ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

AN EXPERIMENTAL INVESTIGATION ON THE EFFECTS OF RELATIVE DENSITY AND GRAIN SIZE DISTRIBUTION ON CYCLIC LIQUEFACTION OF SILTY SANDS

M.Sc. THESIS

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GÖRECELİ SIKILIK VE DANE ÇAPI DAĞILIMININ SİTLİ KUMLARIN SİSMİK SIVILAŞMASINA ETKİSİNİN DENEYSEL İNCELENMESİ

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To my mom İnci and my sister Beyza for their precious love, support and encouragement…

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ABBREVIATIONS

ASTM : American Society for Testing and Materials
USCS : Unified Soil Classification System
NGI : Norwegian Geotechnical Institute
SGI : Swedish Geotechnical Institute
CSR : The cyclic Shear Ratio
CRR : The Cyclic Resistance Ratio
CDSS : Cyclic Direct Simple Shear Test
CTX : Cyclic Triaxial Test
DTS : Dynamic Torsional Shear Test
Dr : Relative Density
FC : Fines Content
FCt : Threshold fines content
Gs : Specific Gravity

SYMBOLS

Dr	: Relative Density
Gs	: Specific Gravity
σ_v	: Vertical Total Stress
σ'_v	: Vertical Effective Stress
CUsand	: Coefficient of Uniformity of Sand
CUsilt	: Coefficient of Uniformity of Silt
CUoverall	: Coefficient of Uniformity of Silty Sand
D_{50}**sand**	: Mean Grain Diameter of Sand
d_{50}**silt**	: Mean Grain Diameter of Silt
χ	: Disparity Ratio
e_{max}	: Maximum Void Ratio
e_{min}	: Minimum Void Ratio
e	: Void Ratio
e_s	: Intergranular or Sand Skeleton Void Ratio
Δu	: The Change in Excess Pore Water Pressure
τ	: Shear Stress
γ	: Shear Strain
N_L	: Number of Cycles Required for Liquefaction

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AN INVESTIGATION OF THE EFFECTS OF RELATIVE DENSITY AND SILT GRADATION ON CYCLIC LIQUEFACTION SILTY SAND

SUMMARY

Liquefaction of the sands is a soil behavior frequently encountered in geotechnical engineering that causes crucial damage. Geotechnical research on this topic has started with the Anchorage and Niigata earthquakes in the early 1960s. Much important research has been conducted to understand the conditions that change the liquefaction resistance of clean sands. However, there has been no consensus until the 2000s on the liquefaction of silty or silty clay sands. Especially after the Adapazarı and Chi-Chi earthquakes, case studies and researches have shown that the sands containing silt have also become liquefied. In this context, the effect of some parameters such as sample preparation method, confining pressure (σ'_v), and fines content on the liquefaction resistance have been analyzed in detail. Besides, correlations between seismic liquefaction resistances and in-situ tests have also been investigated.

When grain size distribution of the soil, confining pressure, and dynamic loading conditions are kept constant, the liquefaction resistance of the soil will increase with the increase in the relative density. However, the function of this increasing trend has not been investigated in the literature. Likewise, a few researches examined the effect of grain size, grain size distribution, and different silts on the liquefaction resistance of silty sands.

This thesis aims to investigate the effect of the relative density (Dr), silt content, and silt size on the liquefaction resistance of sand under dynamic loads in geotechnical earthquake engineering. Within the thesis, non-plastic SI, TT, and IZ silts with different grain distributions were mixed by dry weight into clean Sile Sand 20/30. Test samples have been prepared by the dry funnel method and consolidated under 100 kPa. Clean sands and silty sand samples were tested with cyclic direct simple shear test with constant volume control at three different cyclic shear stress ratios (CSR = 0.08, 0.1, and 0.12).

In the thesis, the liquefaction behavior of the samples was analyzed for different relative densities in each cyclic shear stress ratio. N_L and Dr's relationship was expressed with an exponential function for a constant CSR for clean sand and silty sands. At a constant Dr, an equation was proposed between CSR and N_L with a power function. Another finding of the thesis was that the coefficients of the proposed equations were affected by the properties of the soils (e.g., relative density, grain distribution, fines content, etc.).

It is known that there is no consensus about the effect of fines content on the liquefaction behavior in cases where sand contains silt. The liquefaction potential of silty sands when different silts are used in the same fines content is another research topic. It has not been researched widely, like the effect of silt size on the liquefaction behavior.

In this thesis, the changes of liquefaction potential of the soil with the increase of the fines content (between 0% and 25% of the fines content) were shown based on relative density (Dr) and void ratio (e). When the comparison basis was the void ratio, the liquefaction resistance of the samples has decreased with the fines content. In the loose and medium dense samples (Dr = 30% and Dr = 45%) and at the low fines content (≤10%), IZ silty samples have the greatest liquefaction resistance, whereas the liquefaction resistance of the TT and SI silty samples are similar. As fines content increased (= 15%), the liquefaction resistance of IZ silty and TT silty samples continued to increase, while the resistance of SI silty samples had a decreasing trend. In dense samples (Dr = 60%), as the fines content increase, the liquefaction resistance of the IZ silty and TT silty samples increase.

In contrast, the liquefaction resistance of the SI silty sample decreases. At Dr = 75%, the liquefaction resistance of the samples decreases as fines content increases. According to the findings advocated in this thesis, when the other conditions are kept constant, the liquefaction potential of the soils has been affected together by the relative density and fines content.

Finally, the effect of the grain properties of soils, such as average grain diameter ratio (D_{50sand} / d_{50silt}) and coefficient of uniformity (CU), on all silty sand's liquefaction resistance mixtures was investigated. The correlations from the mean grain diameter ratio (D_{50}sand / d_{50}silt), the coefficients of uniformities of the silts (CUsilt), and the coefficients of uniformity of the silty sands (CUoverall) were used. Thus, the relationship between liquefaction resistance and soils' grain size properties was investigated. The findings of the experimental results were evaluated. According to the results, an equation was proposed. In this equation, the coefficient of uniformity (CU) and fines content was used together. This equation's compatibility has been checked with data obtained from specific literature findings.

GÖRECELİ SIKILIK VE DANE ÇAPININ SİTLİ KUMLARIN SİSMİK SIVILAŞMASINA ETKİSİNİN DENEYSEL İNCELENMESİ

ÖZET

Kohezyonsuz zeminlerin(kum, siltli kum, silt) sıvılaşması geoteknik mühendisliğinde sıkça karşılaşılan ve ciddi hasarlara sebep olan bir zemin davranışıdır. Bu konuyla ilgili bilimsel araştırmalar ciddi bir şekilde 1960'ların başlarında meydana gelen Anchorage, Alaska ve Niigata , Japonya depremleriyle birlikte başlamıştır. Temiz kumların sıvılaşma direncini değiştiren koşulları anlamak için birçok önemli çalışma yapılmıştır. Ancak siltli ya da siltli killi kumlar ile çakıllı zeminlerin sıvılaşabilirliği konusunda ise 2000'li yıllara kadar fikir birliği sağlanamamıştır. Özellikle 1999 Adapazarı,Düzce ve Chi-Chi,Taiwan depremlerinden sonra yapılan vaka analizleri ve çalışmalar siltli zeminler içeren kumların da sıvılaştığını göstermiştir.

Bu kapsamda yapılan araştırmalarda, numune hazırlama yöntemi, çevre basıncı (σ'_v) , ince dane yüzdesi gibi birçok parametre ve sismik sıvılaşma dirençlerinin arazi deneyleriyle korelasyonları oldukça fazla çalışılmıştır. Zeminin dane dağılımı, çevre basıncı, dinamik yükleme koşulları vb. diğer etkenler sabit tutulduğunda, göreceli sıkılıktaki artış ile beraber sıvılaşma direncinde artış olacağı bilinmektedir. Ancak bu artışın nasıl bir fonksiyon ile ifade edilebileceği hakkında literatürde pek fazla çalışma bulunmamaktadır. Aynı şekilde dane boyutu, dane dağılımı ve farklı siltlerin varlığının siltli kumların sıvılaşma direncine etkisini inceleyen çalışmaların azlığı da dikkat çekmektedir. Bu tezin amacı geoteknik deprem mühendisliğinde dinamik yükler altında göreceli sıkılık (Dr), silt yüzdesi ve silt dane çapı dağılımının siltli kumun sıvılaşma direncini nasıl etkilediğini sorgulamaktır.

Bu çalışma kapsamında, farklı dane çapı dağılımlarına sahip üç silt ve temiz Şile Kumu 20/30 kullanılmıştır. Deney programındaki siltlerden; koyu gri renkli TT(taş tozu) silt, İstanbul'un Şile bölgesindeki taş ocağından elde edilmiş ve taş tozunun 200 No'lu standart elek (0.075mm) ile ıslak elenmesiyle üretilmiştir. Beyaz renkli SI (silis) silt, Kırklareli ilinde Lüleburgaz bölgesinde bir kum ocağından elde edilmiştir. Koyu sarı renkte olan İZ (İzmir) silt, İzmir ilinden elde edilen doğal olarak oluşmuş bir zemindir. Her üç silt numunesi de Birleştirilmiş Zemin Sınıflandırma Sistem(USCS)'ine göre ML,düşük plastisiteli silt olarak sınıflandırılmıştır.

Plastik olmayan SI, TT ve İZ siltleri temiz Şile Kumu 20/30 içerisine kuru ağırlıkça karıştırılmıştır. Numuneler Şile Kumu 20/30'un içerisine , SI silt %10 ve %20 , TT silt %15 ve %25 , İZ silt %15 ve %20 olacak şekilde karıştırılarak hazırlanmıştır. Deney numununeleri kuru huni yöntemiyle hazırlanmış ve 100 kPa düşey gerilme altında konsolide edilmiştir. Temiz ve siltli kum numununeleriyle üç farklı çevrimsel kayma gerilmesi oranında (CSR=0.08, 0.1 ve 0.12) sabit hacim kontrollü dinamik basit kesme deneyi yapılmıştır.

Tezde CSR=0.08, 0.1 ve 0.12 olmak üzere her bir çevrimsel kayma gerilmesi oranında değişik göreceli sıkılıklarda oluşturulan numunelerin sıvılaşma davranışı analiz edilmiştir. Hem temiz hem siltli kumlar için, sabit bir CSR değerinde ve100 kPa düşey gerilme altında yapılan tekrarlı yüklemeler için N_L ile Dr arasındaki ilişki üstel bir fonksiyon ile ifade edilmiştir.Sabit bir Dr değerinde ise, CSR ile N_L arasında kuvvet fonksiyonuyla değişen bir denklem önerilmiştir.Önerilen denklemlerdeki katsayıların zeminin birçok özelliğinden.(ör: göreceli sıkılığı, dane dağılımı, ince dane yüzdesi vs.) etkilendiği tezin bir başka bulgusudur.

Kumun plastik olmayan silt muhteva ettiği durumlarda, ince dane yüzdesinin sıvılaşma davranışını nasıl etkilediği konusunda fikir birliği olmadığı yapılan literatür taraması sonuçlarında gösterilmiştir. Bu tezde, numunelerin ince dane yüzdesinin artışıyla (ince dane oranın %0 ile %25 arasında) zeminlerin sıvılaşma potansiyelinin nasıl değiştiği hem göreceli sıkılık(Dr) hem de boşluk oranları (e) baz alınarak gösterilmiştir. Seçilen sabit boşluk oranları kullanıldığında ise tüm numunelerin sıvılaşma dirençlerinin ince dane yüzdesiyle azaldığı görülmektedir. Gevşek ve orta sıkı numunelerde (Dr= % 30 ve Dr= % 45) düşük ince dane yüzdelerinde (≤%10) İZ siltli numuneler, en büyük sıvılaşma direncine sahipken, TT siltli ve SI siltli numunelerin sıvılaşma dirençleri benzerlik göstermektedir. İnce dane oranları arttıkça (= %15) İZ siltli ve TT siltli numunelerin sıvılaşma direnci artmaya devam ederken SI siltli numunlerin direnci azalış trendine girmiştir. Sıkı numunelerde (Dr=% 60), ince dane oranları arttıkça İZ siltli ve TT siltli numunelerin sıvılaşma direnci artarken SI siltli numunenin sıvılaşma direnci azalmaktadır. Dr= %75 iken ise ince dane oranları arttıkça tüm numunelerin sıvılaşma direnci azalmaktadır.Tezde savunulan bir diğer bulguda diğer koşulların değişmediği deney ortamlarında zeminlerin sıvılaşma potansiyelinin göreceli sıkılık ve ince dane oranı değişiminden kompleks bir şekilde etkilendiğidir. Kumun plastik olmayan silt muhteva ettiği durumlarda, ince dane yüzdesinin sıvılaşma davranışını nasıl etkilediğini araştıran çalışmalar oldukça fazla olmasına rağmen, aynı ince dane yüzdelerinde(aynı silt yüzdelerinde) farklı siltlerle hazırlanan numuneler kullanıldığında sıvılaşma direncinin değişimi ise bir başka araştırma konusudur ve silt boyutunun sıvılaşma davranışı üzerindeki etkisi gibi oldukça az araştırılmıştır.

Bu tez çalışması, siltli kumun sıvılaşma direncinin; aynı baz kumun kullanıldığı ve göreceli sıkılık, Dr, ince dane yüzdesi, FC ve ince danelerin plastisitesi, gerilme geçmişi, yükleme koşulları gibi temel parametrelerin aynı olduğu durumlarda bile farklı siltlerden etkilendiğini kanıtlamaktadır. Siltli kumun sıvılaşma direnci, incelenen ince dane aralığı için $CRR_{IZ\ siltli\ kum} > CRR_{TT\ siltli\ kum} > CRR_{SI\ siltli\ kum}$ sırasına göre değişmiştir.

Bu sonuçların arkasında yatan mekanizmanın araştırılabilmesi maksadıyla, sonuçlar ek olarak kullanılan zeminlerin boyut özellikleri üzerine irdelenmiştir. Tez çalışmasında kullanılan bütün siltli kum karışımları için, dane dağılımları gözönüne aldığında, ortalama dane çap oranı (D_{50kum} / d_{50silt}) ve üniformlük katsayısı (CU) gibi zeminlerin boyut özelliklerinin sıvılaşma direncini nasıl etkilediği irdelenmiştir. Ortalama dane çap oranının (D_{50kum} / d_{50silt}) değişimi, siltlerin üniformlük katsayıları (CUsilt) ve siltli kumların üniformlük katsayıları (CUsiltlikum) kullanılarak geliştirilen korelasyonlar ile sıvılaşma dirençleri arasındaki ilişki incelenmiştir. Bulgular değerlendirildiğinde, siltli kumlar için yapılan analizlerdede χ, CU, CUsiltlikum ve sıvılaşma direnci, CRR arasında kesin bir ilişki bulunamamıştır.

Çalışmalara devam edildiğinde, zeminlerin üniformlük katsayısı (CUkum ve CUsilt) ve ince dane oranının birlikte kullanıldığı bir denklem önerilmiştir. Bu denklemdeki katsayıların hem göreceli sıkılık hemde zeminlerin boyutlarından etkilendiği bilinmektedir. Bu sebeple silt şeklinin etkisinin incelenmesi tezin kapsamı dışında tutulsa da muhtemelen denklemin katsayılarının şekil etkilerini de içerdiği düşünülmektedir. Tez kapsamında son olarak ise önerilen denklemin literatür verileriyle uyumu kontrol edilmiştir. Sabit göreceli sıkılıkta [(CUkum) / (CUsilt x FC)) azaldıkça zeminlerin sıvılaşma direncinin, CRR azaldığı ve denklemin literatürdede siltli kumlar için oldukça iyi çalıştığı görülmüştür.

1. INTRODUCTION

When the pore water pressure that occurs under cyclic loads brings the effective stress of the soil closer to zero, the soil loses its bearing capacity and then behaves as a viscous liquid. The most characteristic feature of this condition, which is named liquefaction, is the excess pore water pressure occurring under undrained conditions. Soil liquefaction is a devastating phenomenon in charge of the damage caused by the soil during earthquakes worldwide. Liquefaction potential is increased even more, especially when it comes to soils consisting of loose saturated sand or non-plastic silty sands. In undrained conditions, this type of soil tends to contraction. When the saturated soil is subjected to seismic or dynamic loads such as earthquakes, a rapid increase in excess pore water pressure occurs. If it is not damped in a short time, this increase can cause loss of soil strength due to the reduction of the effective stress between the soil particles. In such a case, the soil behaves like a liquid and is exposed to deformations. The deformations in the soil can cause the loss of the ability to support the structures such as retaining structure, bridge, dam, etc. As a result, the structures take catastrophic damage and become unusable. In general, fine sands and sands containing low plastic silt provide low drainage conditions due to their low permeability.

For this reason, they are more susceptible to liquefaction. Research studies have been too focused on the liquefaction resistance of sands in the past five decades. Several parameters were investigated that affect this resistance. Many laboratory studies have been conducted to investigate some parameters such as the effect of fines content, confining stress (σ'_v) on the liquefaction resistance of soils. There are also a few researches about the effect of relative density (Dr). On the other hand, there are not many studies on silt gradation, silt size, and grain size distribution of silty sands on the liquefaction resistance of sands.

1.1 Scope of the Thesis

Existing experimental data for Sile Sand 20/30 and their mixture with different silts types came from past research studies. However, this data is focused on the static liquefaction behavior of soil. The purpose of this thesis is to provide a thorough characterization of the seismic liquefaction resistance of Sile Sand 20/30. During the previous years, liquefaction was thought to be limited to clean sands. Fine-grained soils were considered inadequate for generating the excess pore water pressures commonly associated with soil liquefaction. However, the Adapazarı earthquake also has shown, the soils containing low plastic silts that cause the vital damage. That was a significant finding for geotechnical engineering. These studies have clarified that soils previously considered non-liquefiable were found to liquefy. In this way, the lack of knowledge about the seismic response of silty sand was exhibited. Observations of liquefaction cases in past earthquakes revealed several aspects regarding the liquefaction research. Stewart et al. (2001), Bray et al. (2004), and Bhattacharya et al. (2011) have observed many of the in-situ liquefaction cases concern sandy soils involving certain silt or clay content. In this context, laboratory investigation and liquefaction experiments in a controlled condition have vital importance to understand the effect of various parameters such as fines type, fines content, plasticity, grain size, and grain distribution on the liquefaction potential of sandy soils (Monkul et al., 2015). There have been many studies that investigate the effect of silt content on liquefaction resistance. Still, there is no information about the effect of silt size and silt gradation on cyclic liquefaction. When different silt gradations are considered in the same silt content, it is unknown how different silts affect the liquefaction potential of silty sand. Although the relative density effect on liquefaction of clean sands is conceptually known, studies are needed to derive a mathematical function of relative density on silty sand. A research program was performed in this thesis to explain the topics mentioned outlined and to understand the effect of variable parameters on liquefaction resistance of sands and silty sands. Even if the effect of fines content on the liquefaction resistance of clean sands was frequently studied in the literature, it was examined in this thesis again. The experiments were carried out in a wide range of relative density values that were not previously studied in the literature. How are the liquefaction resistances change in the same fines content ratio when using silts with different gradations? This question has not been discussed in detail. Thus, the effect of gradation parameters of silt on the liquefaction resistance of silty sand is not known. The thesis aims to discuss these topics. For this purpose, cyclic direct simple shear tests have been performed. The investigation of the effects of the relative density, fines content, and silt gradation on the liquefaction of silty sand are contributions to the literature.

2. LITERATURE REVIEW ON PREVIOUS LABORATORY STUDIES

The behavior of soils under cyclic loads was researched from the 1960s until today. Especially after the 1995 Kobe and 1999 Kocaeli earthquakes, the researches on the dynamic properties of sandy and silty sandy soils have become important. Thus, liquefaction has been one of the most exciting topics for geotechnical earthquake engineering in the past years. In many years, studies on liquefaction have concentrated on the sand. The liquefaction behavior of clean sands under cyclic loads was investigated extensively. Later, Ishihara (1984, 1985) and Seed (1987) have shown liquefaction may occur in silts with low cohesion. Ishihara (1993) has implied that sand sediments containing fine and medium sand and fine grains with low plasticity are very susceptible to liquefaction during earthquakes.

Many conditions are considered and examined in liquefaction analysis carried out in the field. The magnitude and distance to the earthquake are among the fundamental parameters in the analysis. However, the ground layer's condition, geological history, and relative density also affect the liquefaction analysis. In literature, Seed (1983), Vaid and Sivathayalan (1996), and Boulanger (2003) have discussed the effects of the relative density. For liquefaction, the generation of pore water pressure occurred under the effect of cyclic shear stresses. The approach that makes it possible to compare these cyclic shear stresses during the laboratory and in-situ experiments were developed by Seed and Idriss (1971). Seed et al. (1985) indicate an increase in the liquefaction resistance of soils with increasing fines content for data from field performance of soil. However, in contrast, Cetin et al. (2004) have shown that 201 liquefaction cases involve silty sands among the liquefied deposits. Stewart et al. (2001), Bray et al. (2004), and Bhattacharya et al. (2011) have observed similar trends in the field of liquefaction cases. Well-documented cases of ground failure and its effect on buildings, like in the Adapazari earthquake are critically important in broadening our knowledge (Bray et al.,2004). These case studies have shown that sands containing silts with various percentages were liquefied. Later, in this context, many laboratory studies have been done about the effect of fines content, e.g., Monkul and Yamamuro (2011), Polito and Martin (2001), Carraro et al. (2003), Cubrinovski et al.(2010). However, fewer studies have investigated the effect of the silt size and grain distribution on the liquefaction resistance of the sand. The available literature on the liquefaction resistance data corresponding to individual coefficients of uniformities is extremely limited. The studies found are summarized in Chapter 2.3.

2.1 Effect of Relative Density on Liquefaction Resistance of Sands

Cyclic direct simple shear, triaxial, dynamic torsional shear, shaking table experiments have been developed to examine the dynamic behavior of soils in the laboratory. Cyclic shear stress that causes soil liquefaction and the number of cycles can be determined experimentally with dynamic simple shear, dynamic triaxial, and dynamic torsional shear experiments. Researchers working on geotechnical earthquake engineering from past to present, have investigated the effects of several topics with the CDSS, CTX, DTS experiment, etc. These researches have implied many ideas and results. One of the most significant aspects in the cyclic experiments has been representing the in-situ condition of soils. Liquefaction occurs as a result of pore water pressure generation under cyclic loads.

For this reason, the influence of grain size distribution, grain matrix, and its packing on the volume change potential and permeability of the soil are important aspects to be examined for liquefaction. According to Mitchell and Soga (2005), laboratory conditions not only refers to the stress and density of the soil. At that same time, refer to the fabric and/or particles' arrangement within the soil. Relative density has been accepted as a dominant factor that affects the liquefaction resistance of sands (Robertson and Wride,1998; Eseller Bayat et al., 2019). Nevertheless, the mathematical function between the liquefaction resistance and relative density has not been investigated in detail. However, the relative density effect on the cyclic stress ratio or cyclic resistance ratio of clean sands is conceptually known (e.g., an increase in D_r would increase the liquefaction resistance). The mathematical function related to the number of cycles required to liquefaction (N_L) and relative density (Dr) does not exist. For example, studies by Ladd (1974), Mulilis et al. (1977), and Tatsuoka et al. (1986) have been focused on the effect of the sample preparation method on liquefaction resistance. The relationship between the number of loading cycles and cyclic stress ratio at three or four relative density values is shown in Figure 2.1.

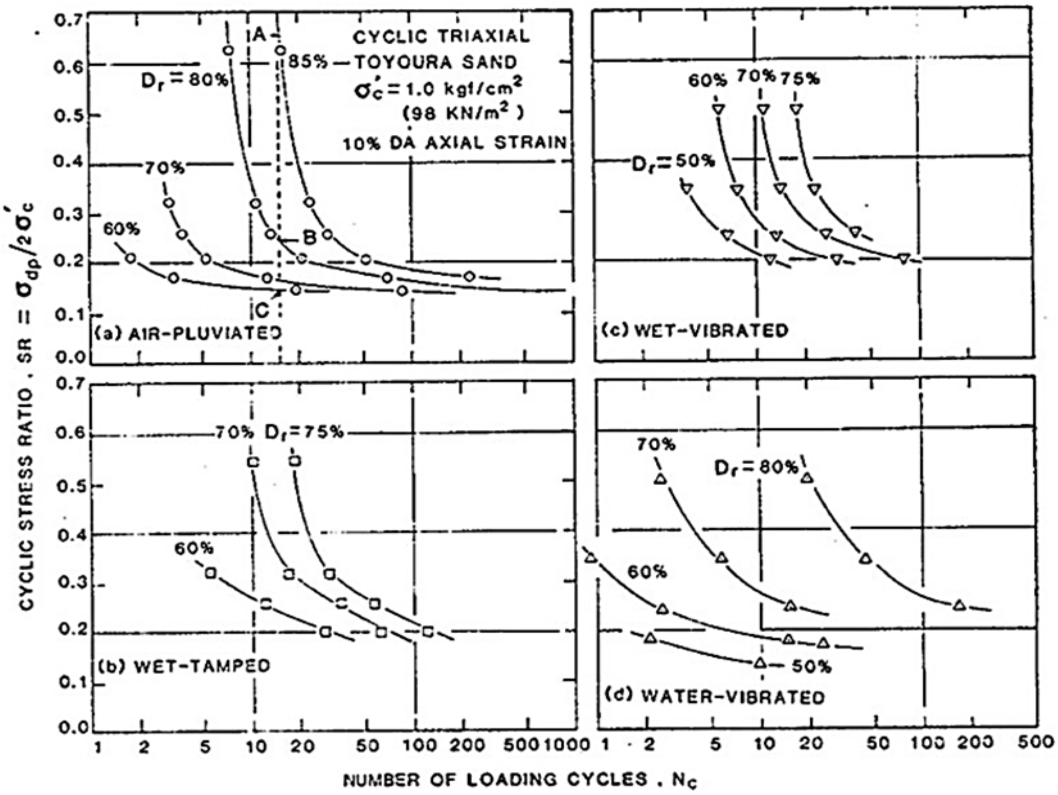


Figure 2.1 : Stress ratio vs. Nc to 10% DA axial strain by triaxial tests on Toyoura Sand (Tatsuoka et al., 1986).

Vaid and Sivathalayan (1996) investigated the liquefaction resistance of clean Fraser Delta sand with simple shear. This paper showed the effect of confining stress and relative density on the liquefaction resistance of the sand. The relation between the cyclic stress ratio to cause liquefaction versus relative density was shown in Figure 2.2. A different relationship exists for each confining stress level. The cyclic resistance increased with increased relative density at all levels of confining stress as in other sands. The convergence of resistance curves towards each other in the loosest states indicated that loose sands' cyclic resistance is essentially independent of the confining stress level. Even so, the soil's relative density has affected the behavior of the cyclic resistance.

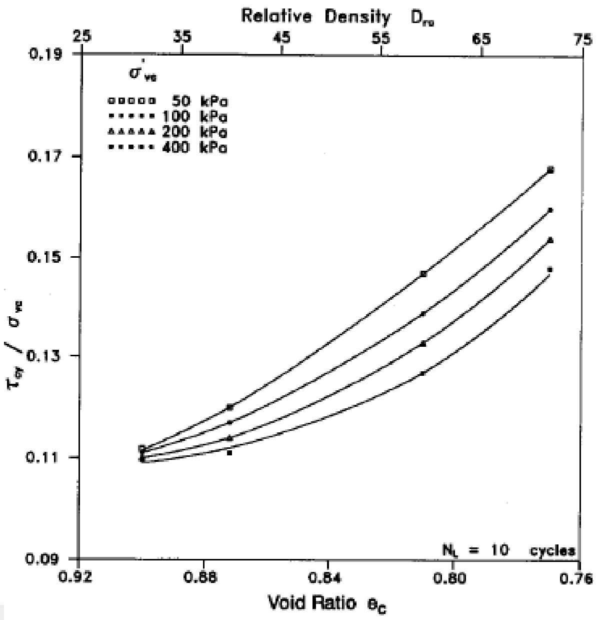


Figure 2.2 : Liquefaction resistance of Fraser Delta sand in simple shear: effects of relative density and confining stress level(Vaid and Sivathayalan,1996).

Sitharam et al. (2004) had performed cyclic stress-controlled undrained tests on liquefied soil samples from the liquefied Bhuj area of Gujarat State in India. Each set of specimens was prepared at three relative density (Dr) values as 51, 60, and 69.7%, as shown in Figure 2.3. In this study, no relation was investigated between relative density and liquefaction resistance. These tests performed for investigation of the dynamic properties such as shear modulus and damping ratio at the large strain levels.

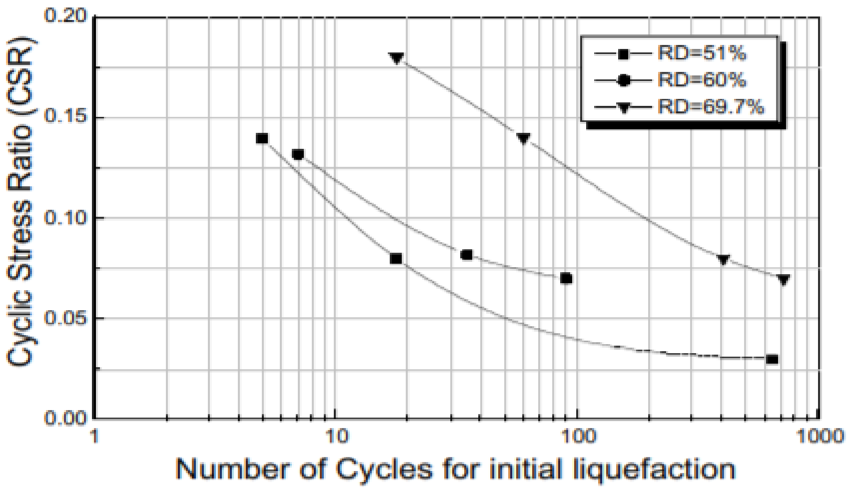


Figure 2.3 : Variation of Cyclic Stress Ratio with number of cycles, Dr=51,60 and 69.7%(Sitharam et al.,2004).

