimen gets denser. Also, at higher cyclic stress ratios, the number of cycles required to reach liquefaction reduces.

Figure 4.8 gives the NoC to liquefaction vs void ratio (e) for clean sand.

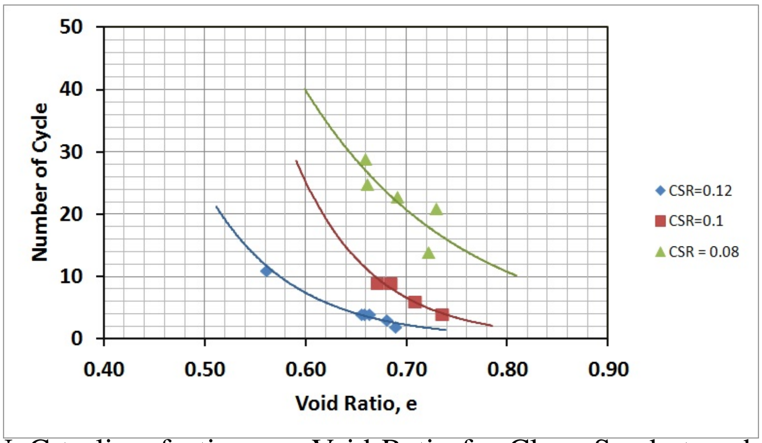


Figure 4.8: NoC to liquefaction vs. Void Ratio for Clean Sand at each CSR values, 0.12, 0.1, 0.08

It is observed that decreasing CSR has increasing effect on cyclic resistance of clean sand at any void ratio that ranges between 0.55 and 0.75. In other words, at constant void ratio as CSR gets lower, cyclic resistance of clean sand increases. At high values of CSR, the rate of increase of NoC with decreasing void ratio is less compared to the rate of increase at lower values of CSR. On the other hand, cyclic resistance of clean sand's relation with void ratio is observed more precisely at low values of CSR.

Figure 4.9 gives NoC to liquefaction vs relative density (Dr). The values of Dr ranges between 15% and 70%. The increasing effect of CSR is similar with the the findings obtained from Figure 4.8

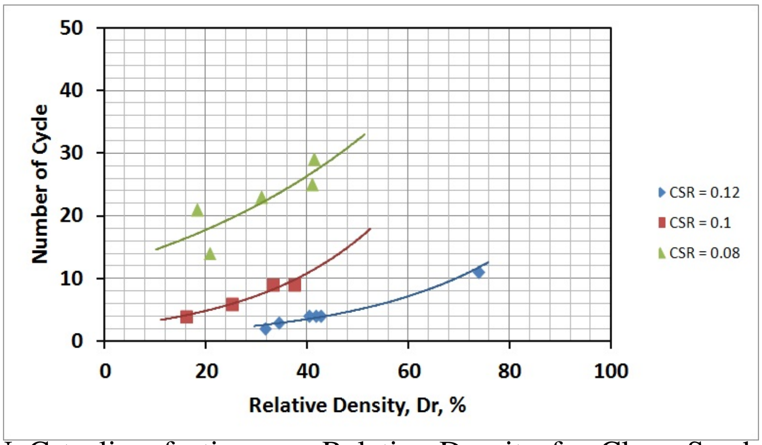


Figure 4.9: NoC to liquefaction vs. Relative Density for Clean Sand at each CSR values, 0.12, 0.1, 0.08

Figure 4.10 gives the Number of Cycles (NoC) required to reach liquefaction vs void ratio and relative density at 0.12, 0.1, 0.08 CSR values for sand with 5% and 10% Silt. Specimes with silts were prepared at loose (Dr=25-40%) and at medium-dense states (Dr=40-60%). This enabled to make comparisons with the results of clean sand tests, more reasonably.

As the silt content increased from 5% to 10%, the liquefaction strength curves demonstrated higher values.

Figure 4.11 gives the Number of Cycles(NoC) required to reach liquefaction vs void ratio and relative density at 0.12, 0.1, 0.08 CSR values for sand with 5% and 10% Kaolinite. In a and c of Figure 4.3. present the Number of Cycles (NoC) to liquefaction vs void ratio and relative density for sand with 5% Kaolinite. The specimens prepared with Kaolinite resulted at high relative densities. The effect of the Kaolinite content got more evident, since sand specimens prepared with 5% Kaolinite content were obtained at Dr= 75%-85%, whereas specimens with 10% Kaolinite had Dr values between 80-95%. This result might be the consequence of the settlement occurred during the saturation process. This effect made it difficult to make a comparison with specimens involving other fine types at loose conditions. In terms of liquefaction strength, it is seen that decreasing CSR has an increasing effect on cyclic resistance of sand containing 5% and 10% Kaolinite similar to clean sand and silty sand. This result is valid for void ratio and relative density as well. It can be also inferred from the figures 4.11(b) and 4.11(d), even at high relative densities as the content of Kaolinite increases the liquefaction strength reduces.

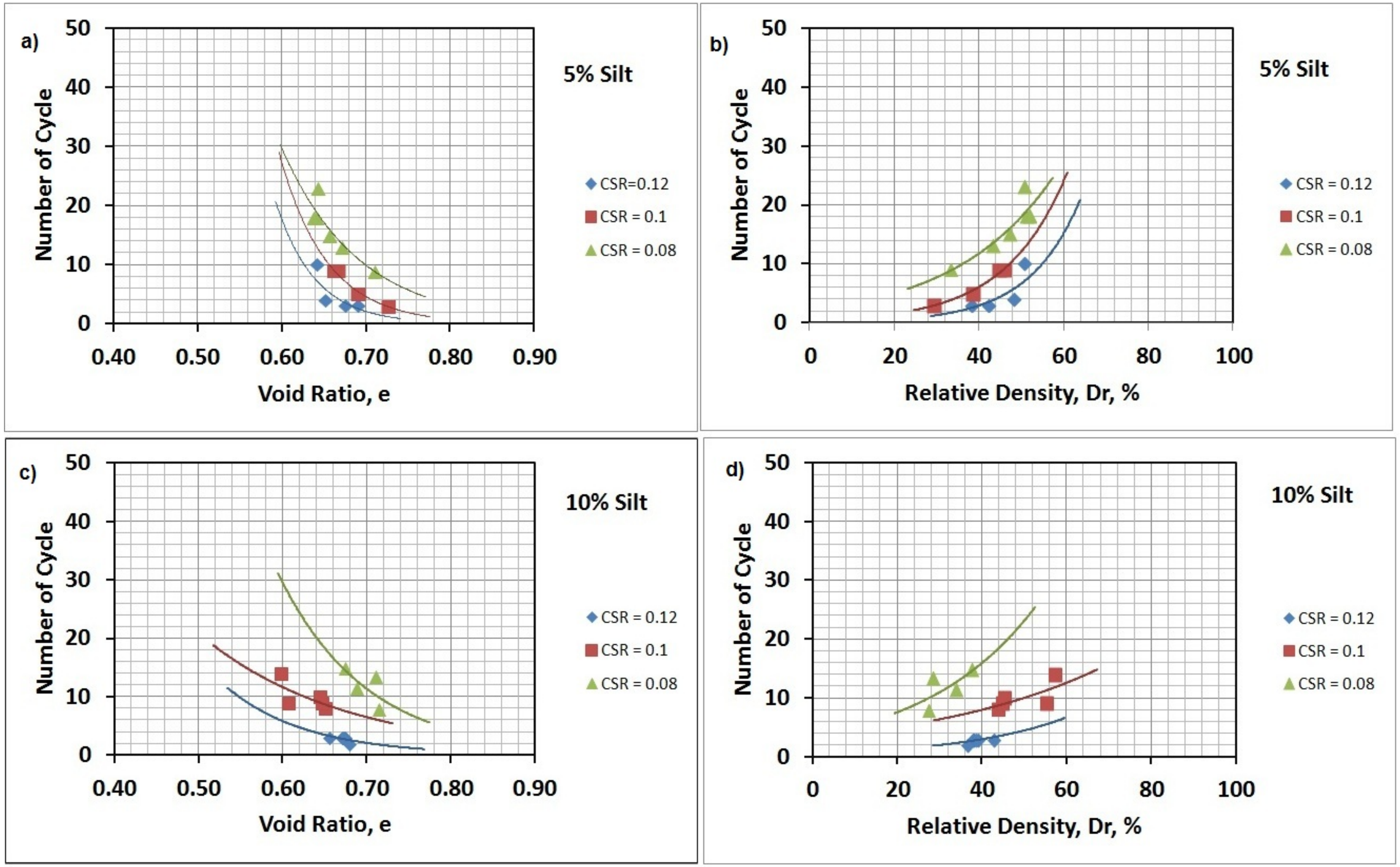


Figure 4.10: Number of Cycles (NoC) required to reach liquefaction vs void ratio for sand with (a) 5% Silt, (c) 10% Silt and vs relative density for sand with (b) 5% Silt, (d) 10% Silt at 0.12, 0.1, 0.08 CSR values

