Evaluation of an engineered material of large damping ratio

Zahid Khan
Department of Civil Engineering – American University of Sharjah, Sharjah, UAE
Giovanni Cascante
Department of Civil Engineering – University of Waterloo, Waterloo, ON, Canada
Hesham El Naggar
Department of Civil Engineering – University of Western Ontario, London, ON, Canada
Magdi El Emam
Department of Civil Engineering – *American University of Sharjah, Sharjah, UAE*

ABSTRACT
Many geotechnical problems such as seismic resistant designs and machine vibrations require the installation of dampers or isolators to control the amplitude of vibrations. Engineered fills designed with increased capability of dissipating energy can provide a more economical approach to control excessive vibrations. This study presents a technique to increase the damping ratio of a sand without affecting its stiffness significantly. The increase in damping ratio is evaluated by performing resonant column tests on the engineered soils. The damping ratio of the sand is increased by adding controlled amount of viscoelastic material to the sands. The resonant column tests indicate that the damping ratio of the sand can be increased by a factor of 10 without a significant effect on the shear modulus. The micromechanical evaluation of the results shows a good correlation between the particle surface area in contact with the pore-mixture and the damping ratio of the sand.

RÉSUMÉ
De nombreux problèmes géotechniques tels que la conception de systèmes résistants aux séismes et les vibrations de machines requièrent l'installation d'amortisseurs ou d'isolateurs pour contrôler l'amplitude des vibrations. Des remblais conçus avec une plus grande capacité à dissiper l'énergie peuvent fournir une approche plus économique pour contrôler des vibrations excessives. Cette étude présente une technique pour augmenter le taux d'amortissement d'un sable sans affecter sa rigidité de façon significative. L'augmentation du taux d'amortissement est évaluée en effectuant des essais à colonne résonnante sur le sol synthétique. Le taux d'amortissement du sable est augmenté en ajoutant une quantité contrôlée de matériau viscoélastique dans le sable. Les essais à colonne résonnante indiquent que le taux d'amortissement du sable peut être augmenté d'un factor 10 sans effet significatif sur le module de cisaillement. L'évaluation micromécanique des résultats montre une bonne corrélation entre la surface des particules en contact avec le mélange présent dans les pores et le taux d'amortissement du sable.

1 INTRODUCTION

Shear modulus and damping ratio are important soil properties that influence the response of soils to dynamic loads. Many geotechnical problems such as seismic resistant designs and machine vibrations involve measures to control the amplitude of vibrations by incorporating dampers or isolators. Engineered fills designed to increase the ability of the foundation soil to dissipate energy can provide a means for control of excessive vibrations. This study presents the results of experiments performed on engineered soil to explore the possibility of increasing the damping ratio without affecting its stiffness.

Soils are generally viscoelastic in nature at shear strains below linear cyclic threshold shear strain level; therefore, viscous damping coefficient is used to represent energy dissipation (Lo Presti and Pallara 1997; Kramer 1996). Mechanisms of energy dissipation in soils occur due to combination of viscous damping representing the relative motion of the materials and frictional damping at the inter-particle contacts. Frictional damping ratio is a function of shear strain level and increases predominantly due to an increase in shear strain level. On the other hand, material type governs the viscous damping component (Ellis et al. 2000). Mechanisms of energy dissipation in heterogeneous materials are not easy to quantify, especially at low strain levels due to complex interaction of cohesive and normal forces at the interface of contacts. Moreover, internal interfaces between particles of different elastic properties add to the energy dissipation in mixtures (Santamarina et al. 2001).

2 OBJECTIVES AND SCOPE OF WORK

This study explores the possibility of producing an engineered fill with increased damping ratio, without compromising its stiffness. The study involves adding controlled amounts of high viscosity material to dry sand of constant void ratio and evaluating its affect on the damping ratio. Dry sand specimens with varying percentages of bentonite-glycerin mixture (viscosity = 2700 cps) in the voids are tested in resonant column (RC). A simple cubic packing model is used to simulate the varying percentages of bentonite-glycerin mixture in the voids. The amount of bentonite-glycerin mixture in the voids is represented as degree of bentonite-glycerin saturation (D_{BG}) and is correlated to the damping ratio measured in RC.

