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MODELING THE DYNAMIC PROPERTIES OF CEMENTED SAND FOR SITE RESPONSE ANALYSIS

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ABSTRACT

A new formulation is presented that can be used to predict the small strain stiffness and damping of cemented sands, which is based on the SimSoil model. In the new formulation, material parameters describing the cementation are now used in the hysteretic component of the model that controls the change in small strain properties with increasing strain. Varying densities and confining pressures have less effect on the predicted modulus reduction and damping curves for cemented sand with the updated formulation. Another improvement in the updated formulation is the cement type and level have greater influence on the shear modulus reduction and damping curves. The performance of the model is evaluated by comparing its predictions with data from tests on Monterey, Michiana, and Ottawa sand cemented with Portland Cement and gypsum. The new model can be used to predict the response of cemented sand sites to earthquake ground motions.

Introduction

Nonlinear site response analyses can provide more accurate predictions of ground motions during an earthquake than equivalent linear procedures, especially for higher amplitude ground motions. However, the accuracy of the nonlinear analysis is limited by the availability and accuracy of the models used to represent the soil profile. There are few models available to represent cemented soil even though natural cementation occurs in many seismically active areas, and significant damage has occurred in cemented deposits during earthquakes. The lack of models to describe the behavior of cemented soils is due largely to the scarcity of research on the small strain properties of cemented sands. Furthermore, the reliability of much the limited available data, e.g. Saxena et al. (1988), is uncertain since samples tested in resonant column devices may not have been adequately fixed to the devices (Lovelady and Picornell 1990).

A new model, based on the SimSoil model (Pestana and Salvati 2006), to predict the small strain stiffness of cemented sands is described in this paper. The formulation for the maximum shear modulus, G_{max}, and the hysteretic formulation that describes the reduction in

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shear modulus and increase in damping with increasing shear strain are detailed. The new model is evaluated over a range of confining pressures, densities, cement contents, and cement types using recent tests performed on Ottawa, Michiana, and Monterey sand cemented with two different types of cement (Yang 2007). The Ottawa, Michiana, and Monterey samples tested in that study were attached to the resonant column device using a method that was shown to provide rigid coupling by Lovelady and Picornell (1990).

Maximum Shear Modulus

The formulation proposed by Pestana and Salvati (2006) for the maximum shear modulus of cemented sand continues to be used in the updated model, and is shown below.

$$\frac{G_{max}}{p_{at}} = G_b\, e_o^{-1.3}\left(\frac{p}{p_{at}} + a_{cc}CC^2\right)^n \tag{1}$$

where G_b is a material constant for the sand, e_o is void ratio of the sand skeleton before cementation, p is the confining pressure, p_{at} is atmospheric pressure, a_{cc} is a constant to describe the cementing agent and process, CC is the percent cement by weight, and n is a material parameter for the sand. Pestana and Salvati (2006) provides guidance on the selection of the material parameter G_b, and found that a value of 0.5 can be used as a default value for n in the G_{max} relationship for sands through an examination of available data for sands.

Figure 1 shows the results from bender element tests on the uncemented sands normalized by the void ratio function with the values of G_b and n determined for each sand. The value of n used was 0.5 for all of the sands. The G_b values from the best fit curves were 450 for Ottawa 20/30, 490 for Michiana, and 505 for Monterey 0/30 sand.