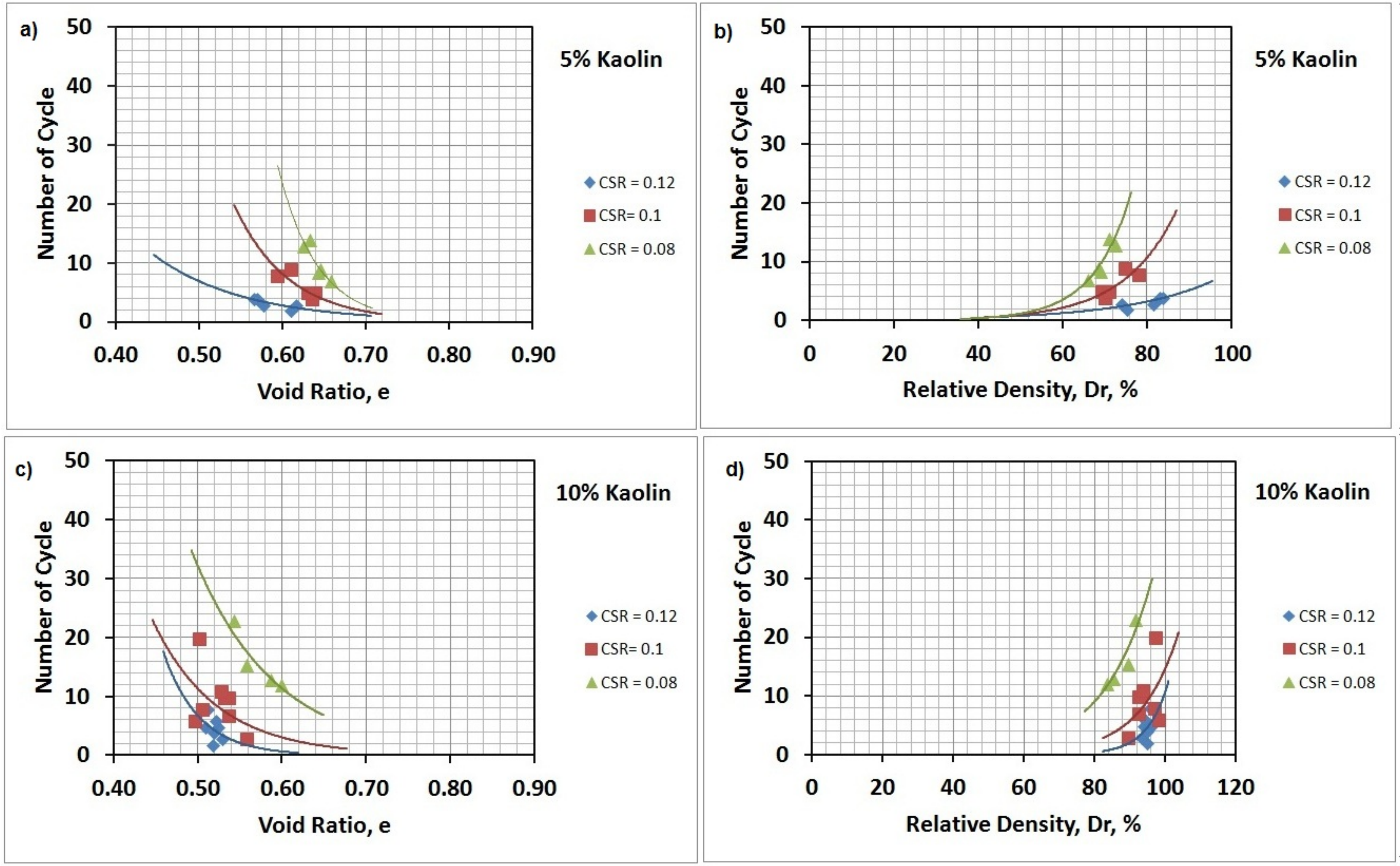


Figure 4.11: Number of Cycles (NoC) required to reach liquefaction vs void ratio for sand with (a) 5% Kaolinite, (c) 10% Kaolinite and vs relative density for sand with (b) 5% Kaolinite, (d) 10% Kaolinite at 0.12, 0.1, 0.08 CSR values

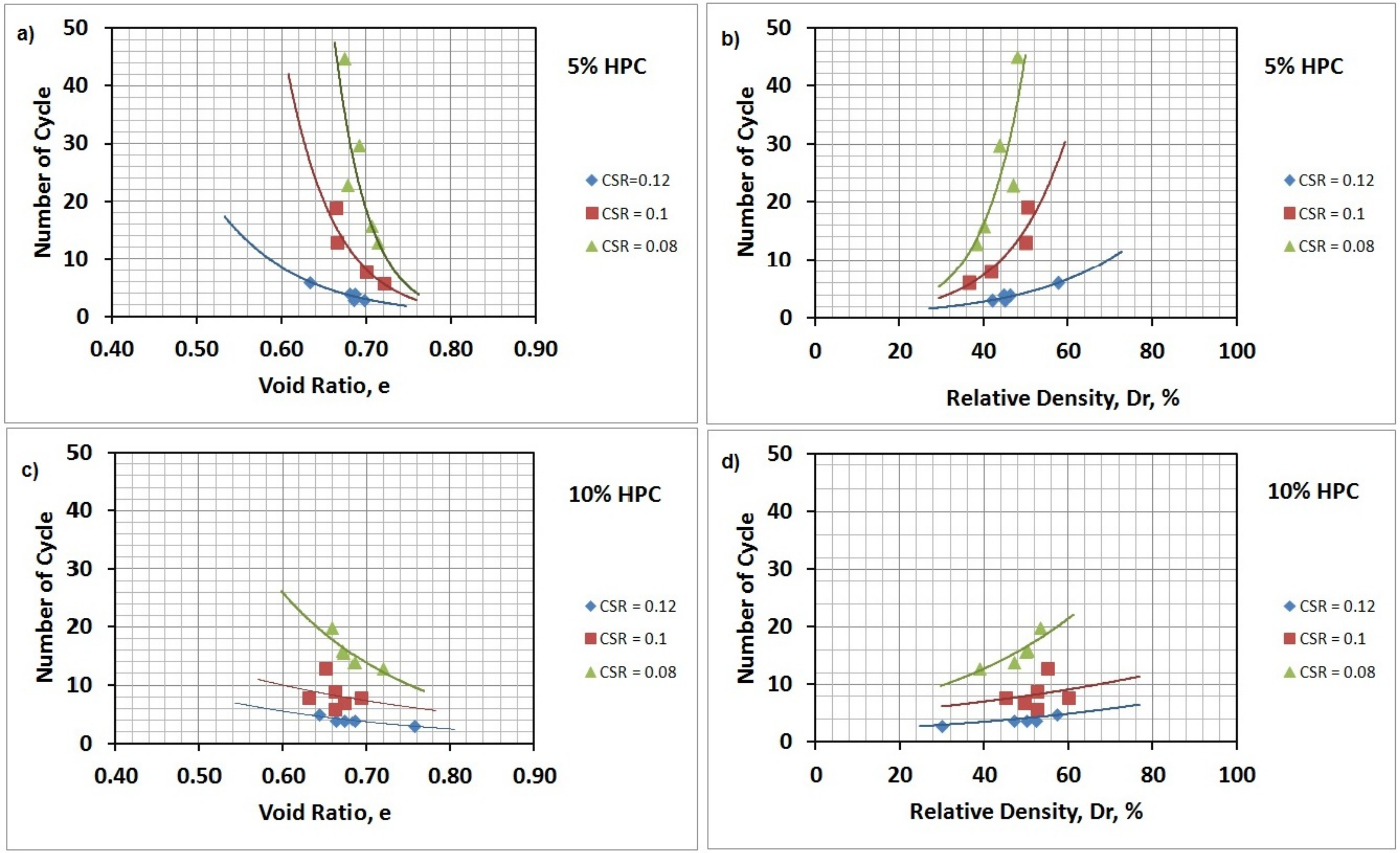


Figure 4.12: Number of Cycles (NoC) required to reach liquefaction vs void ratio for sand with (a) 5% CH, (c) 10% CH and vs relative density for sand with (b) 5% CH, (d) 10% CH at 0.12, 0.1, 0.08 CSR values

Figure 4.12 gives the Number of Cycles (NoC) required to reach liquefaction vs void ratio and relative density at 0.12, 0.1, 0.08 CSR values for sand with 5% and 10% High Plastic Clay (CH). Specimens were obtained at realive densities between 25-60% again, enabled to make reasonable comparisons with the liquefaction strength of other specimens. For specimens with 5% CH, it was observed that as relative density increases, the liquefaction strength of the specimen increases more rapidly than in specimens with 10% CH.

Similar to the results observed in specimens with Kaolinite, the liquefaction strength curves were obtained at lower values for sand specimens with 10% CH when compared with specimens with 5% CH.

In order to better understand the effect of fines content and plasticity on the liquefaction strength, the results of clean sands and sand with fines were compared in the following sections.