3 BACKGROUND

Elliss et al. (1998) showed that changing the pore fluid characteristics can increase the damping ratio of sand. The material damping ratio of oil saturated sand evaluated from centrifuge model tests was higher than quasi-static low frequency torsional shear tests on water saturated sand. Similarly, Ko (1994) suggested that the inter-particle contact behaviour and total damping might be modified due to high viscosity pore fluid.

The relative movement of pore fluid or high viscosity pore mixture to sand particle generates an additional component of damping. This damping is identified as viscous damping (ξv). Local fluid flow occurs at the inter-particle contacts due to local build up of pore pressures. Stoll (1989) defined this motion as "squeeze film motion". He showed that this effect can be pronounced at frequencies as low as 20 Hz for silts. Elliss et al. (2000) presented a model for the contribution (ξv) of pore fluid viscosity to the damping ratio, i.e.

$$\xi_v = \frac{14100\,\gamma^{0.72}\;\mu\, f}{d_{50}\; G} \qquad [1]$$

where μ is the viscosity of the pore fluid, f is the frequency, G is the shear modulus, γ is the shear strain level, and d_{50} is particle diameter at 50 % passing. Ellis et al., (2000) showed that using oil as pore fluid (μ = 100 mPa-s) increased total damping of fine silica sand (at f = 25 Hz) by 10%. However, the increase was small and even undistinguished at smaller frequencies.

Pamuksu and Akbulut (2006) used synthetic rubber to enhance the attenuation characteristics of Ottawa sand. They noticed an increase of about 250 % in damping ratio at an optimum volume of synthetic rubber in the mix.

3.1 Bentonite-glycerin mixture

The viscous damping component in natural sand is small. One possible way to increase the viscous damping component is to add a high viscosity pore mixture to the sand specimen. In this study, glycerin-bentonite mixture is used, with glycerin to bentonite ratio of 164 %. The viscosity of the glycerin measured at room temperature (22°C) is 1135 cps. The variation of glycerin viscosity with temperature is presented in Fig. 1a. The results indicate sensitivity of viscosity to temperature.

The viscosity of the 164% glycerin-bentonite mixture cannot be measured in viscometer; therefore, mixtures of different ratios of glycerin to bentonite are tested to extrapolate the viscosity of the specified ratio. The results are presented in Fig. 1b, which indicates an extrapolated value of 2715 mPa-s. However, the actual viscosity of the mixture may be even higher.

3.2 Phase relationships and calculation of masses

Masses of dry sand (MS), bentonite (MB), and glycerin (MG) required in a mixture are computed from phase relationships. Degree of bentonite-glycerin saturation (D_{BG}) is computed by,

$$D_{BG} = \frac{M_{BG}}{\rho_{BG}}\frac{1}{V_{OS}\; e} \qquad [2]$$

where ρ_{BG} is the bulk density of bentonite-glycerin mixture determined experimentally (1482 kg/m^3). In all specimens, the ratio of glycerin to bentonite is kept constant (164 %). Four degrees of bentonite-glycerin saturation are used (D_{BG} = 0 %, 26 %, 52 %, and 99 %). Finally, the mass density of sand is given by

$$\rho_s = \frac{\rho_b}{\left(1+B_C\right)\left(1+GL_C\right)} \qquad [3]$$

where B_C is bentonite content (MB/MS), GL_C is glycerin content (MG/(MS+MB)), and e is the void ratio of sand skeleton.

