

DYNAMIC PROPERTIES OF COLLOIDAL SILICA GEL AND SAND MIXTURES

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ABSTRACT

An experimental comparative study of different concentrations of colloidal silica gel and sand mixtures is presented. Resonant column tests were performed on samples of No. 120 Nevada sand permeated with colloidal silica of 5, 7 and 9 weight percent solution to determine the dynamic properties, the shear modulus and damping ratio, of the gelled sand. The behavior of the gelled samples is compared to pure sand samples. The influence of cyclic shear strain on the shear modulus and damping ratio was studied. Results show the influence of the concentration of the colloidal silica solution used for permeating the sand samples on the dynamic properties, indicating an increase in shear modulus with increasing concentration and a higher damping ratio for cyclic shear strains greater than approximately 0.01% for pure sand. The gel-sand mixtures result in a lower shear modulus than the pure sand samples.

Keywords: colloidal silica gel, resonant column, shear modulus, damping ratio, liquefaction mitigation

INTRODUCTION

Liquefaction is the rapid loss of soil strength in saturated soils due to seismic loading. Certain soils are more susceptible to liquefaction, such as loose sand deposits, hydraulic fills, and mine tailings. Liquefaction-induced ground failure can cause large deformations and settlements, resulting in structural damage, floating of buried structures and loss of foundation support. Lateral spreading is the lateral displacement of large, surficial soil blocks as a result of liquefaction in a subsurface layer. Gently sloping waterfront areas are most susceptible to lateral spreading (Gallagher et al., 2006). Liquefaction and lateral spreading caused billions of dollars of damage to port facilities during the 1995 Kobe earthquake (Gallagher et al., 2002; Hamada et al., 1996).

Ports require pier and wharf structures that provide a work surface for port operations. The most common type of wharf structure at large U.S. ports is a pile-supported marginal wharf. These structures consist of long, narrow pile-supported deck segments on sloping subsurface materials ranging from rock dikes to hydraulic fills, and they support material handling equipment, such as container cranes, and storage facilities. The seismic response of this system is inherently a complex soil-structure interaction problem involving ground shaking, large ground displacements due to liquefaction of the fill, the coupled transverse, longitudinal, and torsional response of the wharf, and the response of above-ground structures such as container cranes.

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The liquefaction susceptibility of loose fills and liquefaction-related ground deformations may be reduced by a variety of soil improvement methods. Generally, these soil improvement methods rely on one or more of the following mechanisms to mitigate liquefaction hazards: (a) densification of loose soils, (b) rapid dissipation of excess pore pressures via drainage so that the excess pore pressure ratio ($\Delta u/\sigma'_v$) remains below about 0.6, (c) stiffening of the soil mass to limit the development of strains and thus excess pore pressures within the soil mass, and (d) reinforcement of the soil mass via stiff inclusions that limit ground deformations even if liquefaction occurs.

At ports, traditional soil improvement methods can be used to treat soils in the backland, but these methods are difficult, impractical, and expensive to treat soils beneath existing wharf structures due to lack of access or sufficient clearance. In addition, traditional soil improvement methods are often poorly suited for developed sites such as port facilities because of adverse effects on adjacent structures due to vibration, densification, or increased lateral stresses as well as the disruption of ongoing port operations.

Passive soil improvement methods are an attractive alternative for situations requiring minimal disruption. Passive site stabilization involves slow injection of stabilizing materials at the up-gradient edge of a site and delivery of the stabilizer to the target location using natural or augmented groundwater flow. Prior studies of candidate stabilizing materials (Gallagher and Mitchell, 2002; Gallagher et al., 2006; Persoff et al., 1999) have identified colloidal silica (Iler, 1979) as an ideal, environmentally benign grouting material with low initial viscosity, controllable gel times, and good long-term mechanical stability. Colloidal silica is an aqueous dispersion of silica nanoparticles that can be made to gel by adjusting the pH and ionic strength of the solution. Upon delivery to the target location, the stabilizer starts to gel or set rapidly at a predetermined time to bind the soil particles and stiffen the soil mass. In concentrations of 5 percent by weight, it significantly improves the deformation resistance of loose sands to cyclic loading (Gallagher, 2000; Gallagher and Mitchell, 2002).