4.4 Effect of Fines Content

The cyclic behaviour of sandy soils are affected by many parameters. Literature documents that the void ratio, e, and the relative density, Dr, are the most common parameters that are used to compare the soil mixtures with each other. Hence, the effect of fines content in the experiments performed will be discussed based on void ratio and relative density, respectively in this section.

4.4.1 Effect of fines content based on void ratio

Void ratio is one of the major factors that affects the soil response in liquefaction analysis. So in this section test results are discussed first in terms of void ratio. NoC vs e graphs are given four all four different soil types and the cyclic behaviour of these soil mixtures are compared to each other at different CSR values, 0.12 0.1 and 0.08, respectively.

In the literature, Vaid (1994) [18] mentioned that liquefaction resistance increases as void ratio decreases when the FC is constant. Also, the author stated that, at constant void ratio, resistance increases as silt content increases.

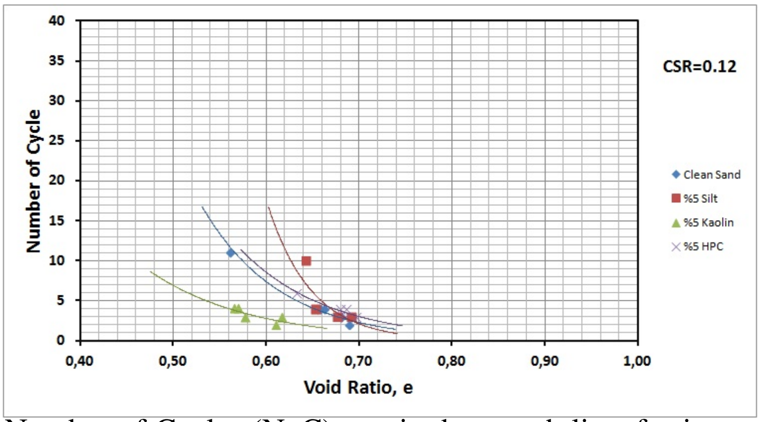


Figure 4.13: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.12 CSR for sand specimens with 5% fines

Figure 4.13 shows four different soil types behaviour at CSR value of 0.12. As it is mentioned before, soils are more liquefable at high CSR values. Therefore, the number of cycles to initial liquefaction are very low and close to each other. Moreover, it can be concluded that clean sand, 5% silt and 5% CH give very similar responses at void ratio range of 0.65-0.7. However, the cyclic resistance of sand containing low plastic clay is a bit lower than that of other soil types at the same void ratio. As void ratio decreases, the difference between cyclic resistance of soil mixtures becomes clearer. It is observed in Figure 4.13 that at void ratios lower than 0.65 silty sand is the strongest soil whereas low plastic clayey sand is the weakest one.

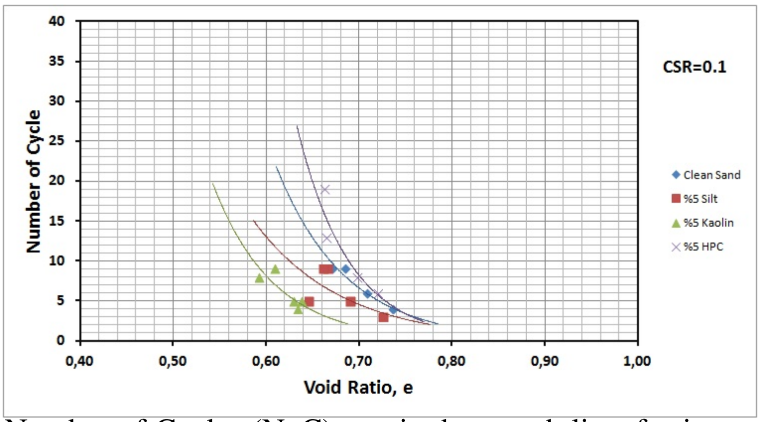


Figure 4.14: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.1 CSR for sand specimens with 5% fines

Figure 4.14 shows four different soil types behaviour at CSR value of 0.1. At this CSR value, the cyclic responses are much more clear compared to results at CSR 0.12. In this case, at the same void ratio sand with CH is the strongest soil and sand with Kaolinite is the weakest one. Also it can be inferred that silt causes a decrease in cyclic resistance compared to clean sand.

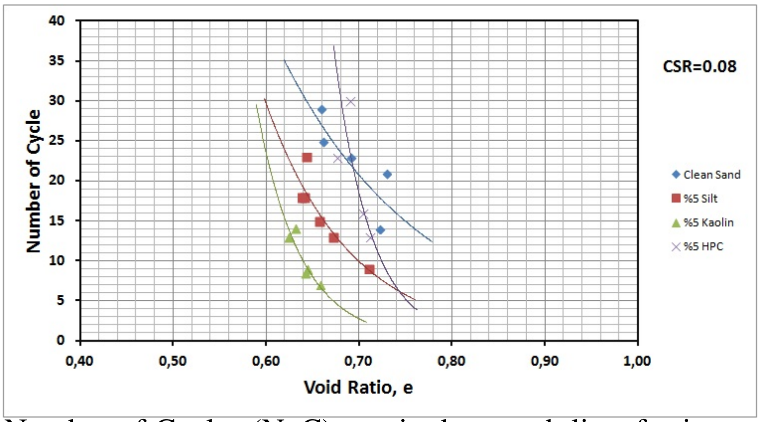


Figure 4.15: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.08 CSR for sand specimens with 5% fines

Figure 4.15 shows the behaviour of four different soil types behaviour at CSR value of 0.08. As mentioned above, silty sand and low plastic clayey sand decreases the cyclic resistance of sand at the same void ratio. In addition to this, trends of clean sand and sand with CH converges at void ratio of 0.69. Therefore, it can be inferred that when void ratio is higher than 0.69 the high plastic clay causes a decrease in liquefaction strength of clean sand. On the other hand, when the void ratio gets lower than 0.69 high plastic clay causes an increase in cyclic resistance of clean sand. This result is consistent with the steeper trend of CH that explained in section 4.3.

In summary, the liquefaction resistance of sand with 5% High Plastic Clay, Silt and Clean Sand are almost similar when CSR is 0.12, but this trend changes when CSR value decreases. Also, when the CSR takes value of 0.08, clean sand is stronger than all the other soil types if the void ratio is higher than 0.69. But if the void ratio is lower than 0.69, high plastic clay causes an increase in cyclic resistance of sand. Based on these test results, it can be clearly seen that low plastic clay leads to a decrease in the liquefaction resistance independently of CSR value.

To clarify the effect of fines content, sandy soils containing 10% fines content were prepared and experiments were performed at three different CSR values. The results of these experiments are discussed.

Figure 4.16 demonstrates Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.12 CSR for sand specimens with 10% fines. It is seen that at this CSR value low plasticity clay is the weakest soil type.

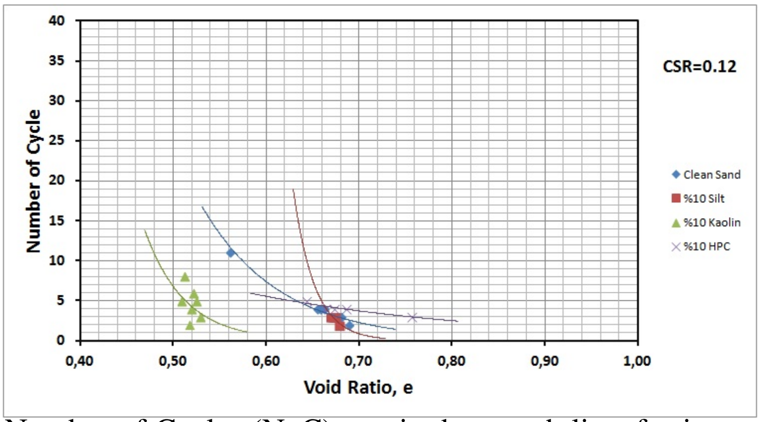


Figure 4.16: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.12 CSR for sand specimens with 10% fines

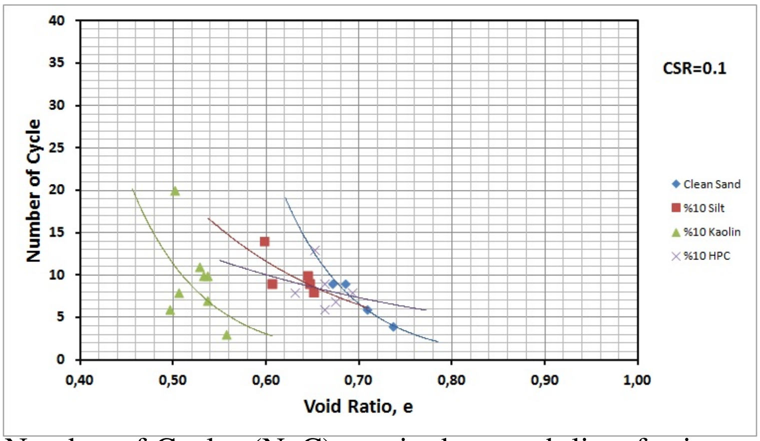


Figure 4.17: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.1 CSR for sand specimens with 10% fines