Cubrinovski et al. (2010) indicate liquefaction resistance curves using cyclic triaxial tests. The liquefaction resistance curves showed a relationship between the cyclic resistance ratio (CSR) and the number of cycles NL(=NC) required to 5 % double amplitude (DA) strain. The liquefaction resistance curves with different relative densities were shown in Figure 2.4, and it showed liquefaction resistance of soil increased with an increase in relative density.

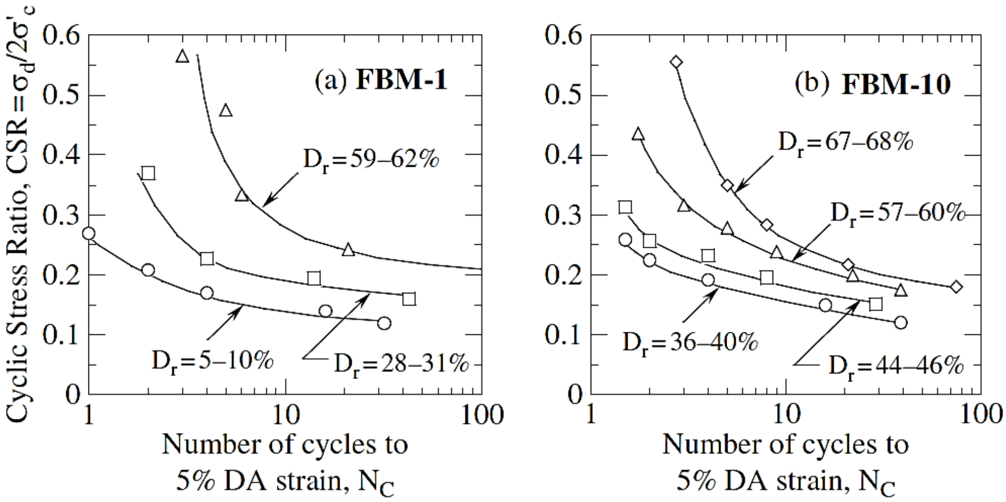


Figure 2.4 : Liquefaction resistance curves for different relative densities: (a) Clean sand (FBM-1). (b) Sand with 10% fines (FBM-10)(Cubrinovski et al.,2010).

Idriss and Boulanger (2008) indicated that the greater cyclic stress ratio would trigger liquefaction in fewer loading cycles, and a smaller cyclic stress ratio will require more loading cycles. They supported this behavior with Figure 2.5 from the study of De Alba et al. (1976). The CSR required to reach liquefaction in a specified number of cycles was called the sand's cyclic resistance ratio, CRR. The relationship between the CRR and N was proposed with a power function (Equation. 2.1). However, it should be noted, due to this figure's semilog plot format, CRR and N relationship graphs have been seen as a curve (Idriss and Boulanger, 2008).

$$CRR = a.\ N^{-b} \tag{2.1}$$

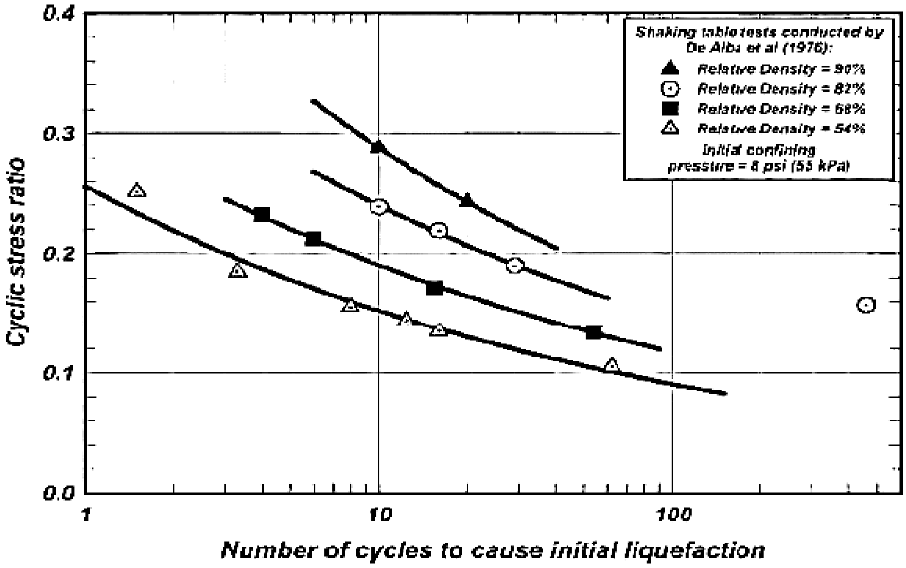


Figure 2.5 : The CSR required to reach initial liquefaction *(r_u = 100%)* from shaking table tests by De Alba et al. (1976) (Idriss and Boulanger,2008)

Polito and Martin (2001) investigated the effects of non-plastic silt content on the liquefaction resistance of sands. Cyclic resistance had been evaluated in terms of relative density. For specimens which is below the limiting silt content(FCt=30%), cyclic resistance increased with the relative density increased. The liquefaction resistance of sand was shown in Figure 2.6 for the Monterey sand.

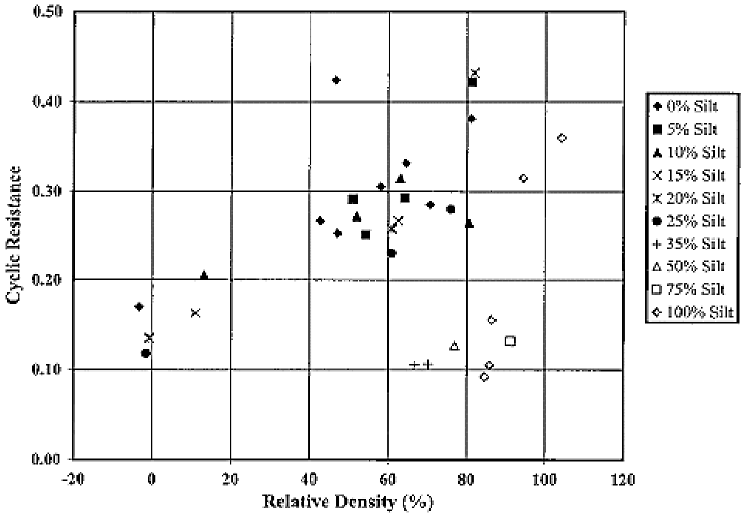


Figure 2.6 : Variation in Cyclic Resistance with Relative Density for Monterey Sand (Polito and Martin,2001).

Carraro et al. (2003) wanted to find the relation between the curves of cyclic resistance ratio (CRR) versus stress-normalized cone resistance from cone penetration test (CPT). A combination of numerical analysis and cyclic laboratory testings was conducted to develop this relationship. The liquefaction resistance curves of silty sand obtained from the cyclic triaxial tests and were shown in Fig 2.7.

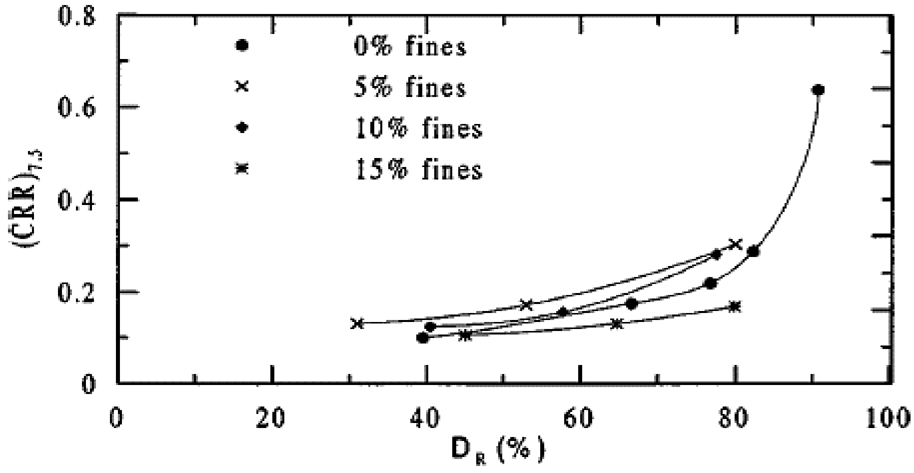


Figure 2.7 : Cyclic resistance ratio $(CRR)_{7.5}$ versus relative density (Carraro et al. 2003).

Oka et al.(2018) compared laboratory-based liquefaction resistance of sand with non-plastic fines via shear wave velocity-based field case histories. In the same study, the change of CRR with Dr is shown in Fig. 2.8.

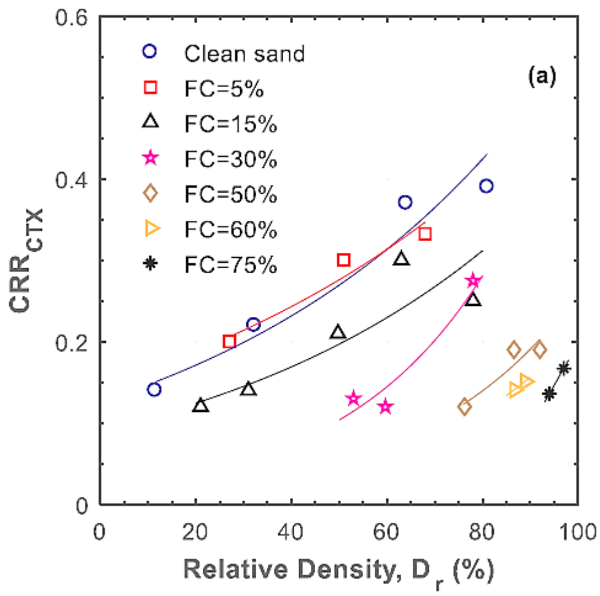


Figure 2.8 : Effect of relative density on laboratory cyclic resistance ratio, CRR_{CTX} for various fines contents (Oka et al.,2018).

Data in graphs, which be seen in Figures 2.7 and 2.8, were observed in the cyclic experiment and compared with the comparison basis of relative density. This graph also indicates that the liquefaction resistance of soil increases with an increase in relative density for different fines content. This argument is consistent with some investigations published literature such as Cubrinovski et al. (2010), Monkul & Yamamuro (2011), Belkhatir et al. (2011), and Monkul et al. (2016).

The CRR of sand increases with increasing relative density, as known. The literature discusses the effects of the relative density directly and indirectly. The liquefaction resistance of sand depends on the confining stress, stress history, preparation method, fines content, and several other factors. Therefore, while investigating other parameters' effect, a constant relative density or a few relative density values were used generally. The function of the relationship between N_L and Dr has not been studied in the literature. Although the effect of relative density on liquefaction resistance of clean sands is conceptually known as mentioned based on the relevant literature, researchers have not investigated its mathematical function and its effects on silty sand in detail.

2.2 Effect of Non-Plastic Silt Content on Liquefaction Resistance of Silty Sands

The liquefaction potential of silty sands has been investigated in the last 20 years. Previous studies were examined to determine the effects of the fines content of silty sands. The effects of non-plastic fines content on the liquefaction potential of silty sand have been investigated by several researchers. In these researches , comparison basis are void ratio, relative density, loosest possible density after deposition, equivalent intergranular void ratio, sand skeleton void ratio. The following literature review would show no clear conclusion about the effect of fines content on the silty sands' liquefaction resistance. Due to this observation, this thesis argued that the effect of fines content on the liquefaction resistance of silty sands depends on the comparison basis. However, the subject investigated in the thesis does not focus directly on this comparison basis effect. The relative density are chosen as a comparison basis. In this regard, the literature has been reviewed on the basis of relative density substantially. In this literature review, the effect of fines content was examined according to two comparison basis (void ratio and relative density). A summary review of different results is shown in Table 2.1.

2.2.1 Tests at constant void ratio and constant sand skeleton void ratio

Erten and Maher (1995) performed cyclic triaxial tests on Ottawa sand and non-plastic silt mixtures. The cyclic resistance slightly decreased when the silt content increased to 10% (Figure 2.9). Moreover, a 10-20 % FC resulted in a significant decrease in cyclic resistance of silty soil, while a 20-30% FC also showed a slight decrease pattern.

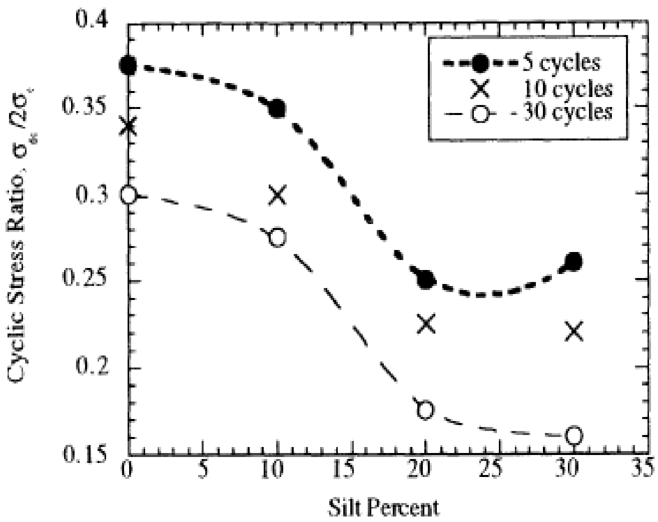


Figure 2.9 : Silt percent vs. Cyclic Stress Ratio (Erten and Maher,1995).

In Polito and Martin (2001), Monterey sand and non-plastic silt were analyzed using cyclic triaxial tests. Fines content ranged from 0 to 100%. Liquefaction resistance decrease as the silt content increase to 35%, remained relatively constant between 35% and 75% FC, and then cyclic resistance increased with FC till 100% is reached (Figure 2.10).

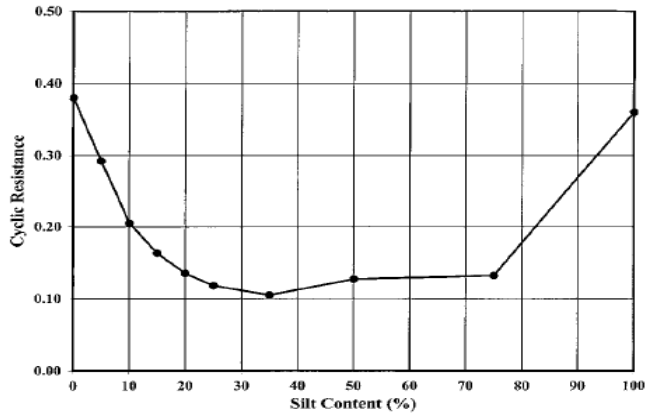


Figure 2.10 : Cyclic Resistance of Monterey Sand at Constant Void Ratio with Variation in Silt Content(Polito and Martin,2001).

Thevanayagam et al. (2002) performed a cyclic triaxial test on Foundry sand (F55) and a non-plastic silt mixture. In this study, liquefaction resistance decreased when the silt content reaches up to limiting(threshold) fines content (FCt =25 %), and liquefaction resistance increased with increasing FC. Xenaki and Athanasopoulos (2003) performed a cyclic triaxial test on Shinias-Marathon sand and non-plastic silt mixture for FC= 10,30,42 and 55 %. The cyclic resistance decreased while the silt content increased to 44 %(Figure 2.11).

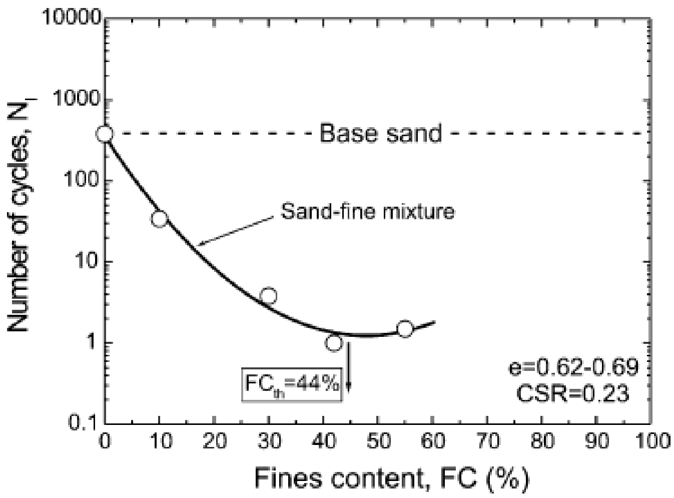


Figure 2.11 : Effect of fines content on the liquefaction resistance of sand–non-plastic fines mixtures for constant values of void ratio (Xenaki and Athanasopoulos,2003).

In Papadopoulou and Tika (2007), sand and non-plastic silt mixtures were used by conducting cyclic triaxial tests on specimens at a constant void ratio. Fines contents ranged from 0 to 100%. Liquefaction resistance decreased as the silt content increased to 30%, and then cyclic resistance increased until 100% fines content was reached (Figure 2.12).

As in the studies mentioned above, Sitharam and Dash(2008), Porcino and Diano (2017), Oka et al. (2018), and Wei, Xiao et al. (2020) found that liquefaction resistance of silty soils decreased when FC increased.

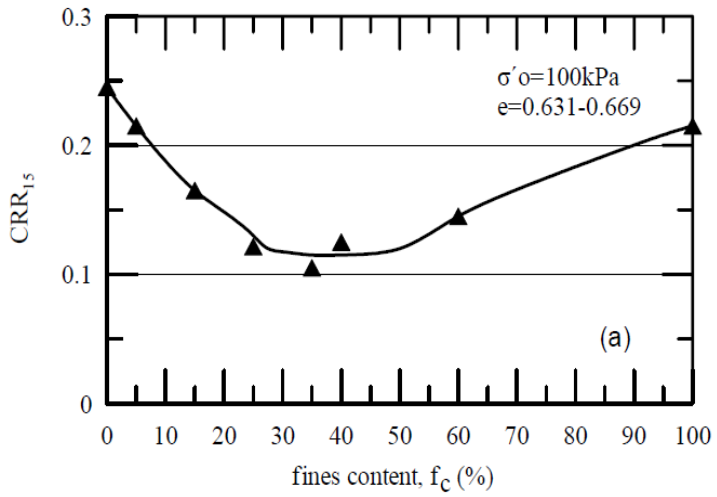


Figure 2.12 : Effect of fines content, fc on liquefaction resistance, CRR15, at the constant void ratio, e, at σ′o=100kPa (Papadopoulou and Tika,2007).

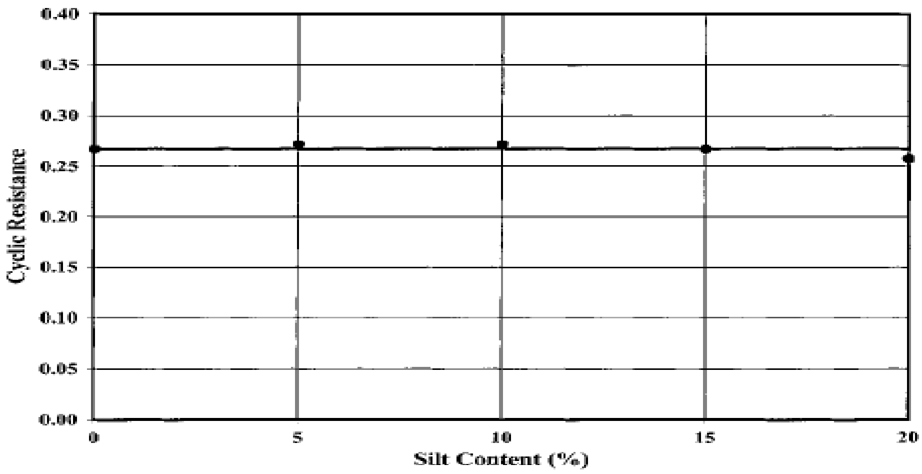


Figure 2.13 : Variation of Cyclic Resistance with Silt Content for Monterey Sand Prepared to Constant Sand Skeleton Void Ratios(Polito and Martin,2001).

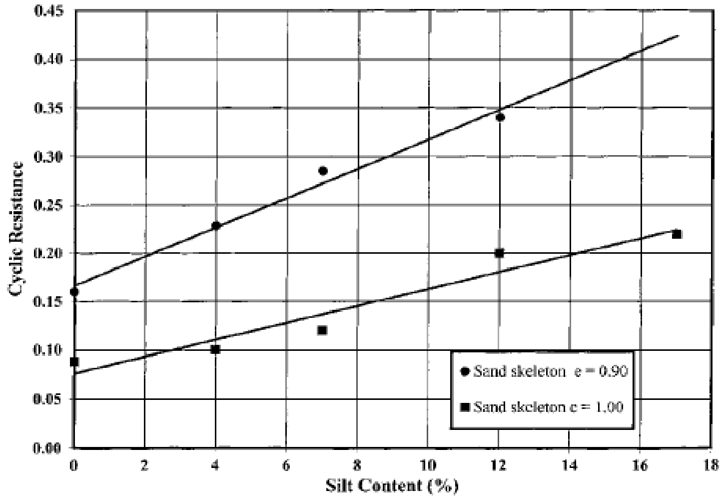


Figure 2.14 : Variation in Cyclic Resistance with Silt Content for Specimens Prepared at Constant Sand Skeleton Void Ratio Using Yatesville Sand(Polito and Martin,2001).

Polito and Martin (2001) 's research showed a constant cyclic resistance for up to 20% FC when Monterey sand was used (Figure 2.13). As for that Yatesville sand, cyclic resistance of silty sand increased with the increased silt content while using a constant sand skeleton void ratio(Figure 2.14).

2.2.2 Tests at constant and various relative density

Researchers have carried out various studies on whether silty sands positively or negatively affect liquefaction resistance when relative density is selected as the comparison basis. The liquefaction resistance of soils has generally compared at the constant and almost one or two relative density. Amini and Qi (2000) performed cyclic triaxial tests on specimens with low-plasticity silt content from 10 to 50% FC (Figure 2.15). Liquefaction resistance increased with increasing FC at a constant relative density.

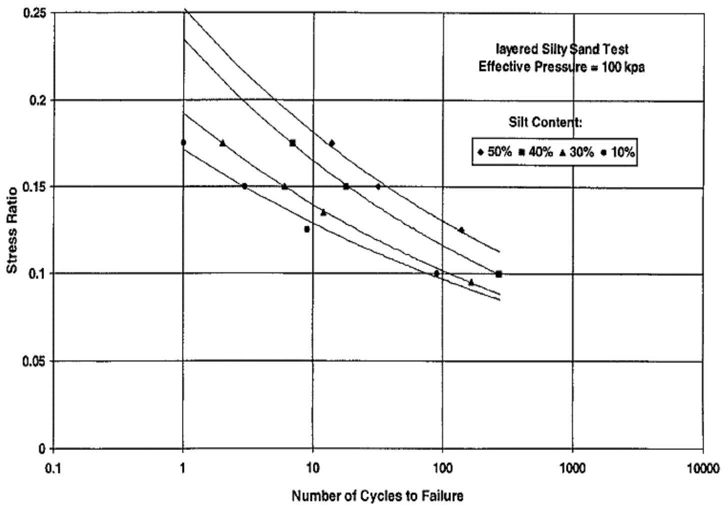


Figure 2.15 : Effect of Silt Content on Liquefaction of Layered Silty Sands (Amini and Qi,2000).

Another study results, such as in Figure 2.16, imply an initial increase in the cyclic liquefaction resistance up to a low fines content (e.g., 5%) and the subsequent decrement in liquefaction resistance with an increment in FC(Polito and Martin, 2001).

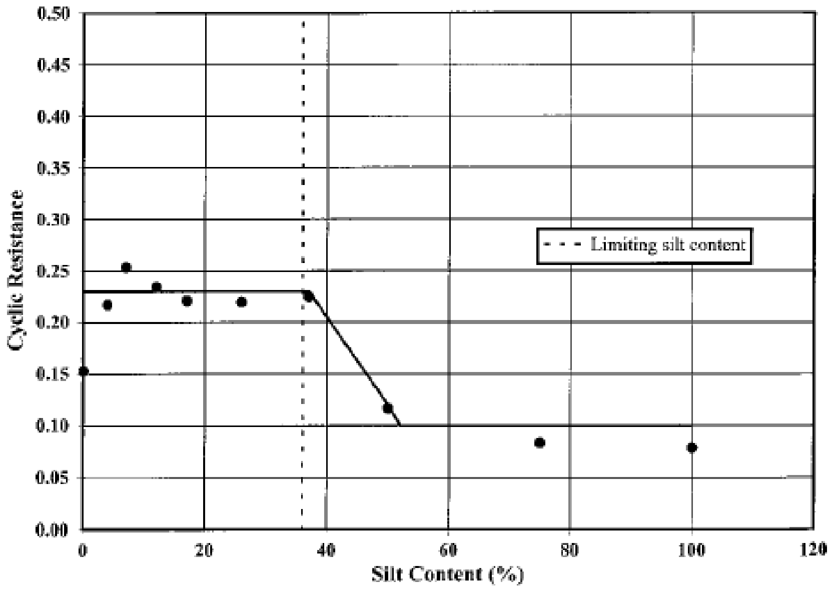


Figure 2.16 : Variation in Cyclic Resistance with Silt Content for Yatesville Sand Specimens Prepared by Moist Tamping Adjusted to 30% Relative Density (Polito and Martin,2001).

Hazirbaba and Rathje (2009) performed cyclic simple shear tests at a constant relative density of 50%. Liquefaction resistance in this study indicated an initial increasing trend between 0 and 10% FC, and then and a decreasing trend between 10 and 20% fines content. Salgado et al. (2000), Amini & Qui (2000), and Hazirbaba & Rathje (2009) reported that the liquefaction resistance increased with increasing silt content in their studies when the response of silty sands are compared at the tested constant relative density. Kokusho (2007) investigated the effect of fines content, up to 30% FC, on the cyclic resistance at three different relative densities, Dr = 30, 50, and 70%, for RSI sands using cyclic triaxial tests. The results indicated nearly constant cyclic resistance at Dr = 30% with increasing FC. However, dense samples (Dr = 50 and 70%) showed decreased cyclic resistance with increased FC. The decrease appeared to be more pronounced up to 10% FC. (Figure 2.17) includes the results from Kokusho (2007).

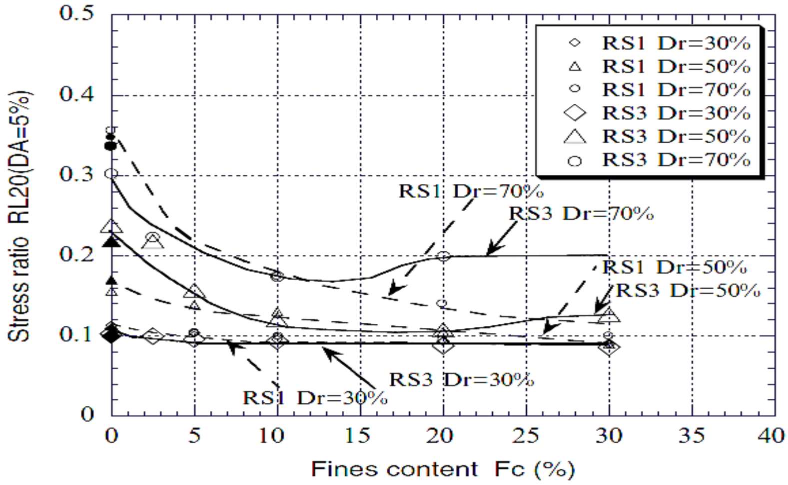


Figure 2.17 : Liquefaction strength (stress ratio) versus fines content ,Fc for RS1 with different relative density Dr% (Kokusho,2007).

Eseller-Bayat et al. (2019) investigated the coupled effect of CSR, fines content, plasticity, and relative density on the seismic liquefaction resistance of soils on sandy soils obtained by adding 5% and 10% of non-plastic silt into clean sand. In their study, all tests were carried out with a cyclic direct simple shear test. Liquefaction resistance of sand decreased with fines content. The fines content, plasticity of soil, CSR, and relative density effect add complexity to the liquefaction resistance of silty sand (Figure 2.18).

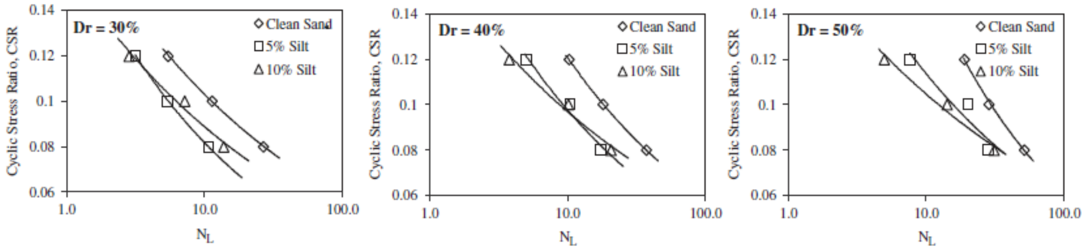


Figure 2.18 : CSR versus N_L for clean sand and sand with silt at constant relative densities of 30%,40%, and50% (Eseller-Bayat et al.,2019).

Monkul and Yamamuro (2011) performed monotonic undrained triaxial tests at the loosest possible density, producing silty sand specimens at a fairly narrow relative density range. Fines content ranged from 0 to 20%. The test results indicate a visible drop in liquefaction resistance with increasing fines content. Cubrinovski et al. (2010) and Oka et al. (2018) performed a cyclic undrained triaxial test with different relative densities. Fines content ranged from 0 to 100%. The test results indicate liquefaction resistance drop with increasing FC for all studies.

In summary, the recent studies that focused on specimens at a constant void ratio generally show a decrease in liquefaction resistance with increasing fines content. In contrast, those that focused on specimens at a constant sand skeleton void ratio show an increase in resistance or a constant resistance. On the other hand, the studies suggest that non-plastic fines increase or decrease the cyclic resistance ratio of soils if the relative density is used as the base for comparison. When the literature briefly summarized above is considered, it seems that the influence of silt content is still unclear, even though the density index parameter for comparison is the same (e.g., Dr). The literature review shows no clear conclusion about how changing the fines content affects the liquefaction resistance of the soil under cyclic loading conditions such as an earthquake.

