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KOLLOİDAL SİLİKA ENJEKSİYONUNUN SIVILAŞAN ZEMİNLERİN GEOTEKNİK ÖZELLİKLERİNE ETKİSİ ÜZERİNE BİR İNCELEME

A REVIEW OF THE EFFECT OF COLLOIDAL SILICA GROUTING ON THE GEOTECHNICAL PROPERTIES OF LIQUEFIABLE SOILS

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ÖZET

Ülkemizde 1999 Kocaeli Depremi ve 6 Şubat 2023 Kahramanmaraş Depremlerinde sıvılaşmaya bağlı olarak can kaybına neden olan çoğunlukla ekonomik kayıplar meydana gelmiştir. Kolloidal silika (CS), ülkemizde en sık kullanılan enjeksiyon malzemesi olan çimento şerbetine alternatif olabilecek bir malzemedir. Bu inceleme, mevcut yayınlanmış çalışmaların eleştirel bir değerlendirmesi değil, daha ziyade literatürde yayınlanmış çalışmalarda CS ile ilgili araştırma eğilimlerinin bir yansımasıdır ve bazı parametreler diğerlerinden daha derinlemesine sunulmuştur. Literatürde CS ile zeminlerin taşıma gücünün arttığı, zeminlerin G/Gmax kayma modülü değerleri ve döngüsel dayanım gibi dinamik davranış parametrelerinin arttığı tespit edilmiştir. CS enjeksiyonlu zeminlerin dinamik davranışı ve dayanım parametreleri, literatürde laboratuvar çalışmalarıyla kapsamlı bir şekilde çalışılmış olmasına rağmen, fiziksel ve saha araştırmaları ile ilgili çalışmalar hala sınırlıdır. Literatürdeki elde edilen sonuçlarda CS enjeksiyonun sıvılaşabilen zeminlerde sıvılaşma direncini arttırdığı açıkça gösterilmiştir. Özellikle, CS enjeksiyonlu zeminin kayma modülü ve döngüsel dayanımı, enjeksiyonsuz zemin numunelerinden daha yüksek olduğu bulunmuştur; ancak, zeminlerde sönüm oranının CS enjeksiyonlu zeminden ne kadar etkilendiği konusunda literatürde hala birbiriyle çelişen bazı uyumsuz sonuçlar vardır. CS enjeksiyonlu zeminin sıvılaşmayı azaltmak için zemin iyileştirme mekanizmasının boşlukları doldurup doldurmadığı veya zemin taneleri ile boşluk suyu arasındaki kohezyon/adezyon kuvvetlerini arttırdığı henüz tam olarak açıklığa kavuşturulmamıştır. Sonuç olarak, konuyla ilgili mevcut araştırmalara göre CS grout ile stabilize edilen zeminin davranışının çok karmaşık olduğu açıktır. CS enjeksiyonunda şu hususlar daha fazla araştırılmalıdır: CS enjeksiyonunun zemin sıkıştırılabilirliği üzerindeki etkileri; CS harcının sönüm oranına etkisi; Harcın zemin içinde çökme davranışı; Stabilize zeminin davranışını tanımlamak için analitik modellerin geliştirilmesi.
Anahtar Kelimeler: *Kolloidal silika (CS), zemin sıvılaşma, zemin enjeksiyonları*

ABSTRACT

In the 1999 Kocaeli Earthquake and February 6, 2023, Kahramanmaraş Earthquakes in our country, damages due to liquefaction, which caused partial life, mostly economic losses, occurred. Colloidal silica (CS) is a material that can be an alternative to cement grout, which is the most frequently used injection material in our country. This review is not a critical evaluation of existing published studies but rather a reflection of trends in studies published in the literature with some themes explored in greater depth than others. It was determined in the literature that the bearing capacity of the soils increased with CS, and the dynamic behavior parameters of the soils, such as G/Gmax shear modulus values and cyclic strength, were found to increase. Although the dynamic behavior and strength parameters of CS-injected soils have been extensively studied