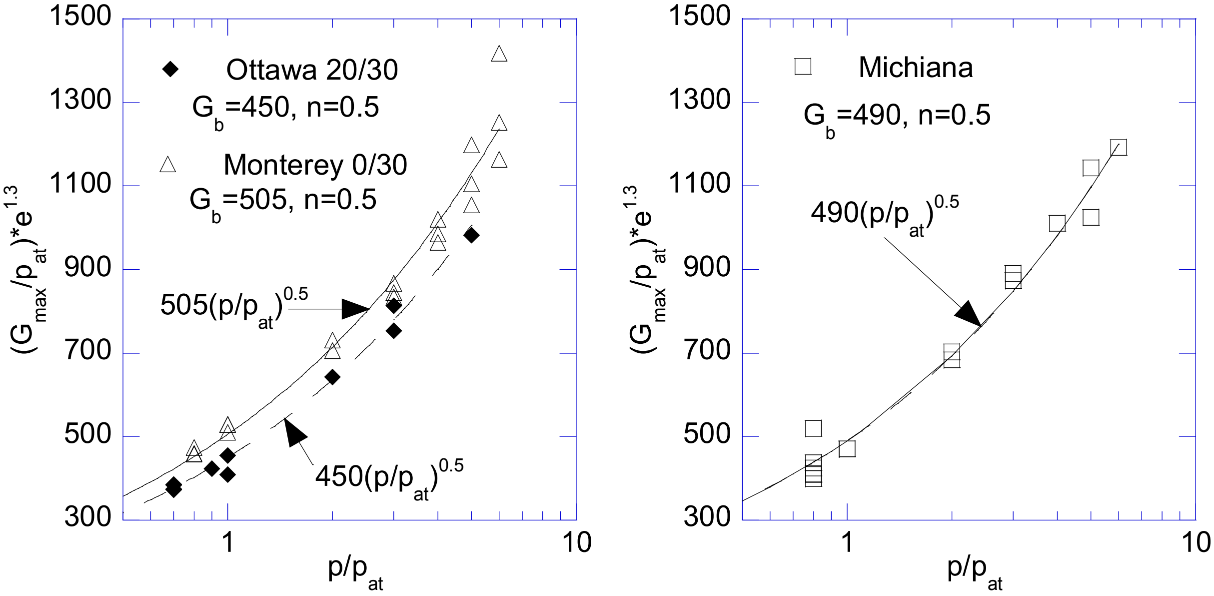

Figure 1. Material parameters, G_b and n, for Monterey 0/30, Ottawa 20/30, and Michiana sand.

The cement content, CC, is known for the samples prepared in the lab for the tests by Yang (2007), but the material parameter, a_{cc}, needs to be determined for Type III Portland Cement (PC) and gypsum. Given G_b and n for each type of sand, a_{cc} is estimated by plotting normalized results from ultrasonic tests for the different cemented sands. Using a least square fit on the normalized test results by Yang (2007), the a_{cc} value determined for Type III Portland Cement was 20, and the a_{cc} value determined for gypsum was 2.8.