Table 2.1 : Summary of literature review on the effect of non-plastic fines content on liquefaction resistance with comparison basis

Reference	Type of testing	Type of sand	Type of fines	Comparison basis	FC range (%)	Effect of FC on liquefaction resistance
Erten and Maher (1995)	Cyclic Triaxial Test	Ottawa sand	Non-plastic Silt	Constant void ratio	10, 20 and 30	decreased with increased silt content
Singh (1996)	Cyclic Triaxial Test	Flint Shot No.4 Sand Ottawa Sand	Non-plastic Silt	Constant relative density, Dr=50%	10, 20 and 30	decreased till 20% FC and then increased and clean sand more resistive than clean silt
Salgado et al. (2000)	Cyclic Triaxial Test	Ottawa Sand	Non-plastic Silt	Relative density 0-100%	5, 10, 15 and 20	increased with increased silt content
Amini and Qi (2000)	Cyclic Triaxial Test	Ottawa 20-30 Sand	Low Plasticity Silt	Constant relative density	10,30,40 and 50	increased with increased silt content
Polito and Martin (2001)	Cyclic Triaxial Test	Monterey Sand	Non-plastic Silt	Constant void ratio , e=0.68	5, 10, 15, 20, 25 35, 50 and 75	decreased till 35% FC and then increased
Polito and Martin (2001)	Cyclic Triaxial Test	Monterey Sand	Non-plastic Silt	Constant sand skeleton void ratio	5, 10, 15, 20, 25 35, 50 and 75	constant until FC=20%

Table 2.1 (continued) : Summary of literature review on the effect of non-plastic fines content on liquefaction resistance with comparison basis

Reference	Type of testing	Type of sand	Type of fines	Comparison basis	FC range (%)	Effect of FC on liquefaction resistance
Polito and Martin (2001)	Cyclic Triaxial Test	Yatesville Sand	Non-plastic Silt	Constant relative density, Dr=30%	0-100	increased FC up to about 5% then decreased
Thevanayagam et al. (2002)	Monotonic Undrained Triaxial Test	F55, Foundry Sand	Non-plastic Silt	Constant void ratio	7, 15, 25, 40, 60 and 100	decreased till ~25% FCt and then increased
Carraro et al. (2003)	Cyclic Triaxial Test	Ottawa Sand	Non-plastic Silt	Relative density 30-90%	5, 10 and 15	increased until 5% FC then decreased
Xenaki and Athanasopoulos (2003)	Cyclic Triaxial Test	Shinias-Marathon Sand	Non-plastic Silt	Constant void ratio	10, 30, 42 55 and 100	decreased until FCt = 44% then increased
Kokusho (2007)	Cyclic Triaxial Test	RS1	Non-Plastic Silt	Relative density 30, 50 and 70 %	5, 10, 20 and 30	constant with increased silt content at Dr= 30% , decreased with increased silt content at Dr=50 and 70%

Table 2.1 (continued) : Summary of literature review on the effect of non-plastic fines content on liquefaction resistance with comparison basis

Reference	Type of testing	Type of sand	Type of fines	Comparison basis	FC range (%)	Effect of FC on liquefaction resistance
Papadopoulou and Tika (2007)	Cyclic Triaxial Test	Quartz Sand	Non-Plastic Silt	Constant void ratio	0,5,15,25,35, 40,60 and 100	decreased with until FCt = 30 - 35% then increased
Sitharam and Dash (2008)	Cyclic Triaxial Test	Ahmedabad Sand	Non-plastic Silt	Constant void ratio	10, 20, 30, 40,50 and 75	decreased with until FCt = 26% then increased
Hazirbaba and Rathje (2009)	Cyclic Simple Shear Test	Monterey #0/30 Sand	Non-plastic Silt	Constant relative density, 50%	5, 10, 15 and 20	increased with increased silt content at between 0 and 10% FC. decreased with increased silt content at between 10 and 20% FC.
Cubrinovski et al. (2010)	Cyclic Undrained Triaxial Test	FBM	Non-plastic Silt	Relative density, 10-80%	1, 10, 20 and 30	decreased with increased silt content
Monkul and Yamamuro (2011)	Monotonic Undrained Triaxial Test	Nevada Sand-B	Non-plastic Silt	Loosest possible density	0 - 20	decreased with increased silt content

Table 2.1 (continued) : Summary of literature review on the effect of non-plastic fines content on liquefaction resistance with comparison basis

Reference	Type of testing	Type of sand	Type of fines	Comparison basis	FC range (%)	Effect of FC on liquefaction resistance
Belkhatir et al. (2011)	Cyclic Triaxial Test	Chlef Sand	Non-plastic Silt	Constant relative density, 53%	0,10,40	decreased with increased silt content
Monkul et al. (2017)	Undrained Monotonic Triaxial Test	Sile Sand	Non-plastic Silt	Loosest possible density	5, 15 and 25	decreased with increased silt content (similar Dr)
Eseller-Bayat et al. (2019)	Cyclic Direct Simple Shear Test	Sile Sand 20/55	Non-plastic Silt	Relative density, 30, 40 and 50 %	5 and 10	Clean sand has more resistant than FC 5 and 10% CRR changed with Dr changed, FC equal from 5 to 10% (Couple effect)
Porcino and Diano (2017)	Cyclic Direct Simple Shear Test	Ticino Sand	Non-plastic Silt	Constant void ratio e=0.68	5, 10, 20 30 and 40	decreased with increased silt content up to FCt =25-35 then increased with the increased silt content,
Oka et al. (2018)	Cyclic Triaxial Test	F-75 Sand	Non-plastic Silt	Relative density, 0-100%	5, 15, 30, 50 and 75	decreased with the increased silt content
Oka et al. (2018)	Cyclic Triaxial Test	F-75 Sand	Non-plastic Silt	Constant void ratio e=0.68	5, 15, 30, 50 and 75	decreased with the increased silt content

Table 2.1 (continued) : Summary of literature review on the effect of non-plastic fines content on liquefaction resistance with comparison basis

Reference	Type of testing	Type of sand	Type of fines	Comparison basis	FC range (%)	Effect of FC on liquefaction resistance
Doygun et al. (2019)	Cyclic Direct Simple Shear Test	Silica Sand	Non-plastic Silt	Constant void ratio e=0.69	1, 15 and 50	increased with the increased silt content up to FC=15% then decreased with the increased silt content
Monkul and Kendir (2019)	Cyclic Direct Simple Shear Test	Sile Sand 20/30	Non-plastic SI Silt	Relative density 0-100%	10 and 20	For Dr < ~53%, FC 10% has more resistance than clean sand For Dr > ~53%, FC 10% has lower resistance than clean sand FC %20 has lower resistance than clean sand at all relative density values.
Wei, Xiao and et al. (2020	Cyclic Triaxial Test	Toyoura, Fujian Ottawa (20-30 / 50-70)	Non-plastic Silt	Constant void ratio	0 - 20	decreased with the increased silt content
Jradi et al. (2020)	Cyclic Triaxial Test	Fontainebleau Sand	Non-plastic Silt	Relative density Loose and Dense	1, 3 and 5	increased with the increased silt content

2.3 Effects of Silt Size and Grain Size Distribution on Liquefaction Resistance

Today it is known that sands with different amounts of fines had liquefied during many different earthquakes in the last 20 years. Due to this, many researchers started to investigate the effects of various parameters (silt content, relative density, void ratio, confining pressure, deposition method, etc.) on the liquefaction of silty sands. Moreover, a great deal of study has been done on the parameters affecting the liquefaction resistance of clean and silty sands. When the influence of fines content on the liquefaction resistance of sands is considered, an important question arises as "What is the appropriate comparison basis or density index parameter to compare the liquefaction resistance of clean and silty sands at various fines contents?". Such a question is a milestone and, at the same time, does not have a simple answer. As the literature was reviewed, it can be seen that different density index parameters such as void ratio, relative density, sand skeleton void ratio, etc., had been used for investigating the effect of fines content on liquefaction resistance of sands. Another critical question is whether silt content has a positive or negative effect on the liquefaction resistance of sands. The laboratory research-based answer to that question is also confusing and partly depends on the answer to the first question asked above. For instance, the liquefaction resistance of sand could decrease with increasing silt content (up to a limiting value) compared to the same void ratio. Meanwhile, it could be vice versa compared to the same sand skeleton void ratio.

In summary, the recent studies that focused on specimens at a constant void ratio generally show a decrease in liquefaction resistance with increasing fines content, while those that focused on specimens at a constant sand skeleton void ratio show an increase in resistance or a constant resistance. The literature review indicates that there is no clear conclusion about how changing the fines content affects the liquefaction resistance of the soil under cyclic loading conditions such as an earthquake. Extensive literature review which is in order to understand this behavior has shown some interesting arguments. The assessment of liquefaction resistance of silty sands should not just be evaluated with the density-based comparison basis such as void ratio, sand skeleton void ratio, and relative density. For example, at the same density and stress conditions, silty sands were found to be more liquefiable as the $\chi = D_{50}sand/d_{50}silt$ ratio decreased, which implies the importance of mean grain size ratio effect (Monkul and Yamamuro, 2011). This observation has provided different perspectives on the investigations and analyses. In this context, one of the affecting parameters of the cyclic liquefaction resistance of sands may be the grain size distribution. Therefore, research on silt size and grain distribution on the liquefaction resistance of sands has been scanned. Researches related to this effect have been summarized below.

The available literature related to the relation between the coefficient of uniformity of sand and their liquefaction resistance is extremely limited. In Vaid et al.(1990), three sands were used with the same mean grain size, D_{50}, the same linear grain-size-distribution curves, and identical mineralogy. The effect of the coefficient of uniformity was desired to be investigated alone. Results showed that the soil's grain size distribution might control the cyclic liquefaction resistance of sands. Poorly graded sands have shown lower liquefaction resistance at lower relative densities than well-graded samples.

Monkul and Yamamuro (2011) have investigated the effect of silt size and content on static liquefaction of sand. Researchers concluded that the liquefaction resistance of silty sands was also largely affected by the mean grain diameter ratio (D_{50}sand / d_{50}silt).

In a later study by Monkul et al. (2016), the effect of grain size distribution characteristics on static liquefaction behavior of loose clean and silty sands was investigated with the three base sands and three different non-plastic silts. As a result, two new equations were proposed to show the relationship between normalized peak deviator stress (a function of undrained shear strength) and coefficient of uniformity as given below (one for stable and temporarily liquefied specimens and the other one for liquefied specimens). Equation 2.2 proposed for loose specimens that are stable or temporarily liquefied. The proposed equations were also checked with the other literature data (for different silty sands), as shown in Fig. 2.18. As can be observed from Fig. 2.18, liquefaction resistance of silty sands was shown to decrease with increasing CU of mixtures.

$$\frac{q_{peak}}{\sigma'_{3c}} = a - b.CU \tag{2.2}$$

Equation 2.3 proposed for loose specimens that liquefied.

$$\frac{q_{peak}}{\sigma'_{3c}} = \frac{1}{c.CU^{-d}} \tag{2.3}$$

Further interesting findings regarding the influence of grain size distribution on static liquefaction behavior of clean and silty sands were reported by Monkul et al. (2016). When clean sands at the same relative density or quasi-natural void ratio, liquefaction resistance of the clean sands decreased with the became smaller (e.g., D_{50}sand decreases). At the same time, liquefaction resistance of the clean sands decreased as they became more uniform (i.g., CUsand decreases). When silts were added to the sands, the mentioned trend for clean sands was oddly reversed for silty sands (e.g., silty sands became more liquefiable as base sand became coarser (D_{50}sand increases) and relatively well-graded (e.g., CUsand increases)). Monkul et al. (2016) hypothesized that the gap gradation is induced by different base sand and silts' mixtures.

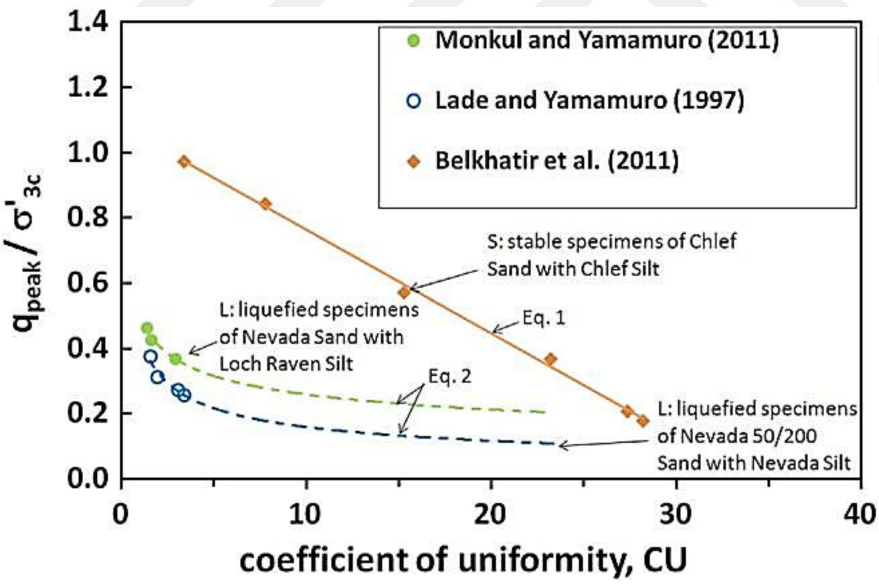


Figure 2.19 : Change in normalized peak deviator stress (q_{peak}/s'_{3c}) with a coefficient of uniformity (CU) for different types of soils in the literature (Monkul et al.,2016).

In Belkhatir et al. (2011), the cyclic liquefaction resistance of silty sand has decreased linearly with decreased effective diameter, $D_{10,}$ and mean size, D_{50}. This decrement of effective diameter and mean size was occurred with fines content increment from 0 to 40. The variation of the liquefaction resistance with the average diameter, D_{50} was shown in Figure 2.20. Belkhatir et al.(2011) proposed Equation 2.4. This equation proposed for the estimate of the CLR used the average diameter (D_{50}) for the range of 0–40% fines content. Fundamentally, D_{50} does not contain the fines content effect at the lower fines content. Thus, the above approach is not correct at the lower fines content.

$$CLR = 0.017 + 0.31\,(D_{50}) \quad \text{for Dr=53\%} \tag{2.4}$$

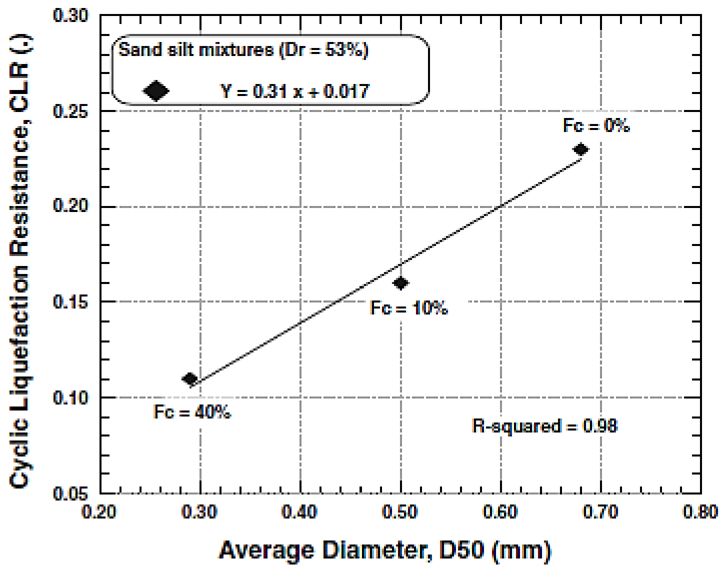


Figure 2.20 : Cyclic liquefaction resistance versus average diameter and fines content. at σ=100 kPa, Dr =53% (Belkhatir et al.,2011).

3. CHARACTERISTICS OF SOILS TESTED

This chapter summarizes the index characteristics obtained from laboratory testings for base sand and the three types of IZ, SI, and TT silts. Grain size distribution & grain characteristics, minimum void ratios (e_{min}), and maximum void ratios (e_{max}), the specific gravity of solids (G_S), and Atterberg limits are described in the upcoming chapters.

3.1 Grain Characteristics and Grain Size Distributions of the Examined Soils

Due to the reason that this investigation was conducted on the effects of relative density and silt gradation on cyclic liquefaction resistance of silty sands (a contrast to recent researches), it prefers to use three different types of silt and base sand. The Sile Sand 20/30 is the base sand of this experiment set and ıt was obtained from the Sile region located in Istanbul. Sile Sand 20/30 was classified as a poorly graded sand (SP) according to the unified soil classification system (USCS). This sand is yellow, as shown in Figure 3.1.

Figure 3.1 : Sile Sand 20/30 used in the experiment

The grain size distribution of Sile Sand 20/30 is shown in Figure 3.2. Table 3.1 summarizes grain diameters D_{10} and D_{60} corresponding to 10% and 60% passing percentages by weight, coefficient of uniformity (CU) and USCS classification of soils and silts.

Table 3.1 : Gradation properties of the sand and silt used in the experimental program.

Soil Type	Sile Sand 20/30	IZ Silt	TT Silt	SI Silt
D_{60}	0.63	0.029	0.0159	0.025
D_{10}	0.31	0.0063	0.0015	0.0013
CU	2.03	4.60	10.6	18.77
USCS classification	SP	ML	ML	ML

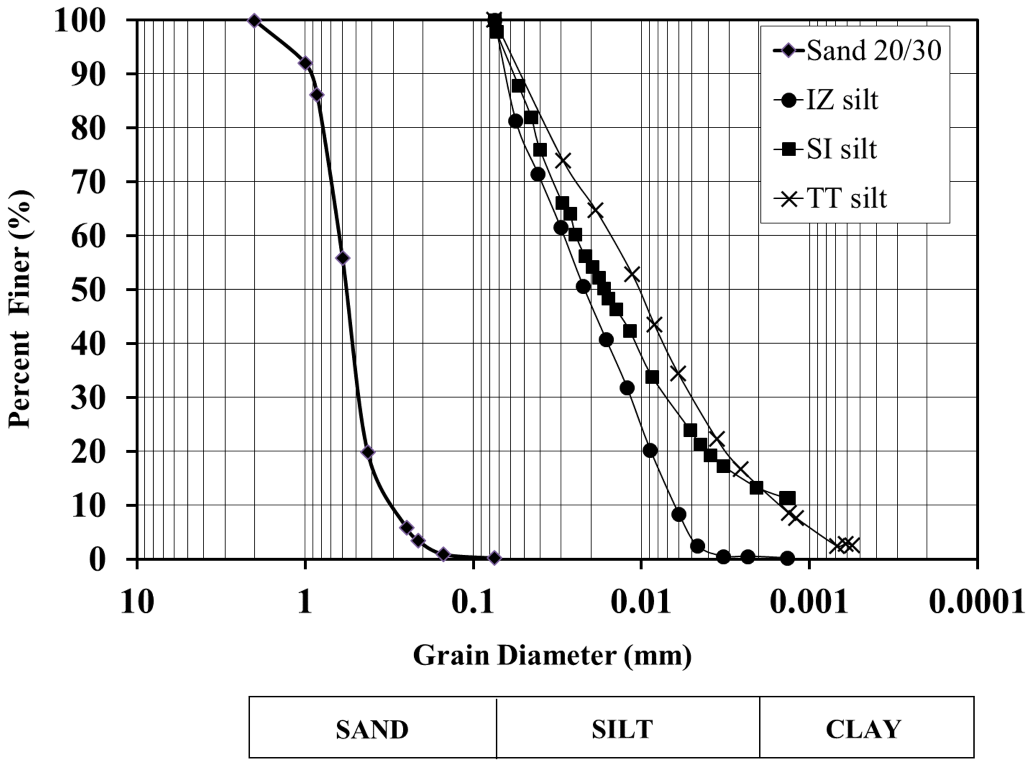


Figure 3.2 : Grain size distribution curves of soils in this experimental program

The grain size distribution curves of silty sand with various silt contents are shown in Figure 3.3. The coefficient of uniformity (CU), the mean grain size (D_{50}) and D_{50}sand / d_{50}silt ratios are presented in Table 3.2.

Table 3.2 : Gradation properties of the silty sand at various fines content used in the experimental program

Soil Type	FC	CUoverall	D_{50}	d_{50}	$\chi=D_{50}/d_{50}$
IZ Sılt	15	16.19	0.565	0.022	25.68
IZ Sılt	20	25.68	0.565	0.022	25.68
SI Sılt	10	7.93	0.565	0.017	33.24
SI Sılt	20	31.39	0.565	0.017	33.24
TT Sılt	15	28.44	0.565	0.0103	54.85

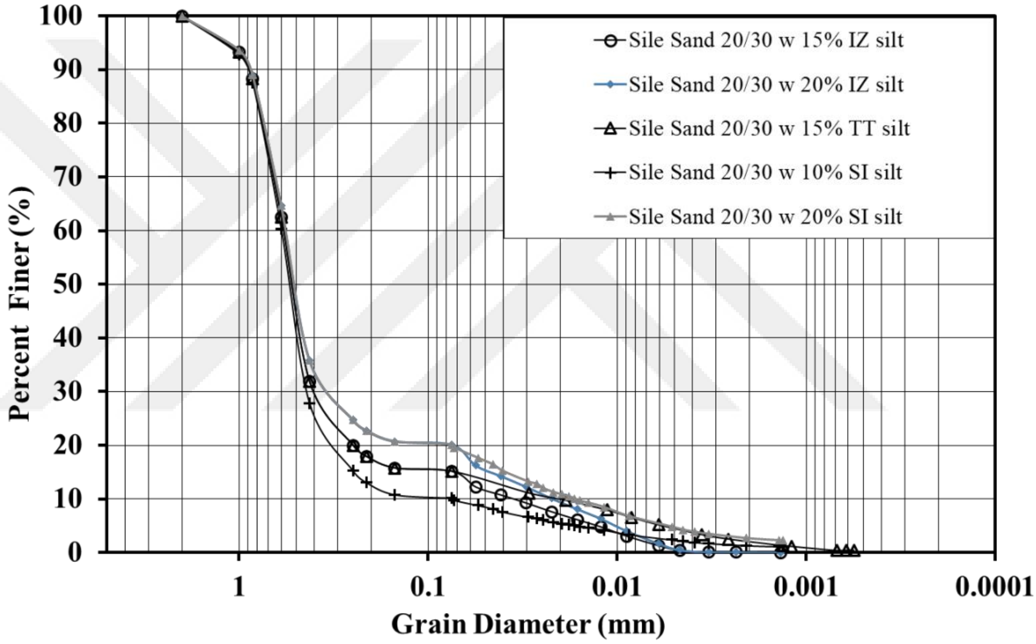


Figure 3.3 : The grain size distribution of silty sands with various fines contents

The grain size distributions (Figure 3.2 and Figure3.3) were obtained from the ASTM D422-63 (2007) procedure. Data obtained for Sile Sand 20/30 from grain size curves, Table 3.1 & Table 3.2 are: D_{10}=0.31 mm, D_{50}=0.565 mm, D_{60}=0.61 mm, CU=2.03. The same sand has a maximum grain size of 2mm, a minimum grain size of 0.02 mm. The silts used in the thesis for fine-grained soils are three different non-plastic silts and named IZ, SI, and TT silts. TT silt is dark gray and obtained from a stone quarry in Şile. It was obtained in the laboratory by wet sieving of quarry dust using the No. 200 standard sieves (0.075mm). SI silt, which is white, was obtained from a sand quarry in Lüleburgaz. IZ silt is a dark yellow, brown in color, a naturally formed soil obtained from Izmir. It has a natural fines content of 74%.

For this reason, the -No 200 portion (<0.075mm) of this silt was obtained by using wet sieving in the laboratory. In this experimental research, all silts have no liquid or plastic limits and are classified as non-plastic silts (ML) according to UCSC. (Etminan, 2016). They have a maximum grain size of 0.074 mm for all silts, a minimum grain size of 0.0013 mm, 0.0006 mm, and 0.0013 mm for IZ, TT, and SI silt, respectively. Figure 3.3, 3.4, and 3.5 show the silty sand combinations used in these experiments. In these pictures, it is seen how the appearance of the mixture changes as the fines content ratio increases.

a)

b)

Figure 3.4 : Sile Sand 20/30 with a)10% SI silt b)20% SI silt used in this experimental program

a)

b)

Figure 3.5 : Sile Sand 20/30 with a)15% IZ silt b) 20% IZ silt used in this experimental program

a)

b)

Figure 3.6 : Sile Sand 20/30 with a)15% TT silt b) 25% TT silt used in this experimental program

In this study, the question of "How do the silt gradation at same fines contents affect the liquefaction resistance of silty sands ?" has also been investigated. For this reason, silts with different gradations were mixed with clean sand using constant mixing percentages. First, the tests were performed with clean base sand. Then, the experiments were continued to be done with silty sands and finally, the results were compared.

3.2 Maximum and Minimum Void Ratios

In this thesis, soil mixtures include more than 15% of fines contents. Vibratory method (ASTM D4253-ASTM D4254) procedures can only be used to determine void ratios of cohesionless soils with a maximum of 15% silt content. Lade et al. (1998) have shown that results from (Kolbuszewski 1948; Mulilis et al. 1977; Vaid and Negussey 1988) were different values for extreme void ratios than the experiments performed by using ASTM procedures mentioned above. The void ratios of soils depend on the determination methods and the application. Thus, a method that Lade et al. (1998) suggested was used. This method has performed well for silty sands, considering that their void ratios are sensitive to small variations. In this method, the sample was obtained and weighed approximately 822 g. The sample was poured in the 2000-mL graduated cylinder by sieving 50 grams each time. The sample that remained on the sieve was cleaned with a brush. The densification process was applied; the sample was slammed two times with medium intensity from the graduated cylinder's four sides for every 50 g of soil (Figure 3.7) to achieve a minimum void ratio. A total of 822 g samples were wholly poured into the graduated cylinder. Next, the determination of the minimum void ratio was started. The deposited sample's height was measured from four sides, as shown in Figure 3.9. Since the cylinder diameter was constant, the poured soils' volume was calculated easily.

Figure 3.7 : Tested soil in the 2000-mL graduated cylinder

The maximum void ratio of tested soils was also measured, as mentioned below. The sample (822 gr) used to calculate the minimum void ratio was used again. The graduated cylinder was covered with the laboratory film (parafilm). The graduated cylinder was turned upside down and up very slowly (approximately 45 to 60 seconds each time and by rotating 180 degrees) until the sample reached a maximum volume.

Figure 3.8 : Turned upside down procedure of e_{min}

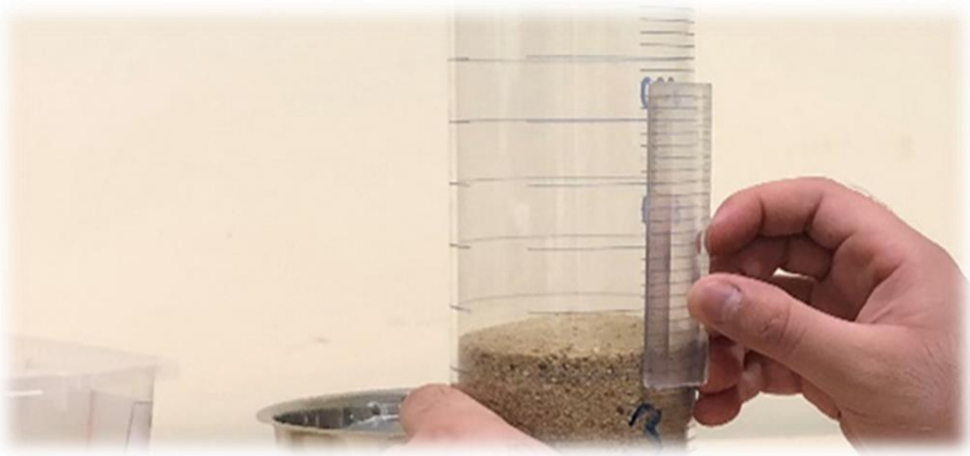


Figure 3.9 : The height of the poured sample measured from four different directions

Table 3.3 : Maximum and minimum void ratios of soils used in the experiment.