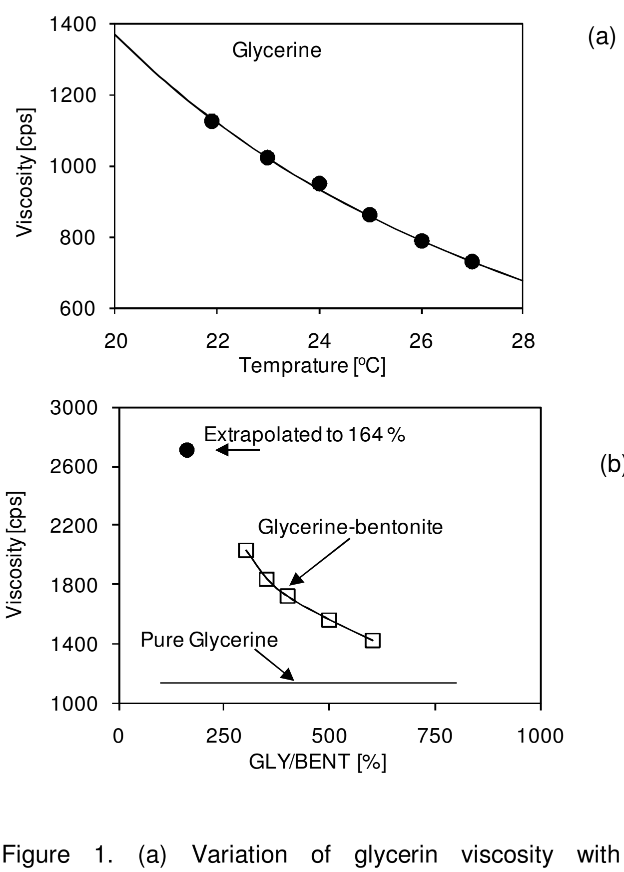

Figure 1. (a) Variation of glycerin viscosity with temperature; (b) variation of viscosity of glycerin-bentonite mixture at 22°C.

3.3 Numerical Simulation of void filling in simple cubic packing

Bentonite-glycerin saturations are simulated using simple cubic packing (SCP) of spheres. A basic unit cell sphere (SCP) is presented in Fig. 2a. The volume of the bentonite-glycerin mixture can be approximated by using the dimensions a and h in Fig. 2a. If r is the radius of the sphere, then degree of saturation of mixture (bentonite-glycerin) is,

$$D_{BG} = \frac{h^2}{2} \frac{\left[h\,(12-\pi) + r\,(3\,\pi - 24)\right]}{r^3\,(\pi - 6)} \qquad [4]$$

The base area of the contact (πa^2) and surface area of the contact (2π□rh) at the corresponding degree of bentonite-glycerin saturation (i.e. 0 % (sand), 26 %, 52 %, and 99 %) are correlated with the damping ratios measured in the resonant column tests. The variation of normalized areas of contacts (normalized by areas obtained at 100 % saturation) with different degrees of pore mixture saturation (Eq. 4) is presented in Fig. 2b.

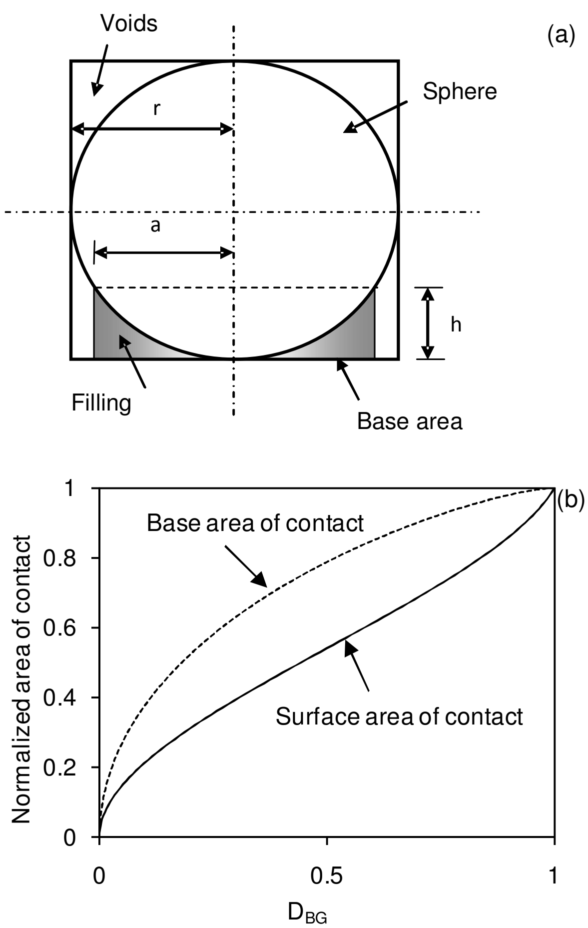

Figure 2. (a) Illustration of simple cubic packing with pore mixture filling, and (b) variation of base and surface contact area with degree of pore mixture saturation.