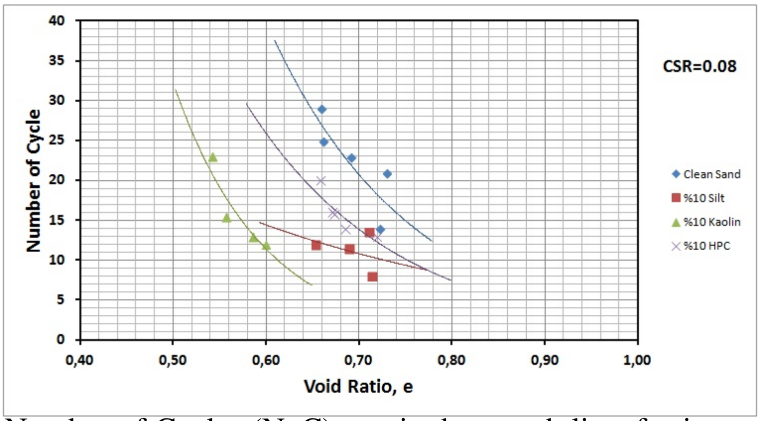


Figure 4.18: Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.08 CSR for sand specimens with 10% fines

The difference in cyclic behaviours of clean sand, High plastic clayey sand and silty sand can not be observed clearly because of low number of cycles. For instance, when the void ratio is lower than 0.68 it seems that silt causes a significant increase in cyclic resistance. However, as the void ratio gets higher than 0.68, response becomes more complex. This complexity makes it difficult to interpret the results.

Figure 4.17 gives Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.1 CSR for sand specimens with 10% fines. Although this figure is more clear than the graph of CSR 0.12, it is still difficult to identify the exact trend. It can be said that the low plastic clay reduces the cyclic resistance of sand and this result in line with results obtained with CSR 0.12.

Figure 4.18 gives Number of Cycles (NoC) required to reach liquefaction vs void ratio at 0.08 CSR for sand specimens with 10% fines. As the number of cycles increases at this lower CSR value, the trend becomes clearer. Clean sand, sand with CH and sand with Kaolinite have similar trends whereas the trend of silty sand is a bit different. At the same void ratio, e, clean sand is the strongest type of soil and the low plastic clayey sand is the weakest one. At this CSR value, it can be inferred that all fines types cause a decrease in cyclic resistance of sand when the amount of fines is 10%. This results are also applicable to results that are obtained with 5% fines content.

Lastly, the effect of FC can be understood from the pore pressure generation curves. The pore pressure generation curves of Silty and High Plastic Clayey Sand are given in Figure 4.19, and these curves are compared to Clean Sand Curve.

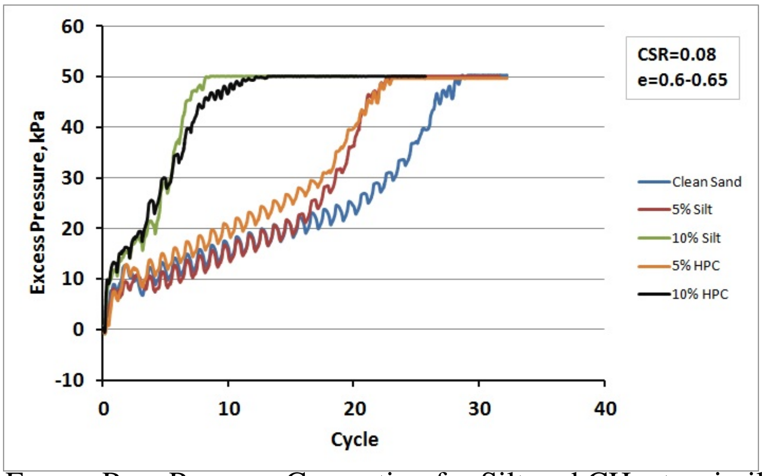


Figure 4.19: Excess Pore Pressure Generation for Silt and CH, at a similar void ratio, 0.6-0.65, and constant CSR, 0.08

The effect of FC can be clearly seen from this Figure. Independent form the fine type, sand containing 10% FC is more liquefiable than Clean Sand. Also, the pore water is generated more quickly from the sand containing 5% fines compared to clean sand. This graph can be identical to clarify the complexity between Silty Sand and sand with CH behaviour. As it is mentioned above, because of the special property of Kaolinite, Low Plastic Clayey Sand data could not be plotted and interpreted into this Figure 4.19.

As the fines content amount increased in order to identify the FC effect, it was seen that the behaviour became more complex. For this reason, the effect can only be analysed at low CSR values. The effects at low CSR values shows that clean sand is the strongest and low plastic clayey sand is the weakest soil type. These findings hold in both 5% and 10% FC cases.

4.4.2 Effect of fines content based on relative density

Relative density is the main parameter to describe the cyclic behaviour of sandy soils. For this purpose, emax and emin tests were performed for each type of samples and relative densities of specimens were compared to each other.

In the literature, Singh (1994) wrote that, sands with 10, 20 or 30 percent silt have slightly lower resistance to liquefaction than clean sand at the same relative density(i.e. Dr=50%). Wang and Wang (2010) [2] concluded that when the Dr reaches the maximum value at the fines content of 30%, the liquefaction resistance also reaches the maximum values at the same fines content. Lastly, [5] indicated that the behaviour of sandy soils at dense states was significantly influenced by the plasticity and particle size of fines. They mentioned that, regardless of the plasticity, the cyclic resistance increases with increasing relative density.

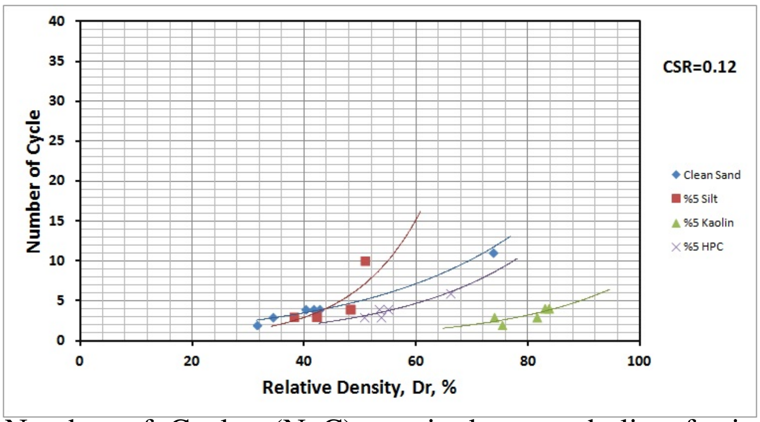


Figure 4.20: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.12 CSR for sand specimens with 5% fines

Figure 4.20 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.12 CSR for sand specimens with 5% fines. Test data are cumulated around 40%. At Dr=40% no clear difference in trend is observed. But the relative density of

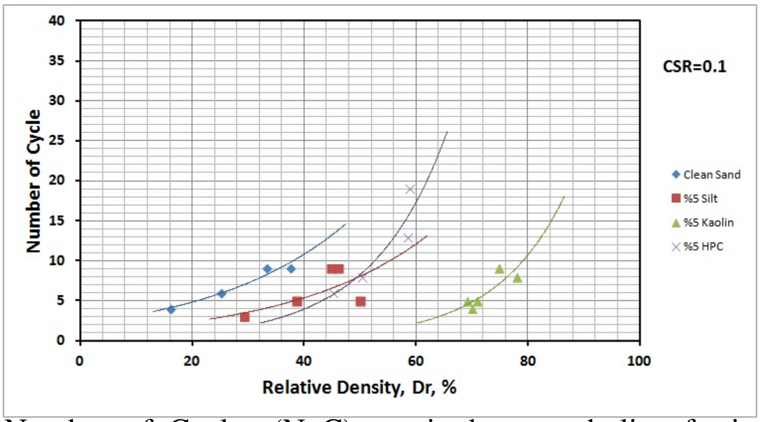


Figure 4.21: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.1 CSR for sand specimens with 5% fines

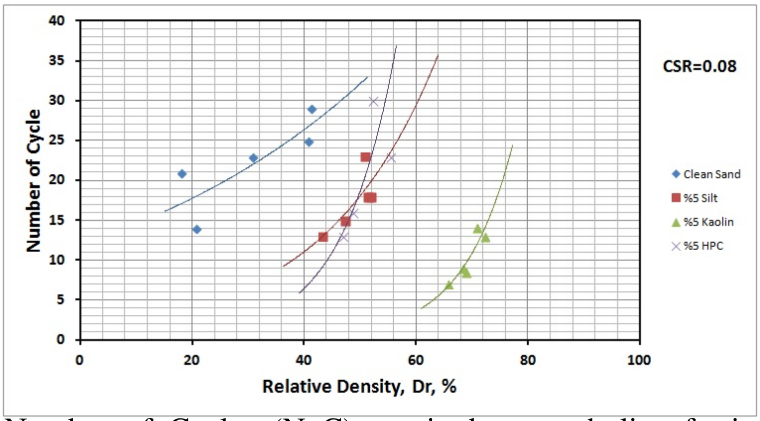


Figure 4.22: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.08 CSR for sand specimens with 5% fines

low plastic clayey sand is around 80%. However at lower relative density values the response gets closer to the other soil responses.