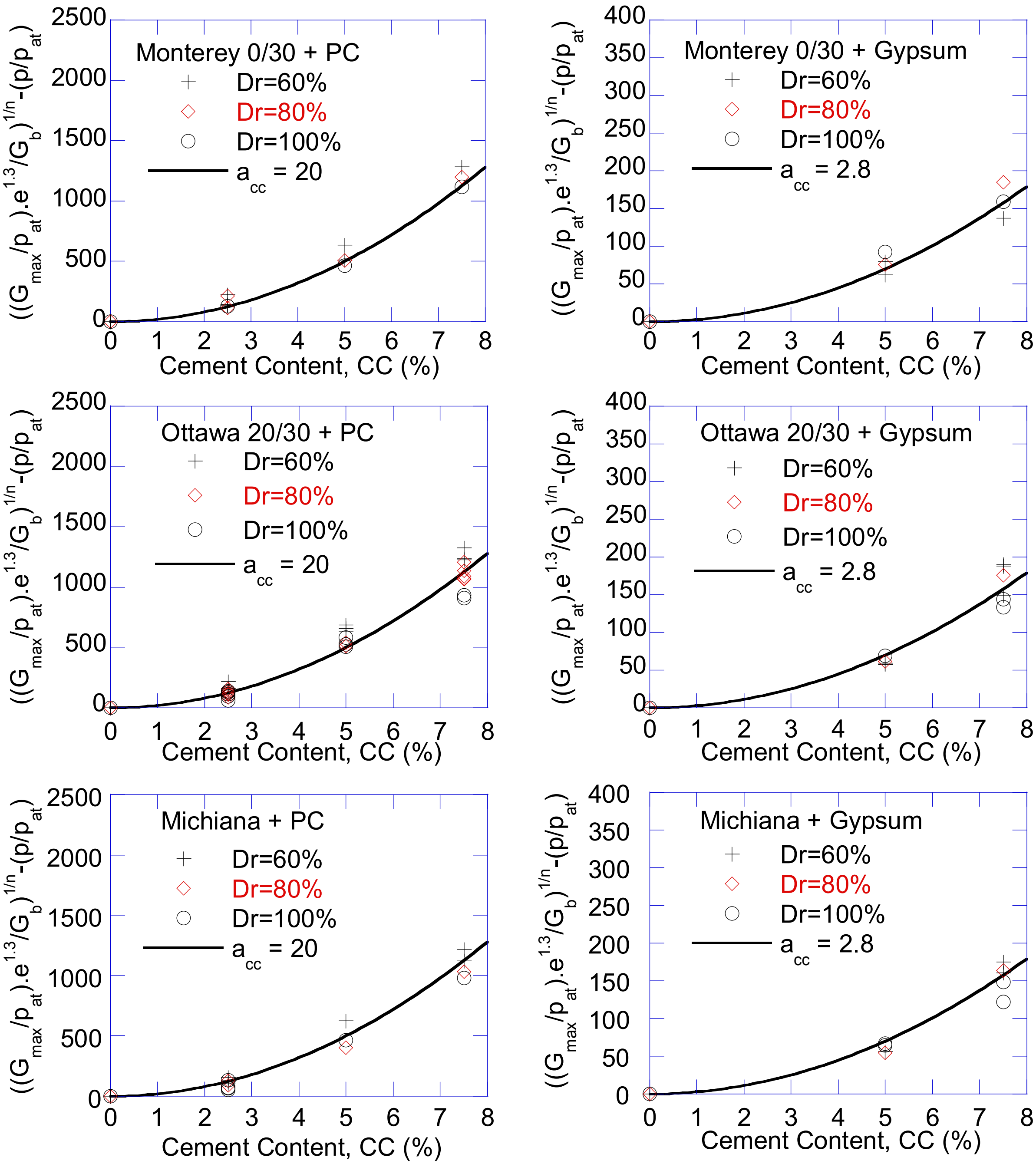

Figure 2. Material parameter, a_{cc}, for Type III Portland Cement (PC) and gypsum.

Model predictions with the proposed model parameters were compared with the maximum shear modulus values measured for Ottawa 20/30, Michiana, and Monterey 0/30 sand in Figure 3. For both Portland Cement and gypsum cemented samples, the predictions were very close to the test results from Yang (2007).