Soil Type	Fine Percent %	e_{min}	e_{max}
Sand 20/30	0	0.519	0.812
TT Sılt	100	0.513	1.738
IZ Silt	100	0.821	1.366
SI Silt	100	1.553	1.929
15% TT Silt + 85% Sand 20/30	15	0.409	0.739
25% TT Silt + 75% Sand 20/30	25	0.458	0.785
15% IZ Silt + 85% Sand 20/30	15	0.389	0.667
20% IZ Silt + 80% Sand 20/30	20	0.484	0.702
10% SI Silt +90% Sand 20/30	10	0.39	0.671
20% SI Silt +80% Sand 20/30	20	0.355	0.667

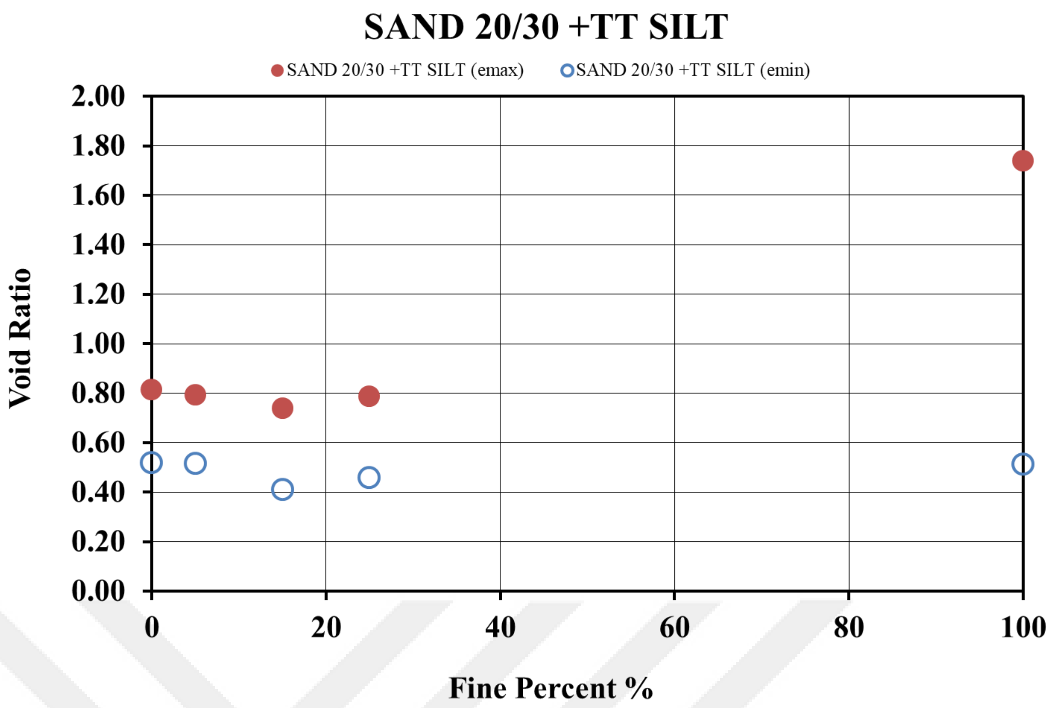


Figure 3.10 : Variations of maximum and minimum void ratios for combinations of Sile Sand 20/30 with TT Silt

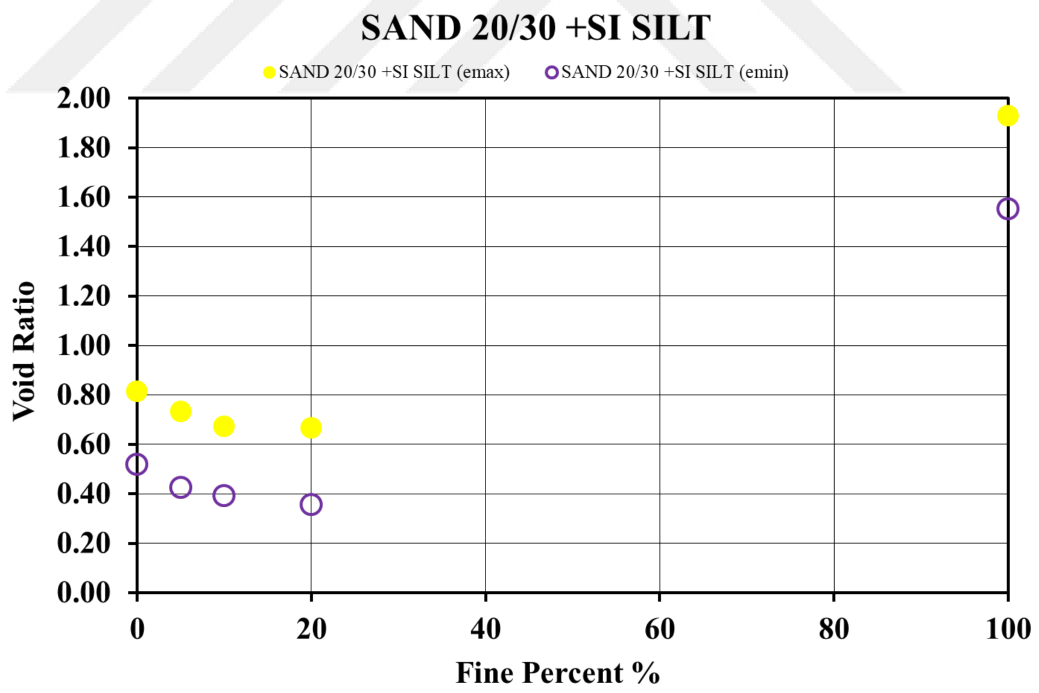


Figure 3.11 : Variations of maximum and minimum void ratios for combinations of Sile Sand 20/30 with SI Silt

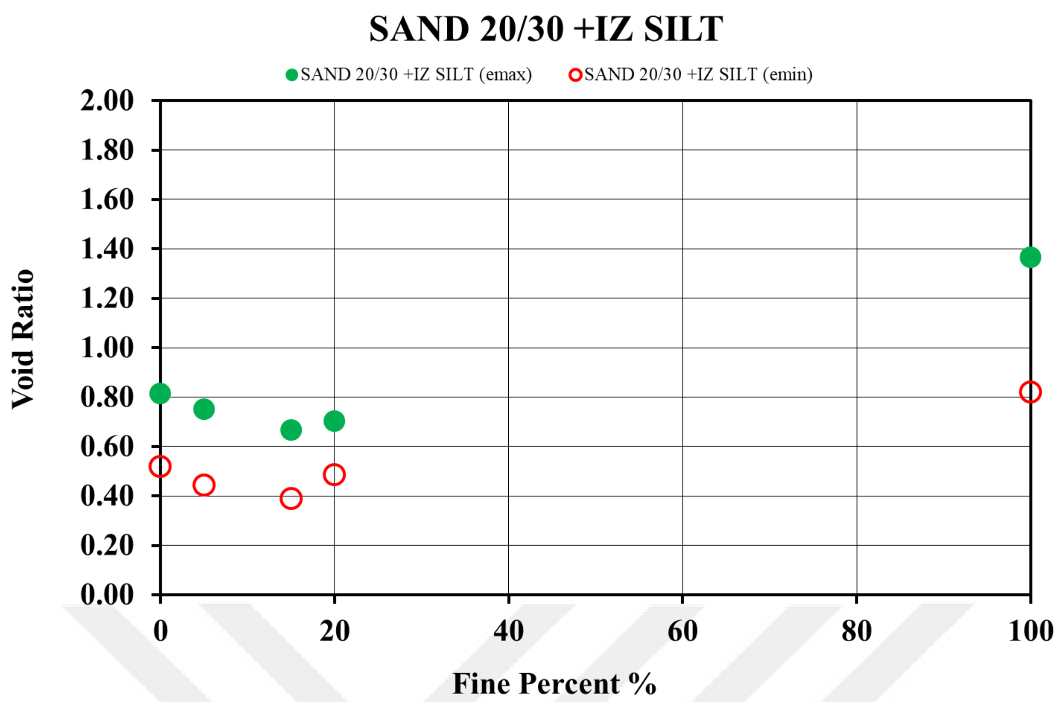


Figure 3.12 : Variations of maximum and minimum void ratios for combinations of Sile Sand 20/30 with SI Silt

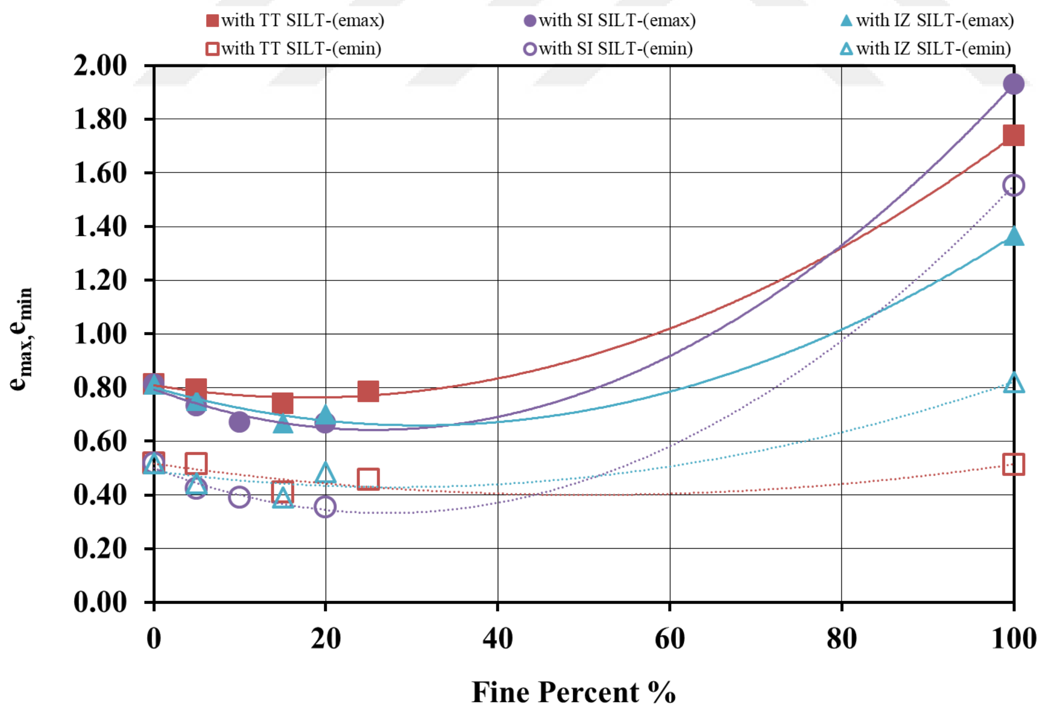


Figure 3.13 : Variations of maximum and minimum void ratios for combinations of Sile Sand 20/30 with non-plastic fines used in this experiment

As seen in Figure 3.13, the void ratio has decreased as the fines content has increased and reached a threshold value. Then the void ratio increased when the fines content percentage increased. As the fines content increases, the gap between the sand particles and the void ratio decreases. However, when the fines content increases and reach the threshold value, the fine particles enter the sand particles and cause an increase in the void ratio. This situation can be explained by Figure 3.14 (Yamamuro and Covert,2001).

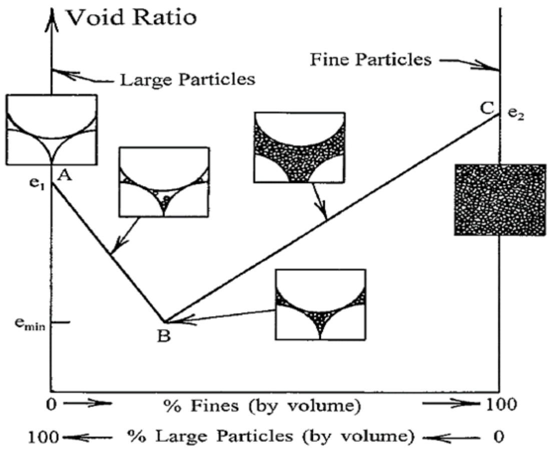


Figure 3.14 : The explanation of different particle' structures at different silt contents (Yamamuro and Covert,2001).

3.3 Specific Gravity

The specific gravity of a given material is the ratio of the weight of a given volume of material to an equal volume of distilled water. In soil mechanics, soils' specific gravity is an essential parameter for evaluating the weight-volume relationship, void ratio, and hydrometer test analysis. Specific gravities of the sand and sand silt mixtures were determined by Etminan (2016) sticking to ASTM D 854. Table 3.3 includes the specific gravity of sands and silts used in this thesis.

Table 3.4 : Specific gravities of soils used in the experiment

Soil Type	G_s
Sile Sand 20/30	2.65
TT Silt	2.75
SI Silt	2.68
IZ Silt	2.70

3.4 Atterberg Limits

In nature, fine-grained soils have several states which depend on the amount of water in the soil particles. If water is added to dry soil, each particle surface is covered with a water film layer. When water addition continues, the water film's thickness on a particle increases. Increasing the thickness of the water film can cause the particles to slide over each other. A plastic soil can be expressed as the one that can be deformed without permanent deformation or change in volume. Therefore, it is evident that the soils' behavior is related to the value of their Atterberg limits (Etminan, 2016). In this study, according to the standard used for the determination of Atterberg limits (ASTM D4318), the liquid limit or plastic limit of soil can not be determined. Therefore these soils have been categorized as non-plastic silts.

4. CYCLIC DIRECT SIMPLE SHEAR TESTS

In order to take precautions against damages that may occur in earthquakes, it is crucial to evaluate the dynamic soil properties in advance. Although a wide variety of site and laboratory methods are applied in the projects' geotechnical design, they have advantages and limitations in terms of various problems. On the other hand, laboratory experiments have importance in determining the dynamic soil parameters precisely and investigating these parameters' effect on dynamic soil behavior. The most important reason for this is that all parameters, including drainage conditions and loading conditions, can be precisely controlled in the laboratory. That is why geotechnical design in large and important projects needs to be based on a well-balanced field and laboratory experiment program. While investigating the dynamic behavior of soils, cyclic triaxial and cyclic simple shear experiments appear to be very prominent in the literature. However, in our country, the cyclic direct simple shear experiment is not commonly used in soil mechanics laboratories and engineering applications as far as direct shear and triaxial experiments.

4.1 Direct Simple Shear (DSS) Test

The simple shear test that emerged in the UK and Sweden in the first half of the 1950s was used primarily to investigate the stress-strain behavior of clayey soils, and it was used to determine the liquefaction behavior of sandy soil in the late 1960s. The simple shear test is one of the laboratory experiments that best represents the soils' dynamic properties and liquefaction conditions. It is not easy to create and model the complex field condition with experimental systems in the laboratory. On the other hand, when investigating soils' behavior under dynamic loads, there are cases where the dynamic simple shear experiment is more advantageous than other experiments. It was observed that the situation closest to the field conditions could be realized with a simple shear test system, literally considering the field conditions. During the shear phase in the experiment, the sample was kept constant under plane deformation, thus allowing the principal stresses to rotate. Therefore, it has created a more realistic loading situation. The deformations occurring during the simple shear test are more uniform than the direct shear experiment. The loading conditions during earthquakes are modeled better with DSS than the dynamic triaxial experiment because smaller size samples are used and more uniform waves are produced. Various dynamic simple shear testing types have been developed to determine these features and obtain the ideal simple shear condition. NGI (Norwegian Geotechnical Institute) type, SGI (Swedish Geotechnical Institute) type and Cambridge type are the best known of these devices. Stress-strain behavior of soils with this experiment can be investigated either with monotonic (Monkul and Dacic, 2017; Monkul et al.,2020) or cyclic (Monkul et al., 2015; Eseller-Bayat et al., 2019) loading conditions.

4.1.1 DSS Apparatus at Yeditepe University

All CDSS experiments carried out within this thesis's scope have been carried out at the Yeditepe University Soil Mechanics Laboratory. DSS testing apparatus uses a computer-controlled Shear Track II system developed by Geocomp Company, in which undrained condition is sustained by a constant volume-controlled CDSS experiment system (Figure 4.2). In this thesis's scope, a short and cylindrical sample in the dynamic simple shear test is limited by several coated teflon stacked rings and membrane (SGI type device), which can also be seen below. The soil sample was deformed similarly to the vertical propagated S waves, which were exposed by applying cyclic horizontal shear stresses to the sample's bottom or top.

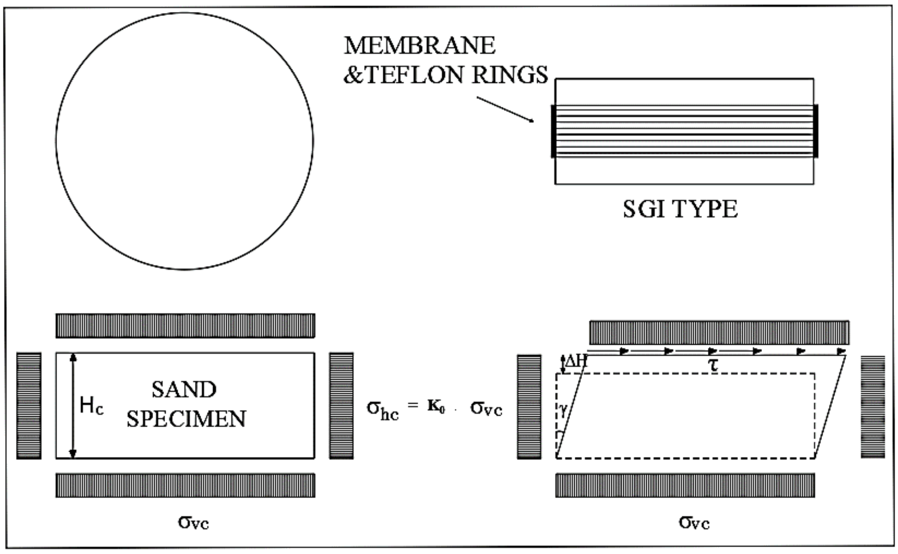


Figure 4.1 : SGI type CDSS test apparatus

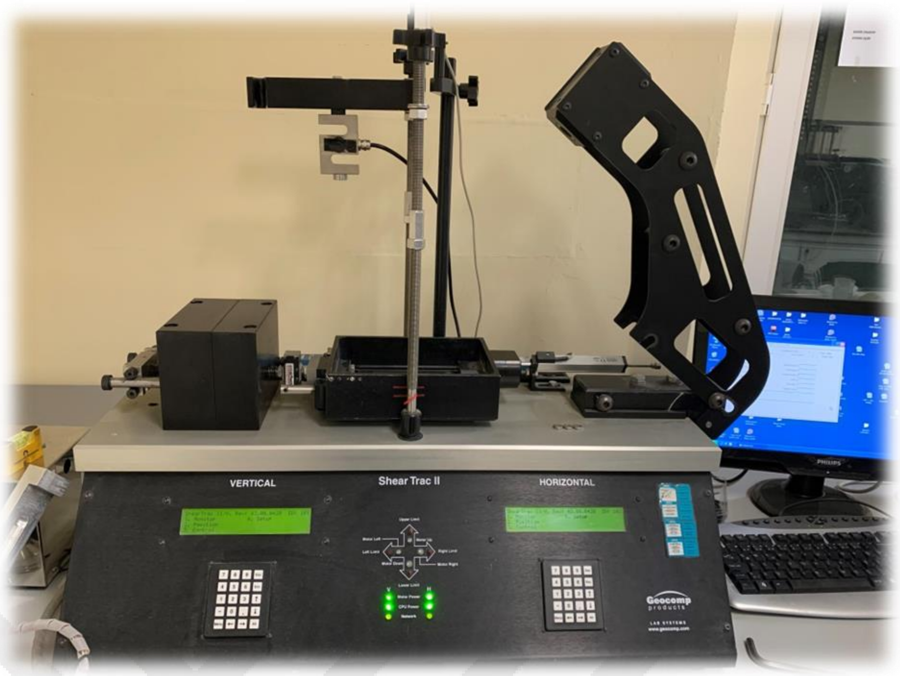


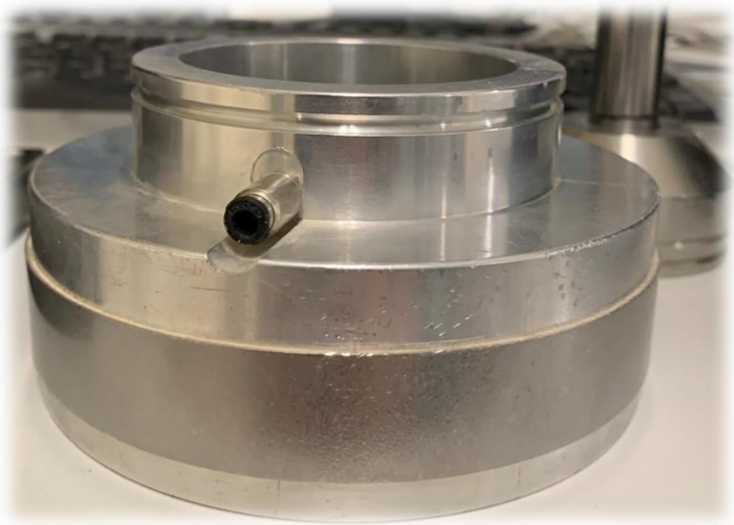
Figure 4.2 : Shear Track II, CDSS test equipment in YU

4.2 Specimen Preparation

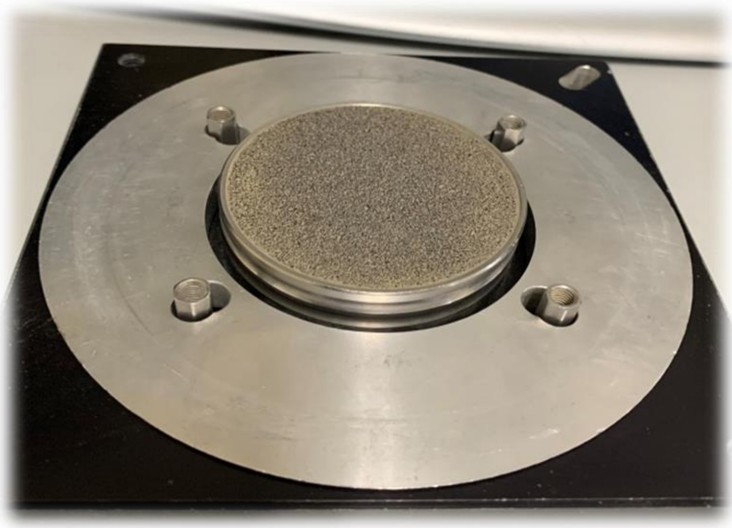
It is a well-known fact that to obtain reliable results; it is necessary to use the appropriate sample preparation method in the experiments. It is very important to prepare the samples very carefully and understand the effect on the test result when there is a parameter change. For the experiments to be repeatable, it is necessary to prepare the samples in the same way in all experiments. Due to the above reasons, the dry funnel method, which has been applied as a sample preparation method, is widely used for clean and silty sands. Dry funnel deposition is a very commonly used method, especially for cohesionless specimens to form reconstituted triaxial tests (Lade and Yamamuro, 1997; Monkul and Yamamuro, 2011; Monkul, Etminan and Şenol, 2017), direct shear (Monkul, 2013) and direct simple shear specimens (Monkul and Dacic, 2017; Monkul et al., 2020). The classical dry funnel deposition method was recently modified by Monkul et al. (2018), which involves a computer-controlled funnel raising mechanism named "automatic dry funnel deposition". Automatic dry funnel deposition, which involves a patent-pending system, prevents various problems (e.g., uncontrolled funnel speed, shaking, asymmetrical rise, etc.) that were faced in the manual dry funnel deposition technique (Monkul et al., 2018).

Aluminum funnel tools, specially designed for CDSS, were pulled along the vertical axis at various speeds between 15-150 seconds, and samples with different relative densities (Dr) were obtained (Yenigün et al., 2018).

In the dry funnel method, the experiment's soil was mixed homogeneously in a container. Clean sand and silty sands used in this study were poured into a funnel placed on a special mold base, the funnel was raised along the vertical axis and experimental samples were created. In the dry funnel method with mold, which is used for both dynamic simple shear and triaxial experiments, samples can be saturated by passing CO_2 and aerated water. During the sample preparation, the mold and teflon rings shown below can also align the funnel with the vertical symmetry axis. The mold ensures the correct placement of the teflon rings and applies vacuum to the membrane. The vacuum is applied through the external pipe and the membrane gets fairly well stretched to the mold. Figure 4.3 shows the mold base with porous stone. O-rings attach the membrane on the mold base. Thanks to the mold base, it is ensured that the mold is appropriately placed on the bottom plate and no problems occur during the vacuuming process. In the CDSS test, the effect of ground motion caused by the earthquake is represented with the cyclic shear stress ratio (CSR) and the cyclic shear stress.



(a)



(b)

Figure 4.3 : (a)Mold and (b)mold base used in sample preparation

4.2.1 Testing Dry Specimens

Due to the shear force applied to the soil sample in the experiment, the soil specimen is displaced and deformed. The main technique used for specimen preparation is the dry funnel deposition method. In a drained simple shear test, normal stresses, shear stresses, vertical deformation and shear deformation occur on the soil specimen. However, vertical deformation does not occur in the constant volume test system. In the constant volume-controlled experiment, the vertical stress on the sample was increased and decreased by computer control, the volume of the sample remained constant throughout the shear. Therefore the excess pore water pressure calculated in the undrained condition was calculated from the vertical stress change. Calculation of excess pore water pressure from the vertical stress change gave rise to obtaining liquefaction behavior of sand from dry samples. Studies in the literature have proved the validity of this idea (Monkul et al. 2015, 2017, 2019).

4.3 Experimental Program

All CDSS experiments carried out within this thesis study's scope have been carried out at the Yeditepe University Soil Mechanics Laboratory. DSS testing apparatus uses a computer-controlled Shear Track II system developed by Geocomp Company, in which undrained condition is sustained by a constant volume-controlled CDSS experiment system (Figure 4.1). Sand samples (having 20 mm height and 64 mm diameter) have been prepared with the dry funnel method. They were subjected to cyclic shear stresses in sinus wave form in the shear phase, each corresponded to three different cyclic shear stress ratios (CSR = 0.08, 0.1 and 0.12) frequency of 0.1 Hz. Samples formed in various relative densities were consolidated under 100 kPa vertical stress (σ_{vc} = 100 kPa). Within this study's scope, a total of **314 CDSS** tests were carried out. It is assumed that liquefaction of the samples takes place when the excess pore water pressure is equal to the vertical consolidation stress ($\Delta u = \sigma_{vc}$ = 100 kPa) or when the double amplitude axial strain reaches 7.5% (d. a. γ= 7.5%). This strain criterion was accepted to be reasonable as single-amplitude γ=3.75% in DSS specimen and is equivalent to 2.5% single-amplitude axial strain in a triaxial specimen (which is also a definition for liquefaction in literature)

5. CYCLIC SIMPLE SHEAR TEST RESULTS

This chapter presents the liquefaction analysis obtained from the CDSS experiments of clean sand and silty sand samples. 193 experiments were carried out with clean Sile Sand and silty sand containing various percentages. The distribution of performed experiments is shown in Table 5.1. In the experiments carried out with constant volume control, samples experimented till they reach liquefaction.

Table 5.1 : The number of performed experiments in each CSR' and specimen

Soil Type	CSR=0.08	CSR=0.1	CSR=0.12
Clean Sile Sand 20/30	14	29	8
Sile Sand 20/30+IZ Sılt	20	19	12
Sile Sand 20/30+TT Sılt	16	15	11
Sile Sand 20/30+SI Sılt	19	18	12

Consolidation and shear phase data results are evaluated considering the effects of void ratio and relative density. Which means it, this void ratios or relative densities corresponds the consolidated values.. Excel graphs corresponding to liquefaction criteria are created. Shear stress vs. shear strain, shear stress vs. effective vertical stress, shear strain vs. the number of cycle and excess pore pressure vs. the number of cycle graphs (for each soil mixture) are presented in Figure 5.1. The graphs in Figure 5.1 are typical test results from cyclic stress-controlled tests.

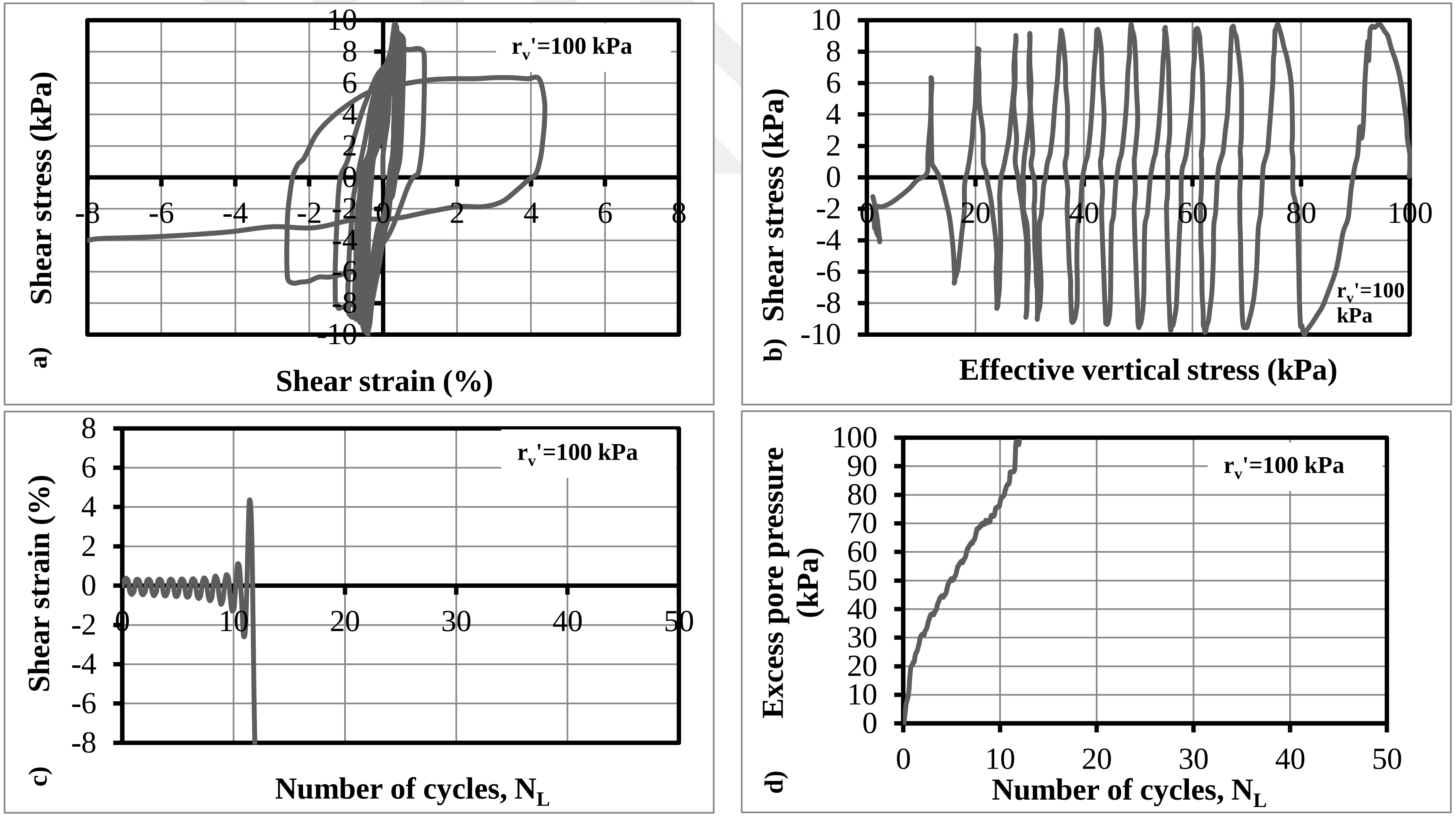


Figure 5.1 : Typical test results from a constant volume(undrained) cyclic stress-controlled tests a) Shear stress vs. Shear Strain, b) Shear Stress vs.Eff.vert. Stress, c) Shear Strain vs. NL and d) Excess Pressure vs. N_L graph for Clean Sile Sand 20/30, Dr=30% and CSR=0.1.