Previous work on the applicability of colloidal silica gel as a passive liquefaction mitigation method has focused on the ability of the gel to resist deformations. However, no research has been conducted on the dynamic properties of sand treated with colloidal silica gel in the small and intermediate strain range. To accurately characterize the response of the sand and gel mixtures to seismic loading, the dynamic properties of the mixture is essential. The purpose of this experimental study is to determine the influence the colloidal silica gel has on the shear modulus and damping ratio and to investigate the effect of cyclic shear strain on these properties.

TEST PROCEDURE

Sample Preparation

Samples of No. 120 Nevada sand were prepared using an air pluviation device. The index properties of No. 120 Nevada sand are shown in Table 1. A schematic of the device is shown in Figure 1. Samples prepared by air pluviation are more uniform than other preparation methods and result in a uniform local void ratio (Jang, 1997; Park, 1999). To maintain a constant fall height during pluviation, the pluviation container was raised continuously at the same rate as the rise in the surface of the sand being deposited in the specimen mold.

Table 1. Index properties of No. 120 Nevada sand.

Supplier	Gordon Sand Co., Compton, CA
USCS Classification	Uniform, fine sand, SP
D_{50} (mm)	0.15
Coefficient of uniformity, C_u	1.6
Maximum dry unit weight (kN/m^3)	16.76
Minimum dry unit weight (kN/m^3)	13.98

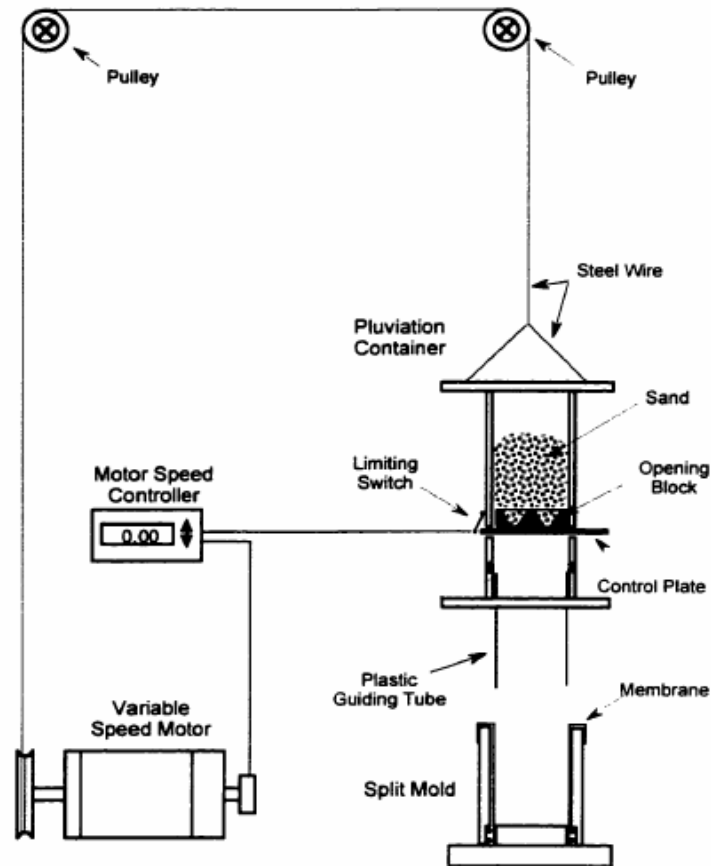


Figure 1. Schematic of air pluviation device (after Park, 1999).

The pluviator was calibrated to obtain 40% relative density of No. 120 Nevada sand for samples with a nominal diameter of 7.1 cm and height of 14.2 cm. Following pluviation, the sample was consolidated at a confining pressure of 50 kPa. Once primary consolidation was complete, the sample was permeated with the colloidal silica gel solution. To perform sample permeation, a triaxial cell and resonant column end platens were modified so only disposable items were exposed to the colloidal silica solution. The sample was pluviated, permeated and tested on the modified resonant column end platens to minimize disturbance of the sample. Colloidal silica permeation was performed by inducing the colloidal silica solution into the sample under low differential pressure of about 5.5 to 8 kPa, as shown in Figure 2. Ionic concentrations of the colloidal silica solutions were chosen to achieve gel times of approximately three hours. After permeating, the sample was left to gel for a period of 10 times the gel time to ensure the gel in the sample was at a resonating gel state before testing and to test each sample at the same progression of bond formation to make accurate comparisons between the different colloidal silica concentrations (Gallagher, 2000).