Figure 4.21 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.1 CSR for sand specimens with 5% fines. At loose state (i.e. Dr=30%) clean sand shows the strongest resistance to liquefaction. But at medium-dense states (i.e. Dr=60%) high plastic clayey sand increases the cyclic resistance of sand. Low plastic clayey sand decreases the liquefaction strength at any relative density values. Silt content causes a decrease in liquefaction potential of clean sand at all relative density values. The intersection between silt and high plastic clay trends is located at Dr=50%. For Dr values lower than 50%, high plastic clay is more liquefable than silt but at dense states this trend reverses.

Figure 4.22 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.08 CSR for sand specimens with 5% fines. At loose state (Dr=30%) clean sand is the strongest soil type and all fine types lead to a decrease in cyclic resistance of sand. Similar to CSR=0.1 case, silt and high plastic clay soils intersects at Dr=50%. Similar to the previous case silt is stronger than high plastic cay if Dr is less than 50%. All results obtained in this step are in line with the results of CSR=0.1

To understand the effect of fines content in terms of relative density, sandy soils containing 10% fines content were prepared and experiments were performed at three different CSR values. The results of these experiments are discussed.

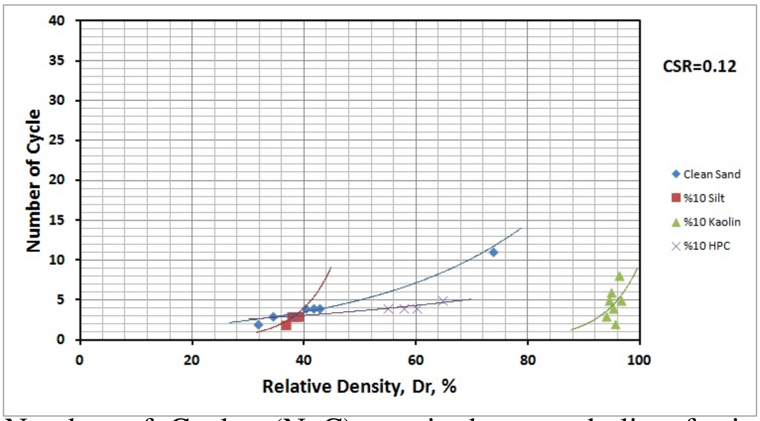


Figure 4.23: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.12 CSR for sand specimens with 10% fines

Figure 4.23 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.12 CSR for sand specimens with 10% fines. The low number of cycles does not allow us to infer any clear trend from the figure. The data mainly locate around 40%. The results of low plastic clayey sand is significantly different form other soil mixtures.

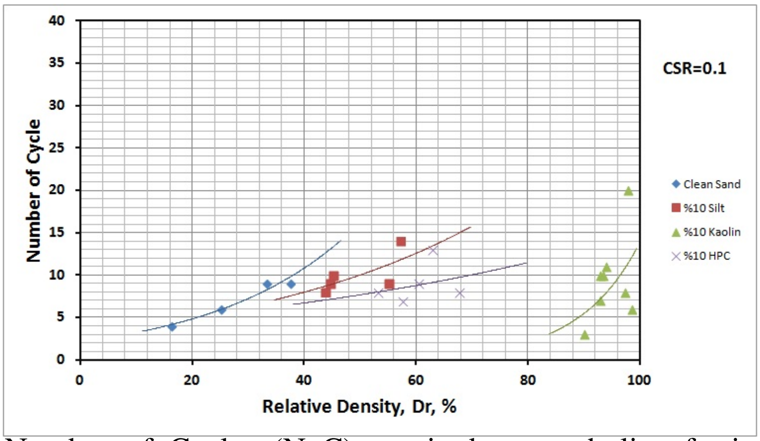


Figure 4.24: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.1 CSR for sand specimens with 10% fines

Figure 4.24 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.1 CSR for sand specimens with 10% fines. According to test results all fine types cause a decrease in cyclic resistance of clean sand at Dr=50%. At loose state (Dr=30%) trends of clean sand silty sand and high plastic clayey sand are similar to each other. The effect of fines content in cyclic resistance of sand can be observed more clearly at dense states. Low plastic clayey sand is the weakest soil.

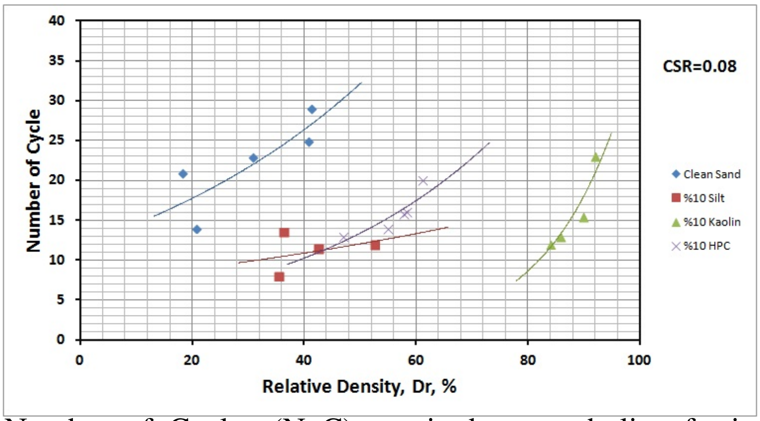


Figure 4.25: Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.08 CSR for sand specimens with 10% fines

Figure 4.25 gives Number of Cycles (NoC) required to reach liquefaction vs relative density at 0.08 CSR for sand specimens with 10% fines. In line with the previous results all fine types lead to a decrease in cyclic resistance of sand. When Dr is lower than 50%, high plastic clay is more liquefiable than silt. But this trend changes at Dr=50%. Low plastic clay has the lowest cyclic resistance to liquefaction.

From Figures 4.26 and 4.27 for Dr=30% and 40%, it can be inferred that at high CSR values, the effects of fines content on liquefaction strength of sandy soils are not significant. However, as CSR value reduces. the reducing effect of fines on the liquefaction strength of sand gets more evident.

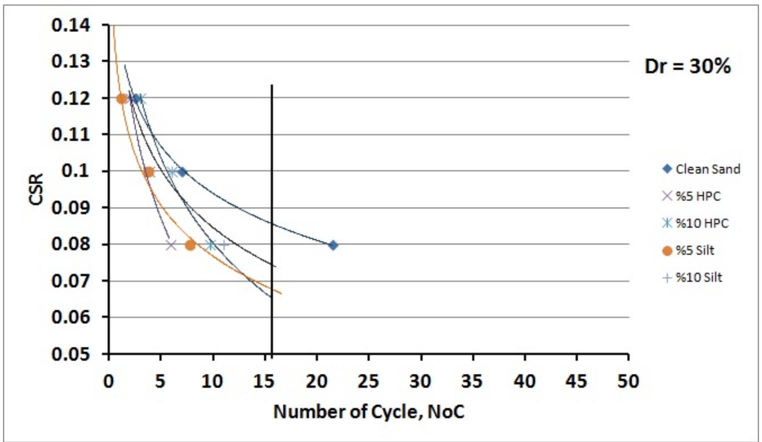


Figure 4.26: CSR vs. NoC for Dr=30%

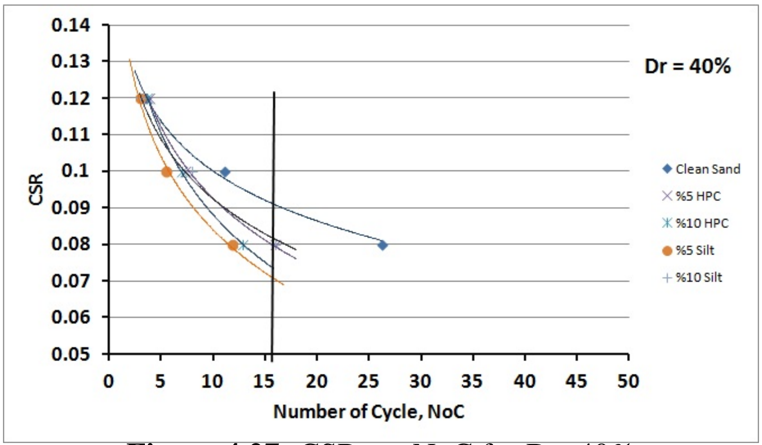


Figure 4.27: CSR vs. NoC for Dr=40%

At denser states where Dr=50% and 60%, the effect of fines on liquefaction strength of sands gets more complicated. Figure 4.28 and 4.29 demonstrate that sand with 5% and 10% CH show higher liquefaction strength than clean sand and silty sand at Dr=50% where as at Dr=60%, sand with 10% CH shows lower strength than sand and silty sand. As stated before, sand with Kaolinite (low plastic clay) shows the lowest strength in dense state.

