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MITIGATION OF LIQUEFACTION RISK USING COLLOIDAL SILICA STABILIZER

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SUMMARY

This paper summarizes the experimental results of cyclic simple shear tests in liquefiable sands before and after sample improvement with colloidal silica. The objective of the paper is to evaluate the effectiveness of chemical grouting in reducing liquefaction potential. Colloidal silica was selected as a stabilizing material due to its properties: low viscosity, wide range of gel times, nontoxic, and low cost. Different behavior was obtained, specifically pore pressure response and deformation properties were observed between treated and untreated samples on a natural sand obtained from the Port of Lázaro Cárdenas, México. Liquefiable sands treated with colloidal silica grout had significantly higher resistance to liquefaction phenomena due to cyclic loading than untreated sands.

INTRODUCTION

The liquefaction of saturated sands has been identified as a major cause of damage to buildings and earth structures during earthquakes. Liquefaction and the resulting loss of strength in soil was the cause of considerable damage in the 1964 earthquake in Niigata, Japan (Seed and Idriss [1]), the 1964 Alaskan earthquake (Ross et al. [2]), and the 1989 Loma Prieta earthquake in Northern California (Pease and Rourke [3]; Boulanger [4]).

An assessment of susceptibility to soil liquefaction has been included in most of the design manuals or codes all over the world. However, the remedial measures to mitigate liquefaction-induced damage do not seem to be fully exploited and used in routine practice. The objective of remediation of liquefiable ground is reducing the effects of liquefaction on buildings, transportation structures, and lifeline facilities.

Several instances arise where soils at a site are inadequate for supporting a proposed structure, and where the needed improvement cannot be obtained using traditional methods such as deep dynamic compaction (Menard and Broise [5]; Mayne [6]; Welsh [7]) blasting, (Lyman [8]; Kummeneje and Eide [9]; Prugh [10]) or vibroflotation (Steuerman [11,12]; D'Appolonia [13]; D'Appolonia and Miller [14]). Furthermore, at constrained sites, ground improvement by densification may not be possible due to the presence of structures sensitive to vibrations.

On the other hand, grouting (Karol [15]; Donovan et al. [16]) has been used for the prevention of loose sand densification under adjacent structures due to earthquake loads. Usual grouting materials include clay, cement, and chemical. Mixtures of two or more of these are often used.

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Recent developments in chemical grouting have produced materials that are approaching to the ideal in terms of viscosity and control of setting terms.

At locations where the potential for liquefaction exists, the basic options are: abandoning the site, living with the risk of liquefaction, or implementing remedial measures to minimize the risk of failure. Implementation of remedial measures may be the only option available for many existing structures and lifeline systems (Silver [17]; Marcuson and Franklin [18]).

The naturally cemented sand requires stress level and a number of loading cycles to induce liquefaction that is unlikely to be achieved in any earthquake. Artificial cementation of poor sandy deposits can mitigate such earthquake-induced damage considerably so that important structures can be protected (Li and Mitchell [19]; Saxena et al. [20]; Clough et al. [21]; Reddy and Saxena [22]; Huang and Airey [23]). The use of chemical grouts is becoming more common with the increasing demand for utilization and reclamation of unstable soils.

Grouting is especially useful when the soil to be treated is difficult to reach, as in the case of soils under existing foundations. It may also be the only option available when other complicated soil densification procedures are not applicable due to undesirable vibration and noise levels associated with these methods.

Chemical grouting has been shown to increase resistance to liquefaction, with the increase being a function of factors such as grout type and concentration (Maher, Ro and Welsh [24]). The existing Knowledge on the liquefaction potential of chemically grouted soil is very limited.

This paper summarizes the extensive experimental program undertaken at Faculty of Engineering-UNAM and presents results of cyclic simple shear tests in liquefiable sands before and after sample improvement with colloidal silica grout.