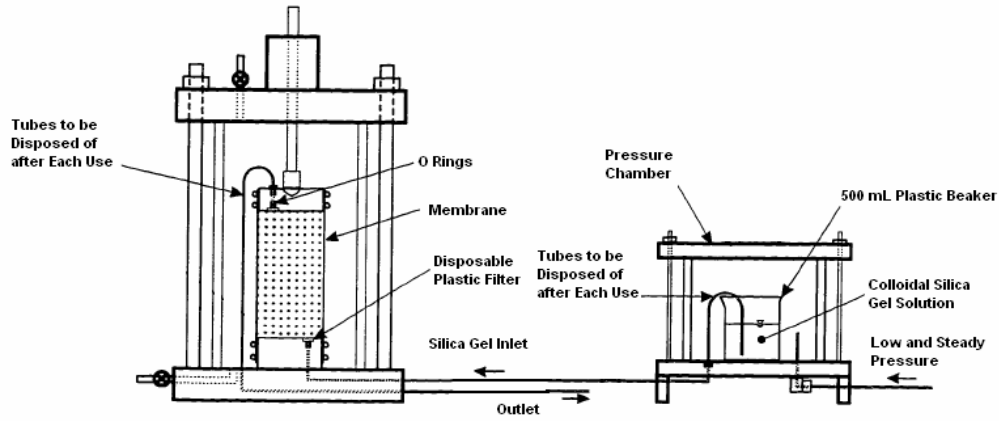


Figure 2. Schematic of colloidal silica gel permeation device (after Jang, 1997).

Resonant Column Test Procedure

The resonant column test is a widely used test that employs the torsional vibrational method to measure the dynamic properties of soils (Ni, 1987; Woods, 1994). The resonant frequency of each specimen for a particular shear strain level was determined by measuring the frequency response between the voltage applied to the coils of the resonant column and the output of the accelerometer used to monitor the angular acceleration of the top of the specimen. The resonant frequency was used to determine the shear wave velocity of the specimen using:

$$\frac{I}{I_0} = \frac{\omega_r L}{V_s} \cdot \tan\left(\frac{\omega_r L}{V_s}\right) \quad (1)$$

where:

I = mass polar moment of inertia of the soil specimen,

I_0 = mass polar moment of inertia of the drive system determined via calibration,

ω_r = circular resonant frequency of the system in torsion ($= 2\pi f_r$),

L = length of the soil specimen, and

V_s = shear wave velocity of the specimen.

The corresponding value of shear strain was determined using:

$$\gamma_{avg} = 0.79 \frac{r_0 \cdot \theta}{L} \quad (2)$$

where r_0 is the radius of the specimen and θ is the angle of rotation.

The material damping ratio of the specimen was calculated using the half-power bandwidth method:

$$D = \frac{f_2 - f_1}{2f_r} \quad (3)$$

where f_1 and f_2 are the frequencies of the half-power points defined as 0.707 times the amplitude of the resonant peak. Equipment-generated damping in the resonant column test due to the interaction between the magnets and solenoids results in a bias error in the measurement of material damping. Meng and Rix (2003) demonstrated that a current-mode source significantly reduces equipment-

generated damping in comparison to a conventional voltage-mode source. In this study, a current-mode source was implemented via a voltage-to-current converter.

After 50 kPa confining pressure was applied, the resonant column tests were performed starting at low cyclic shear strain amplitudes and increasing to a maximum strain of approximately 0.05%, depending on the stiffness of the sample. A final low-strain test was performed after the higher-strain testing was completed. Cyclic prestraining tends to cause a small increase in the shear modulus (Drnevich and Richart, 1970; Alarcon-Guzman, et al., 1989); however, the final low-strain tests for both the gel-sand and pure sand samples resulted in a shear modulus slightly lower than the initial low-strain test which indicates a small change in sample properties due to the cyclic straining. According to Alarcon-Guzman, et al. (1989), the shear moduli at shear strain amplitudes larger than the previous maximum strain are not affected by cyclic prestraining.

RESULTS

Samples of varying concentrations of colloidal silica gel and sand mixtures were tested to investigate the effect of strain amplitude on the shear modulus and damping ratio. Pure sand samples were tested as a reference. Shown below in Figures 3 through 5 are the results for the 5, 7 and 9 weight percent colloidal silica and sand mixture samples. At least three specimens of each weight percent colloidal silica gel were tested at the same time interval (gel time multiple) after gelling to evaluate the repeatability of the measurements.