4 EXPERIMENTAL SETUP AND EXPERIMENTAL PROGRAM

The shear modulus and damping ratio are measured in resonant column test (ASTM 2000, D4015-92) using a modified stokoe type resonant column. The solution (Cascante and Santamarina 1997), which employs the Raleigh method, is used to calculate the shear wave velocity (V_S) from the resonant column test results, i.e.

$$V_S = \sqrt{\omega_o^{\,2}\,\left[(0.33I + I_o)H\right] / \left[J_P\,\rho\right]} \qquad [5]$$

where J_P and I are the area polar moment of inertia of specimen and the mass polar moment of inertia of specimen, respectively, ω_o is the angular resonant frequency, H and ρ are the height and mass density of the specimen, and I_o is the mass polar moment of inertia of the driving system. Damping ratios are calculated using current-based measurements (Cascante et al. 2003).

Measurements were obtained at two different confinements (σo=33 kPa and 630 kPa) and at large strains at an isotropic confinement of σo=33 kPa.

5 SAMPLE PREPARATION

Specimens of dry sand with four different levels of degree of bentonite-glycerin saturation were prepared (D_{BG} = 0 % (sand), 26 %, 52 %, and 99 %). Three specimens were prepared for each bentonite-glycerin saturation for repeatability. In all cases, void ratio of sand skeleton is approximately equal to e ≈ 0.66 (Eqs. 3 and 4).

All specimens are prepared under vacuum (-20 kPa). Dry sand specimens are prepared by pouring sand through a funnel. Slightly lower densities are targeted. The specimen mould is then tapped gently to achieve the required height and density.

Dry sand specimens with different saturation of bentonite-glycerin mixture are also prepared under the vacuum. The sand and bentonite and glycerin mixture are mixed thoroughly in a pan. The mixture is then poured in 5 layers of approximately 3 cm in height.

Viscosity of glycerin and bentonite-glycerin mixture is sensitive to the temperature (Fig. 1a); therefore, all the ingredients are kept at room temperature (22^{o}C) for at least 24 hours.

6 RESULTS AND DISCUSSIONS

The low strain dynamic properties of dry sand with different saturations of bentonite-glycerin mixtures were measured in resonant column (RC). The results are presented in Fig. 3. The change in damping ratio was significant compared to the change in shear modulus at similar confinements. The variation in shear modulus between sand and D_{BG} = 99% specimens at σo = 33 kPa is 14% whereas the variation of damping ratio is 900%.

Similarly, the variation of shear modulus and damping ratio at σo = 630 kPa is 12% and 2000% respectively.

The small change in shear modulus is attributed to practically similar void ratio of sand skeleton ($e \approx 0.66$) in all specimens. Whereas, damping ratio is influenced by energy dissipation due to the viscous damping component of the bentonite-glycerin mixture. The viscous component predicted by Eq. 1 at σo = 33 kPa is ξv = 2%, which is 3 times smaller than measured. The additional damping ratio (4.2% for D_{BG} = 99%) is generated possibly from within the pore mixture or at sand-mixture interface as discussed later in this section.

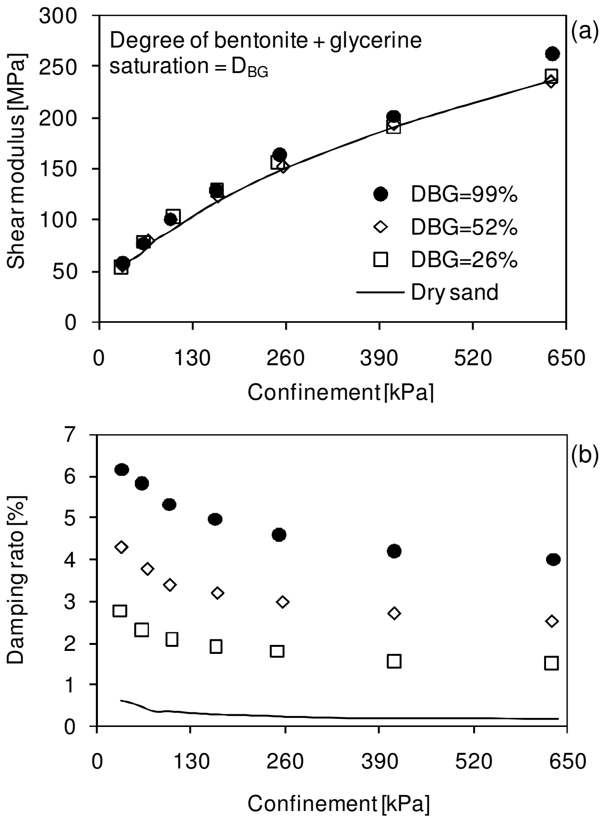

Figure 3. Dynamic properties of dry sand and different pore mixture saturations in resonant column tests ($\gamma < 10^{-6}$).