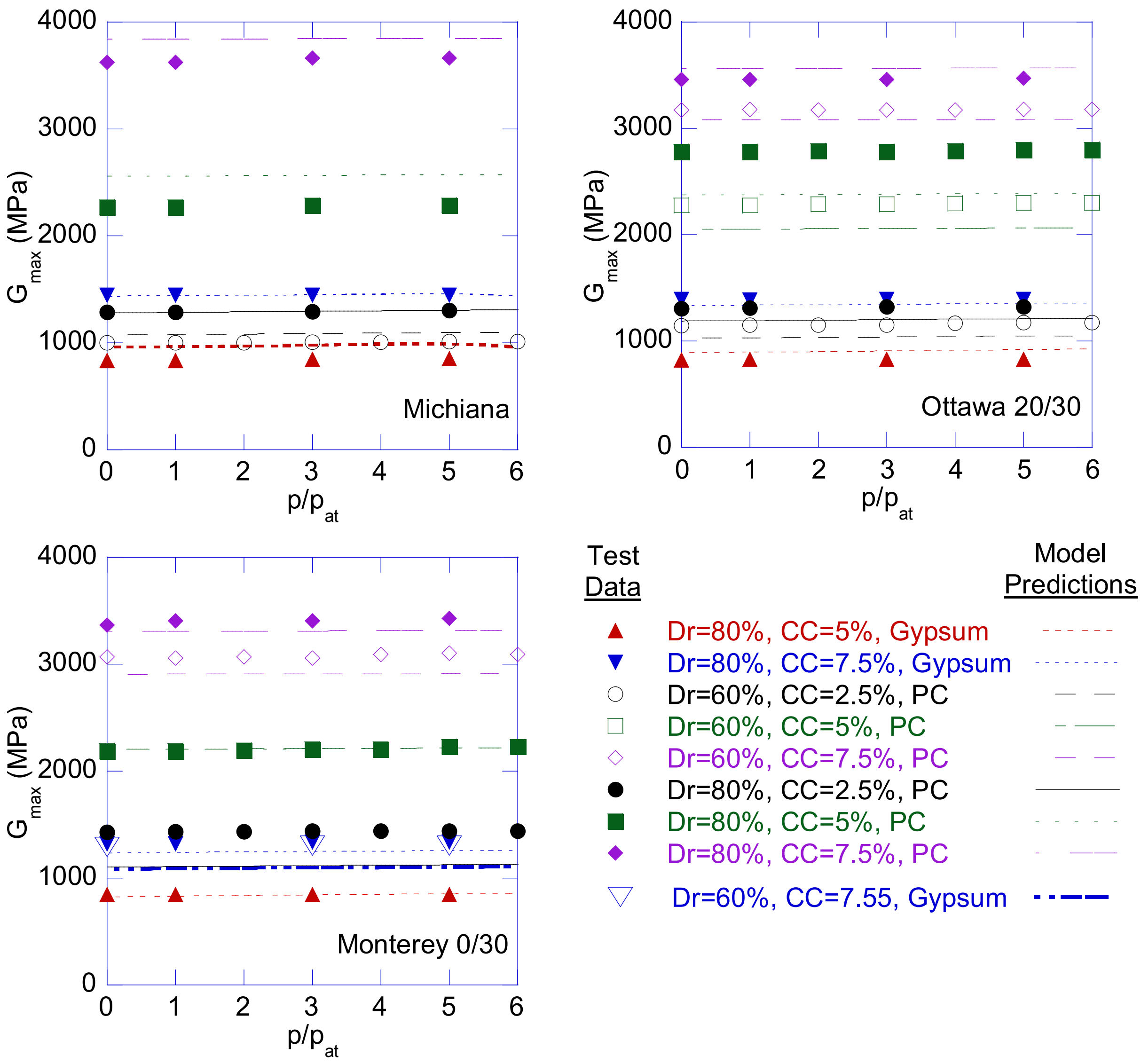

Figure 3. Comparison of measured and predicted G_{max} values for cemented Monterey 0/30, Ottawa 20/30, and Michiana sand

Small Strain Nonlinearity

Previous Formulation

The SimSoil model (Pestana and Salvati 2006) uses a hysteretic formulation (Huekel & Nova 1979) to describe the shear modulus reduction with increasing strain for sands and gravels in which the shear modulus is a function of the most recent stress reversal state. The formulation is given by

$$\frac{G_{\tan}}{G_{\max}} = \frac{1}{1 + \omega_s \xi_{s*}^{0.75} + \omega_s \xi_s + {\omega_a}^2 \xi_s^2} \tag{2}$$

where ω_s is a material parameter that controls the small to intermediate strain behavior, ω_a is a material parameter that controls the intermediate to large strain behavior, ξ_s is a dimensionless stress measure defined below, and ξ_{s*} is capped so that it cannot exceed 0.005 to limit its effect in the intermediate to large strain range. The dimensionless stress measure, ξ_s is given by

$$\xi_s = \left\| \eta - \eta_{rev} \right\| \tag{3}$$

where η is the stress ratio, which is the ratio of deviatoric to mean effective stress, and η_{rev} is the stress ratio at the most recent stress reversal point. The stress reversal point is set at the transition between loading and unloading, and is defined by the strain direction, since the strain history describes the nonlinearity of soil well (Hight et al. 1983; Hardin and Drnevich 1972). The loading/unloading condition is based on the vector product of the accumulated strain (from the last reversal point), χ, and the incremental strain, strain, $\dot{\chi}$, as shown below.

$$\chi : \dot{\chi} = \begin{cases} \geq 0 & \text{loading} \\ < 0 & \text{unloading} \end{cases} \tag{4}$$

New Formulation

The previous hysteretic formulation describes the response of uncemented sands and gravels over a wide range of confining pressures and densities well, but it does not describe the response of cemented sands adequately. For cemented sands, the influence of density and confining pressure on the modulus reduction and damping curves was too great with the previous formulation. Also, the influence of cement type and level on the modulus reduction and damping curves could not be accounted for with the previous formulation. Therefore a new formulation was developed for cemented sand, which includes the cement material parameters, a_{cc} and CC, as defined earlier. The updated version of the model is given below.

$$\frac{\mathrm{G}_{\tan}}{\mathrm{G}_{\max}} = \frac{1}{1 + \omega_c \zeta_{s*}^{0.75} + \omega_c \zeta_s + {\omega_a}^2 \zeta_s^2} \tag{5}$$

Where ω_a is the same material parameter as in Eq. 2, ω_c is a material parameter that includes the effects of cement as defined in Eq. 6, ζ_s is a dimensionless stress measure defined in Eq. 7, and ζ_{s*} is capped so that it cannot exceed 0.005 to limit its effect in the intermediate to large strain range

$$\omega_c = \omega_s + \frac{1}{2} a_{cc} CC^2 \tag{6}$$

where, a_{cc} and CC are cement material parameters defined in Eq. 1 and ω_s is a material parameter of the sand defined in Eq. 2. For one-dimensional (1D) site response analyses, a simplified version of ζ_s is given below

$$\zeta_s = \frac{\sqrt{2}\,\tau/p_{at}}{\sigma/p_{at} + a_{cc}CC^2} - \frac{\sqrt{2}\tau_{rev}/p_{at}}{\sigma_{rev}/p_{at} + a_{cc}CC^2} \tag{7}$$

where τ is the horizontal shear stress and σ is the mean effective stress, which is considered to be constant. The factor of $\sqrt{2}$ is a result of the transformed variables that are used by Pestana (1994) and the MIT family of models (Potts and Zdravkovic 1999). The new formulation reduces to the previous formulation if the cement content is set to zero.

