Modeling of dynamic properties of cemented clay

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ABSTRACT
A new shear stiffness model, Simsoil-CC, is proposed to represent dynamic properties of cemented clay. The model predicts maximum shear modulus and variation of modulus and damping as a function of shearing strain amplitude. Model parameters are determined for different types of clay and cementation agents based on laboratory data from this study and previous studies. The model, Simsoil-CC, for cemented clay is an extension of Simsoil-CS for cemented sand. The model can be combined to predict the response of cemented soil to dynamic loads. This can be useful for performing earthquake site response analysis for naturally cemented sites or sites that have been improved by cementation.

RÉSUMÉ
El nuevo modelo Simsoil-CC para arcillas cementadas es propuesto para representar el máximo modulo de corte y variación del modulo de corte y amortiguamiento con deformación. Los parámetros del modelo son determinados para diferentes tipos de arcilla y agentes cementantes basado en ensayos de laboratorio ejecutados en esta investigación e investigaciones previas. Los modelos Simsoil-CC y Simsoil-CS propuesto previamente para arenas cementadas pueden ser usados en análisis de respuesta sísmica para suelos naturalmente o artificialmente cementado.

1 INTRODUCTION

Understanding the shear stiffness behavior of soil is very important in site response analysis for predicting the response of the soil during an earthquake. Comparing to equivalent linear site response analysis, nonlinear analysis can provide more accurate predictions of ground motions during an earthquake, especially considering higher amplitude ground motions. To realize the benefit from performing a nonlinear analysis, a model that can accurately represent the nonlinear behaviour of the soil must be used.

Research on cemented soils has been ongoing since the 1960s. Most of the research has concentrated on static or large strain properties, such as the angle of internal friction and cohesion from triaxial. However, the large body of literature on the static properties has not been accompanied by an equal effort to investigate small strain properties, and the database of dynamic tests results for cemented soils is limited. Nevertheless, in applications such as seismic site response analysis, seismic slope stability analysis and machine foundation design, the small strain shear modulus and damping ratios can control the design rather than the large strain soil properties which quantify soil strength.

Research described here investigates the shear modulus and damping of cemented clay through laboratory tests using pulse generating transducers, bender elements, and resonant column devices. The effect of different factors, including the cement type, cement content, void ratio, confining pressure, and clay type, have on the reduction of shear modulus and increase in damping with increasing shear strain as well as the maximum shear modulus are examined herein. A new shear stiffness model, Simsoil-CC for cemented clay, based on the model Simsoil by Pestana and Salvati (2006), is proposed to represent dynamic properties of the cemented clay. This research advances the understanding of cemented clay by providing a database of test results and creation of a model which can be used to predict the response of cemented soils to dynamic loads.

2 SAMPLE PREPARATION

Two pure, commercially available clays were chosen for the study of cemented clay: kaolinite and bentonite. They were obtained commercially in powdered form to ensure purity and uniformity. Three clay mixes were used for cemented clay samples, they are: kaolinite alone, bentonite alone, and an equal mix of kaolinite and bentonite. The kaolinite mineral is the simplest and most understood clay mineral, having a relatively low plasticity index (PI=20), and will be used as the low end of the plasticity index range. Bentonite has a very high plasticity index (PI=450), which makes it suitable for simulating highly expansive soils forming the other extreme soil for this study. The equal mix of bentonite and kaolinite has a medium plasticity index (PI=200) and will be included to simulate medium plasticity soils. The properties of each mix are listed in Table 1. In this study, kaolinite is cited as Clay K, bentonite is cited as Clay B, and the equal mix of bentonite and kaolinite is cited as Clay KB.

Type III Portland cement and gypsum are selected as cementing agents. Type III Portland Cement is a type of high early strength cement with a compressive strength (w/c=0.5) after 1 week of 50 MPa. The gypsum cement used is plaster of Paris. The maximum compressive strength of ordinary plaster of Paris is about 12-15 MPa (Singh and Garg, 2005). These two cementing agents were selected to examine the effect of cement strength on the low-strain shear modulus of the cemented soil.