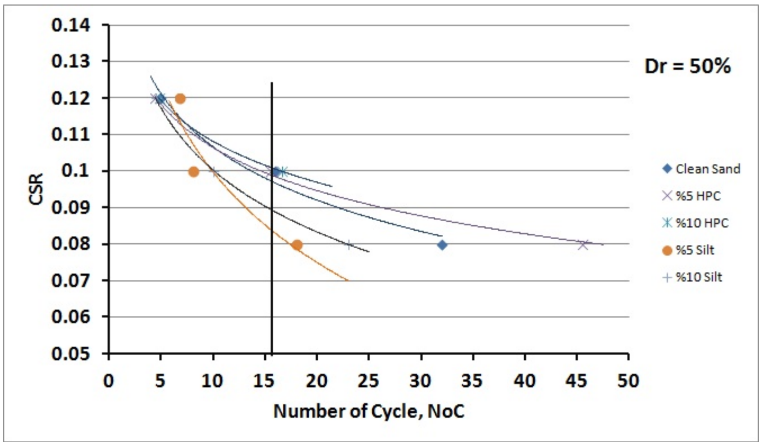


Figure 4.28: CSR vs. NoC for Dr=50%

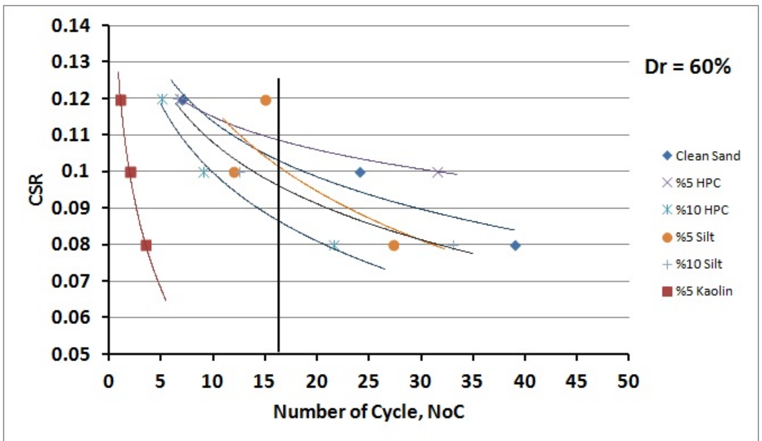


Figure 4.29: CSR vs. NoC for Dr=60%

4.4.3 Effect of fines content on CRRM=7.5

Number of Cycles to initial liquefaction is one of the most important parameters which indicate the cyclic strength of soil specimen. So, the CSR vs. NoC graphs at a constant void ratio, which is shown in Figure 4.3, can be very useful to identify the liquefaction potential of soil samples. In addition to this, liquefaction resistance for an earthquake of magnitude 7.5 was determined from the CSR vs. NoC graph. From this graph, a cyclic stress ratio required to cause liquefaction at 15 cycles was chosen as Cyclic Resistance Ratio (CRRM=7.5) value which represents the liquefaction resistance of the soil (CRRM=7.5) to a moment magnitude of an earthquake of 7.5.

The effect of fines content can be clearly seen from the CRRM=7.5 vs FC graphs which is given in Figure 4.30 that shows the relation between CRRM=7.5 and fines content for a constant void ratio, 0.65.

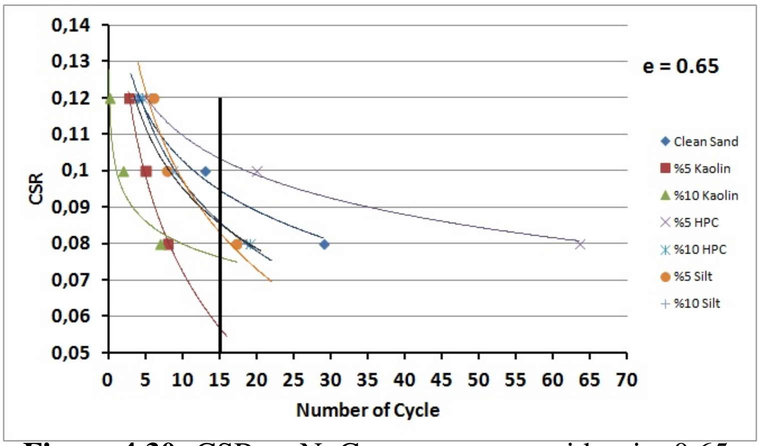


Figure 4.30: CSR vs NoC at a constant void ratio, 0.65.

At low levels of fines content High Plastic clay response is increasing with fines content amount whereas silt's response is decreasing. After 5% fines content level, these trends reverse and the response of silt and CH converges around 10% FC level. Kaolinite response has a strong negative trend until 5% FC level at where it starts to increase. The Figure 4.31 shows that trend reverses around 6% FC level.

The effect of fines content can be also seen from the CRRM=7.5 vs FC graphs which is given in Figures 4.32 and 4.33 that show the relation between CRRM=7.5 and fines content for a constant relative densities, 40% and 50%.

Figure 4.32 shows the results for constant relative density of 40%. As explained in the previous sections, density values of low plastic clayey sand (Kaolinite) is not available

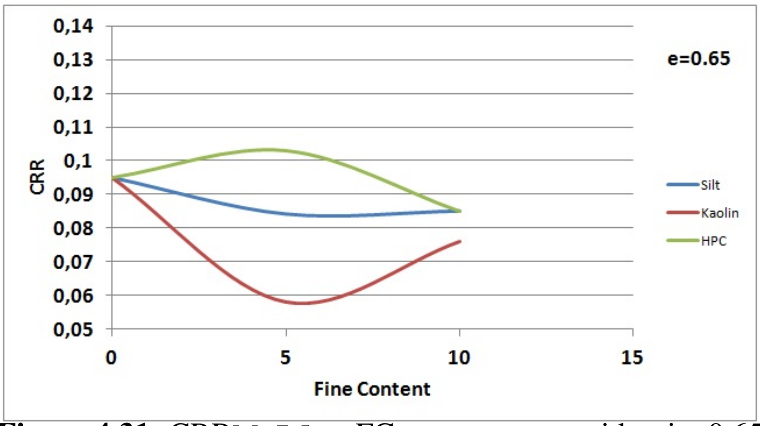


Figure 4.31: CRRM=7.5 vs FC at a constant void ratio, 0.65

at this relative density ratio. For this reason, Figure 4.32 and Figure 4.33 presents only Silt and CH results. The response has a decreasing trend until FC level of 6% for both silt and CH and then trend slightly reverses after this level. Their trends converge around at 10% FC level.

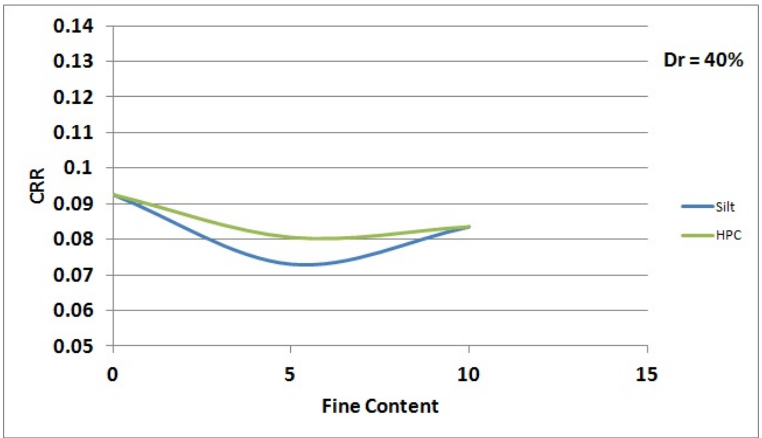


Figure 4.32: CSR vs FC at a constant relative density, 40%.

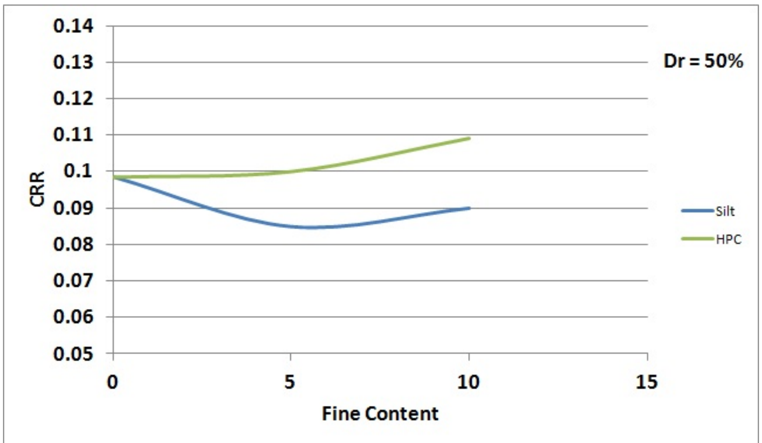


Figure 4.33: CSR vs FC at a constant relative density, 50%.