DESCRIPTION OF THE SITE AND OBSERVED DAMAGE

The Industrial Port of Lázaro Cárdenas, situated at Michoacán State of México, where the Balsas River meets the Pacific Ocean, comprises an important industrial complex of recent development which includes steel mills, metal-mechanic factories, fertilizer plants, petroleum related installations, etc. Most of the industrial facilities have been sited upon delta deposits, which were progressively filled with materials coming from the dredging of the navigable channels for the port zone.

The earthquake of 19 September 1985 (M_s = 8.1) ruptured a region known as the Michoacan seismic gap, and is the second largest earthquake of past century in México. A magnitud 7.5 aftershock followed two days later.

During the earthquake of September 19, 1985, sand boils were produced at different parts of the Port of Lazaro Cárdenas. Due to this reason, settlements varying from 10 to 40 cm were recorded at the surface that buckled pavements and sidewalks.

MATERIALS PROPERTIES AND EXPERIMENTAL METHODS

Sand tested

Lázaro Cárdenas sand was used in all the tests performed in this study. The granulometric properties of the sand are: specific gravity, 2.67; coefficient of uniformity, 2.71; maximum void ratio, 1.17; and minimum void ratio, 0.77. The sand has rounded particles, and a uniform grain size with little fines content (Fig. 1).

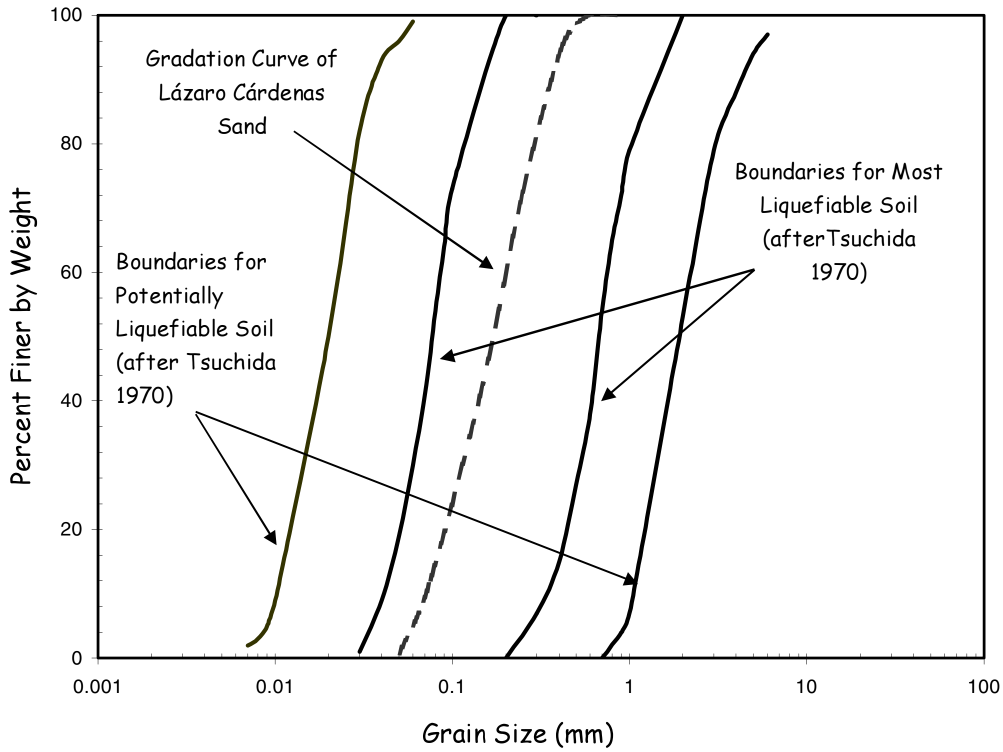


Figure 1. Grain size distribution of Lázaro Cárdenas sand

Grout

The grout used was colloidal silica (CS). CS is an aqueous suspension of tiny silica particles that can be made to gel by adjusting the pH or the salt concentration of the solution. The main criteria used for grout selection were availability, cost, and potential for toxicity.

Laboratory sample preparation

The sample preparation procedure used was based on ASTM Tests Method for Laboratory Preparation of Chemically Grouted Soil Specimens for Obtaining Design Strength Parameters (D4320). Loose sand samples were made by pluviatings dry sand into mold containing colloidal silica grout.