5.1 The Relationship Between Relative Density and the Number of Cycles Required for Liquefaction

Liquefaction behavior of Clean Sile Sand 20/30 was determined by the CDSS tests using dry samples. The experiments were carried out in three different cyclic shear stress ratios (CSR = 0.12, 0.1, 0.08). The relation between the number of cycles required for liquefaction (N_L) and relative density (Dr) was investigated with clean Sile sand samples. N_L vs. relative density (Dr) relationship is shown in Figure 5.2.

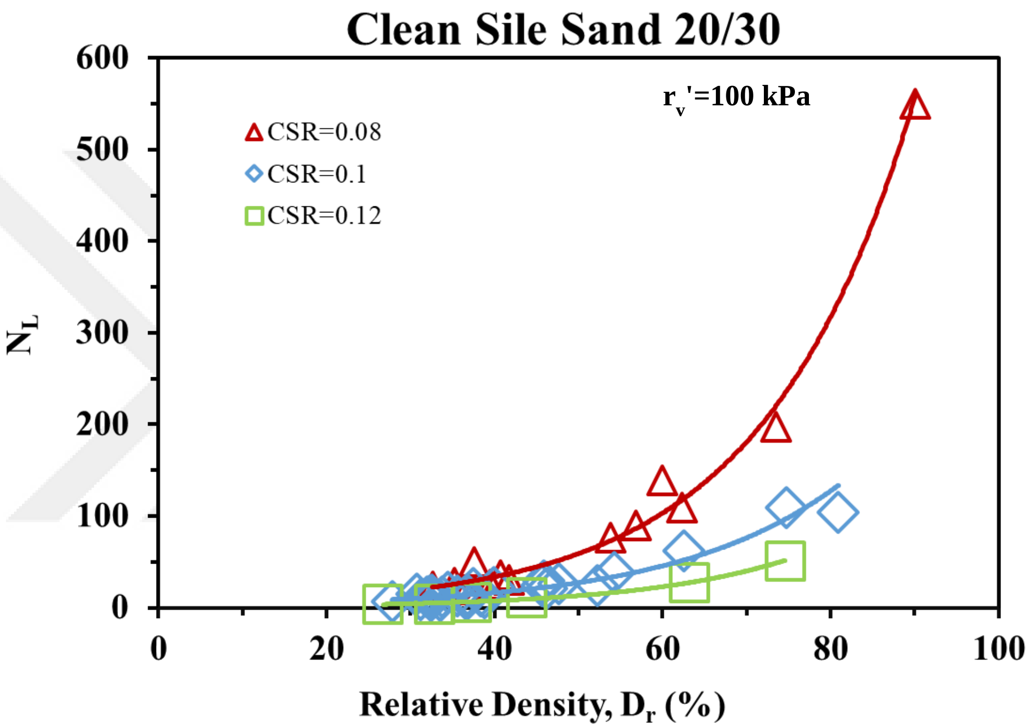


Figure 5.2 : Number of cycles (N_L) required for liquefaction of Clean Sile Sand 20/30 vs. relative density (Dr) under different CSR values

As expected, the liquefaction resistance of clean sand for all three CSR values increased as the relative density increased. Experiment at a constant CSR value, the relationship between N_L and Dr can be expressed with an exponential function, as shown in Equation 5.1. In this equation, a and b are the exponential function coefficients, and e is the Euler’s number, 2.718 (not to be confused with the void ratio).

$$N_L = a.\, e^{[b.\, Dr(\%)]} \quad \text{for } \sigma'_v = 100 \text{ kPa.} \tag{5.1}$$

This equation is proposed for σ'_v=100 kPa. The variation of a and b coefficients in Equation 5.1 with CSR is given in Table 5.2. In this table, the coefficient a is important in terms of expressing the initial value of the equation. When physically considered, if Dr = 0%, the coefficient "a" expressed the number of cycles that the samples will liquefy. The coefficient "b" in Table 5.1 is essential in terms of being the coefficient that affects the increase rate in the function. When the values in Figure 5.2 and Table 5.1 are examined carefully, it is observed that the coefficient a decreases as the CSR increases.

Table 5.2 : Coefficients a and b gave in Equation 5.1 for Clean Sile Sand 20/30

CSR	a	b	R^2
0.08	3.558	0.056	0.95
0.1	2.077	0.052	0.89
0.12	0.788	0.056	0.98

During this study, besides the liquefaction behavior of clean sand (under direct simple shear conditions), the liquefaction behavior of silty sands was examined by adding three non-plastic silts into the sand at the same cyclic shear stress ratios. The silty sands are obtained by mixing 10 % SI silt,15% IZ and TT silts, 20% IZ and SI silts, and 25% TT silt into Sile Sand 20/30. The number of cycles required for liquefaction of IZ silty sands is shown in Figures 5.3 and 5.4. The N_L versus Dr graphs for the TT silty sand was shown in Figures 5.5 and 5.6. Likewise, the SI silty sand graphs were also shown in Figures 5.7 and 5.8. When these figures shown below are examined, various issues attract attention. The liquefaction resistance increases as the relative density increases for the containing silt samples. An exponential relationship between liquefaction resistance and relative density is also observed. The relationship between N_L and Dr can be expressed very preciously with Equation 5.1, as for every silty sand, as it did for Sile Sand 20/30.

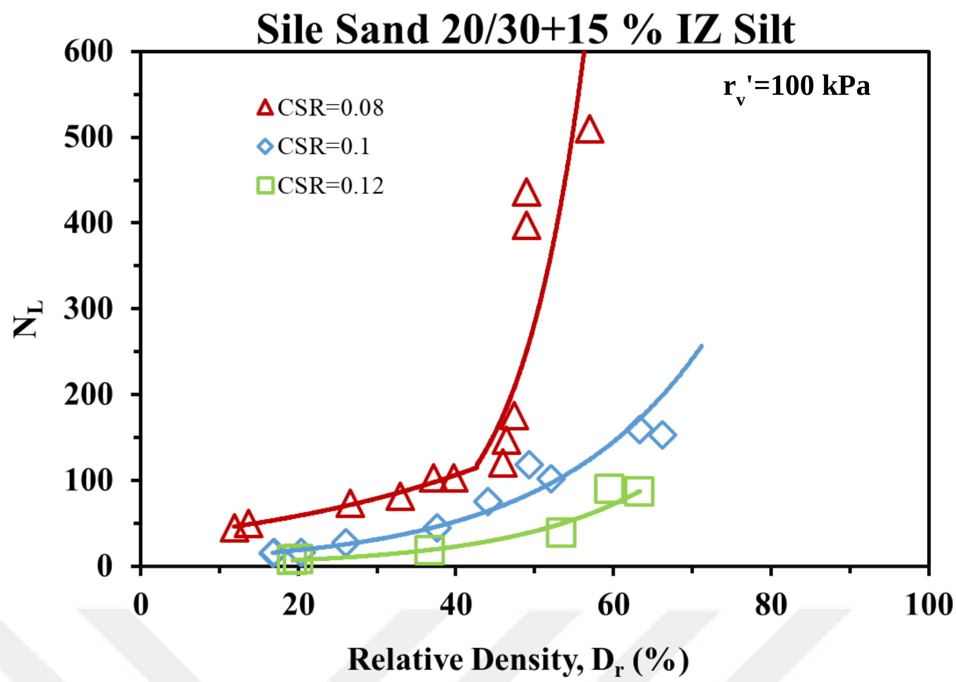


Figure 5.3 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+IZ Silt vs. relative density (Dr) under different CSR values, FC = 15%

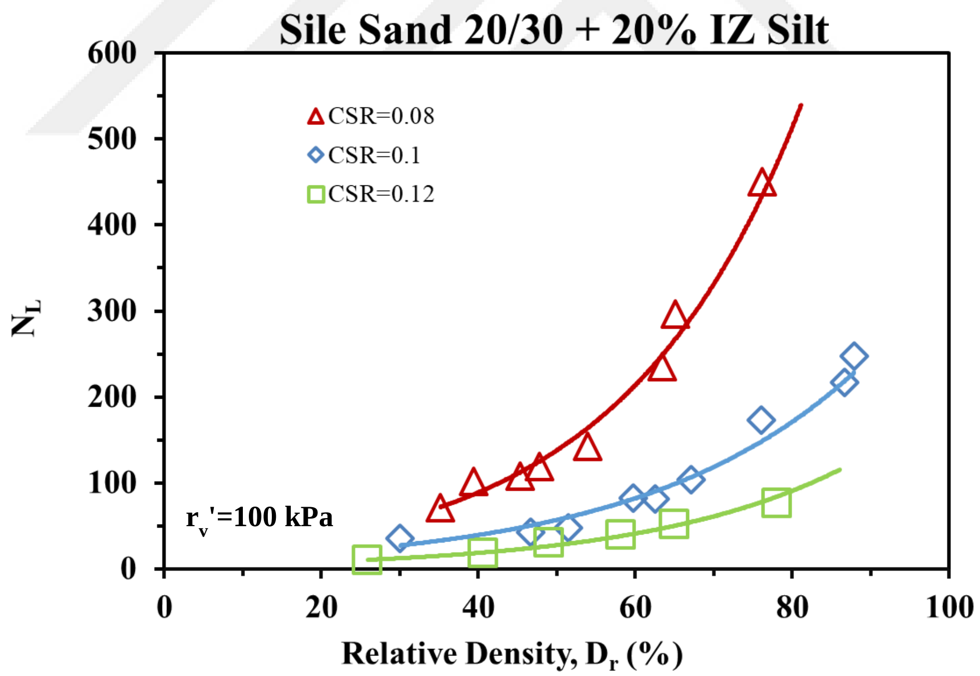


Figure 5.4 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+IZ Silt vs. relative density (Dr) under different CSR values, FC = 25%

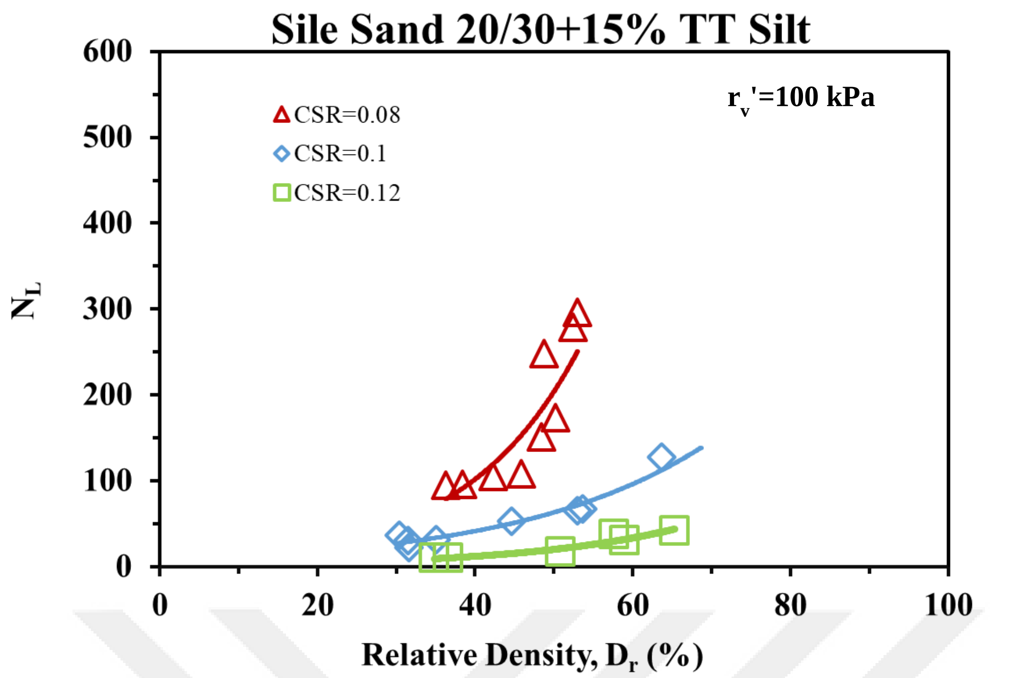


Figure 5.5 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+TT Silt vs. relative density (Dr) under different CSR values, FC = 15%

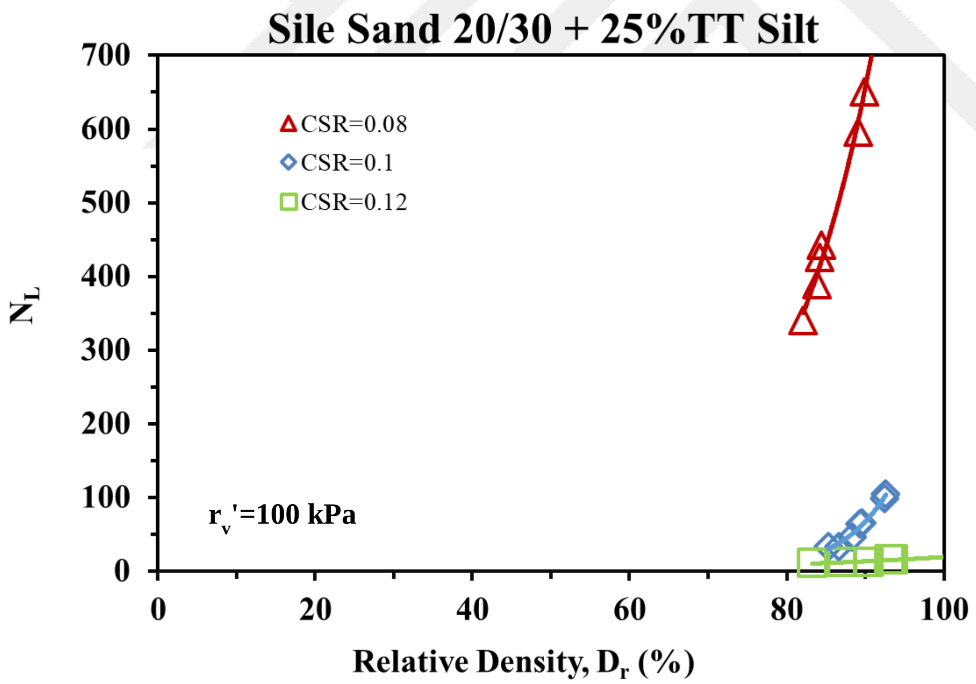


Figure 5.6 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+TT Silt vs. relative density (Dr) under different CSR values, FC = 25%

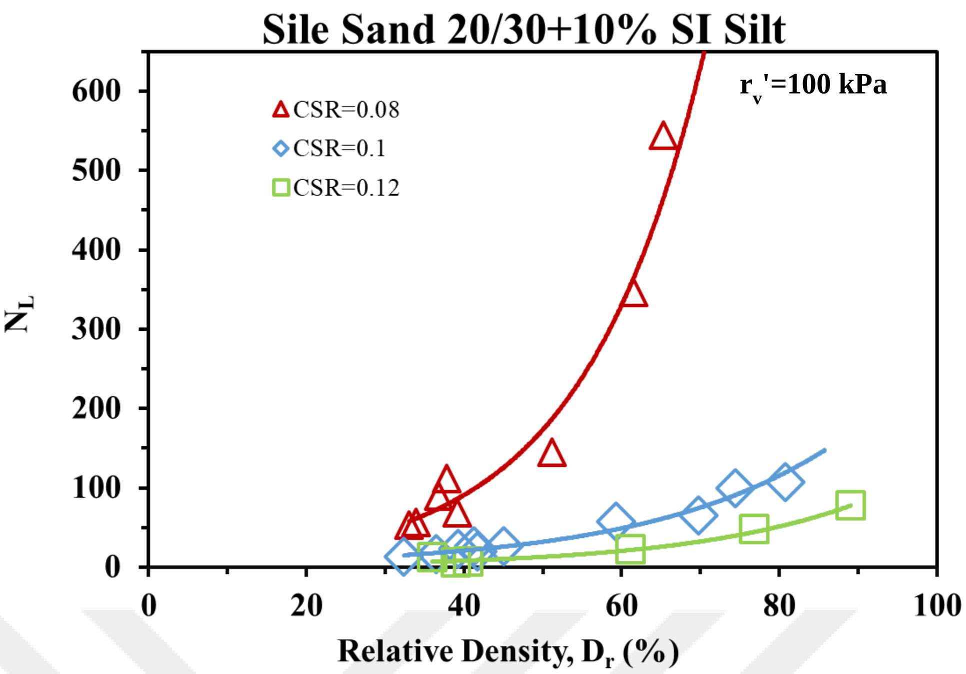


Figure 5.7 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+SI Silt vs. relative density (Dr) under different CSR values, FC = 10%

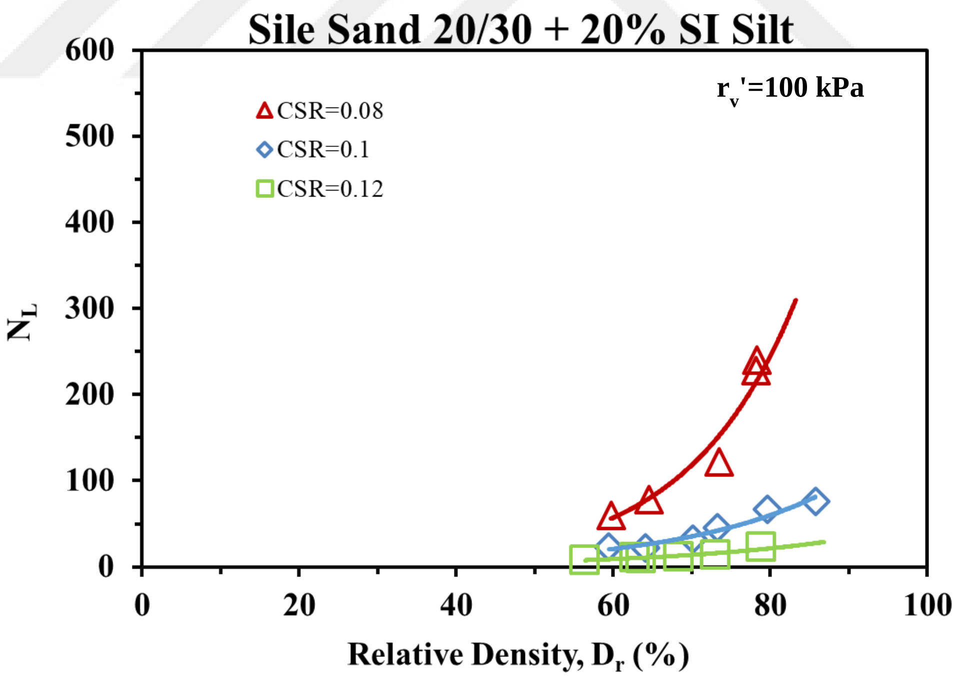


Figure 5.8 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+SI Silt vs. relative density (Dr) under different CSR values, FC = 20%

In Equation 5.1, the coefficient a indicates the number of cycles in which the samples will liquefy when Dr = 0%. When considered in this context, the b coefficient expresses the function's rate very clearly. Tables 5.3, 5.4, and 5.5 indicate the a and b coefficients of Sile Sand 20/30 samples mixed with silt. When these values are carefully examined, various factors such as CSR and FC have an essential effect on the sand and silty soils' liquefaction behavior. For example, the coefficient a decreases with increasing CSR.

Table 5.3 : Coefficients a and b gave in Equation 5.1 for Sile Sand 20/30+IZ

FC	CSR	a	b	R^2
15	0.08	32.602	0.030	0.99
15	0.1	6.822	0.051	0.97
15	0.12	2.351	0.057	0.98
20	0.08	15.438	0.044	0.98
20	0.1	9.122	0.037	0.95
20	0.12	3.823	0.040	0.98

Table 5.4 : Coefficients a and b gave in Equation 5.1 for Sile Sand 20/30+TT

FC	CSR	a	b	R^2
15	0.08	5.963	0.071	0.84
15	0.1	7.726	0.042	0.91
15	0.12	1.495	0.052	0.93
25	0.08	0.518	0.079	0.98
25	0.1	0.000	0.170	0.96
25	0.12	0.507	0.036	0.80

Table 5.5 : Coefficients a and b gave in Equation 5.1 for Sile Sand 20/30+SI

FC	CSR	a	b	R^2
10	0.08	6.885	0.065	0.94
10	0.1	3.769	0.043	0.97
10	0.12	1.307	0.046	0.91
20	0.08	0.724	0.073	0.96
20	0.1	0.873	0.053	0.94
20	0.12	0.666	0.043	0.93

In the second part of the analysis, three different relative density values were chosen to correspond to the loose (Dr = 30%), medium dense (Dr = 50%), and dense (Dr = 70%) conditions for the clean and silty sands. The change of N_L values was calculated using Equation 5.1. In this part of the chapter, two outcomes were obtained;

1) Effect of state (which is loose or dense) on ΔNL were analyzed at a constant CSR value (0.08 or 0.12).

2) For ΔDr = 20, NL's change according to both CSR and loose or dense state were examined.

Figure 5.9 showed the analysis results for three constant Dr and CSR for Clean Sile Sand. As expected, at a constant Dr value, N_L increased with the CSR value decreased. As was pronounced in Figure 5.9, the inclination of curves is the same in each other. For example, when Dr increases from 30% to 50% at CSR = 0.12, the change in the number of cycles required for liquefaction (ΔN_L) is 9. When Dr increases from 50% to 70% at CSR = 0.12, the change in the number of cycles required for liquefaction (ΔN_L) increases to 27. Table 5.6 shows that the NL has almost tripled for the same ΔDr (= 20%) while reaching a denser state. The same exciting observation is valid when the CSR = 0.08 in Figure 5.9; the same trend was still observed (27/9 ≈ 122/40 ≈3). As the CSR value increases, e.g., from 0,08 to 0,12, the ΔN_L drop is approximately 4.5 times for all the states (40 / 9≈122 / 27≈4.5).

Table 5.6 : ΔNL- CSR in loose, medium-dense, dense condition for Sile Sand 20/30

CSR=0.12	ΔN_L	CSR=0.08	ΔN_L
Dr=30%		Dr=30%	
	9		40
Dr=50%		Dr=50%	
	27		122
Dr=70%		Dr=70%	

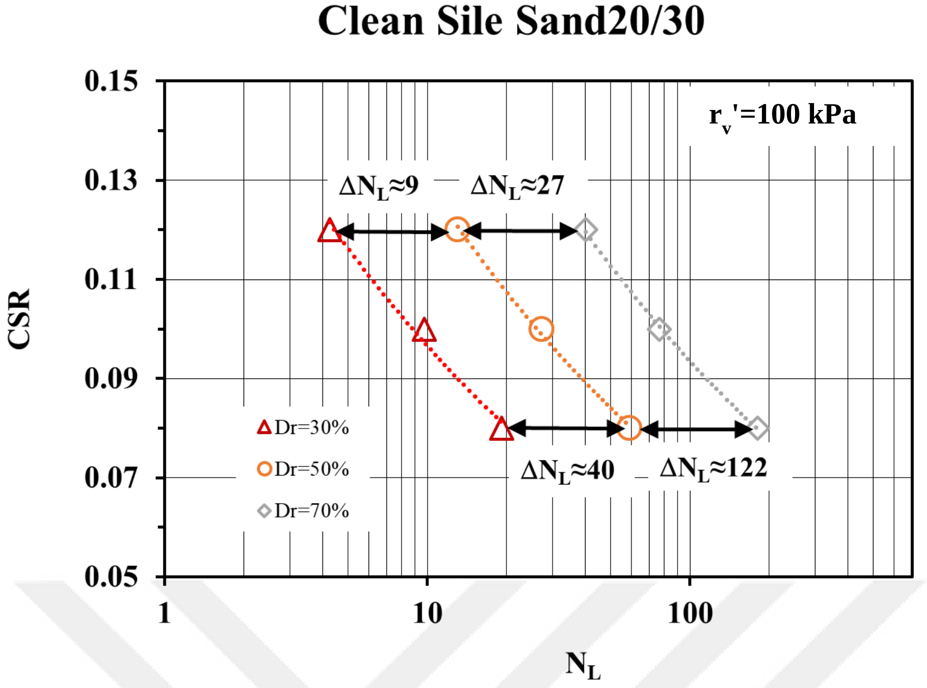


Figure 5.9 : Number of cycles (N_L) required for liquefaction of Clean Sile Sand 20/30 vs. CSR in various relative density

The same procedure was performed for the silty sands obtained by adding 15% and 20% IZ silt into Sile Sand 20/30. The changes in the number of cycles required for the liquefaction corresponding to Dr=30%, 50%, and 70% are given in Figures 5.10 and 5.11. The rise of ΔN_L with CSR or ΔDr is given in Table 5.7. Accordingly, it is noticeable that the increase in CSR (from 0.08 to 0.12) in silty sand with percentages of 15% and 20 %fines content decreases the ΔN_L. This decrease is more in silty sands compared to clean sand. As the CSR value increase, e.g., from 0,08 to 0,12, the ΔN_L drop is approximately 7 times for loose states (204 / 28≈7), and the ΔN_L drop is approximately 34 times for dense states (3000 / 87≈34). While reaching a denser state with CSR=0.12 for 15% silt content and ΔDr (= 20%), the ΔN_L triples time (87/28). While reaching a denser state, when CSR= 0.08, the number of cycles increases by approximately 15 times (3000/204) at a denser state. Although ΔDr = 20% for both cases, CSR's decrease affects the liquefaction behavior much more during the states' transition.

Table 5.7 : ΔNL- CSR in loose, medium-dense, dense condition for Sile Sand 20/30+IZ Silt

CSR=0.12	ΔN_L FC=0	ΔN_L FC=15	ΔN_L FC=20	CSR=0.08	ΔN_L FC=0	ΔN_L FC=15	ΔN_L FC=20
Dr=30%				Dr=30%			
	9	28	15		40	204	33
Dr=50%				Dr=50%			
	27	87	81		122	3000	193
Dr=70%				Dr=70%			

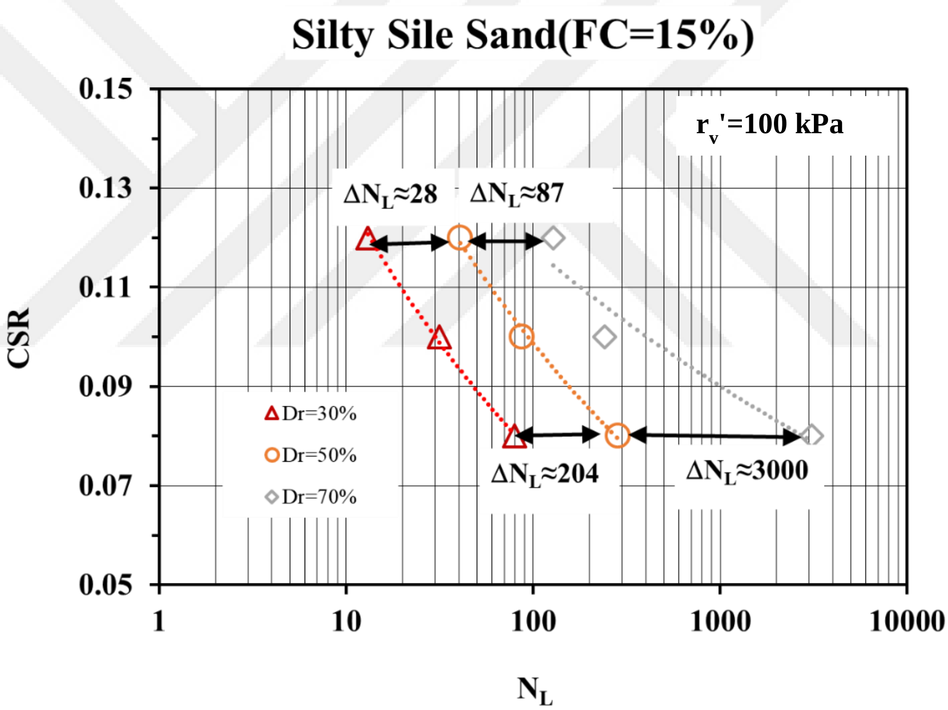


Figure 5.10 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+IZ Silt vs. CSR in various relative density, FC = 15%

In Figure 5.11, when fines content is 20%, a significant decrease is observed in the liquefaction resistance of the sand compared to 15% fines content. Similarly, the effect of the CSR increase (from 0.08 to 0.12) on the ΔDr - ΔN_L relationship has happened in the same manner. When the CSR raised from 0.08 to 0.12, the difference in the number of cycles has kept constant even when the soils were switching to dense or loose states (193/81≈33/15≈2).

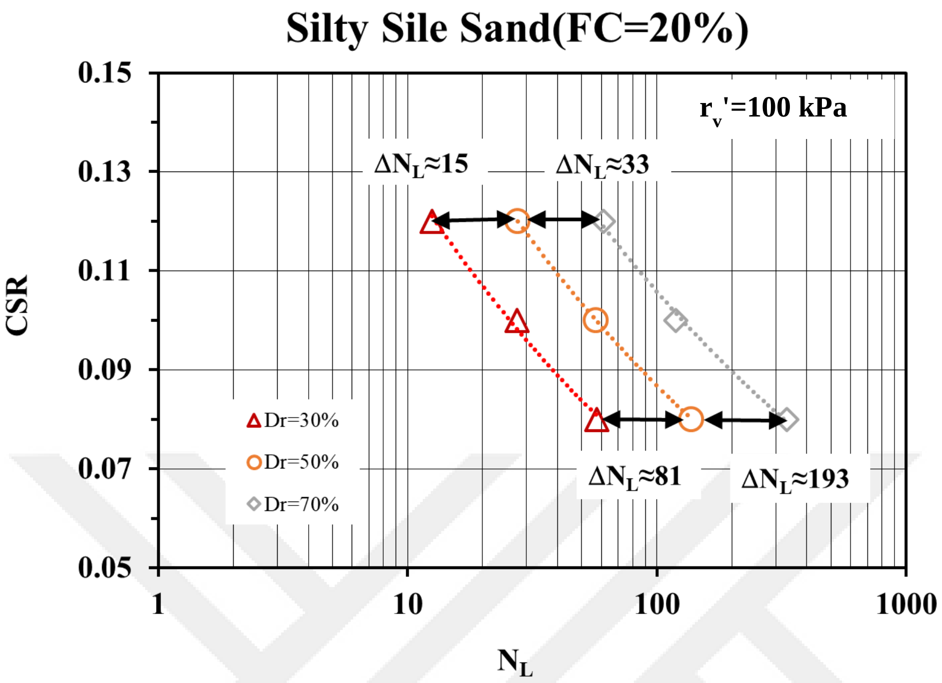


Figure 5.11 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+IZ Silt vs. CSR in various relative density, FC = 20%

The changes in the number of cycles required for the liquefaction corresponding to Dr=30%,50%, and 70% are given in Figure 5.12 for sand included 15% TT silt content. The increment of ΔN_L with CSR or ΔDr is given in Table 5.8. When Figure 5.12 is examined, constant rates specified for clean sand in Figure 5.9 and Table 5.6 did not exist in silty sands. Accordingly, it is obvious that the increase in CSR (from 0.08 to 0.12) in silty sand decreases the effect of ΔDr. This decrease is more in silty sand compared to clean sand. As the CSR value increase, e.g., from 0,08 to 0,12, the ΔN_L drop is approximately 12 times for loose states (155 /13≈12), and the ΔN_L drop is approximately 17 times for dense states (636 / 38≈17).