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in the literature experimentally, investigations on physical and in situ models are still limited. CS injection obviously increases the liquefaction resistance of liquefiable soil. Especially, the shear modulus and cyclic strength of CS-grouted soil are found to be greater than those of the plain soil specimens; however, there is still some disagreement about how much the damping rate is affected by CS-grouting. It has not been fully clarified yet the soil improvement mechanism of CS grouted soil to mitigate liquefaction whether filling the voids or increasing the cohesion/adhesion forces between the soil grains and pore water. In conclusion, from the current state of knowledge on the subject, it is clear that the behavior of soil treated with CS grout is very complex. The following aspects in CS grouting should be investigated further: The effects of CS grout on soil compressibility; The effects of CS grout on damping ratio; The sinking behaviour in the grout delivery process; The development of adequate constitutive laws to describe the behavior of the stabilized soil.
Keywords: *Colloidal silica (CS), soil liquefaction, soil injections*

1. INTRODUCTION

Soil liquefaction occurs when the excessive pore water pressure becomes equal to the effective stress of the soil, acting as a viscous/flowable material instead of a solid during earthquakes and any shocks that occur at regular intervals in water-saturated, mostly sandy and silty soils and non-cohesive soils. During the 2023 Kahramanmaraş earthquake, soil liquefaction was observed, especially in Hatay and Adıyaman Gölbaşı (Figure 1) as well as during the Gölcük-Kocaeli 1999 earthquake. Soil liquefaction causes significant destructive effects on the ground surface and structures. In general, soil liquefaction can be defined as the sudden decrease in the shear strength of the soil due to excessive pore water pressure generation in the soil during a dynamic load. According to Terzaghi (1925), liquefaction can occur when the weight of the solid particles forming the soil is transferred to the surrounding water during the subsidence of the saturated soil. As a result of this event, the hydrostatic pressure rises at any depth of the ground, and its size approaches the unit weight of the soil submerged in water".

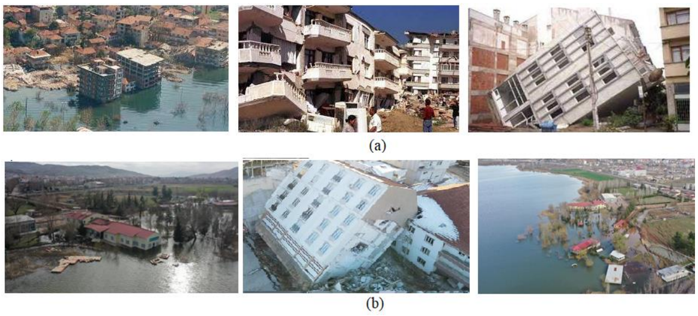

Figure 1. Destructions due to liquefaction of the ground (a) 1999 Kocaeli earthquake, (b) 2023 Kahramanmaraş earthquake

One of the most important results of Terzaghi's research is considered to be revealing the connection between effective stress and pore water pressure in soils. The concepts of effective stress and pore water pressure, which were first introduced by Terzaghi in literature, are the basis of the liquefaction mechanism. (Das 2008, Bao et al. 2019, Mollamahmutoğlu and Kayabalı 2006, Toprak et al. 2019). Earthquakes in Fukui in 1948 and Alaska in 1964 are considered to be the first examples of liquefaction-induced damage. The 1993 Erzincan, 1999 Gölcük and Düzce, 2011 Van and 2023 Kahramanmaraş earthquakes in our country, have once again demonstrated the importance of the liquefaction phenomenon in that much damage can occur in structures due to liquefaction. One of the most effective ground improvement techniques for strengthening soft liquefiable soils is chemical stabilization, which involves injecting and mixing cementitious binders (e.g. Portland cement, OPC) into the ground via an auger. (Sharma et al. 2021). Key criteria such as "economy", "reliability/durability" and "environmental effects" have gained importance in the evaluation of soil improvement methods for sustainability in recent years with increasing environmental awareness around the world (Liu et al. 2021, Sharma et al. 2021, Bao et al. 2019, Huang and Wang 2016, Gallagher and Mitchel, 2002, Agapoulaki and Papadimitriou, 2018).