Testing procedure

Stress-controlled cyclic simple shear tests were performed using natural sand obtained from the Port of Lázaro Cárdenas, México. The testing procedure involves consolidation and finally applying a sinusoidal load (with preassigned stress ratio, SR). All the tests were conduced with a frequency of 1 Hz. Initial liquefaction ($u_e = \sigma'_0$) is defined as failure in all the tests. Although failure could also be defined in terms of the peak-to-peak strain (two percent, five percent, etc.) that a specimen undergoes during cyclic loading, the initial liquefaction criterion was adopted because the observed patterns concerning important parameters such a excess of pore water pressure development for improvement specimens, could be compared easily with untreated specimens.

RESULTS AND INTERPRETATION

The effect of density, colloidal silica content, pore pressure response and shear strain on the liquefaction resistance of treated specimens based on present experimental investigation are briefly discussed in this section. The curing time was fixed to 3 days. Higher curing times would increase the resistance to liquefaction phenomena.

Liquefaction definition
For this paper, initial liquefaction is used as defined by the condition where the excess pore pressure first reaches 100% of effective vertical stresses, σ'_{vc}.

Effect of density
Fig. 2 shows the variation of cyclic strength of untreated sands with relative density. The number of loading cycles to induce initial liquefaction for stress ratio 0.4 and relative densities 40%, 60%, 80% and 100% are approximately 3.5 cycles, 9 cycles, 29 cycles, and 80 cycles respectively. The number of cycles required to cause initial liquefaction for a given stress ratio increase as the relative density increases.

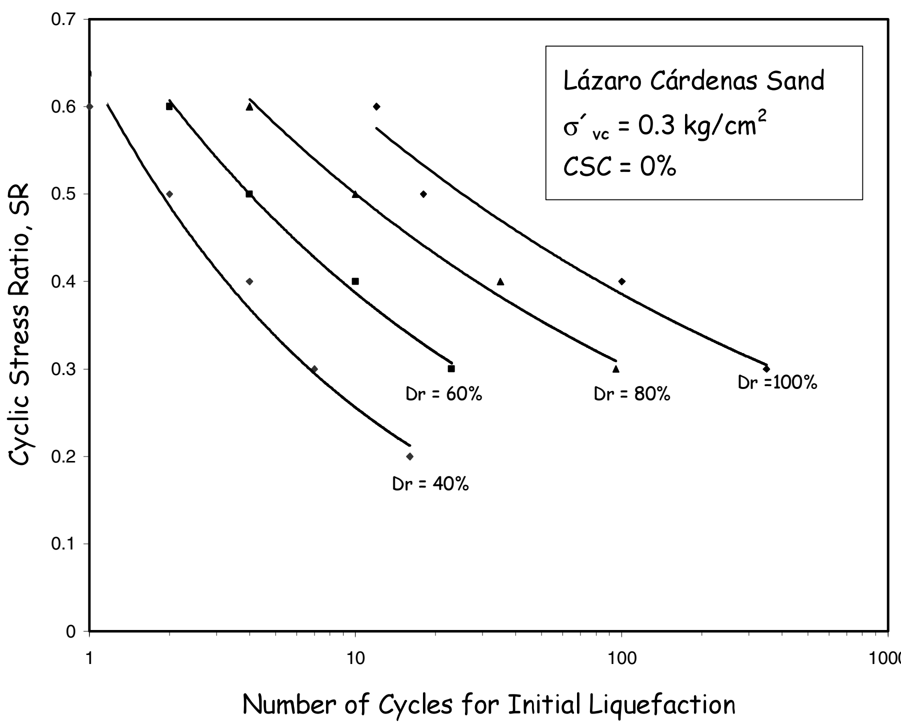


Figure 2. Effect of density on liquefaction resistance for untreated sand.

Fig. 3 shows the effect of 20% of colloidal silica content on the cyclic strength of sands. For this case, the number of loading cycles to induce initial liquefaction for stress ratio 0.4 and relative densities 40% is approximately 40 cycles. Then, the behavior of treated loose sands is similar to that of dense untreated sands.