It should be noted that these ratios and absolute values much higher than clean sand. While reaching a denser state with CSR=0.12 for 15% silt content and ΔDr (= 20%), the ΔN_L triples time (38/13). While reaching a denser state, when CSR= 0.08, the number of cycles increases by approximately four times (636/155), reaching a denser state. While ΔDr = 20% for both cases, the decrease of CSR affects almost stably the liquefaction behavior during the whole transition among the states.

Table 5.8 : ΔNL- CSR in loose, medium-dense, dense condition for Sile Sand 20/30+TT Silt

CSR=0.12	ΔN_L FC=0	ΔN_L FC=15	CSR=0.08	ΔN_L FC=0	ΔN_L FC=15
Dr=30%			Dr=30%		
	9	13		40	155
Dr=50%			Dr=50%		
	27	38		122	636
Dr=70%			Dr=70%		

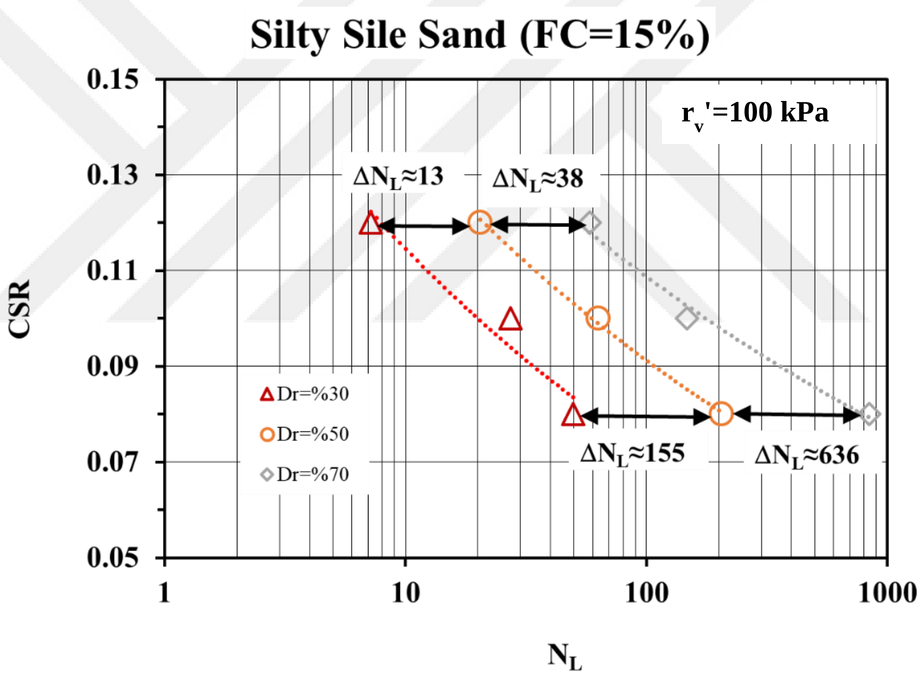


Figure 5.12 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+TT Silt vs. CSR in various relative density, FC = 15%

The analysis was also performed for the silty sands obtained by adding 10% and 20% SI silt into Sile Sand 20/30. The changes in the number of cycles required for the liquefaction corresponding to Dr=30%, 50%, and 70% are given in Figures 5.13 and 5.14, respectively. The increment of ΔN_L with CSR or ΔDr is given in Table 5.9. Accordingly, it is noticeable that the increase in CSR (from 0.08 to 0.12) in silty sand with percentages of 10% and 20 %fines content decreases the ΔN_L. This decrease is more in silty sands compared to clean sand. As the CSR value increase, e.g., from

0,08 to 0,12, the ΔN_L drop is approximately 16 times for loose states (126/8≈16) and the ΔN_L drop is approximately 23 times for dense states (456 / 20≈23). It should be noted that these ratios and absolute values much higher than clean sand. While reaching a denser state with CSR=0.12 for 15% silt content and ΔDr (= 20%), the ΔN_L triples time (20/8). While reaching a denser state, when CSR= 0.08, the number of cycles increases by approximately four times (456/126), reaching a denser state. While ΔDr = 20% for both cases, the decrease of CSR affects almost stably the liquefaction behavior during the whole transition among the states.

Table 5.9 : ΔNL- CSR in loose, medium-dense, dense condition for Sile Sand 20/30+SI Silt

CSR=0.12	ΔN_L FC=0	ΔN_L FC=10	ΔN_L FC=20	CSR=0.08	ΔN_L FC=0	ΔN_L FC=10	ΔN_L FC=20
Dr=30%				Dr=30%			
	9	8	3		40	126	21
Dr=50%				Dr=50%			
	27	20	8		122	456	91
Dr=70%				Dr=70%			

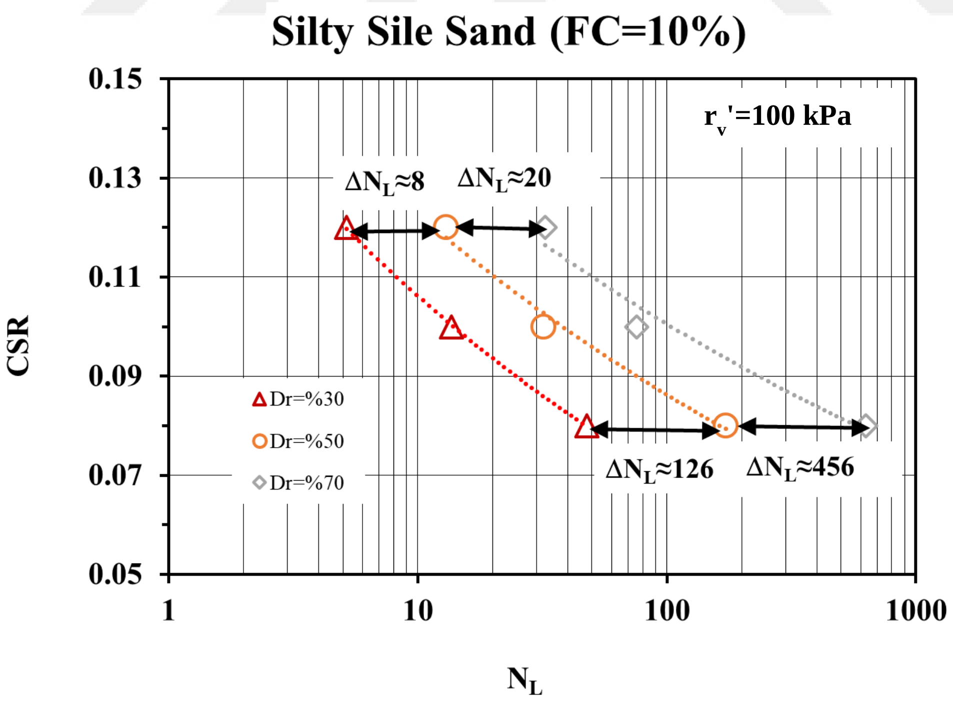


Figure 5.13 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+SI Silt vs. CSR in various relative density, FC = 10%

In Figure 5.14, with the increase of fines content to 20%, a significant decrease is observed in the liquefaction resistance of the sand compared to 10% fines content (the curves have shifted to the left and their slopes have increased). Similarly, the decrease in CSR (from 0.12 to 0.08) on the ΔDr - ΔNL relationship decreased relatively. When the CSR raised from 0.08 to 0.12, the difference in the number of cycles has kept almost constant even when the soils were switching to other states. (8/3≈3 and 91/21≈4).

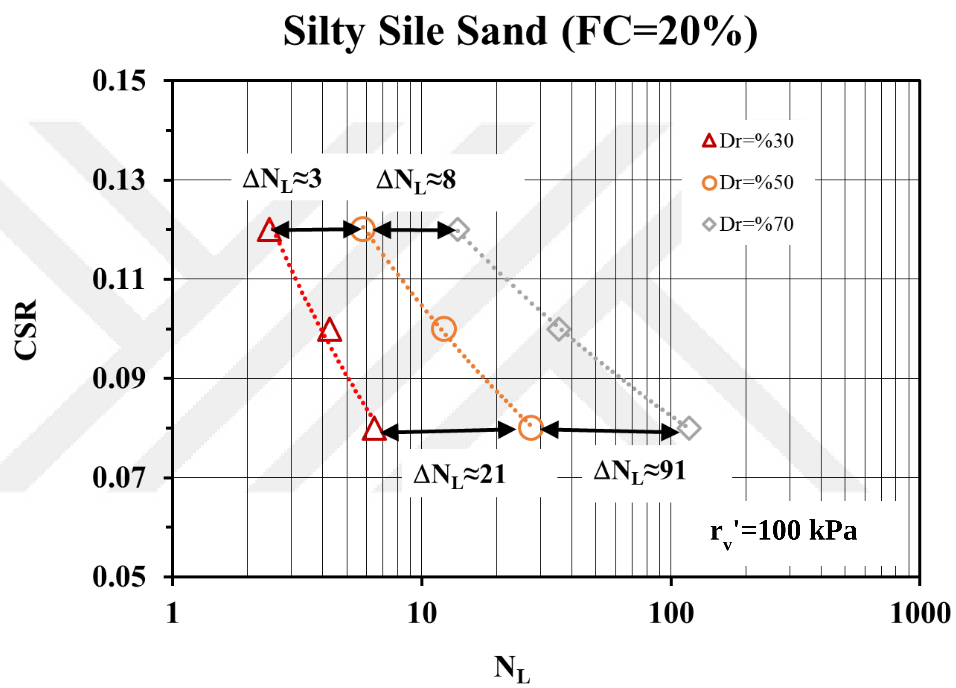


Figure 5.14 : Number of cycles (N_L) required for liquefaction of Sile Sand 20/30+SI Silt vs. CSR in various relative density, FC = 20%

When the figures showed are examined carefully, it will be seen that the change in the cyclic shear stress ratio at a constant Dr value for both clean and silty sands changes the number of cycles required for liquefaction with the power function given in Equation 5.2. Idriss and Boulanger (2008), Doygun et al.(2019) and Wei et al.(2020) have been expressed the relationship between N_L and CSR as like this equation. Coefficients c and d are fitting parameters of the equation.

$$CSR = c.\, N_L^{-d} \tag{5.2}$$

The variation of c and d coefficients in Equation 5.2 with Dr is given in Table 5.10.

Table 5.10 : Coefficients c and d gave in Equation 5.2 for Clean Sile Sand 20/30

Dr	c	d	R^2
30	0.179	0.267	0.99
50	0.241	0.269	1
70	0.322	0.269	1

Table 5.11 : Coefficients c and d gave in Equation 5.2 for Sile Sand 20/30+IZ

FC	Dr	c	d	R^2
15	30	0.215	0.225	1
15	50	0.257	0.208	1
15	70	0.201	0.116	0.93
20	30	0.237	0.266	0.99
20	50	0.278	0.253	1
20	70	0.317	0.238	1

Table 5.12 : Coefficients c and d gave in Equation 5.2 for Sile Sand 20/30+TT

FC	Dr	c	d	R^2
15	30	0.180	0.197	0.93
15	50	0.205	0.176	1
15	70	0.216	0.149	0.99

Table 5.13 : Coefficients c and d gave in Equation 5.2 for Sile Sand 20/30+SI

FC	Dr	c	d	R^2
10	30	0.162	0.182	1
10	50	0.175	0.153	0.99
10	70	0.184	0.131	0.97
20	30	0.177	0.415	0.98
20	50	0.191	0.261	1
20	70	0.197	0.189	1

The variation of c and d coefficients in Equation 5.2 with CSR is given in Tables 5.10, 5.11, 5.12, 5.13. c and d are the coefficients of the power function, and the values should be expected to be influenced by many properties of the soil (e.g., relative density, grain size distribution, FC, plasticity, silt gradation characteristic, etc.). Accordingly, there is a linear relationship between the coefficient c and Dr in both clean and silty sands. However, the slope of the relationship in clean sand is relatively high compared to silty sands. That means that as Dr increases, the coefficient c increases more rapidly in the clean sand. In other words, c is more sensitive to Dr in clean sand. The change of the coefficient of d with Dr was shown in Table 5.10. to Table 5.13. Moreover, the coefficient of d in clean sand was not affected by Dr, but the coefficient of d decreased in silty sands as Dr increased.

5.2 Verification of the Comparison Basis and Effect of Relative Density on Cyclic Resistance Ratio (CRR) of Sile Sand 20/30

In addition to the mentioned above parts of the thesis, liquefaction resistance for an earthquake of selected magnitude was determined from the CSR vs. N_L graph. 20 uniform cyclical loading from the laboratory data is chosen as the cyclic resistance ratio (CRR). (CRR = CSR [@ N_L = 20]) were determined with Equation 5 1 and 5.2 for different relative density values of clean and silty sand. In Figures 5.15 to 5.20, the changes in the liquefaction resistance of silty sands at various fines contents are presented. As known, the liquefaction behavior of clean and silty sands is affected by many parameters. The literature review in Chapter 2 presented some of them. In this context, the void ratio(e) and the relative density (Dr) were different comparison basis and both affected the liquefaction resistance analysis. The effect of fines content in the experiments performed in this chapter will be discussed based on relative density and void ratio, respectively. Therefore, the effect of relative density and fines content and/or effect of void ratio and fines content will be discussed according to experimental results. There are many arguments in Figure 5.15 and Figure 5.16. Perhaps the most important of these were coupled effect of fines content and relative density on the change of liquefaction resistance of silty sands. As shown in Chapter 2, researchers and engineers have discussed whether the presence of fines content affects the liquefaction resistance of sands positively or negatively. However, as can be seen from this thesis's analysis, this question does not have a single answer, but the answer varies depending on the relative density, fines content, and the type of silt used. For example, when using IZ silt, between Dr = 30% to Dr=60%, silty sand's liquefaction resistance with 15% silt content and 20% silt content is very close to each other. In the 20% silt content, silty sand's liquefaction resistance is more than the liquefaction resistance of clean sand in the whole Dr range. Another observation in Figure 5.15 is; when FC is 15% and Dr is increasing to 70% (behaving densely), the liquefaction resistance of silty sand decreases. CRR curves diverge to each other when fines content is 15% and 20% and Dr=70%. In dense soil ,FC=20% becomes more resistant than FC=15%.

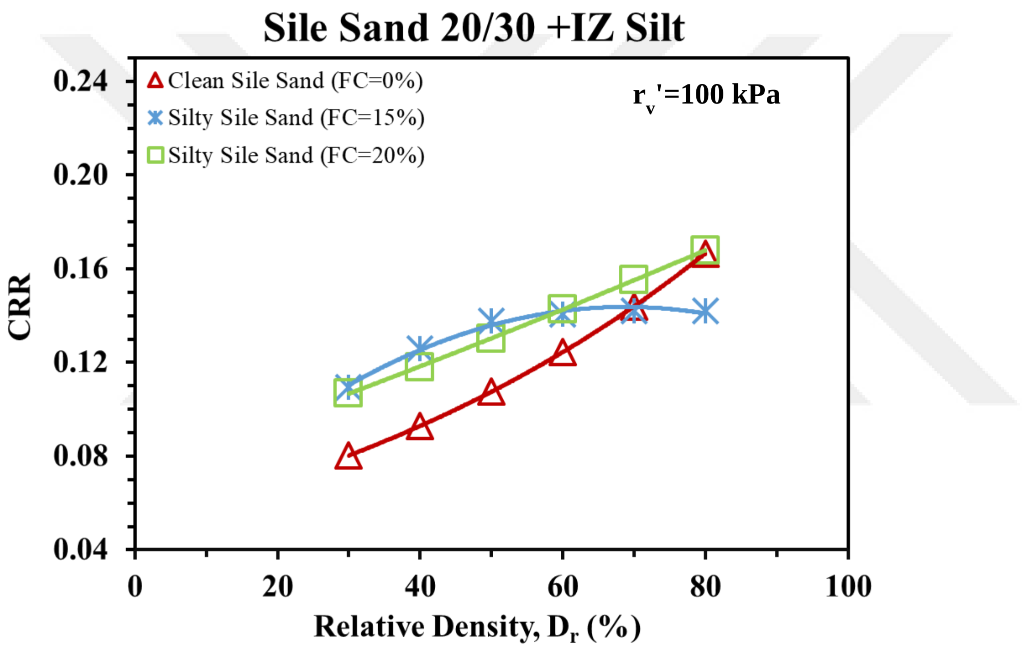


Figure 5.15 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+IZ Silt vs. relative density (Dr) at different fines content (FC)

In order to verify the literature review observations within this thesis, the laboratory experiment results were analyzed according to the void ratio (e=0.5-0.6), as shown in Figures 5.16. As the void ratio increased, the liquefaction resistance of soil has decreased. On the other hand, clean sand's liquefaction resistance is higher than the liquefaction resistance of silty sands. The results are apparent in the void ratio comparison basis. However, there is a complex argument when the CRR graphs are plotted concerning relative density. For CRR graphs plotted versus void ratio, it is seen that CRR decreases as the fines content increases in the selected void ratio. That shows us both the effect of fines content on the liquefaction resistance and also the complex effect with relative density (or with a different parameter) should be examined together.

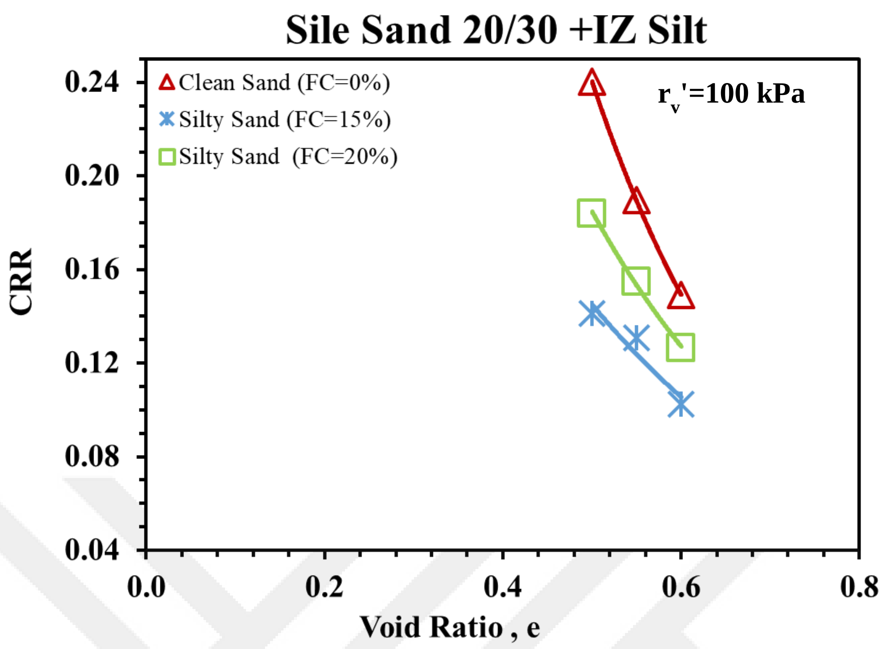


Figure 5.16 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+IZ Silt vs. void ratio (e) at different fines content (FC)

When Figure 5.17 is examined in a loose state, sand's liquefaction resistance with 15% TT silt content is higher than the liquefaction resistance of clean sand. While relative density is almost equal to 63% and at greater values (as the soil becomes dense), clean sand becomes more resistant. Besides, this finding is observed in samples with SI silt. The liquefaction resistance of clean sand is more than sand containing 25% silt content for the whole relative density range. Loose soils specimen containing 25% TT silt could not be performed experimentally, as shown in Figure 5.17. The reason for this may be the properties of silt, the fabric of silt, etc.

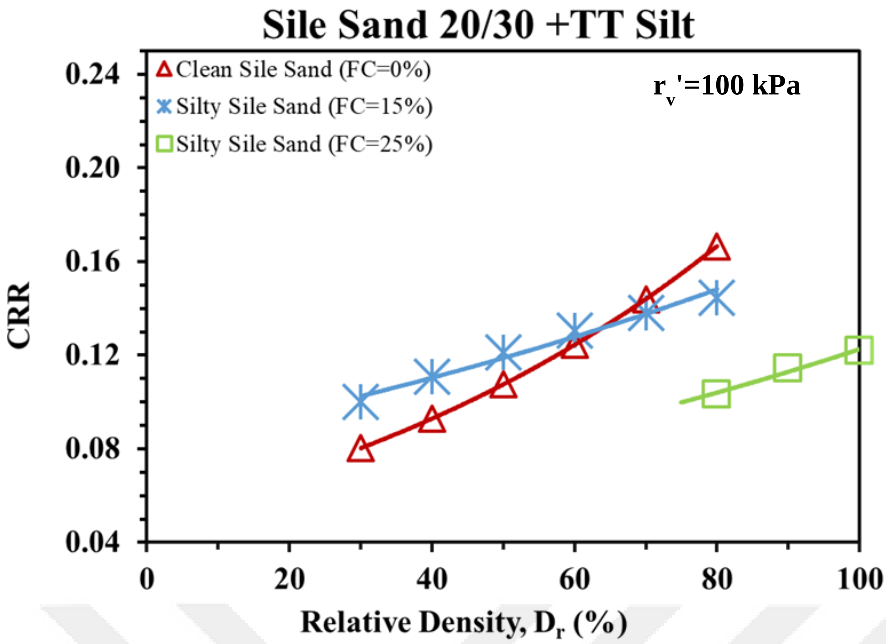


Figure 5.17 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+TT Silt vs. relative density (Dr) at different fines content (FC)

As shown in Figures 5.18, the silty sand graph's cyclic resistance ratio plotted with a void ratio comparison basis shows that the liquefaction resistance decreases as the fines content increases in the selected void ratio (0.45-0.55). However, when relative density is used the findings are more detailed. One of this thesis's purposes is to draw attention to this issue.

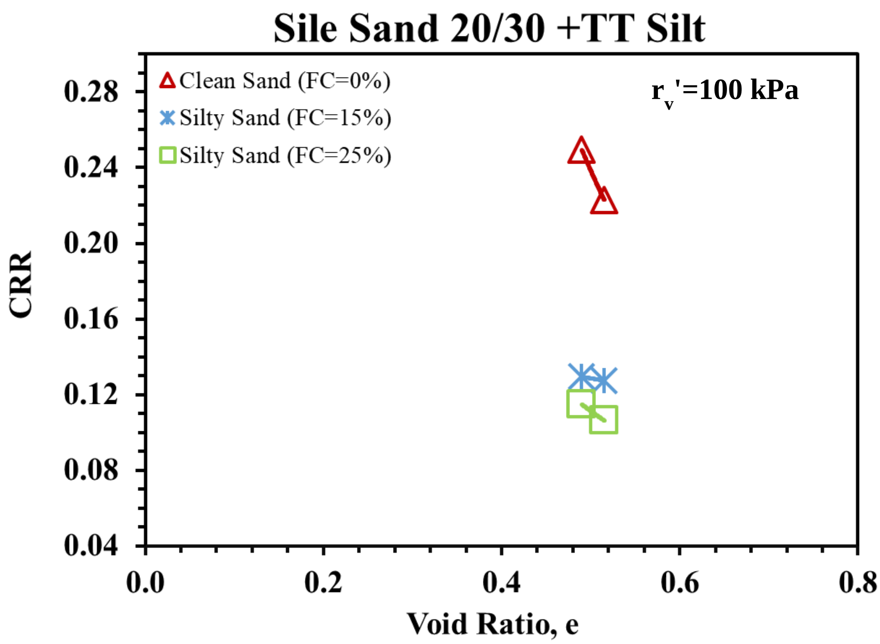


Figure 5.18 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+TT Silt vs void ratio (e) at different fine content (FC)

When SI silt is used in a loose state, the liquefaction resistance of sand with 10% silt content is higher than the liquefaction resistance of clean sand. While relative density is almost equal to 53% and even at greater values (as the soil becomes denser), clean sand becomes more resistant. The liquefaction resistance of clean sand is more than sand containing 20% silt content (for the whole relative density range). Another interesting observation in Figure 5.19 is that; the CRR curves at fines content of 10% and 20% have converged to each other when Dr increased. In other words, it can be expected that in soil improvement, the effect of the fines content on liquefaction resistance will be more significant on loose soil (e.g., Dr = 30%) compared to dense soil (e.g., Dr = 80%).

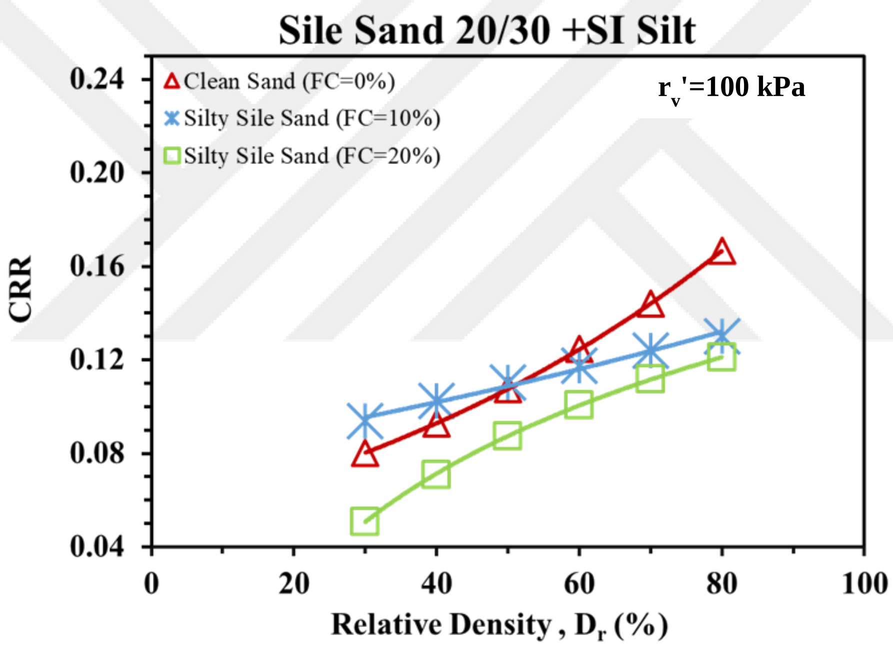


Figure 5.19 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+SI Silt vs. relative density (Dr) at different fines content (FC)

In this place, the laboratory experiments' results were analyzed according to the void ratios (e=0.5-0.6) for Sand 20/30 +SI Sılt. As shown in Figure 5.20, CRR decreases as the fines content increases for the selected void ratio. To summarize, using the void ratio as a comparison basis, the same results were obtained in all three silty sands. In the more detailed discussion, the findings are quite striking. When the literature findings were reviewed, it was proven that the research about liquefaction resistance of soils was generally performed with constant relative density or a few relative density values. The handicap is that; the fines content has changed with a constant relative density. That may mean that any part of Figure 5.16 or Figure 5.20 can be used to make comments for the selected relative density. In this thesis, a wide range of relative density values were used in experimentation. When the experimental results were carefully analyzed, the findings' complexity showed that the literature was incomplete. Relative density is a commonly used parameter in both research and practice linked to several in-situ tests. For this reason, relative density was selected as a comparison basis and then liquefaction resistance analysis was performed in this thesis. Moreover, wide range of Dr values was tested uniquely. As a result, it is argued that relative density and fines content complexly affect soils' liquefaction resistance.

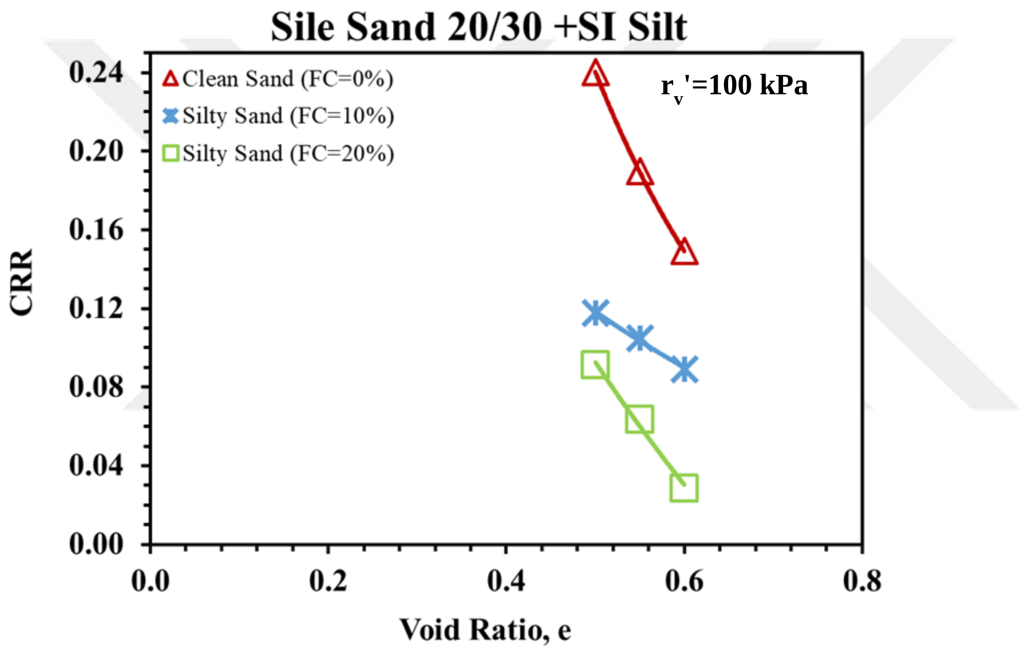


Figure 5.20 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+SI Silt vs. void ratio (e) at different fine content (FC)

5.3 Investigation of the Complex Effect of Relative Density, Fines Content and Gradation of the Silts on the Cyclic Resistance Ratio(CRR) of Sile Sand 20/30

The number of cycles to cause liquefaction is one of the most important parameters which indicate the cyclic strength of soil specimen. In this study, liquefaction resistance of soil (CRR) was chosen as the cyclic stress ratio required for liquefaction in 20 cycles of loading (CSR[@N_L=20]). Using Equations 5.1 and 5.2, the CRR values can be calculated, or the value corresponding to the 20th number of the cycle in the N_L-CSR graph can be taken as liquefaction resistance of the soil. The liquefaction resistance graph can be seen in the previous part e.g., Figures 5.15, 5.17, and 5.19.