The economic benefit created by nanomaterials and related products around the world is increasing by 20% every year. Meanwhile, the cost of nano-manufacturing has decreased significantly due to the stimulating effect of the booming market development (Liu et al. 2021, Zhao et al. 2020, Kodaka et al. 2005, Johansen et al. 2008, El Mohtar et al. 2012, Arabania et al. 2012). Colloidal silica (CS) is an aqueous suspension of silica nanoparticles obtained from saturated silica acid solutions (Figure 2). The particle size is usually between 2 and 100 nm. The gelation based on interaction between particles in CS is initiated by weakening the repulsive

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forces, resulting in the formation of a coherent network of siloxane (Si-O-Si) bonds that bind the soil particles together and retain the pore fluid (Liu et al. 2021, Conlee et al. 2012, Gallagher and Mitchel 2002). The main factors affecting the transfer of colloidal silica to liquefiable sand are the viscosity of the colloidal silica stabilizer and the hydraulic conductivity of the soil. One of the most important features of colloidal silica is that it fills even the microvoid spaces that water can reach since its density is close to water. The gelling time of CS is controlled using accelerator material provides ease of application.

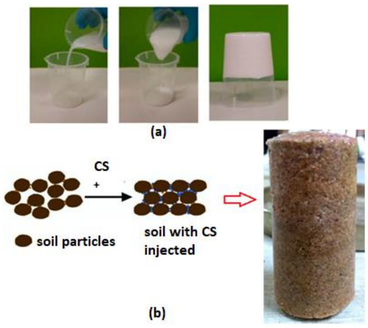

Figure 2. (a) colloidal silica (CS) and (b) Grouted soil specimen with CS (Zhao et al. 2020)

2. AN OVERVİEW OF COLLOIDAL SILICA EFFICIENCY ON SOIL BEHAVIOR UNDER DYNAMİC LOADING

Deformations caused by liquefaction in the soil have been investigated since the 1950s (Ciardi et al 2021, Zhao et al. 2020, Krishnan and Shukla 2021). CS has great potential for making the future of seismic-resistant geotechnical infrastructure engineering designs smarter, more efficient, affordable, and resilient to external environmental factors (such as seismic phenomena and climate change), whilst being environmentally friendly. Since an ideal chemical soil reinforcement injection material, including CS, should have many basic properties, studies in the literature focus on these properties, especially having a low viscosity close to water, being controllable with varying hardening times, and not being sensitive to different storage conditions used for soil penetration and strength against especially dynamic shear stresses. To date, most of the different aspects concerning the colloidal silica grout properties and the effects of grouting on the behavior of granular cohesionless and sandy soils, as well as the entire grouting process, have been investigated. In general, the strength of the treated material was found to increase with the increase in both CS content and gel aging. Relative density (RD) is an important parameter in dynamic shear strength and soil treatment with CS against liquefaction studies (Ciardi et al. 2020-2021, Xiao et al. 2019, Huang and Wang 2016, Huang and Wen 2015, Gallagher and Lin 2009). Towhata and Kabashima (2001) showed that the effect of grout with 4.5% CS content in loose sand samples with a relative density value of 40% was equivalent to the relative density value of untreated sand of 75.1%-77.8%. Porcino et al. (2011) found an increase in liquefaction resistance in the CS-treated specimens due to the effect of particle densification under undrained cyclic loading. Manav et al. (2015) carried triaxial experiments at cell pressures of 100 kPa and 300 kPa using clean sand samples prepared at 40%, 60%, and 80% RDs and CS mixtures at different ratios. They observed that the triaxial strength of the CS-improved samples increased more than two times when the (σ1'/σ3')- Ɛ graphs of clean sand and improved sand samples at 100 kPa cell pressure were compared. Moreover, the strength of specimens improved with CS tested at 300kPa confining pressure was found more than at 100 kPa cell pressure with 40% RD samples. The (σ1'/σ3')-Ɛ graphs of clean sand and improved sand samples at 300 kPa cell pressure show similar results with the 100 kPa cell pressure tests that an increase of strength about two times with the CS treatment of clean sand specimens.