Figure 4.33 shows the results for constant relative density of 50%. Compared to Figure 4.31, we observe that silt shows a similar response, however CH trend looks different. It can be inferred from this figure that trends exhibit a reverse point.

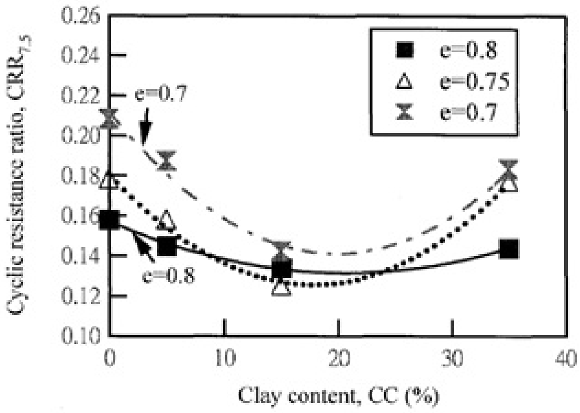


Figure 4.34: Relationship between CRRM=7.5 and clay content for different e, Chang and Hong, 2008 [7]

In literature there is a confusion about the reverse point on clayey sand, but general trend is similar with these findings. For example, Chang and Hong (2008) [7] showed the variation on cyclic resistance ratio with clay content and global void ratio in Figure 4.34. Researchers found the reverse point at a range between 15% and 25%. In addition to this, Polito (1999) [24] indicated that the reverse point for clayey sand can be controlled by LL, and samples which have LL lower than 17 decreases the liquefaction resistance.

4.5 Effect of Plasticity

One of the main interest of this thesis is to investigate the effect of plasticity on cyclic behaviour of sandy soils. For this purpose, clay samples, which have different PI values were added to sand and the PI effect was investigated. To understand the effect of PI, non-plastic silt, high plastic clay and low plastic clay were added to sand specimen. Figures presented in void ratio and relative density analyses (Section 4.5.1 and 4.5.2) can also be interpreted in terms of plasticity.

A review of the literature shows that there is no clear consensus on the effect of PI. Polito (1999) [24] found that the cyclic resistance of clayey sand can be depended on the liquid limit of clay samples. Also, Polito stated that no clear correlation may be drawn regarding the effect of clay content on liquefaction resistance. Gratchev et al (2006) [25] mentioned that the boundary between liquefiable and nonliquefiable clayey mixtures is drawn at PI=15. In addition to this, Sadeh and Saleh (2007) [37] indicated that in most cases the plasticity of entire specimen did not vary significantly because a small amount of plastic fine was included. The effect of the fine's plasticity on liquefaction behaviour has not been clearly understood and more research on the effects of types of fines and plasticity on liquefaction strength of sands is necessary.

More recently, Park and Kim (2013) [5] wrote that when a small amount (10%) of plastic fines is included in sand matrix, the liquefaction resistance of sandy soils appears to be dependent on the plasticity of the fines. This is because the presence of silt increased soil dilatancy but the clay fines reduce the particle friction developed at the contacts between sand grains at medium or dense state. As the plasticity of 10% fines increased, the liquefaction resistance of medium or dense specimens decreased, but that of the loose specimens decreased slightly. Results of high plastic clay-sand mixture and silt-sand mixture that are obtained from this study is given in Figure 4.35.

Figure 4.37 and Figure 4.38 shows the variation of Number of Cycle with CSR value at sand containing 10% Silt and 10% High Plastic Clay (CH) for a constant void ratio, 0.65. From these figures, we could argue that the cyclic response of each state is very close to each other for silty and clayey sand. However, the response is getting closer to each other with increasing plasticity.

So that, again, it can be concluded that the cyclic behaviour of sandy soils change based on the relative density. These findings are also applicable with the results of Park and Kim (2013) [5]; they also concluded that when the specimen becomes denser, the liquefaction resistance becomes stronger (Figure 4.35).

Two different view on the results are as follows:

- To investigate the effect of PI, low plastic clay and high plastic clay could be compared with each other. All graphs show that low plastic clay has the weakest cyclic resistance in all cases. But the cyclic resistance of high plastic clay is always stronger than that of low plastic clay. In this respect, it can be said that increasing PI causes an increase in cyclic resistance. Besides, as explained before this comparison may not be reliable due to the special property of Kaolinite.

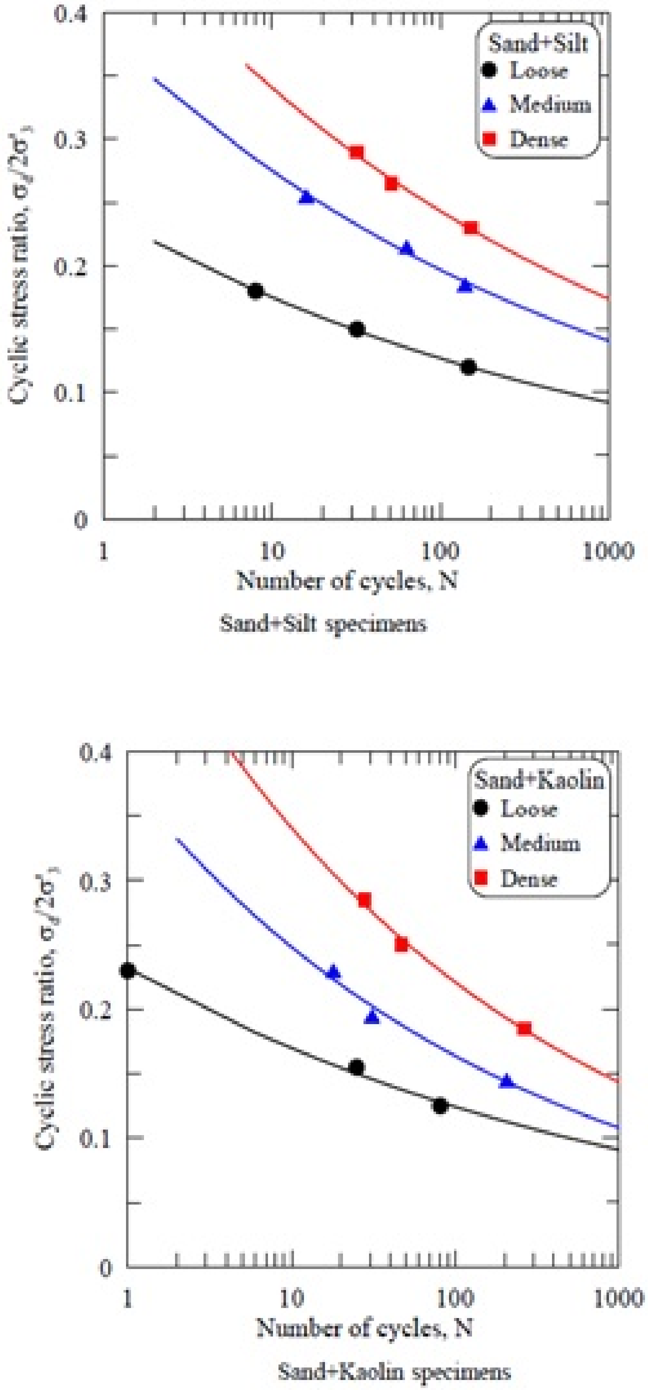
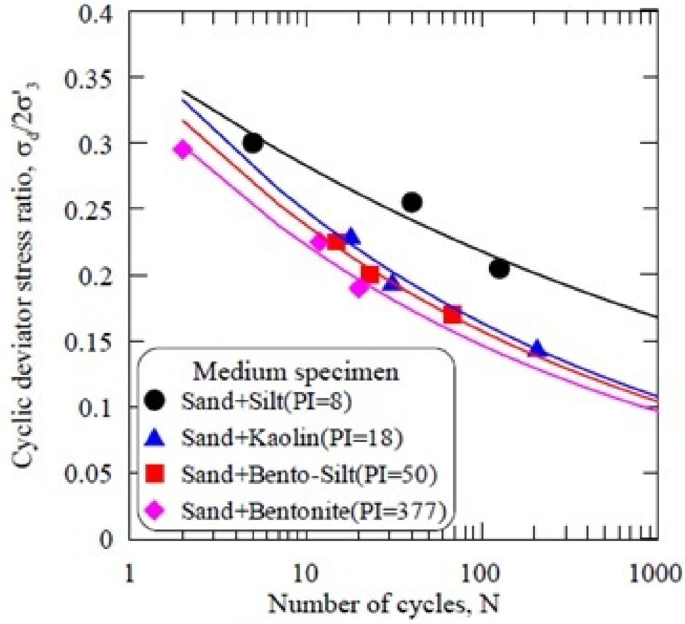
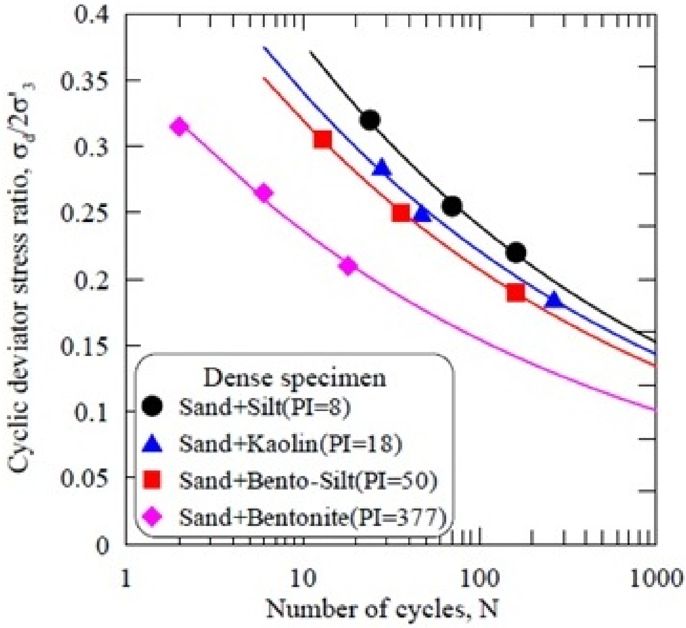