The parameters ω_s and ω_a were determined for each type of sand tested by Yang (2007) based on the resonant column data for the uncemented sands. The parameters selected for Monterey 0/30 and Ottawa 20/30 sand are shown in Figure 4 with the data used to select them, and the parameters selected for all the sands tested by Yang (2007) are given in Table 1.

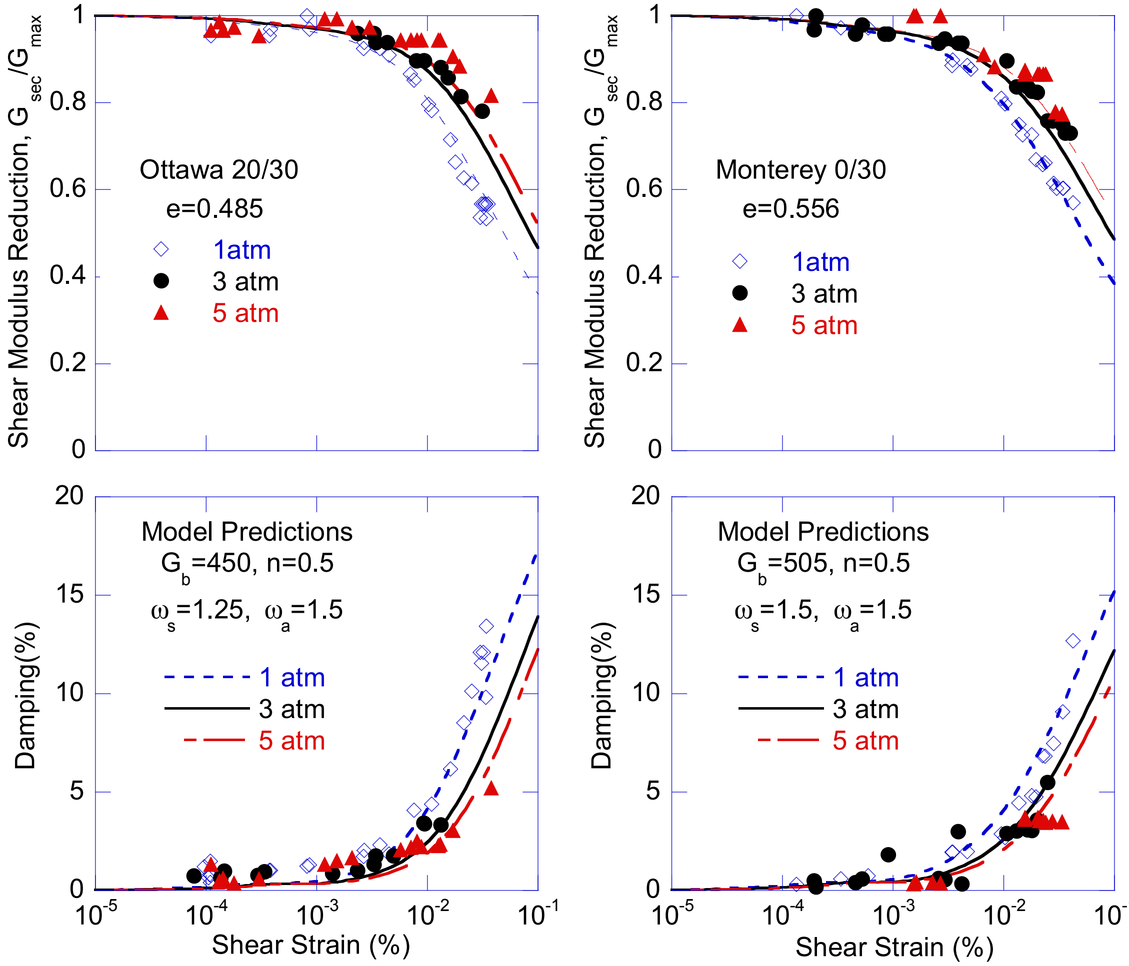

Figure 4. Material parametes ω_s and ω_a determined for Monterey 0/30 and Ottawa 20/30 Sand

Table 1. Material parametes ω_s and ω_a for sand tested by Yang (2007).

Sand	ω_s	ω_a
Monterey 0/30	1.5	1.5
Michiana	3.5	3.5
Ottawa 20/30	1.25	1.5

Model predictions for shear modulus reduction and damping curves are compared with the resonant column data by Yang (2007) for cemented Monterey 0/30, Michiana, and Ottawa 20/30 sands in Figs. 5 to 7. The limited influence that density as well as confining pressure has on the modulus reduction and damping curves of cemented sand is seen in the test results from Yang (2007) and is captured by the model predictions, as shown in Figure 5. Although, the effect of confining pressure may be slightly larger at lower cement contents or higher pressures.