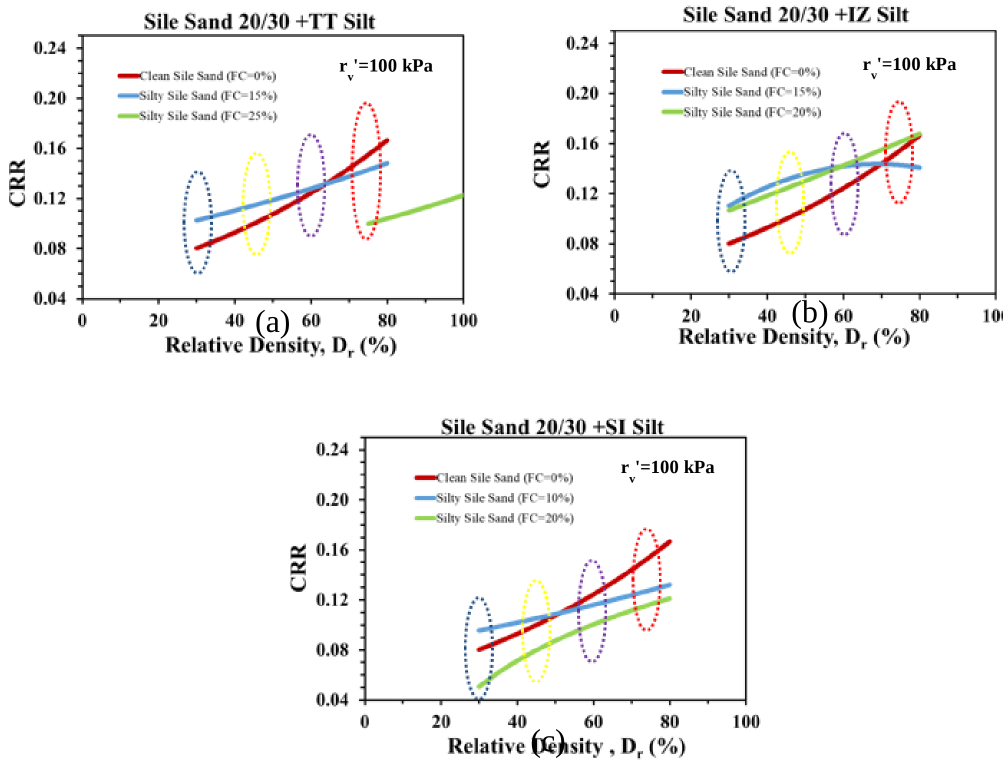


Figure 5.21 : Comparison of the liquefaction resistance of different silty soils at Dr=30% , Dr=45% , Dr= 60% , and Dr=75%

When three different silty samples were analyzed in the same Dr, an argument was obtained about different silty soils' liquefaction resistance. In addition to the significant findings mentioned above, in this analysis, the same relative density (30, 45, 60, and 75%) values were used to compare the liquefaction resistance of a different type of silty sands. Liquefaction resistance of silty sands with various fines content percentages was evaluated. In four different relative densities, the liquefaction resistance of silty sand was compared as circled in Figure 5.21. Nevertheless, previous studies in literature generally focused on a constant void ratio or constant relative density. However, experiments in this thesis have been performed for a wide range of relative densities. That allows a better inference when determining silty sands' resistance to liquefaction. To deal with this topic in detail, SI silty sand was selected and evaluated at four relative densities, as in Figure 5.21(c). Other enlarged graphs about the relative density effect on fines content influence can be seen in Figure 5.22 and Figure 5.23. Figure 5.22 shows silty sand curves (FC=10% and 20%), and Figure 5.23 shows clean Sile Sand with FC=10%. The bar-chart figures in this graph demonstrated the trend of liquefaction behavior affected by the complex effect of relative density and fines content. For example, increasing FC from 10% to 20% had decreased Sile sand's liquefaction resistance curves. However, the curves approach each other as relative density increases towards dense states. This behavior can be seen more simply in the bar-chart in Figure 5.22.

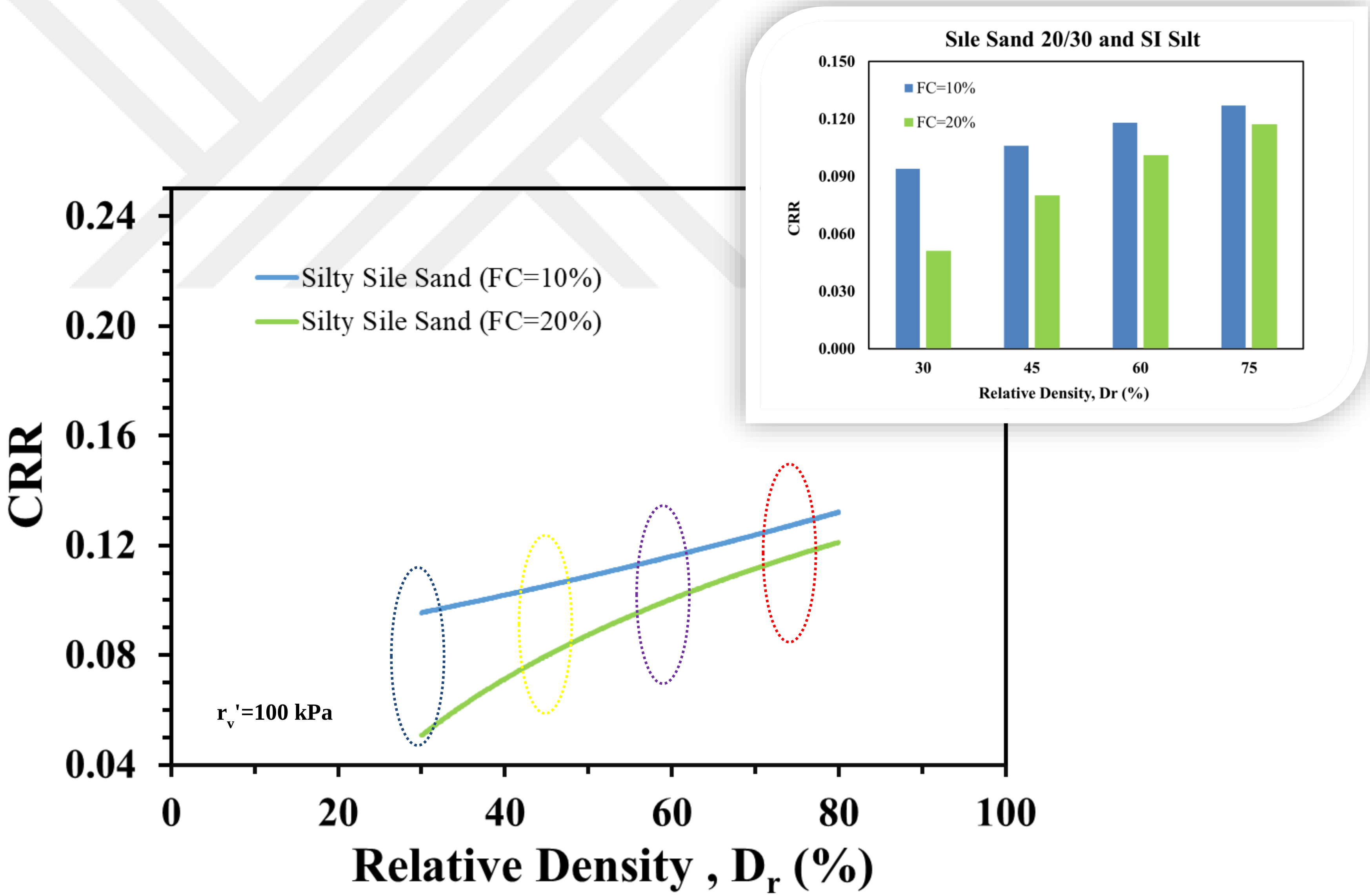


Figure 5.22 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+SI Silt vs. relative density (Dr) at FC=10% and 20% Dr=30% , Dr=45% Dr= 60% , and Dr=75

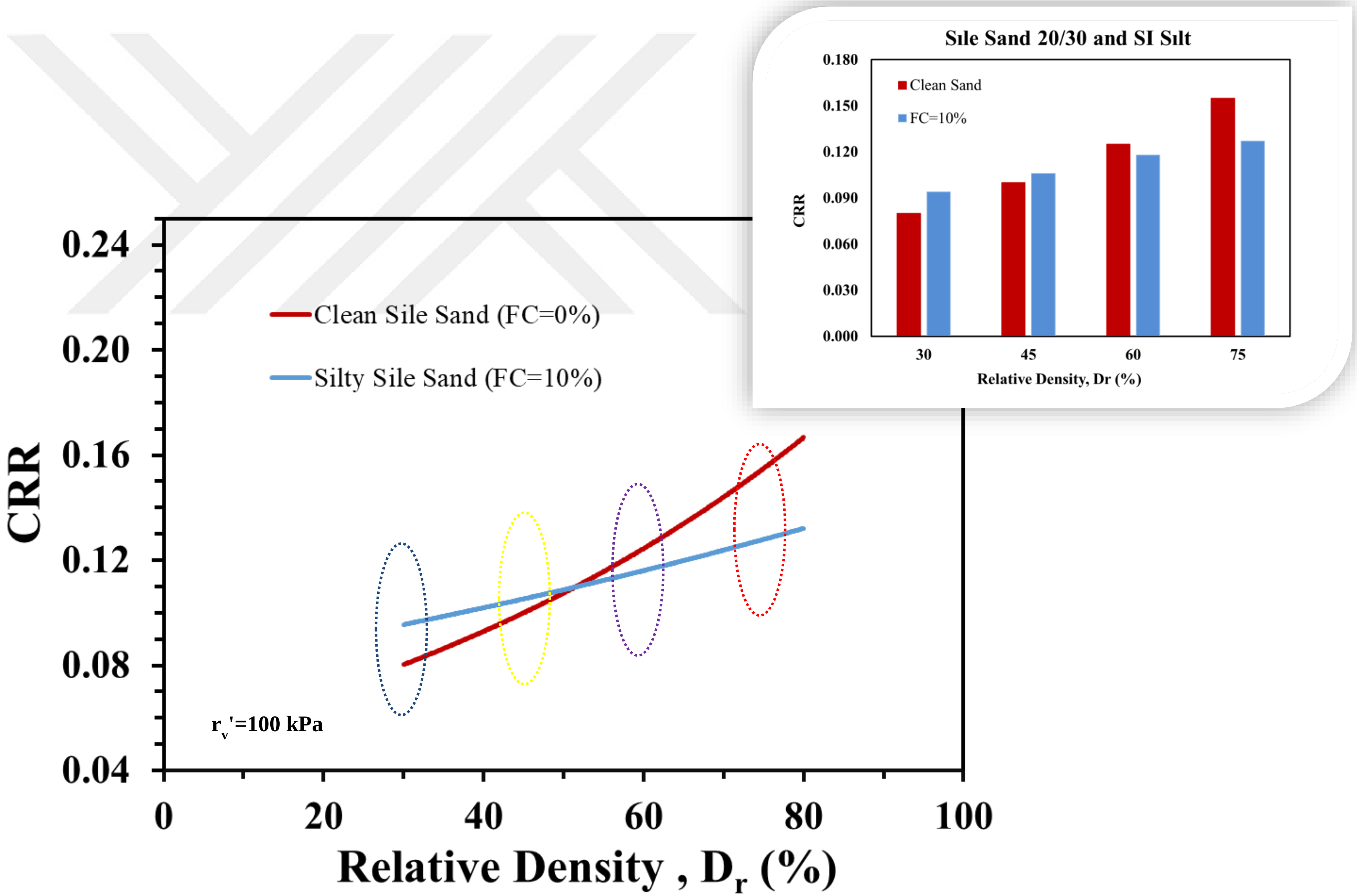


Figure 5.23 : The cyclic resistance ratio (CRR) of Sile Sand 20/30+SI Silt vs. relative density (Dr) at FC=0% and 10% Dr=30% , Dr=45% Dr= 60% , and Dr=75%

The literature data represent only one of these circles because of generally been analyzed at a constant relative density. For this reason, they may comment "silt content makes a positive or negative effect on the liquefaction resistance of silty sand." However, this study argued exciting findings such as the crossing of liquefaction resistance curve at a specific relative density. The discussions about the effect of fines content on three different silty sands and crossing of liquefaction resistance curve reveal that the magnitude of relative density could seriously effect of the influence of fines content.

The change of CRR with fines content of different silts was shown in Figure 5.15, Figure 5.17, and Figure5.19 for selected relative density values. Several trends can be observed in these graphs. These trends form the logical basis of the thesis. The most important one is that CRR of the same base sand is influenced by different silts even though important factors such as relative density (Dr), fines content (FC) and plasticity of the fines, base sand gradation, stress history, loading conditions, etc. are kept the same. In general, these figures imply that at the same Dr and FC, the liquefaction resistance of Sile Sand 20/30 changes with the order of $CRR_{IZ\ silt}$ > $CRR_{TT\ silt}$ > $CRR_{SI\ silt}$ for the studied fines content range. In order to understand to reasons behind such an order, as well as an additional important factor influencing the liquefaction resistance except for the complex effect of relative density and fines content, experiment results were examined. The change of CRR of Sile Sand 20/30 with the addition of IZ, TT, and SI silts was compared for the selected relative density values (Dr=30%, 45%, 60%, 75%). Figures 5.24 to 5.27 show the comparison of CRR with fines content. For Dr = 30%, the liquefaction resistance of Sile Sand 20/30 + IZ Sılt and Sand 20/30 +TT Sılt increased until the fines content reached up to 15%. Although the CRR shows a decrease for 20/30 + IZ Silt afterward, both samples' liquefaction resistance is higher than clean Sile Sand 20/30 for every fines content. However, in the Sile Sand 20/30 + SI Silt sample, it is seen that the liquefaction resistance after FC= 14 % is lower than clean Sand 20/30 (Figure 5.24).

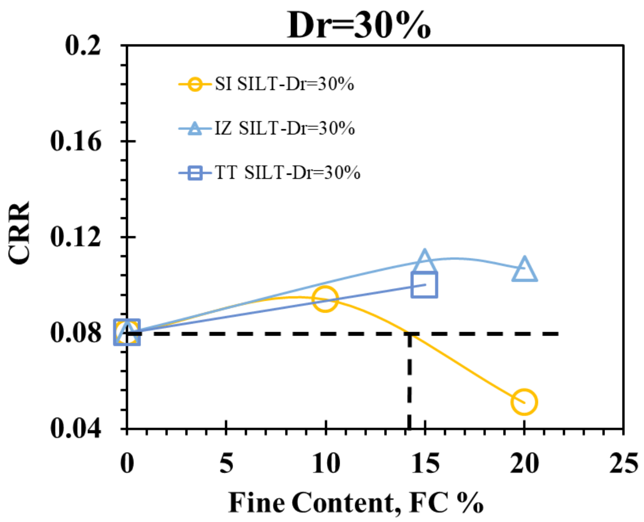


Figure 5.24 : The cyclic resistance ratio (CRR) of soil vs. FC, Dr=30%

When Figure 5.25 is examined, in samples with a Dr=45%, the liquefaction resistance of Sand 20/30 + IZ Silt and Sand 20/30 +TT Silt increased until the fines content reached up to 15%. Although the CRR shows a decrease for 20/30 + IZ Silt, after 15% FC, both samples' liquefaction resistance is higher than clean Sand 20/30 for every fines content. However, in the Sand 20/30 + SI Silt sample, it is seen that the liquefaction resistance after FC= ~13% is lower compared to the clean Sand 20/30.

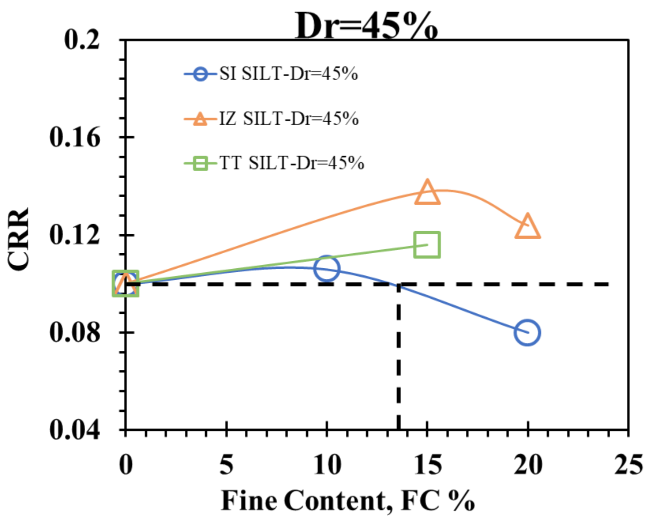


Figure 5.25 : The cyclic resistance ratio (CRR) of soil vs. FC, Dr=45%

In Dr = 60%, the liquefaction resistance of Sand 20/30 + IZ Silt and Sand 20/30 +TT Silt increased as fines content increased. As seen in Figure 5.26, the Sand 20/30 + SI Silt sample has a decreasing liquefaction resistance similar to the previous Dr values. As the relative density increased (became denser), significant changes occurred in the CRR. Figure 5.27 shows that the liquefaction resistance for all samples decreased as fines content increased.

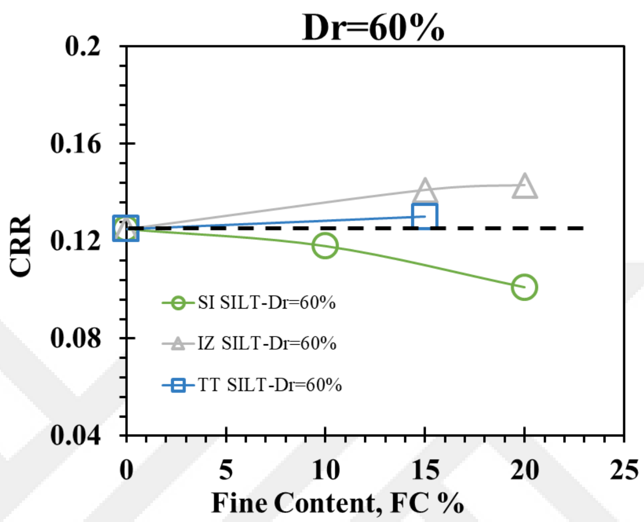


Figure 5.26 : The cyclic resistance ratio (CRR) of soil vs. FC, Dr=60%

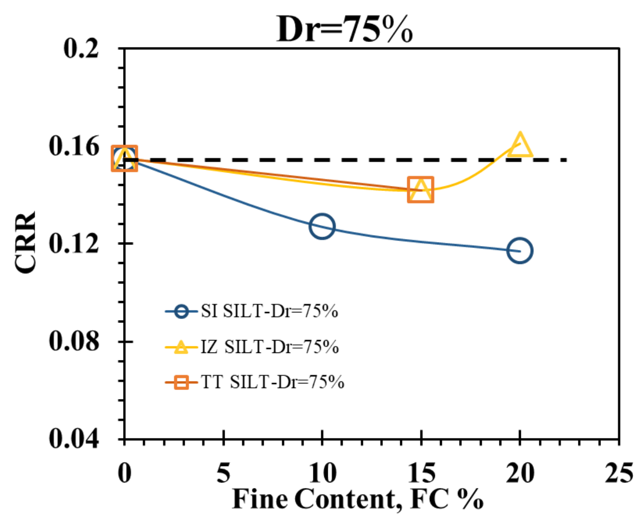


Figure 5.27 : The cyclic resistance ratio (CRR) of soil vs. FC, Dr=75%

5.4 Effect of Soil Gradation on Cyclic Resistance Ratio (CRR) of Sile Sand 20/30

Although the effects of the fines content have been studied considerably, the liquefaction resistance changes for the same fines content ratio using different silts were not discussed in the literature. The previous chapter proves that is the CRR of the same base sand is influenced by different silts even if essential factors are the same (such as relative density (Dr), content (FC) and plasticity of the fines, base sand gradation, stress history, loading conditions kept the same). The liquefaction resistance of Sile Sand 20/30 with silt changed with the order of $CRR_{IZ\ silty\ sand}$,> $CRR_{TT\ silty\ sand}$ >$CRR_{SI\ silty\ sand}$ for the studied fines content range. The results are discussed with different aspects in this thesis to understand the differences in the liquefaction resistance. These discussions have brought exciting findings. For example, the effect of gradation parameters of silt on the liquefaction resistance of silty sand is not known. This thesis aims to enlighten and discuss these topics. Finally, in this chapter, the effect of the gradation properties (e.g., mean grain diameters(D_{50}, d_{50}) and coefficient of uniformity of soil (CU)) of the tested soils was examined on the liquefaction resistance of the soil. Several analyses were made by using the mentioned parameters in correlations in this context. The first of these is the disparity ratio, (χ.). Monkul and Yamamuro (2011) used the particle-size disparity, represent the size difference between the base sand and the silt, which can be characterized by a particle-size disparity ratio (χ) defined in Equation 5.3.

$$\chi = \frac{D50sand}{d50silt} \tag{5.3}$$

D_{50} and d_{50} are the characteristic particle size of the base sand and the fines.

Table 5.14 : Details of gradation effect parameter, Dr=45%

Soil Type	FC	D_{50}sand	d_{50}silt	$\chi=D_{50sand}/d_{50silt}$	CRR
Sand 20/30	0	0.565	-	-	-
IZ Sılt	15	-	0.022	25.68	0.138
IZ Sılt	20	-	0.022	25.68	0.124
SI Sılt	10	-	0.017	33.24	0.106
SI Sılt	20	-	0.017	33.24	0.080
TT Sılt	15	-	0.0103	54.85	0.116

In this chapter, all the analyses have been done for Dr = 30, 45, and 60 %. All relative densities have the same trend. Therefore, the tables and graphs were given for only Dr= 45% to summarize the main idea. The D_{50}sand and d_{50}silt values of the soil used were shown in Table 5.14. The change of the liquefaction resistance of the soils (CRR) with χ was given in Figure 5.28.

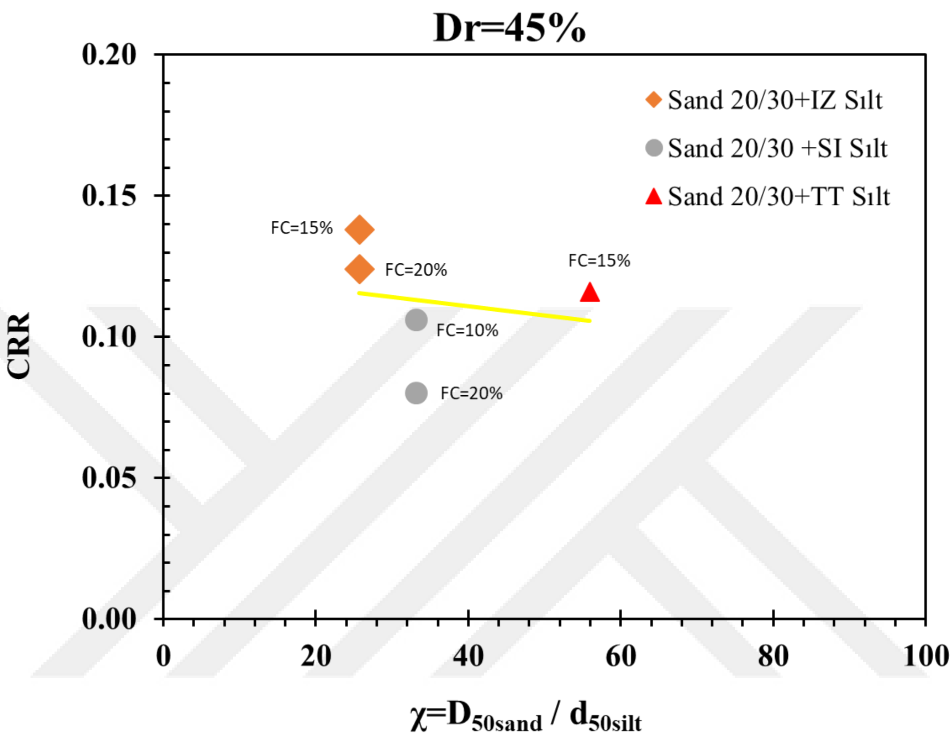


Figure 5.28 : The cyclic resistance ratio (CRR) of silty soil vs. $\chi = D_{50sand}/d_{50}$silt ,Dr=45%

The coefficient of uniformities for silts (CUsilt) and the coefficient of uniformities for silty sands (CUoverall) was shown in Table 5.15. CUoverall represents soil uniformities obtained from different silt sand mixtures various fines contents. The grain size distribution of these soils was mentioned in Chapter 3. The liquefaction resistance of silty sand versus CUsilt and CUoverall was given in Figure 5.29 and Figure 5.30. When the coefficient of uniformities was used alone, there is no clear relationship between the coefficient of uniformities and CRR in the analysis. Therefore an efficient prediction is not made.

Table 5.15 : Details of gradation effect parameter,Dr=45%

Soil Type	FC	CUsilt	CUoverall	CRR
IZ Sılt	15	4.60	16.19	0.138
IZ Sılt	20	4.60	25.68	0.124
SI Sılt	10	18.77	7.93	0.106
SI Sılt	20	18.77	31.39	0.080
TT Sılt	15	10.6	28.44	0.116

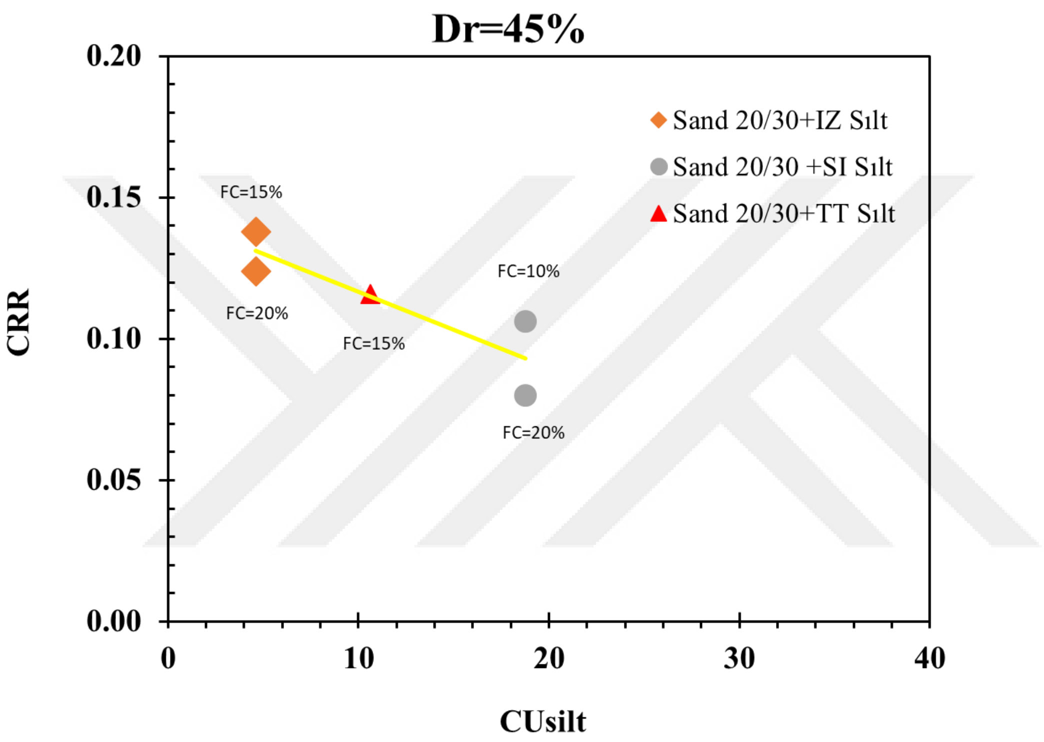


Figure 5.29 : The cyclic resistance ratio (CRR) of silty soil vs. CU_{silt}, Dr=45%

The coefficients of uniformities (CUsilt) in Figure 5.29 represents the silts' CU only. However, the values of CRR placed in the graph are the liquefaction resistance of silty sands containing different silt contents. Although the silty sands have different liquefaction resistances because of different silt contents, the coefficients of uniformity of silt (CUsilt) are the same. For this reason, there is not a reliable relationship between the coefficients of uniformity of silts and liquefaction resistance of soils (Figure 5.29). Liquefaction resistance values are the results of silty sand, as mentioned above. Due to the reason that the coefficients of uniformity are calculated from the mixture of sand and silt, slightly more logical results were obtained when

CUoverall was used(Figure 5.30). However, a full relationship between CUoverall and the liquefaction resistance of soils was not established.