The undrained cyclic triaxial and cyclic torsion tests are widely used in liquefaction (Gallaghar and Mitchell 2002, Hamderi and Gallagher 2015, Ciardi et al 2021, Zhao et al. 2020, Krishnan and Shukla 2021). The relationship between axial strain (ε_a) and the number of loading cycles (Nc) of cyclic triaxial tests performed with CS-treated and untreated sand samples in the study by Ciardi et al (2020) is shown in Figure 3. While the treated sand sample did not fail (5% double amplitude axial strain), the untreated sample failed just after several cycles (Figure 3a). Figure 3b shows that the treated sand sample did not fail despite having a much lower relative density than the untreated dense sand sample for the same CSR. Ciardi et al (2020) found that: (i) 2% CS was sufficient to increase soil strength against the liquefaction; (ii) the liquefaction resistance of the 2% treated soil is 28% greater than that of the untreated after 15 cycles; (iii) soil resistance against liquefaction increases with increasing CS content.

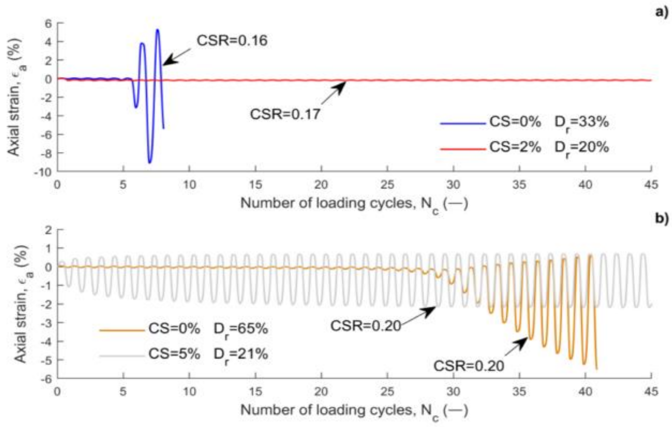

Figure 3. Axial strain versus the number of loading cycles: (**a**) untreated and 2% CS-treated specimens; (**b**) untreated and 5% CS-treated specimens (Ciardi et al 2020)

CS studies with medium to high strain levels considering the liquefaction resistance behavior of CS-treated and untreated soils it is found in general that the resistance values of CS-treated soils are higher than those of untreated soils (Hamderi and Gallagher 2015, Ciardi et al. 2020, Tryantafiyllos et al., 2021, Krishnan and Shukla 2021). Figure 4 shows the typical liquefaction resistance curves of CS-treated and untreated soils, in terms of Cyclic Stress Ratio (CSR) and the number of cycles (Nf) and a comparison between curves obtained from different studies presented in the literature The results given in Figure 4 show the relative soil parameters such as initial shear modulus and damping ratio affected by CS treatment, and it has been found that both initial shear modulus and damping ratio values increase due to CS injection (Kodaka et al. 2005, Porcino 2012, Vranna and Tika 2021, Salvatore et al. 2020). However, there are controversial data on the characteristics and magnitude of this increase (Batilas et al 2018). Spencer et al. (2007) performed resonant column tests with confining stress of 50 kPa on uniform fine sand samples treated with 4–9% CS (Dr = 40%,). Their results showed that the shear modulus of treated sand specimens increased with increasing CS content. The damping ratio was practically unaffected by grouting at small strains. The same researchers did further experimenst one year after and they observed that the shear modulus at small strain levels was higher for treated sand and that negligible effects on damping ratio were measured over the whole cyclic strain range.