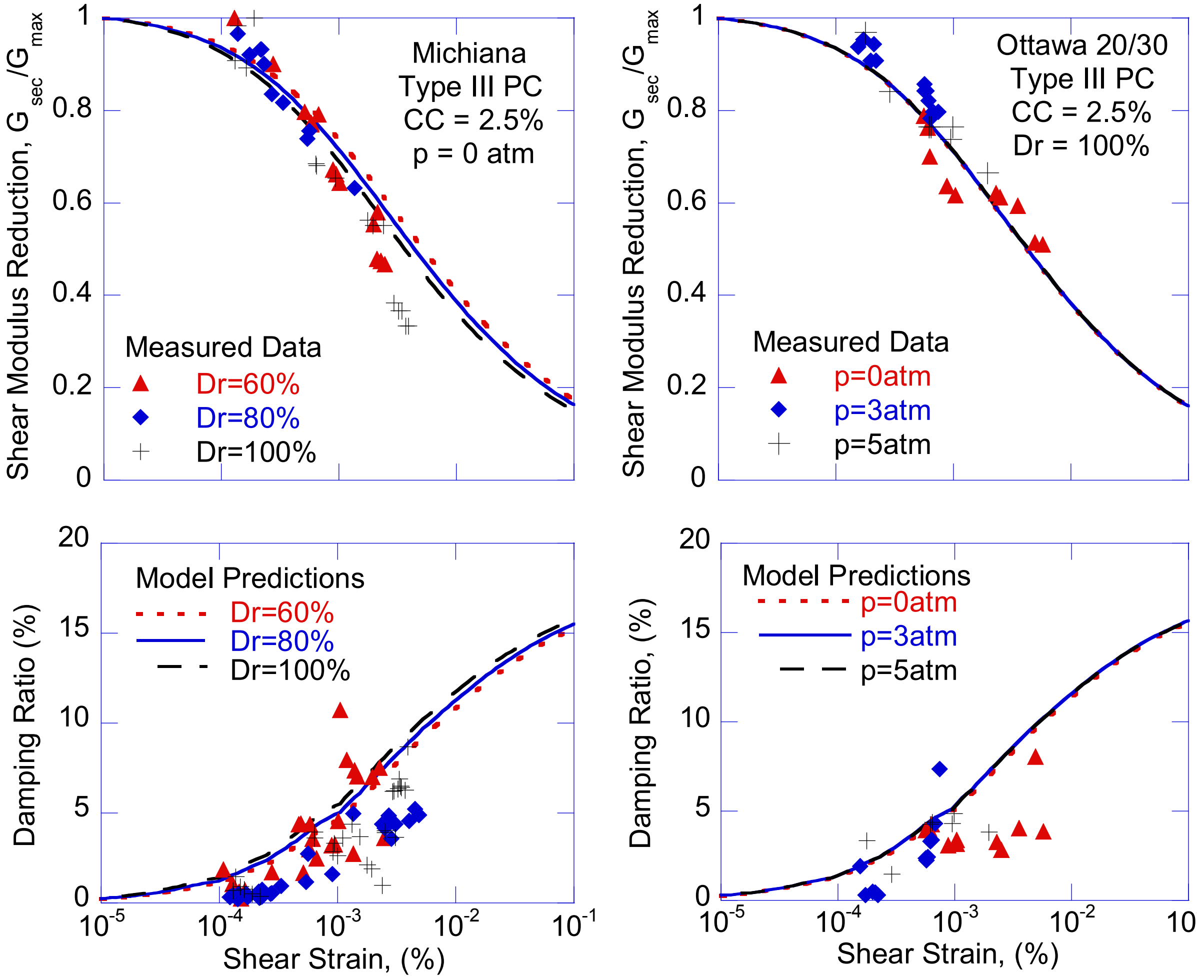

Figure 5. Influence of density and confining pressure on shear modulus and damping curves of cemented Michiana and Ottawa 20/30 sand

In Figure 6, model predictions for Michiana and Ottawa 20/30 sand samples cemented with varying levels of Portland Cement are compared with the data from Yang (2007). The model predictions for the modulus reduction curves match the data well, but the damping values are slightly over predicted for the samples at 5 % and 7.5% cement content. The increasing nonlinearity with increasing cement content predicted by the model is similar to that seen in the test data by Yang (2007).