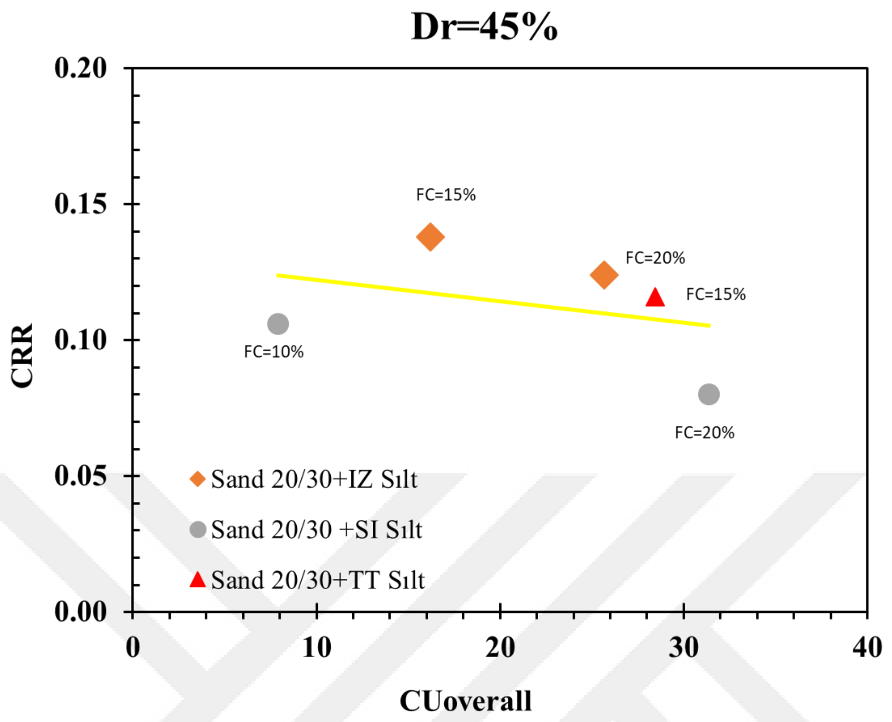


Figure 5.30 : The cyclic resistance ratio (CRR) of silty soil vs. CUoverall, Dr=45%

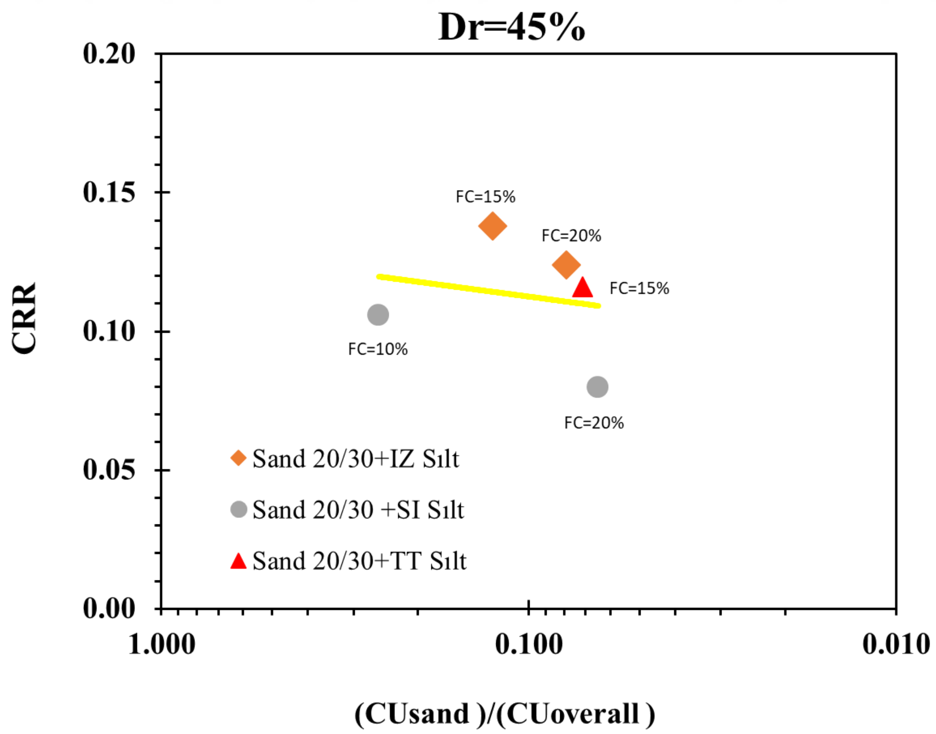


Figure 5.31 : The cyclic resistance ratio (CRR) of silty soil vs. (CU sand)/(CUoverall), Dr=45%

Satisfactory relations were not detected with the above comparisons basis on the analysis performed. Therefore, new correlations were wanted to be tried in the analysis. For example, Figure 5.31 (CUsand) / (CUoverall) was used as an analysis basis. (CU sand) / (CUoverall x FC) was also tried, and no successful relationship was obtained (Figure 5.32).

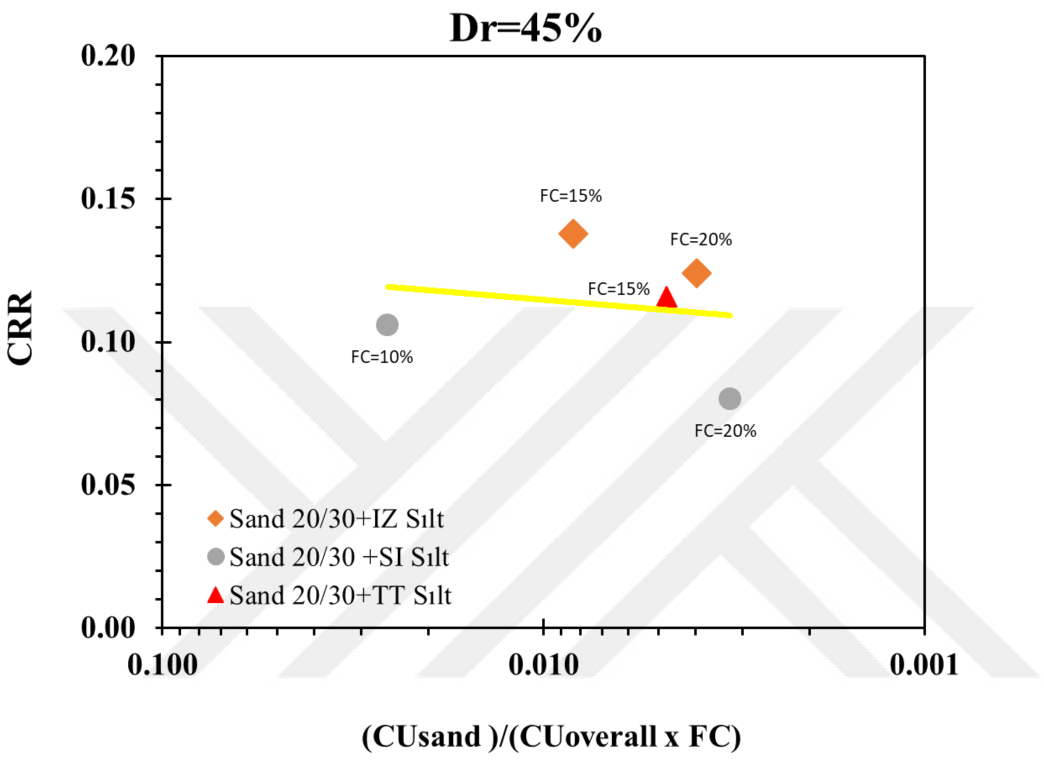


Figure 5.32 : The cyclic resistance ratio (CRR) of silty soil vs. (CUsand)/(CU overall x FC), Dr=45%

The compatible correlations between cyclic liquefaction resistance and gradation parameters have not resulted in the analysis. Accordingly, a correlation was proposed, in which both the coefficient of uniformities and fines content is taken into account. (CU sand)/(CU silt x FC) represents the coupled effect of soil gradation and fines content on the cyclic resistance ratio of the soil. As a result of the analysis, it was observed that this was the best correlation. Table 5.16 indicates the coefficient of uniformity (CU) and fines content values of the soil used. The liquefaction resistance of soils (CRR) was decreased as (CU sand)/(CU silt x FC) decreased.

$$CRR = m_1 . \ln(CUsand)/(CUsilt \times FC) + m_2 \quad (5.4)$$

Equation 5.4 is obtained from the trendline fitted into the data points, which can be observed in Figure 5.33. Coefficients of m_1 and m_2 are fitting parameters of Equation 5.4.

Table 5.16 : Details of gradation effect parameter, Dr=45%

Soil Type	CU	FC	(CUsand)/(CUsilt x FC)	CRR
Sile Sand 20/30	2.03	-	-	-
IZ Sılt	4.60	15	0.029	0.138
IZ Sılt	4.60	20	0.022	0.124
SI Sılt	18.77	10	0.011	0.106
SI Sılt	18.77	20	0.005	0.080
TT Sılt	10.6	15	0.013	0.116

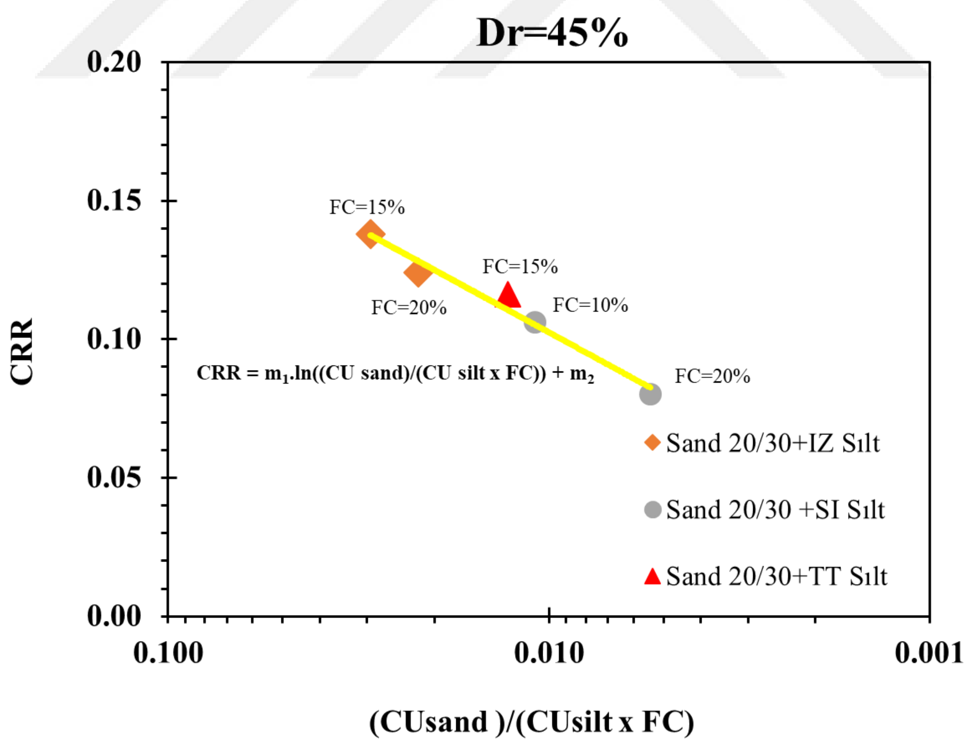


Figure 5.33 : The cyclic resistance ratio (CRR) of silty soil vs. (CUsand)/(CUsilt x FC) ,Dr=45%

The analysis was performed with Dr = 30% and Dr = 60% using the formula given in Equation 5.4. The analysis results were consistent with each other, as seen in Figures 5.33, 5.34, and 5.35. The liquefaction resistance of soils (CRR) has decreased as (CUsand)/(CUsilt x FC) decreased at constant relative density.

Table 5.17 : Details of coupled gradation effect parameter, Dr=30%

Soil Type	CU	FC	(CUsand)/(CUsilt x FC)	CRR
Sile Sand 20/30	2.03	-	-	-
IZ Sılt	4.60	15	0.029	0.110
IZ Sılt	4.60	20	0.022	0.108
SI Sılt	18.77	10	0.011	0.094
SI Sılt	18.77	20	0.005	0.051
TT Sılt	10.6	15	0.013	0.100

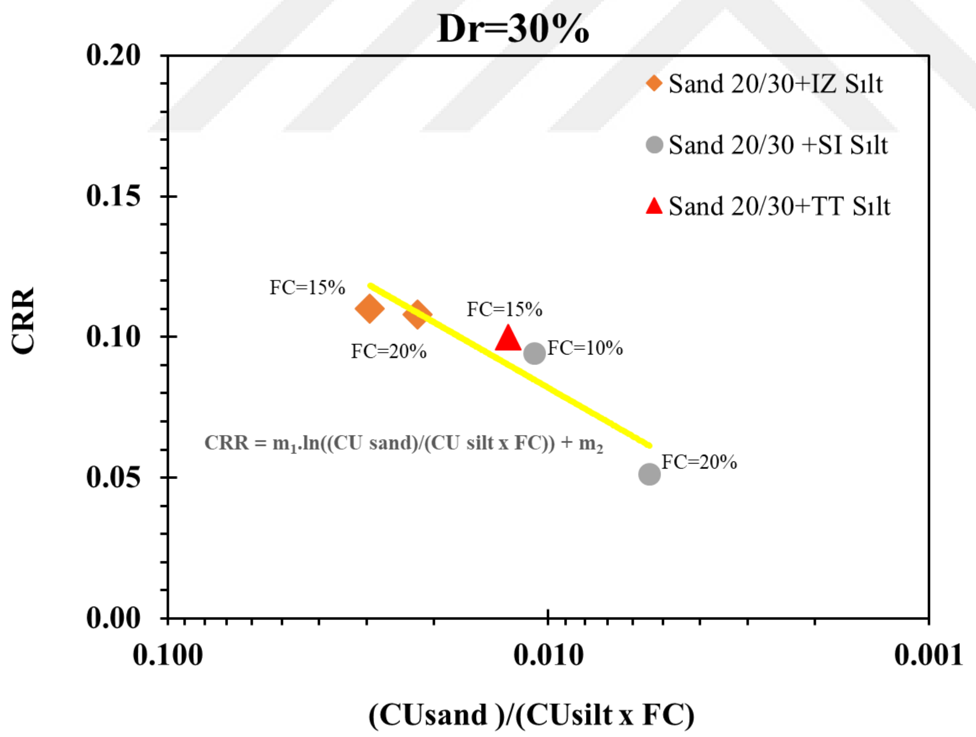


Figure 5.34 : The cyclic resistance ratio (CRR) of silty soil vs. (CUsand)/(CUsilt x FC) ,Dr=30%

Table 5.18 : Details of coupled gradation effect parameter, Dr=60%

Soil Type	CU	FC	(CUsand)/(CUsilt x FC)	CRR
Sile Sand 20/30	2.03	-	-	-
IZ Sılt	4.60	15	0.029	0.141
IZ Sılt	4.60	20	0.022	0.143
SI Sılt	18.77	10	0.011	0.118
SI Sılt	18.77	20	0.005	0.101
TT Sılt	10.6	15	0.013	0.130

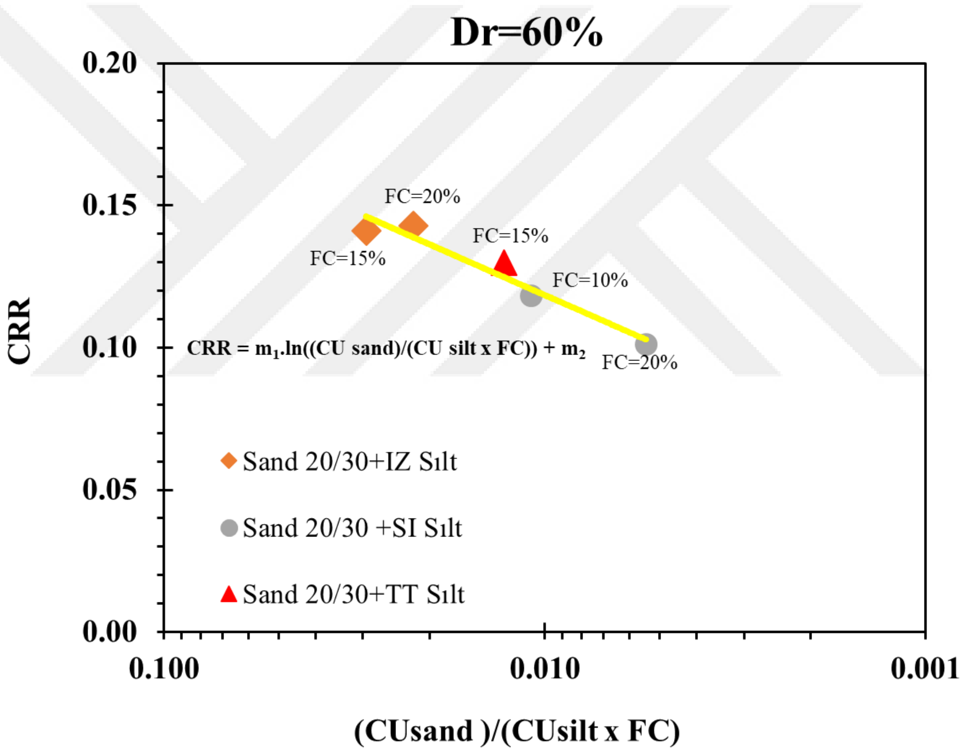


Figure 5.35 : The cyclic resistance ratio (CRR) of silty soil vs. (CUsand)/(CUsilt x FC) ,Dr=60%

m_1 and m_2 are the correlation coefficients of silty sand specimens for at Dr=30,45 and 60 % and are shown in Table 5.19.

Table 5.19 : Coefficients m_1 and m_2 given in Equation 5.4

Relative Density, Dr (%)	m_1	m_2
30	0.0337	0.2371
45	0.0325	0.2523
60	0.0256	0.2363

m_1 and m_2 are influenced by both base sand gradation and the magnitude of relative density. Another question that come to mind is whether the effect of the silt shapes on the liquefaction resistance of the silty sand has been examined? Examination of the effect of silt shape is excluded from the scope of this thesis. However, possibly influenced by both sand and silt gradations as well as other factors such as shape effects. Unfortunately, the available data in the literature regarding the coefficient of uniformities of specimens that have shown the liquefaction resistance of silty sand is extremely limited. In order to determine the compatibility of the proposed equation, data from the literature were used. For this, both gradation curves and CRR data were used. In literature data, as in the experiments carried out within this thesis, the liquefaction resistance of soils (CRR) was also decreased as (CU sand)/(CUsilt x FC) decreased. That proves the reliability of the researcher's test results.

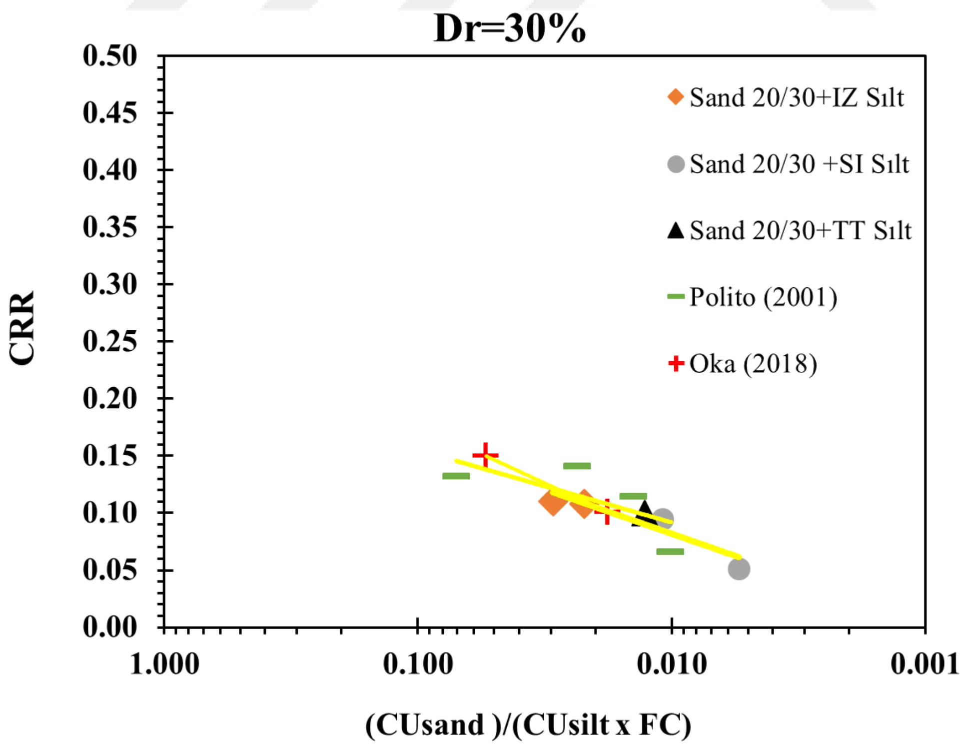


Figure 5.36 : The cyclic resistance ratio (CRR) of silty soil vs. coupled gradation effect, Dr=30%

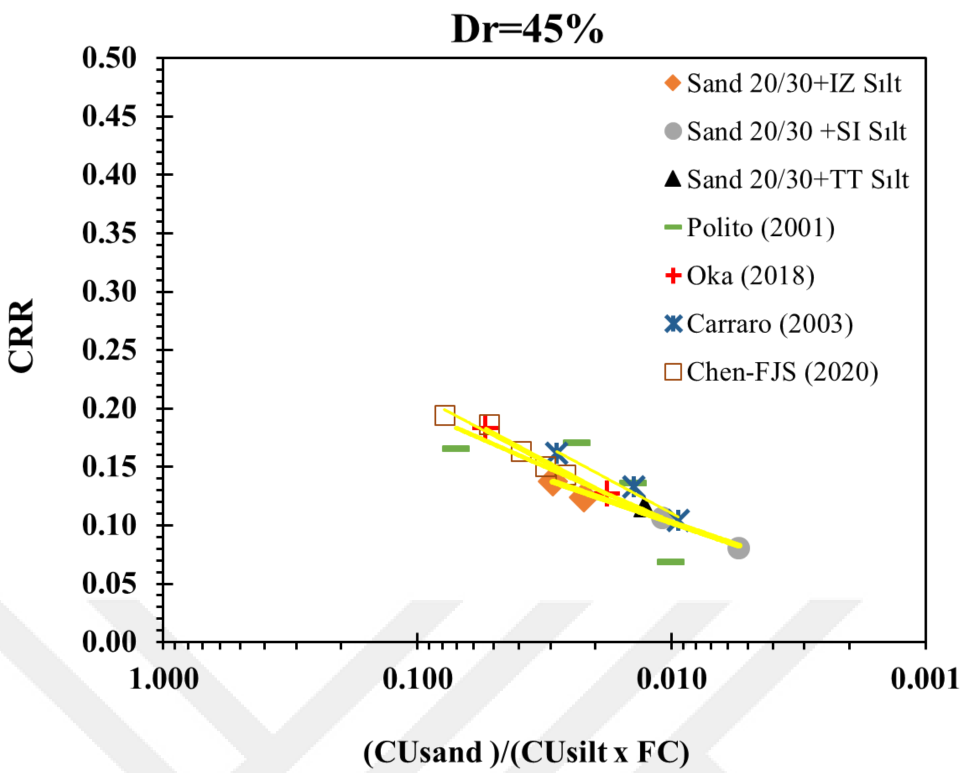


Figure 5.37 : The cyclic resistance ratio (CRR) of silty soil vs. coupled gradation effect, Dr=45%

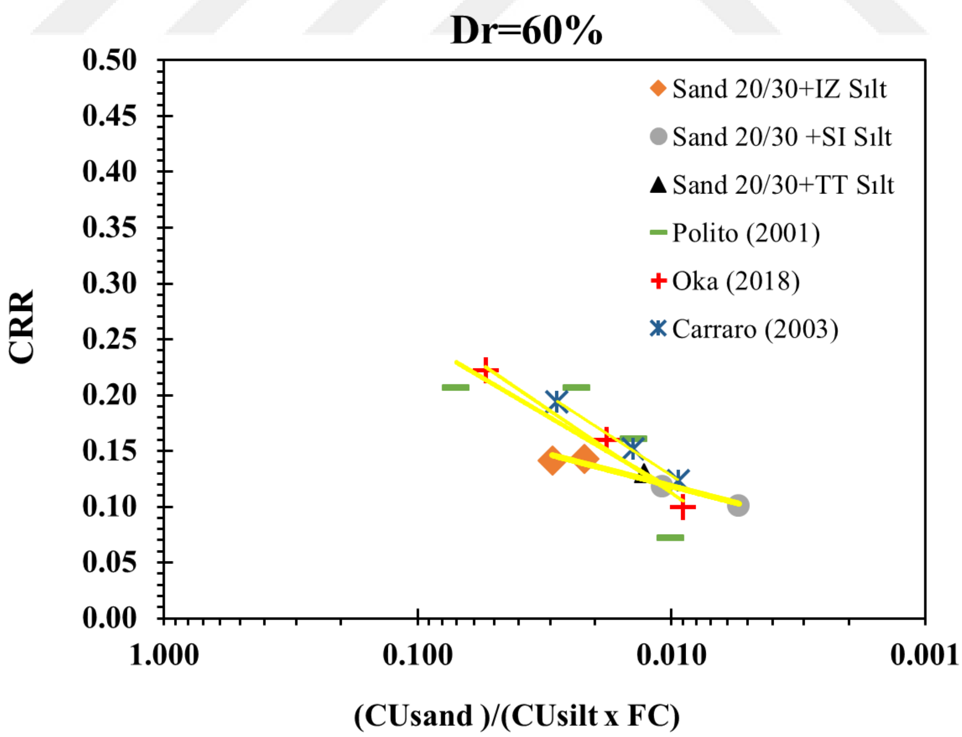


Figure 5.38 : The cyclic resistance ratio (CRR) of silty soil vs. coupled gradation effect, Dr=60%

In assessments of liquefaction for silty sands, mostly PI (Atterberg limits) and/ or fines content takes into account. This thesis showed that the effect of fines content might be significantly affected by the fines' nature. The resulting liquefaction resistance of soil response of sand can be different for the same fines content or same relative density, depending on the silt gradation. This study proves that is the liquefaction resistance of silty sand is influenced by different silts even if essential factors are the same (such as relative density (Dr), content (FC) and plasticity of the fines, base sand gradation, stress history, loading conditions kept the same). The liquefaction resistance of silty sand changed with the order of $CRR_{IZ\ silty\ sand}$ > $CRR_{TT\ silty\ sand}$ >$CRR_{SI\ silty\ sand}$ for the studied fines content range. There is no clear relationship between the soil gradation parameters (such as CUsilt or CUoverall and CRR) either for clean sands or silty sands in the literature on the effect of gradation. The effect of gradation and uniformity coefficients of the silts (CUsilt and CUoverall) on the liquefaction resistance is discussed in this thesis. In consideration of the discussion about gradation effect, a correlation was proposed to predict the CRR of silty sand, in which both the coefficient of uniformities and fines content is taken into account. (CU sand)/(CU silt x FC) represents the coupled effect of soil gradation and fines content on the cyclic resistance ratio of the soil. That is an exciting finding for the contribution to the literature.

6. SUMMARY AND CONCLUSION

In this thesis, the effect of relative density, fines content, and particle size on liquefaction was investigated. For this purpose, Sand 20/30 specimens with IZ, TT, SI silt were tested via Cyclic Dynamic Simple Shear device under constant shear stresses. The tests were performed in undrained constant-volume conditions. A total of 314 tests were performed on clean sand and silty sand at cyclic stress ratios (CSR) of 0.12,0.1 and 0.08. The number of cycles to liquefaction was determined as ru=1($\Delta u = \sigma_{vc}$ = 100 kPa) and/or double amplitude axial strain reached 7.5% (d. a. γ= 7.5%) for all the tests. Based on the experimental results, the following observations are obtained.

1- The effects of various factors (e.g., vertical effective stress, fines content, grain distribution, sample preparation method, etc.) on the liquefaction resistance were investigated enormously.

2- As the literature was reviewed, it can be seen that different comparison basis such as void ratio, relative density, sand skeleton void ratio, etc., had been used for investigating the effect of fines content on liquefaction resistance of sands. Because of some advantages such as being commonly used in both research and practice, relative density was selected as a comparison basis in this thesis.

3- It is known that the relative density is one of the important parameters affecting the liquefaction resistance of soils. However, in the recent literature studies, one or two constant Dr values are generally chosen. This thesis's outcome and uniqueness are that a wide range of Dr values was tested.

4- NL and Dr's relationship can be expressed exponentially for both clean and silty sands at a constant CSR value.

5- At a constant value of Dr, it can be stated that the number of cycles required for liquefaction is interrelated with the cyclic stress ratio (CSR) with a power function.

6- The coefficients in this equations are expected to be affected by the soil's properties (e.g., relative density, fines content, soil gradation, etc.).

7- An interesting finding in this thesis is that CRR vs. Dr curves for clean sand and silty sand could cross each other at a specific relative density value. It means that the cyclic liquefaction resistance of the silty sand could be either smaller or greater than that of the clean sand. It depends on the magnitude of relative density.

8- Another important argument is that the liquefaction resistance of silty sand is influenced by different silts even if essential factors are the same. This thesis showed that at the same Dr and FC, the liquefaction resistance of different silty sand changed.

9- Although the effects of the fines content have been studied considerably, the liquefaction resistance changes for the same fines content ratio using different silts were not discussed in the literature.

10- In the literature on the effect of gradation, there is no clear relationship that was able to be established between parameters of soil (e.g., CU silt or CUoverall and CRR) either for clean sands or silty sands. The effect of gradation and uniformity coefficients of the silts (CU silt and CUoverall) on the liquefaction resistance is discussed in this thesis.

11- There is no clear relationship between χ, CU, CUoverall, and CRR in the analysis using each soil's coefficient of uniformity.

12- A correlation was proposed to predict the CRR of silty sand in this thesis. In correlation coefficient of uniformities and fines content is taken into account. (CU sand)/(CU silt x FC) represents the coupled effect of soil gradation and fines content on the cyclic resistance ratio of the soil.

13- The liquefaction resistance of soils (CRR) has decreased as (CU sand)/(CU silt x FC) decreased at the constant relative density and the correlation works quite well for the silty sands in literature as well.

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