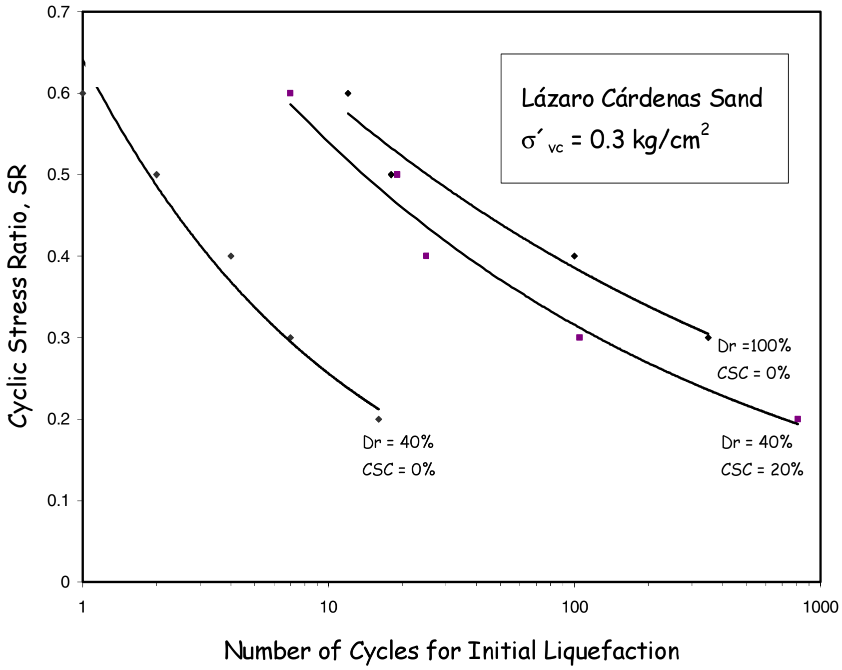
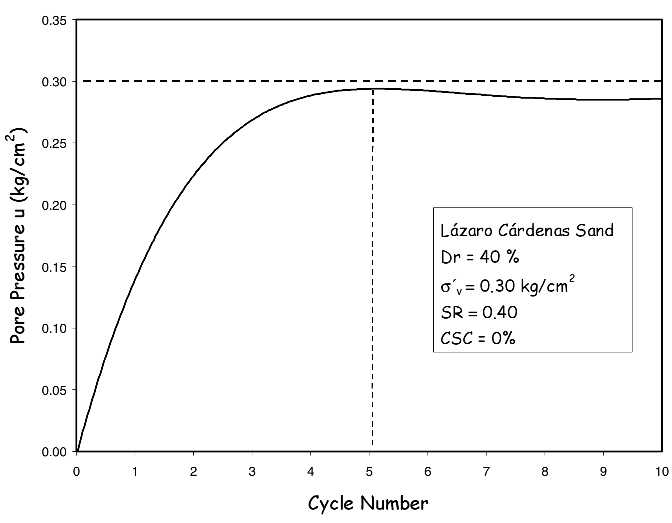


Figure 3. Effect of density for liquefaction resistance for treated sand with colloidal silica.