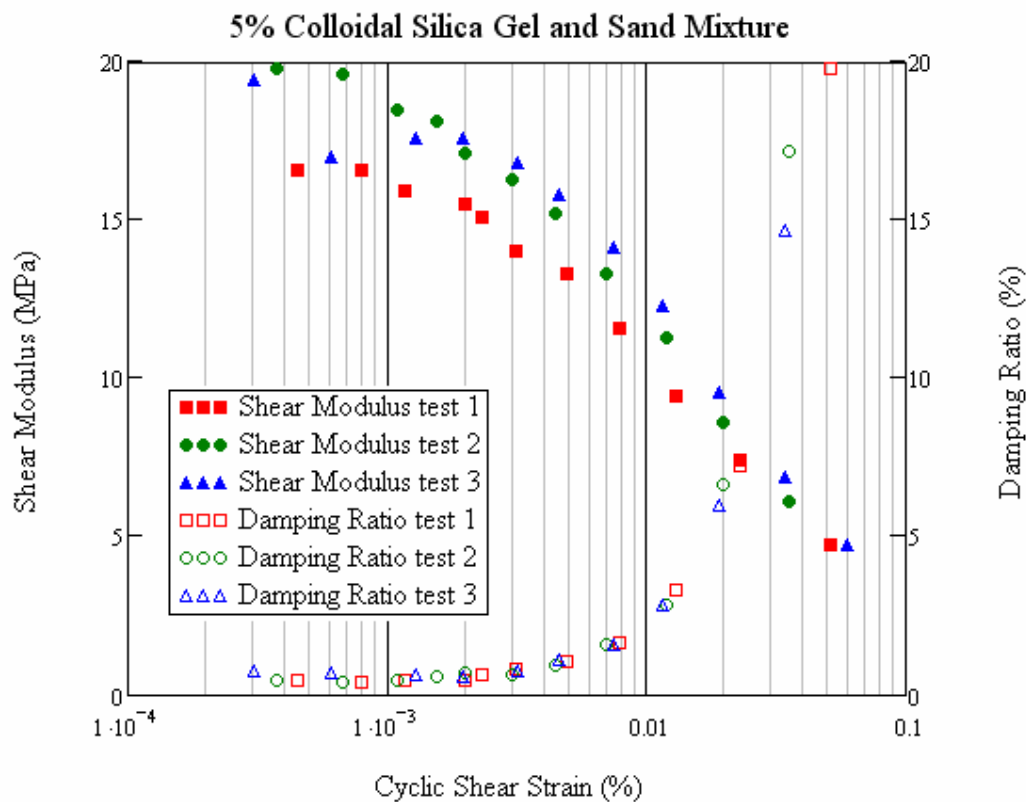


Figure 3. Shear modulus and damping ratio of 5% colloidal silica gel and sand mixture.