Table 1. Properties of Tested Clay Mixes.

Properties	Clay K	Clay KB	Clay B
G_s	2.65	2.55	2.45
$w_{LL}(\%)$	48	240	500
$w_{PL}(\%)$	28	40	50
$I_p(\%)$	20	200	450

Cemented clay specimens were prepared in three wet cement contents (cc) of 2.5%, 5%, and 7.5% based on the total weight of the dry clay powder and water for clay. For Type III Portland Cement samples, the water contents used were liquid limit $\mathrm{w_{LL}}$, plastic limit $\mathrm{w_{PL}}$ and the average of liquid and plastic limit $\frac{1}{2}(\mathrm{w_{LL}}+\mathrm{w_{PL}})$. For gypsum cemented samples, however, it is difficult to form the sample at the water content of liquid limit $\mathrm{w_{LL}}$. Therefore, gypsum cemented samples were prepared at lower water contents compare to Type III Portland Cement cemented samples. Uncemented clay samples were also prepared to study the effect of cementation.

Cemented clay samples were prepared by first mixing a measured amount of clay powder and cement, and then adding the amount of water needed. Mixing was done by a mechanical mixer. The uniform mixture of clay, water, and cement was compacted into a mold according to ASTM D1557. The standard proctor energy was applied for each layer. The cemented clay specimen was cured in the mold for three days, and then was carefully extracted from the mold. The samples were wrapped with two layers of saran wrap and sealed in a plastic bag. All of the cemented clay specimens were cured at least 14 days for Type III Portland Cement samples or 7 days for gypsum cemented specimens, before testing.

3 MODELING OF DYNAMIC PROPERTIES

3.1 Maximum Shear Modulus

The maximum shear modulus of cylindrical confined and unconfined cemented clay specimens with different cement contents and water contents were measured with flush mounted strain transducers and bender elements. Based on the laboratory test results and the model Simsoil (Pestana and Salvati, 2006) and model Simsoil-CS (Yang 2008), the model for the maximum shear modulus of cement clay is proposed as:

$$\frac{G_{max}}{p_{at}} = G_b e^{-2.5}\left(\frac{p^*}{p_{at}} + a_{cc}CC^2\right)^n \qquad [1]$$

where e is the void ratio after cementation; a_{cc} is a cement material constant describing the cementing agent and process; CC is the dry cement content, which is the weight of the cement divided by the weight of dry clay power (calculated by $cc(1+w)$); p^* is the effective stress applied to the sample, $p^* = p + p_u$, (p is the confining pressure and p_u is the pore suction of the clay sample).

The material constant $\mathrm{G_b}$ and n values for the three types of clay are determined by plotting the normalized maximum shear modulus with the pressure as shown in Figure 1. The values of $\mathrm{G_b}$ and n in EQ (1) are listed in Table 2. The cement constant $\mathrm{a_{cc}}$ can be determined by plotting the normalized maximum shear modulus with the cement content and fitting the curve with a power function, as shown in Figure 2. For the two types of cementing agent used in this study, the $\mathrm{a_{cc}}$ value of clay cemented with Type III Portland Cement is 20; whereas for gypsum cemented clay, $\mathrm{a_{cc}}$ is 0.5.