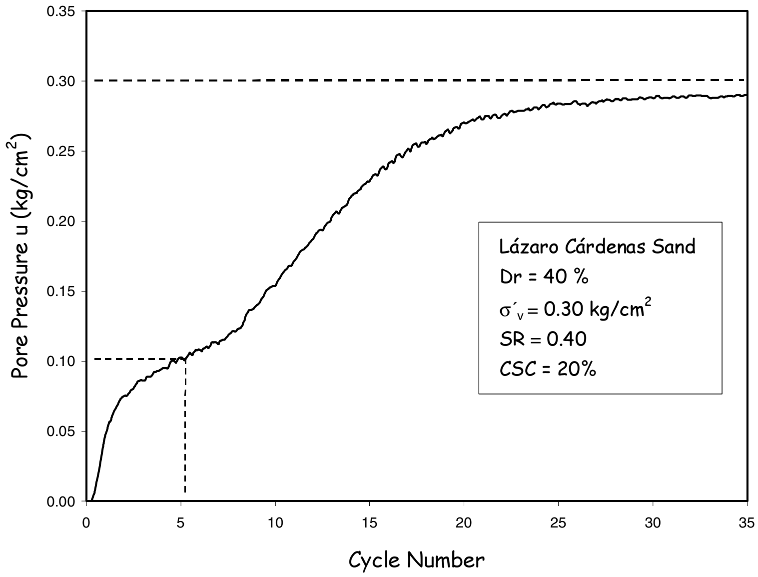
Pore pressure response

Figure 4 shows the development of pore water pressure with the number of loading cycles for D_r = 40% and SR = 0.40. Figure 4a shows that the excess pore water pressure develops rapidly in the untreated specimen (CSC = 0%) and it reaches initial liquefaction in fifth cycle. Figure 4b shows that the excess pore water pressure reaches 0.10 km/cm^2 (only a third of the previous case) in the fifth cycle.



a. Untreated sand (CSC = 0%)

Figure 4. Pore pressure during cyclic loading (SR = 0.40) for untreated and treated sand.



b. Treated sand (CSC = 20%)

Figure 4. (Continuation)

Figure 5 shows the development of the pore water pressure ratio ($\Delta u/\sigma'_c$) with the number of loading cycles for D_r = 40% and SR = 0.50. The colloidal silica contents (CSC) varied from 0% to 20%. The pore pressure ratio for untreated sand becomes approximately equal to 0.35 in the first cycle, 0.68 in the second cycle and it reaches initial liquefaction in the fourth cycle. For the case of CSC = 10%, the pore pressure ratio increase approximately to 0.29 in the first cycle, 0.58 in the second, and reaches initial liquefaction in the sixth cycle. When 15 percent colloidal silica was added to the specimen, the results were 0.35 in the first cycle, 0.68 in the second cycle and it reaches initial liquefaction in the cycle 23. Finally for the case of CSC = 20% the increase in the pore pressure ratio during cycle loading was relatively much slower, particularly in the early stages. This ratio is only approximately 0.09 in the first cycle, 0.19 in the second and reaches initial liquefaction in the cycle 28. These results clearly demonstrate the beneficial increase of the cyclic strength of loose Lázaro Cárdenas sand by colloidal silica grout.

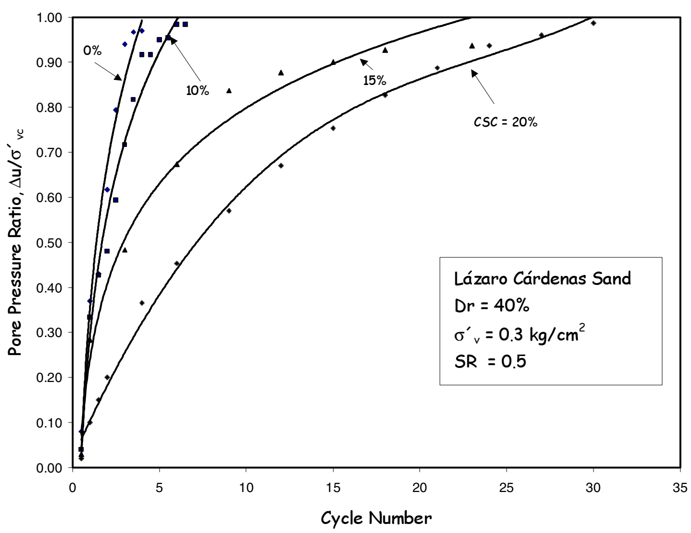
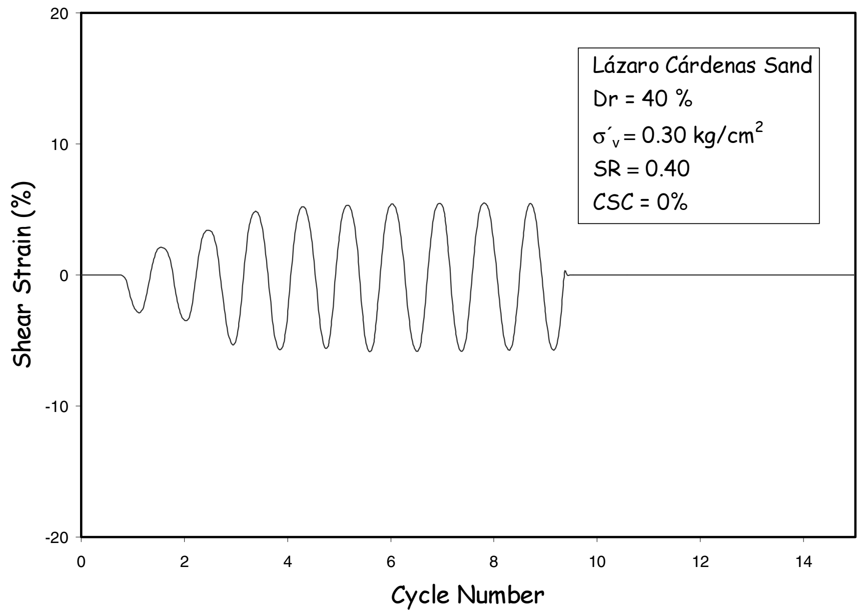