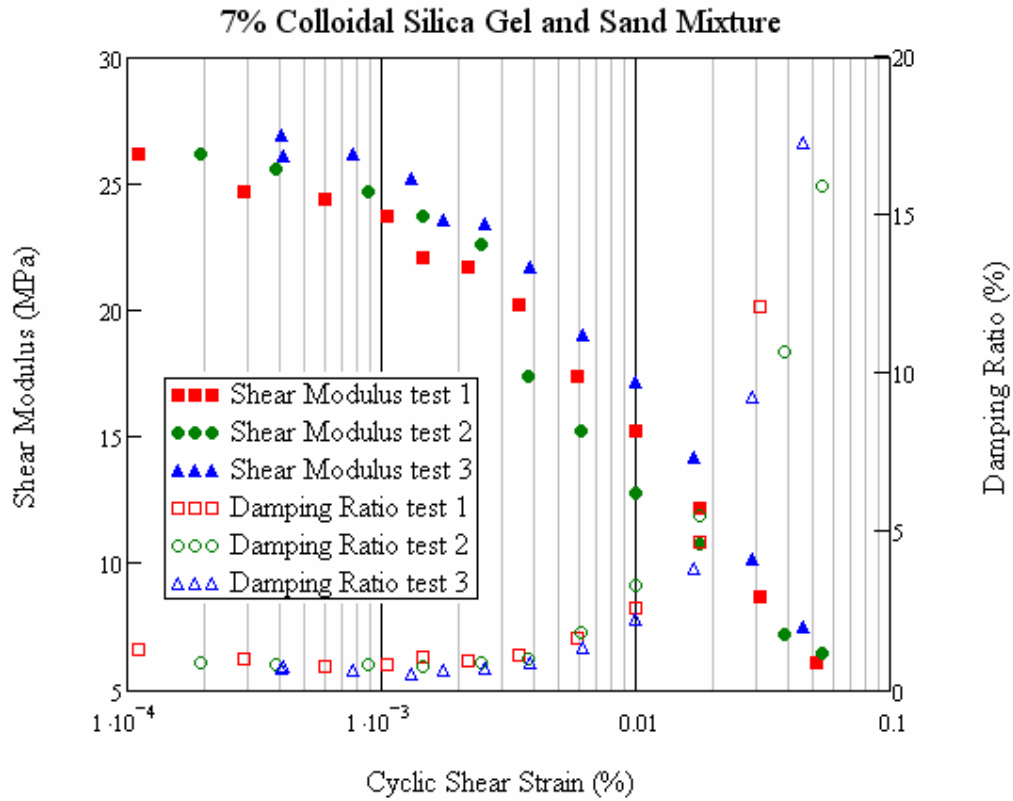


Figure 4. Shear modulus and damping ratio of 7% colloidal silica gel and sand mixture.

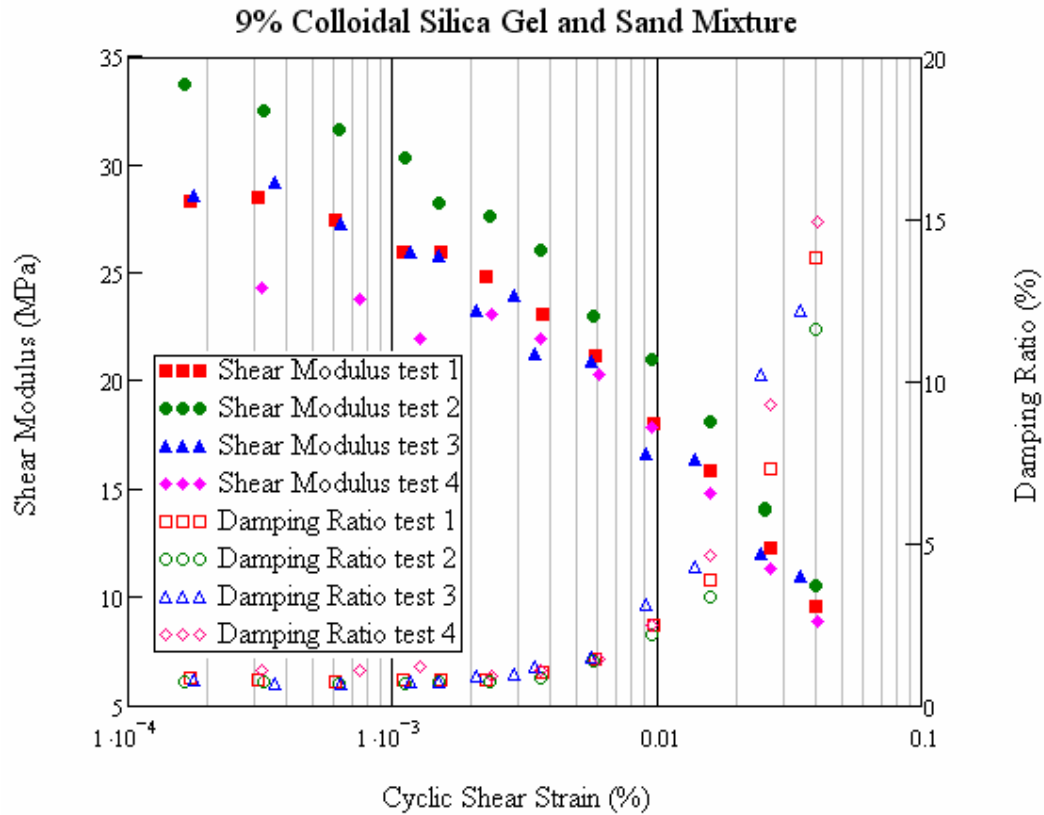


Figure 5. Shear modulus and damping ratio of 9% colloidal silica gel and sand mixture.