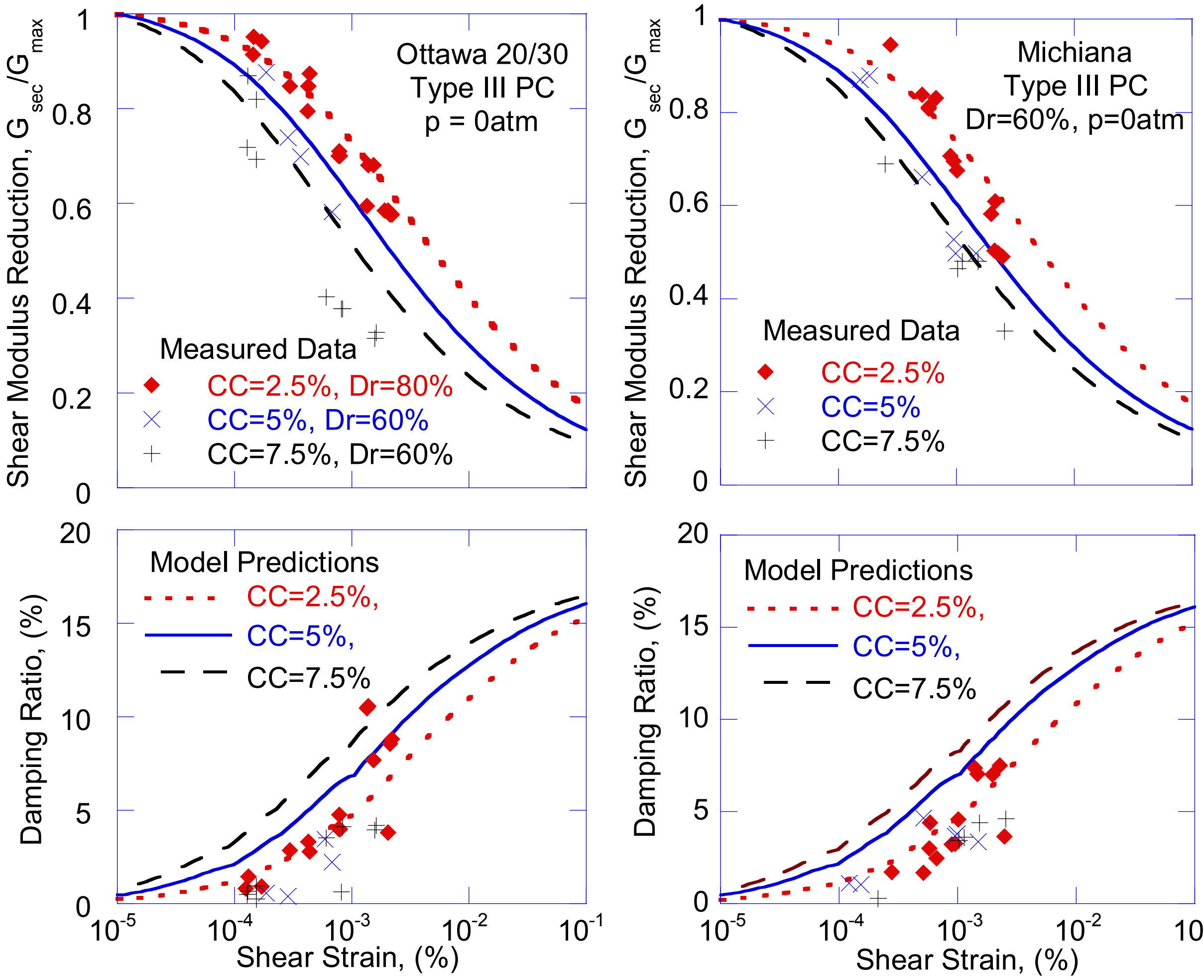

Figure 6. Modulus reduction and damping curves for Ottawa 20/30 and Michiana sand with varying amounts of Type III Portland Cement

Model predictions are compared with the measured data from Yang (2007) for Monterey 0/30 and Ottawa 20/30 sand samples cemented with varying amounts of gypsum in Figure 7. Overall the model predictions for the modulus reduction and damping are close to the test data for both Ottawa 20/30 and Monterey 0/30 sand. The predicted damping values were a little high, but did match the higher values of measured damping, which were rather scattered.

The strength of the Type III Portland Cement is much higher than the gypsum. The cube strength of the Type III Portland Cement after one week is 50 MPa, but it is 14 MPa for gypsum. There was greater nonlinearity in the modulus reduction curves for the sands cemented with the higher strength Portland Cement when compared to the sands cemented with gypsum, which is captured in the model predictions as well.