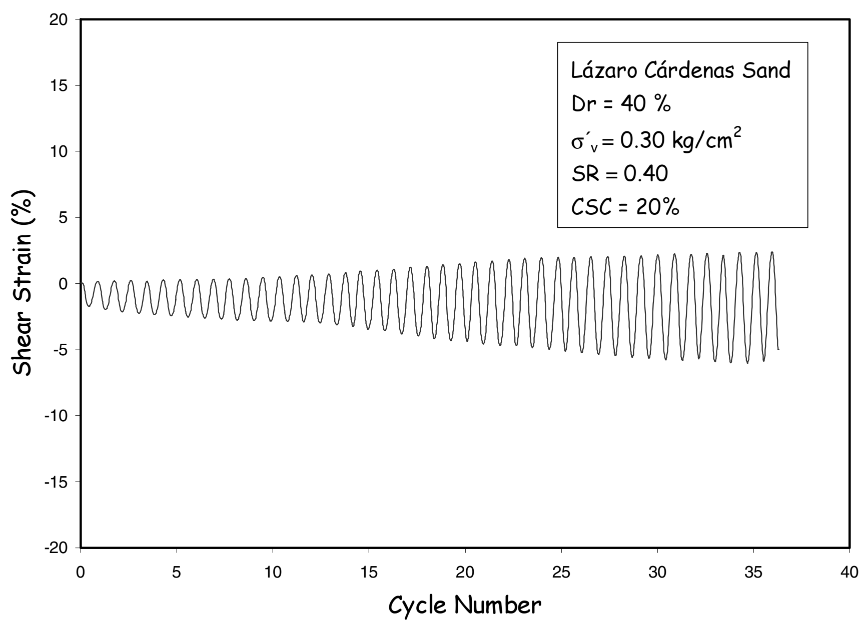
Figure 5. Effect of colloidal silica content (CSC) on pore water pressure ratio

Axial strain response

Figure 6 shows the development of shear strain with the number of loading cycles for D_r = 40% and SR = 0.40. Fig. 6a shows that the shear strain develops rapidly in the untreated specimen (CSC = 0%). The colloidal silica content (CSC) used in Fig. 6b was 20%.



a. Untreated sand (CSC = 0%)



b. Treated sand (CSC =20%)

Figure 6. Shear strain during cyclic loading (SR = 0.40) for untreated and treated sand