A summary plot of the effect of the colloidal silica gel on the shear modulus is shown in Figure 6. The varying concentrations are compared to the pure sand sample. Multiple tests for a particular concentration have been averaged. It is observed that the shear modulus increases with increasing concentration of colloidal silica in the gel-sand mixture. The shear modulus of all colloidal silica gel-sand mixtures is significantly less than the shear modulus of pure sand, regardless of strain amplitude. The stiffness of pure sand samples is attributed to the stiffness of the particle contacts; however, further investigation is needed to identify the chemical and physical properties of the gel and sand mixtures that cause the decrease in stiffness.

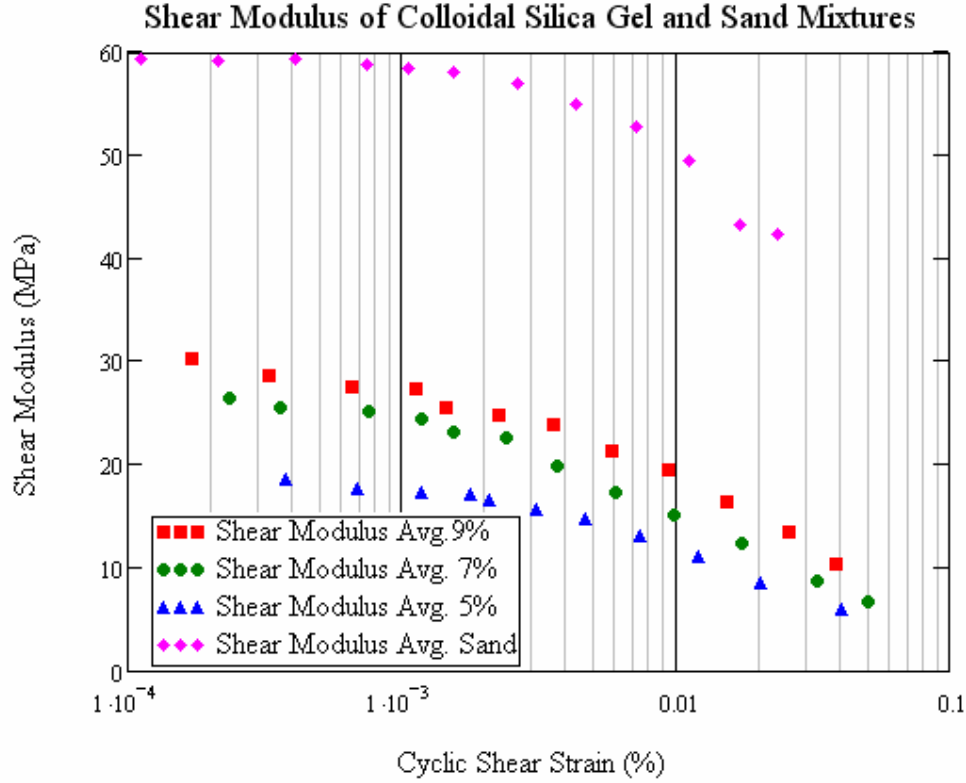


Figure 6. Comparison of shear modulus of all colloidal silica gel percentages with a pure sand sample.

The normalized shear modulus reduction curves are shown in Figure 7. It was observed that the linear threshold strain of the pure sand is larger than the gelled samples, which differs from the expected results. However, the shape of the normalized curves is highly dependent upon the value of G_{\max} used to normalize the data. Low strain results for the gel-sand mixtures do not level off to a clearly identifiable G_{\max} value and therefore this affects the shape of the normalized curve. Further investigation is necessary to verify this behavior and its potential causes.

The damping ratio is shown in Figure 8 and all values shown are the average of multiple tests. It was observed that the damping ratio for the gelled samples is higher than the pure sand for cyclic shear strains greater than approximately 0.01%. The normalized damping ratio is shown in Figure 9. The trend of the normalized damping ratio shows the effect of percentage colloidal silica is minor in the low-strain region. However, there is a noticeable increase in the D/D_{\min} for decreasing colloidal silica concentrations in the mid-strain region. Further, Figure 9 illustrates the similarities between the normalized response of the pure sand and the 9% weight silica gel. Further investigation is needed to validate the physical mechanisms of the gel-sand mixture damping.