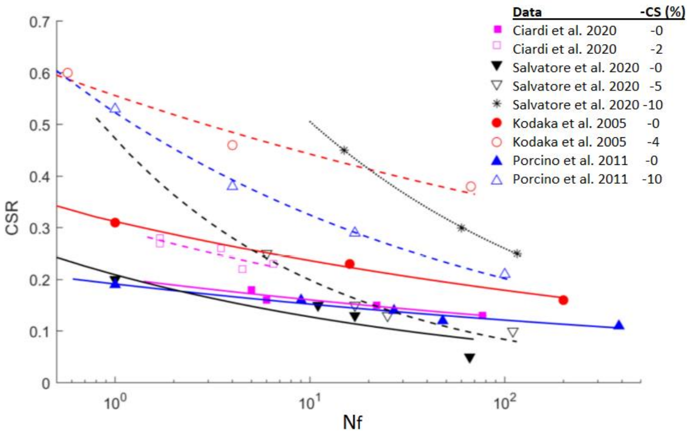

Figure 4. Relationship between CSR and Nf after cyclic tests on loose (Dr _ 45%) untreated and treated sands (Ciardi et al. 2020)

On the other hand, research with low to medium strain values in soil liquefaction studies has shown that dynamic soil parameters such as initial shear modulus and damping ratio are affected by the CS treatment. Both the initial shear modulus and damping ratio were found to increase because of CS grouting (Gallaghar and Mitchell 2002, Hamderi and Gallagher 2015, Ciardi et al 2021, Zhao et al. 2020, Krishnan and Shukla 2021,

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Spencer et al. 2012, Ciardi et al. 2021). However, there are controversial data on the magnitude of this increase. Spencer et al. (2012) performed resonant column tests on sand samples treated with CS contents 4–9% (Dr = 40%, gel time 3 h, and confining stress of 50 kPa). They found that: (i) the shear modulus of grouted sand increased with increasing silica content; (ii) the shear modulus was significantly higher for pure sand than for treated material; (iii) the damping ratio was practically unaffected by grouting at small strains. Conlee et al. (2012) conducted bender element tests and showed that the initial shear modulus increased by 12% for 9% CS-treated sand compared to untreated sand, and by 14% for 5% CS-treated sand compared with 4% CS-grouted sand.
Hydraulic conductivity is an important parameter in soil liquefaction research and many studies have been conducted in the literature on the hydraulic conductivity of CS-treated soil. The results presented in the literatüre highlighted that CS grouting causes a dramatic decrease in the initial hydraulic conductivity (k) of soil and typical clay-like values are expected in sands after the treatment (Pershof et al. 1999, Porcino et al. 2012, Wong et al, 2018, Vranna et al 2019, Ciardi et al. 2020). The decrease in k is correlated with the structure of the gel, which is essentially made of silica chains forming a micro-porous network (CS content-dependent) through which water can flow. Since the grout viscosity increases over time, the change in soil permeability during grouting significantly affects the mechanism of grout delivery, reducing the grout flow.

3. CONCLUSION

To date, most of the different aspects concerning the colloidal silica grout properties and the effects of grouting on the behavior of granular cohesionless and sandy soils, as well as the entire grouting process, have been investigated mostly experimentally. In general, the strength of the treated material was found to increase with the increase in both CS content and gel aging. Although the dynamic behavior and strength parameters of CS-grouted soils have been extensively studied in the literature through laboratory studies, research studies on physical and in situ models are still limited. CS injection obviously increases the liquefaction resistance of liquefiable soil. Especially, the shear modulus and cyclic strength of CS-grouted soil are found to be greater than those of the plain soil specimens; however, there is still some disagreement about how much the damping rate is affected by CS-grouted soil. Moreover, it has not been fully clarified yet the soil improvement mechanism of CS grouted soil to mitigate liquefaction whether filling the voids or increasing the cohesion/adhesion forces between the soil grains and pore water. In conclusion, from the current state of knowledge on the subject, it is clear that the behavior of soil treated with CS grout is very complex. The following aspects in CS grouting should be investigated further: The effects of CS grout on soil compressibility; The effects of CS grout on damping ratio; The sinking behaviour in the grout delivery process; The development of adequate constitutive laws to describe the behavior of the stabilized soil.

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