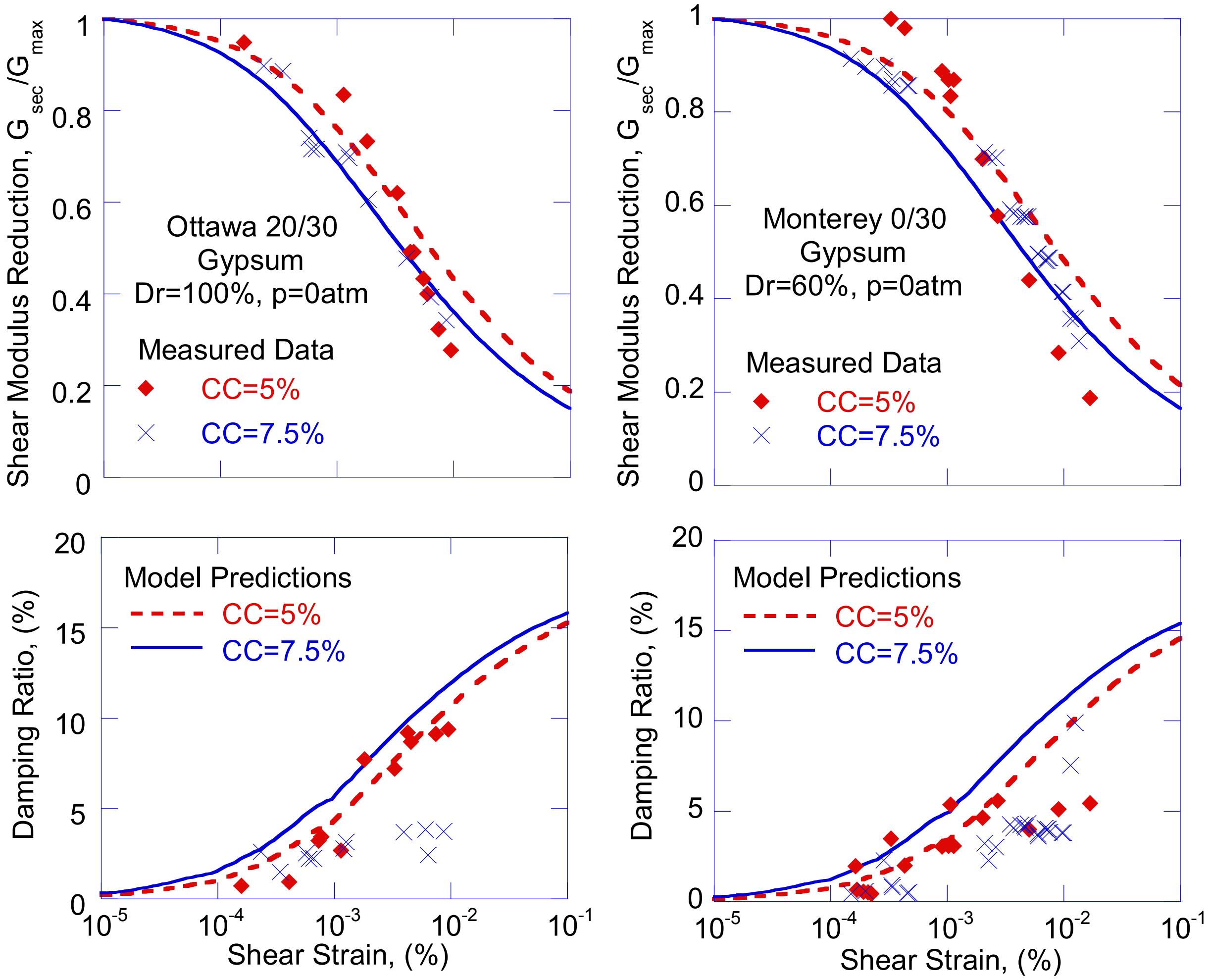

Figure 7. Modulus reduction and damping curves for Ottawa 20/30 and Michiana sand with varying amounts of gypsum

Conclusions

An updated formulation to predict the modulus reduction and damping curves for cemented sand has been presented. The formulation is based on the SimSoil model, which has been shown to predict the maximum shear modulus, modulus reduction, and damping curves for uncemented sands over a wide range of confining pressures and densities well. The original SimSoil model does not accurately predict the modulus reduction and damping curves for cemented sand, however, which is improved in this new formulation by including the cement material parameters in the hysteretic formulation. With the new formulation the predicted effects of confining pressure and density on cemented sand are limited as seen in the test data. The cement type and cement content have the greatest influence on the modulus reduction and damping curves of cemented sands, and the new formulation captures that well. The new formulation also predicts greater nonlinearity in the shear modulus and damping curves for samples with higher cement contents and stronger cements. This updated model can better predict the small strain response of cemented sands and can be used to predict site response at cemented sand sites when implemented in a site response analysis code.

Acknowledgments

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