Figure 4.35: CSR vs. NoC of Sand-Silt and Sand-Bentonite Mixture from Park and Kim, 2013 [5]

- In terms of relative density the cyclic behaviour of high plastic clay shows similar trend with silty sand which is a non-plastic material. According to Figures 4.37 and 4.38, the CSR curves of High Plastic Clay and silt intersect at medium density values (Dr=45% - 55%), actually the general trend looks similar at medium state (Dr=45% - 55%). This result indicates that the plasticity has not a significant effect on cyclic behaviour of sandy soils at this range of Dr. However, as the



(b) Medium specimens



(c) Dense specimens

Figure 4.36: Liquefaction resistance curves for different densities, Park and Kim, 2013 [5]

specimen reaches to a denser state, the cyclic resistance of high plastic clay increases significantly compared to silty sand. In this respect, it can be said that plasticity has an effect on cyclic behaviour of sandy soil in dense state. These results are consistent with Park and Kim (2013) [5]. In a sense that, as it is seen

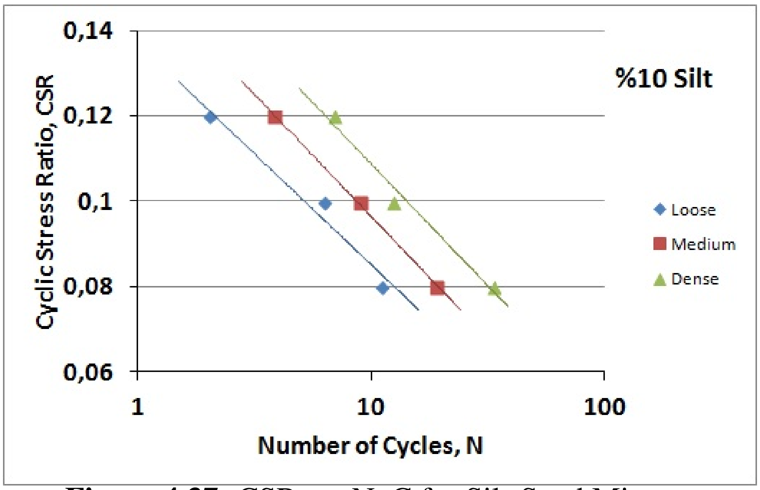


Figure 4.37: CSR vs. NoC for Silt-Sand Mixture

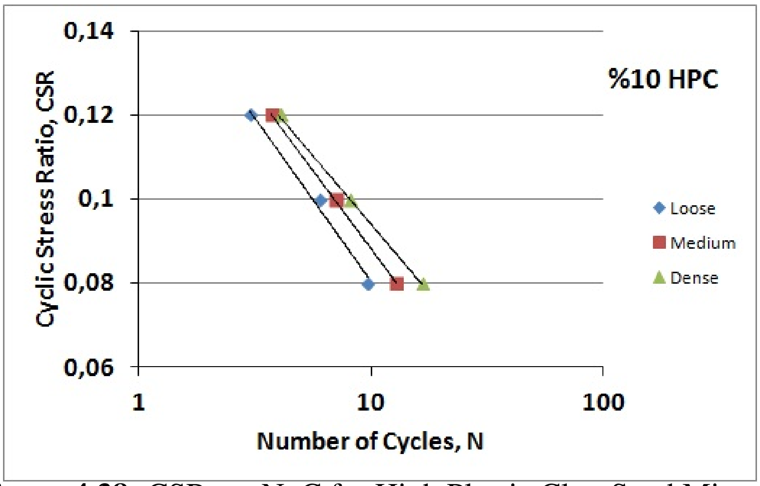


Figure 4.38: CSR vs. NoC for High Plastic Clay-Sand Mixture

from Figure 4.36, fine materials causes a decrease in liquefaction strength on cyclic behaviour of sand but the effect of plasticity was not observed as in their results in denser states. In dense states, the liquefaction strength of sand with CH was either similar to liquefaction strength of silty sand or higher observed because the trends are very similar at medium state.

- Figures 4.32 and 4.33 represents the CSR vs NoC to liquefaction for silty sand mixtures and sand with CH, respectively. It can be inferred from these figures that as the plasticity increases, the effect of relative density diminishes.

- The effect of plasticity can also be interpreted from the Figures 4.31, which shows CRRM=7.5 vs. FC. According to this figure, sand with demonstrates CH has a stronger cyclic behaviour than both Silt and Kaolinite. In other words, as plasticity increases cyclic resistance of sand becomes stronger. Still, the effect of plasticity on liquefaction resistance is not significant.

This leads us to infer that silty sand and sand with High Plastic Clay have similar undrained cyclic behaviour. In this respect, the effect of PI on liquefaction strength should be studied with higher fines content and at different PI values.

5. SUMMARY AND CONCLUSION

In this study, the effect of plasticity and fines content on cyclic behaviour of sand were investigated. For this purpose, sand specimens with non-plastic silt, low plastic clay (Kaolinite) and high plastic clay sand prepared and tested in Cyclic Simple Shear Device under constant shear stresses. The tests were performed in drained constant volume conditions. To obtain fully saturated specimens at desired fines contents, the best specimen preparation technique for Cyclic Simple Shear Device was determined as Dry Pluviation and Flushing with CO2 and H2O.

A total of 110 tests were performed on clean sand, sand with 5% and 10% silt, sand with 5% and 10% Kaolinite and sand with 5% and 10% High Plastic Clay (CH) at cyclic stress ratios (CSR) of 0.12,0.1 and 0.08. Number of Cycles to initial liquefaction was determined as ru=1 for all the tests. Based on the experimental results, following observations are obtained.

1. The liquefaction strength of sand with fines is dependent on several parameters: void ratio (e), relative density (Dr), fines content, plasticity, CSR, soil fabric etc. The comparison basis for liquefaction strength of sands with fines is important in order to draw a conclusion. It was determined that the relative density should be selected as the main comparison parameter when undrained cyclic behaviour of sands with fines is investigated.

2. In general, sand with fines demonstrated lower liquefaction strength than clean sand. This effect was not very significant at loose states whereas it got more evident as the relative density increases. The only exception was observed for silty sand where it demonstrated higher liquefaction strength at high CSR values and in denser states. In order to verify this observation, more tests are needed at high CSR values.

3. Based on both relative density and void ratio, sand specimens with 5% and 10% Kaolinite demonstrated lowest liquefaction strength. The specimens with Kaolinite were obtained at high relative densities Dr ranging from 75% to 95%. Such a

high range of relative density can be attributed to the considerable settlement of the specimens with Kaolinite during saturation.

4. The effect of fines content on liquefaction strength of sands differs depending on the type of fines. In the case of silty sand and sand with Kaolinite, liquefaction strength increased when FC increased from 5% to 10%. In the case of sand with CH, the liquefaction strength increased in loose state however reduced in denser states as the FC increased from 5% to 10%.

5. The effect of FC on liquefaction resistance can be also interpreted from CRRM=7.5 vs FC graphs. The general trend shows that cyclic resistance first reduces as the FC reaches 5% and then increases at FC=10%. Further study is needed to see the cyclic resistance of sand with fines as the FC increases higher than 10%.

6. In terms of plasticity, sand with low plastic clay demonstrate lower liquefaction strength when compared with sand with CH. The results are only limited to dense specimens. Sand with non-plastic fine (silt) and sand with CH show very similar cyclic behaviours in loose and dense conditions. Based on CRRM=7.5 graphs, sand with CH demonstrated slightly higher liquefaction resistance than silty sand. Therefore, the lowest strength low plastic clay may not be contributed to the plasticity Kaolinite show lower liquefaction strength among the other soil types, it can not be said this situation is related to the plasticity. There may be some other aspects that need to be studied, such as the fabric of the sand with Kaolinite specimen.

To conclude, based on the experimental tests performed in this study, in general clean sand has higher liquefaction strength than sand with fines for FC <10%. Further studies needed to better interpret the effect of fines at higher FC and the effect of plasticity.

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