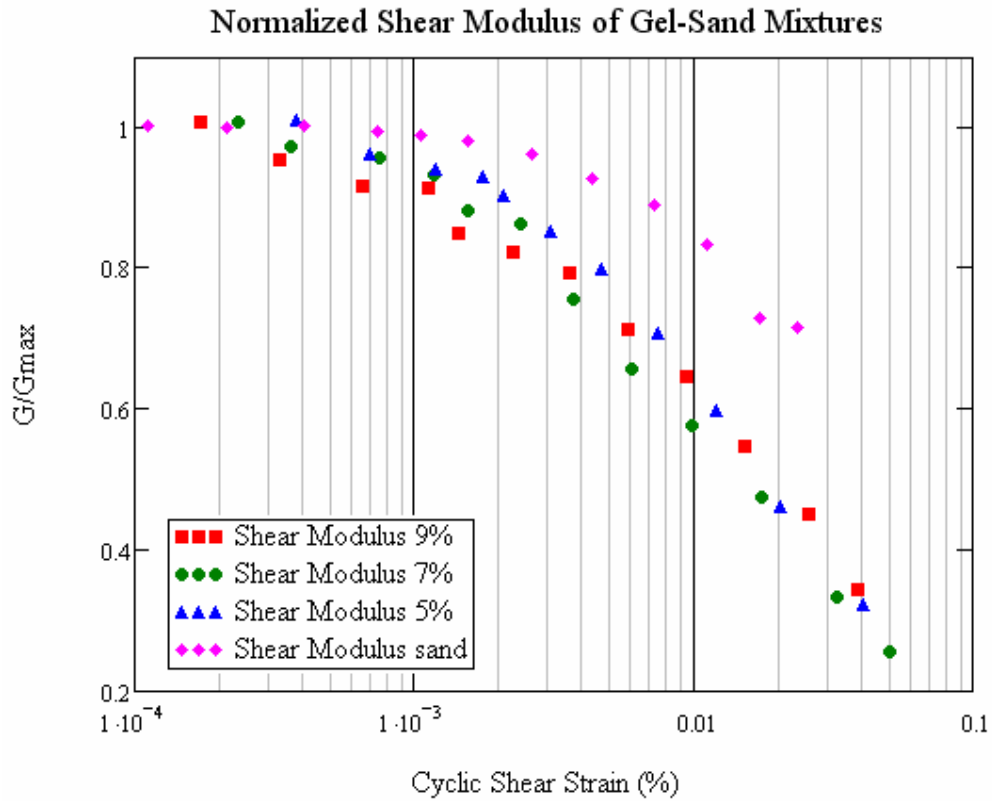


Figure 7. Normalized shear modulus comparison of all colloidal silica gel percentages with pure sand.

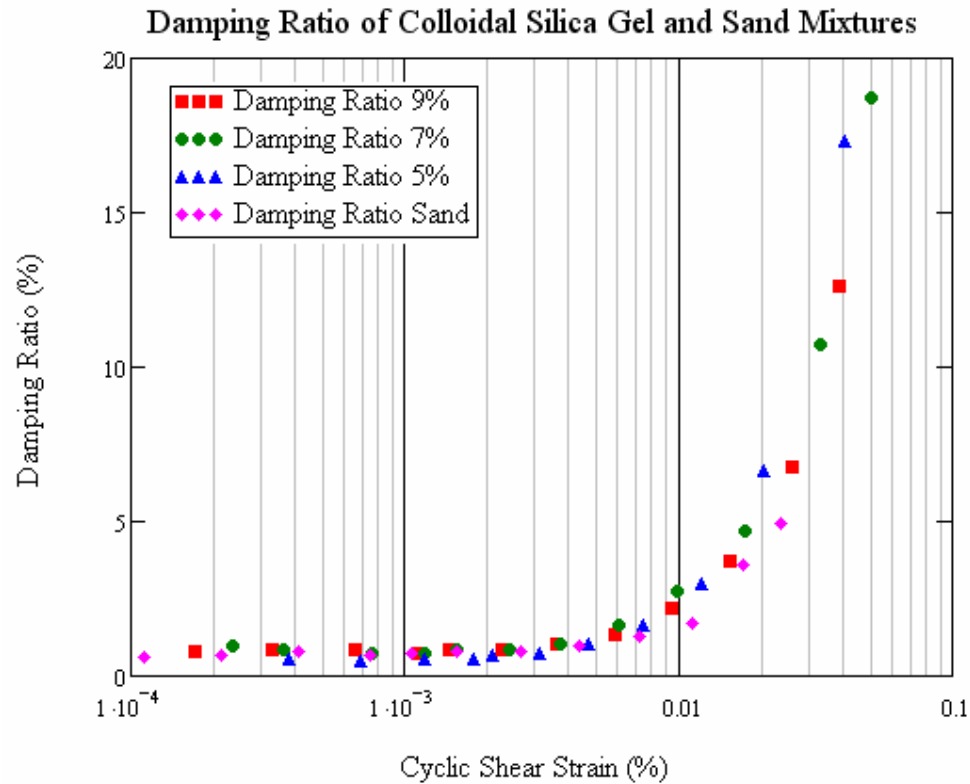


Figure 8. Damping ratio comparison of all colloidal silica gel percentages with pure sand.