The damping ratio for different saturation levels of bentonite-glycerin mixtures at σo = 33 kPa and 630 kPa is presented in Fig. 4. At high confinement (σo = 630 kPa), the damping ratio of D_{BG} = 99% does not decrease proportionally to the damping ratio of dry sand. The total decrease from σo = 33 kPa to 630 kPa for dry sand and D_{BG} = 99 % is 70 % and 35 % respectively. An increase in confinement increases inter-particle normal force in sands thus reducing the deformations and consequently the damping. However, at D_{BG} = 99 % the behaviour of the viscous damping component is different with confinement since the increased stresses are not only transmitted through inter-particle contacts of sand skeleton only but through the larger sand-mixture interface. These results suggest a correlation between the damping ratio and the surface contact area of the mixture with sand particles.

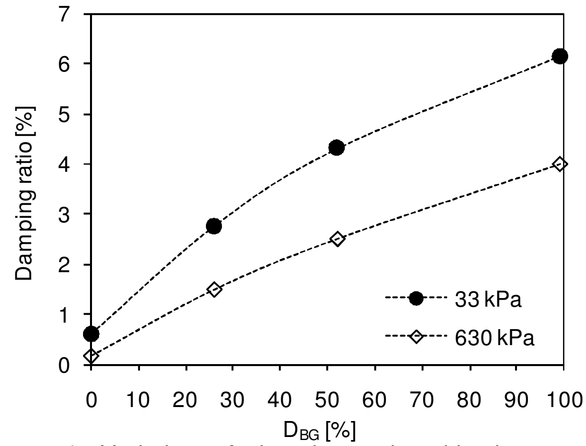

Figure 4. Variation of damping ratio with degree of bentonite-glycerin saturation ($\gamma < 10^{-6}$).

The base and surface areas of contact corresponding to the respective degree of bentonite-glycerin saturation are plotted against the damping ratio in Fig. 5. It can be inferred from Fig. 5 that the surface area of contact is a better indicator of the increase in damping ratio as the degree of bentonite-glycerin saturation increases. This is because the surface area of contact models the whole area of relative movement, whereas the base area models only the inter-particle contact.

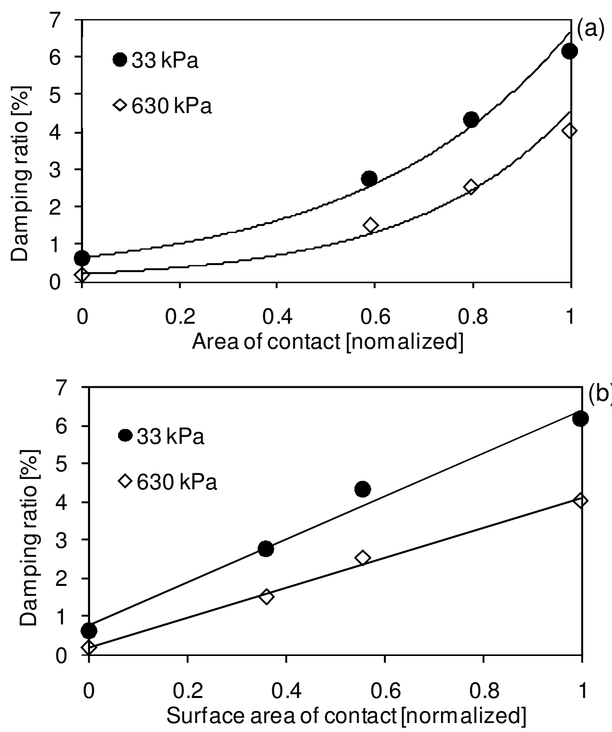

Figure 5. Variation of damping ratio with (a) increase in base area of contact, and (b) increase in surface area of contact ($\gamma < 10^{-6}$).