Fig. 7 shows that the double amplitude of shear strain develops rapidly in the untreated specimen (CSC = 0%). The double amplitude of axial strain, ε_c, becomes approximately equal to 5.3% in the first cycle, 8.20 in the second and it reaches liquefaction in the fourth cycle. For the case of CSC = 10%, double amplitude of axial strain increase approximately to 3.5% in the first cycle, 4.3% in the second, and reaches 7.2% in the sixth cycle. When 15 percent colloidal silica was added to the specimen, this ratio is only approximately 2.8% in the first cycle, 3% in the second and reaches 6% in the 23rd cycle. Finally for the case of CSC = 20% the increase in the double amplitude of axial strain during cycle loading was relatively much slower, particularly in the early stages. The initial liquefaction was not reached and the double amplitude of axial strain, ε_c, becomes approximately equal to 1.6% in the first cycle, 1.8% in the second cycle, and it reaches 2.2% in the fourth cycle. It may be concludes from the negligible axial strains the benefits of colloidal silica grout.

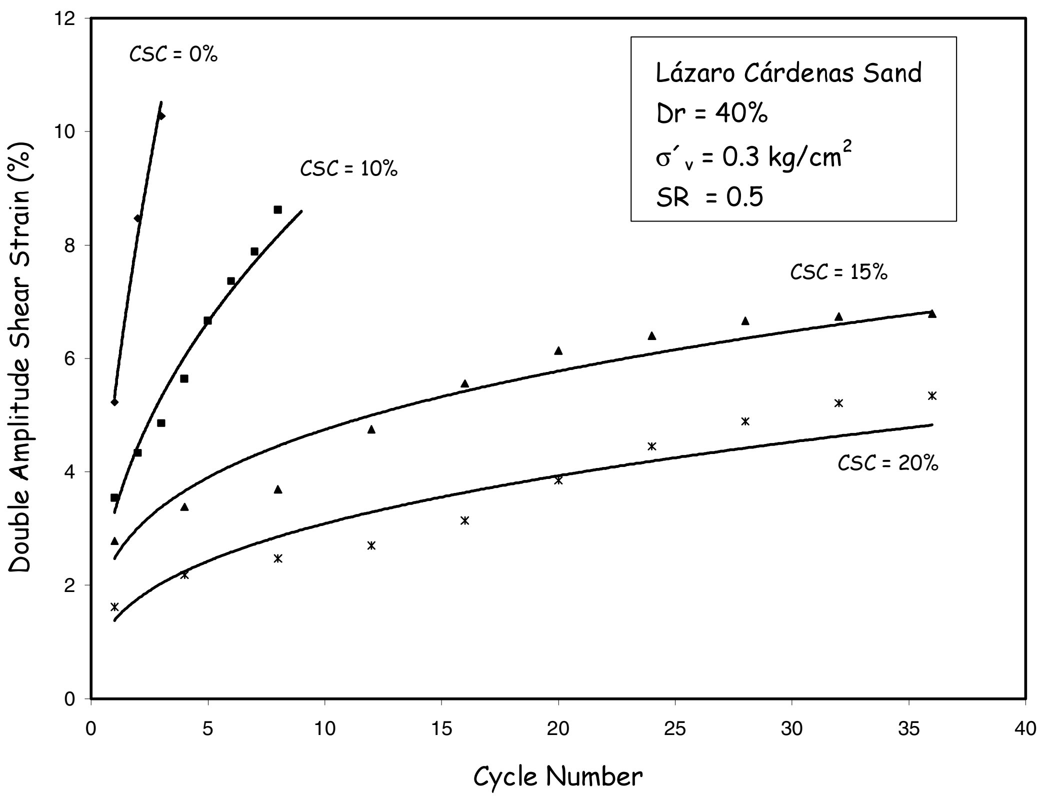


Figure 7. Effect of colloidal silica content on double amplitude shear strain

CONCLUSIONS

The results of this investigation showed that:

A small amount of colloidal silica increases significantly the cyclic strength of untreated sands. In the case of loose sands the addition of colloidal silica greatly reduces the potential for particle movement and reorientation.

The behavior of treated loose sands is similar to that of dense untreated sands.

The results of pore pressure development curves clearly demonstrate the beneficial increase of the cyclic strength of loose Lázaro Cárdenas sand by colloidal silica grout.

It may be concludes from the negligible shear strains the benefits of colloidal silica grout.

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