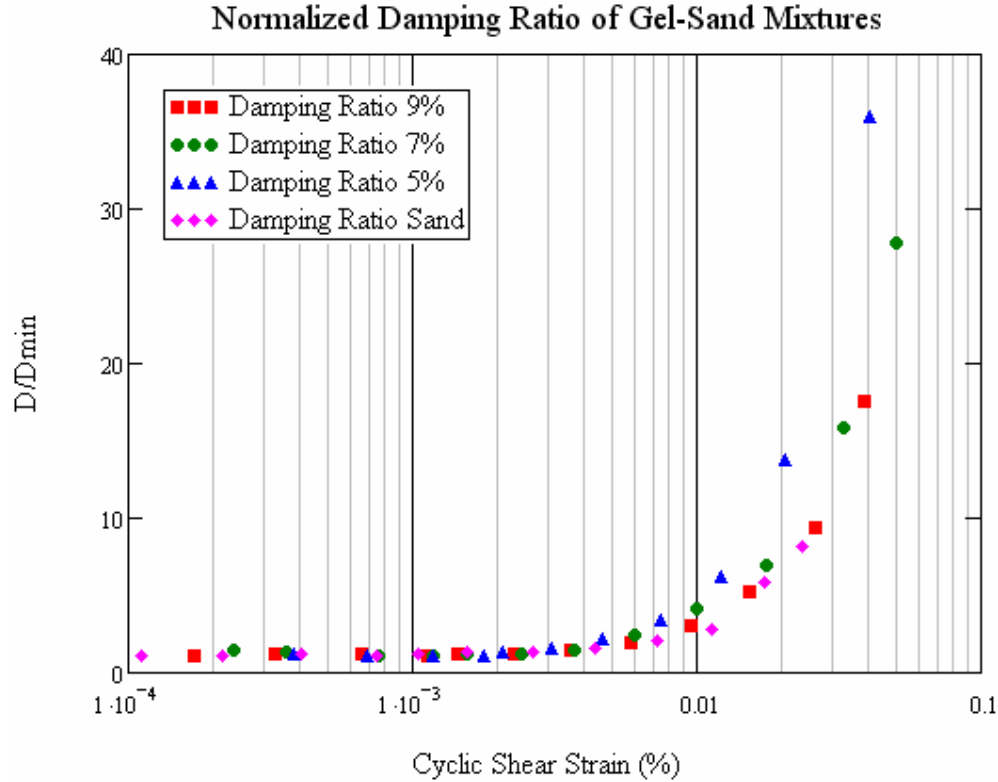


Figure 9. Normalized damping ratio comparison of all colloidal silica gel percentages with pure sand.

CONCLUSIONS AND RECOMMENDATIONS

The shear modulus and damping ratio of pure No. 120 Nevada sand and sand grouted with different concentrations of colloidal silica were determined using resonant column tests. The effects of the concentration of the colloidal silica gel were investigated. Based on the results, it can be concluded that the shear modulus increases as the concentration of colloidal silica in the grouting solution increases and the gel-sand mixtures have significantly lower shear modulus than the pure sand. The influence of different colloidal silica concentrations on the damping ratio shows the presence of the silica gel increases the damping ratio for a given strain amplitude greater than approximately 0.01% cyclic shear strain of the pure sand. The normalized damping ratio also shows an increase in the D/D_{min} for decreasing concentration of colloidal silica and illustrates the similar behavior of normalized pure sand and 9% weight colloidal silica gel and sand mixture.

The results presented here are the first phase of an experimental study to characterize the small-strain behavior of gel-sand mixtures. The results have indicated several areas that need further research, including identification of the linear range of gel-sand mixtures and investigation of the causes of the decrease in shear modulus compared to the pure sand samples. Future work includes tests performed to investigate the influence of aging and confining pressure on the shear modulus and damping ratio of gel-sand mixtures.

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