The variation of dynamic properties with shear strain level for sand specimens with different saturation levels at σo = 33 kPa is presented in Fig. 6. The rate of degradation of shear modulus is slightly larger for bentonite-glycerin mixtures compared to dry sand.

On the other hand, the damping ratio of bentonite-glycerin mixtures increases at a larger rate compared to dry sand. The offsets between the saturation levels remains similar at all shear strain levels indicating that the viscous damping component is almost independent of shear strain level for the range of strains considered in this study.

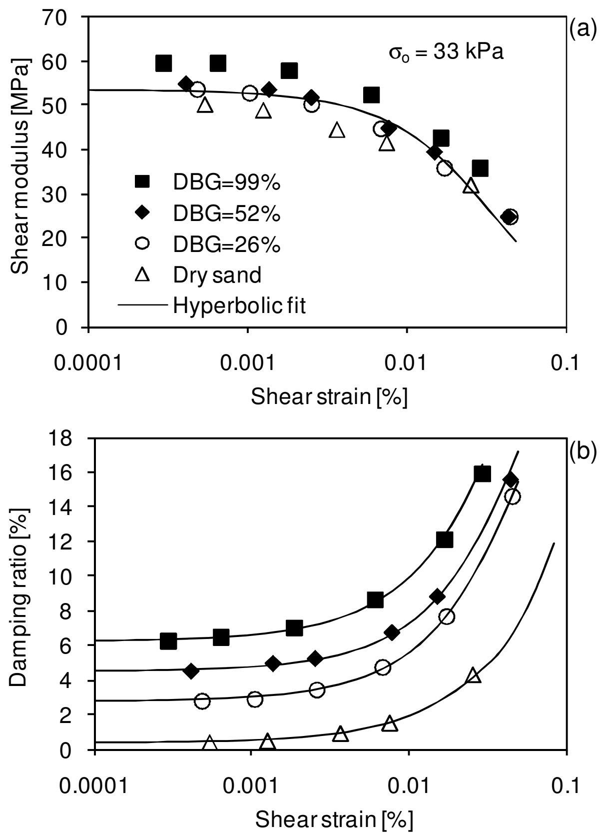

Figure 6. Dynamic properties of dry sand and different pore mixture saturations with shear strain level in resonant column tests (σo □= 33 kPa).

The increase in damping ratio with different volumes of mixture in the voids can not be explained in terms of hysteretic losses only. A complex interaction of a different material at the particle interface contributes significantly towards the energy dissipation. Zener (1938) presented a different mechanism of energy losses that happens at the interface of contacting materials of different thermal properties. This is referred to as Piezocaloric effect by the authors (Zener 1938; Bishop and Kinra 1993, 1995; Lakes 1997). The periodic strains in such mixtures are responsible for generating heat wave that flows between the masses of different thermal coefficients. The phase difference between the applied and thermally generated elastic fields results in additional energy loss. This form of damping is referred to as *thermoelastic* damping (Zener 1938).

The pore mixture of Bentonite and glycerine is very sensitive to temperature and hence exhibit different thermoelastic properties than dry sand. The increase in surface area of contact between the sand particles and this mixture creates larger thermally generated elastic fields resulting in higher damping ratios. In addition, hysteretic damping and frictional losses generated at sand-sand interface also contributes towards the overall damping.

7 CONCLUSIONS

Materials with high damping and stiffness have the potential to become an attractive solution for the control of vibration due to earthquakes, machine operations and traffic loads. Dry sand specimens with different saturation levels of bentonite-glycerin mixture are tested to evaluate the increase in the viscous damping component. A micromechanical model of simple cubic packing is developed to describe the damping behaviour. The main conclusions of this study are as follows:

The thermoelastic and viscous component of damping in dry sands can be increased significantly by increasing the amount of high viscosity and thermally different material in the voids. The increase in damping ratio correlates well with the increase in surface area of contact between pore mixture and sand particles.

The increase in viscous damping component remains evident at all shear strain levels and exhibits strain independent behaviour for the strain range considered in this study.

Efficient engineered fills and isolation barriers can be constructed to control vibrations. Such fills can be especially beneficial due to high damping as well as high stiffness.

ACKNOWLEDGEMENTS

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