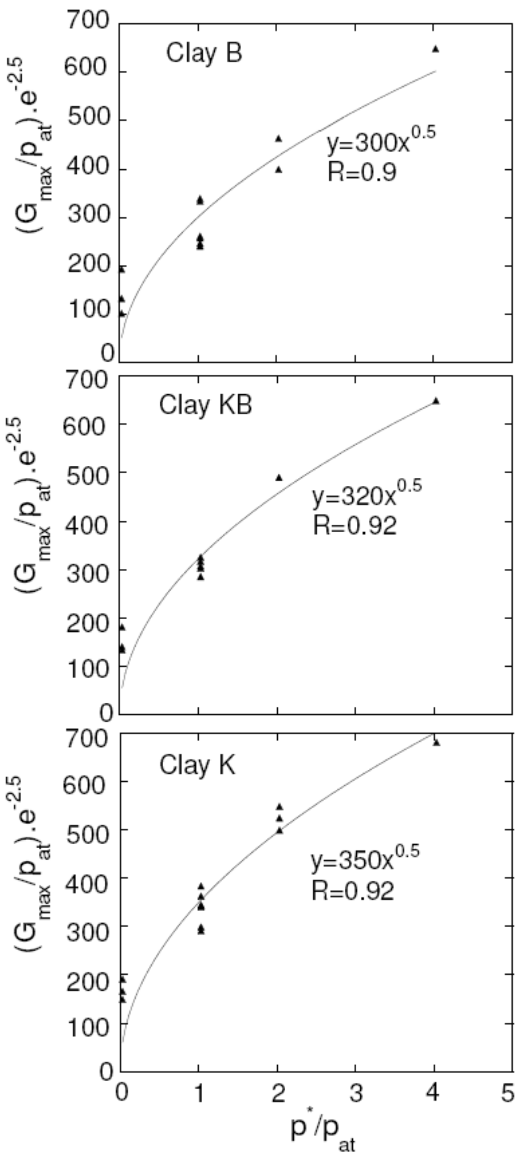

Figure 1. Determination of G_b and n

Table 2. Model Parameters G_b and n

Properties	Clay K	Clay KB	Clay B
G_b	350	320	300
n	0.5	0.5	0.5

The measured maximum shear modulus of cemented clay samples are compared with the predictions of the model in Figure 3, where it can be seen that the measured and model predictions of G_{max} are in general agreement.

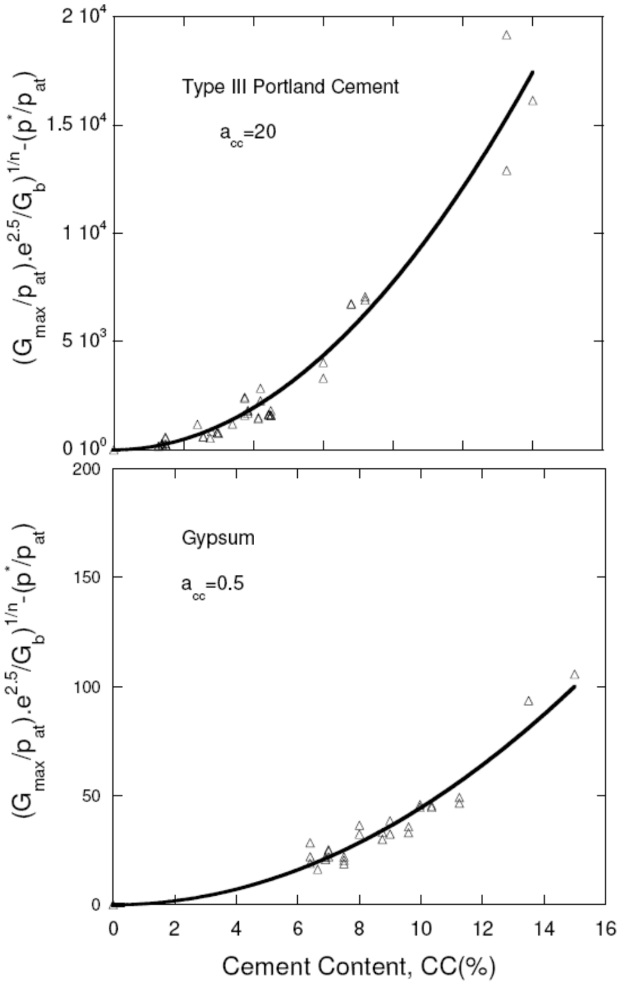

Figure 2. Determination of a_{cc} for Type III Portland Cement and Gypsum

3.2 Small Strain Nonlinearity

The shear modulus degradation with shear strain amplitude for cemented clay samples with different cement and water contents were measured in a resonant column (RC) device. Based on RC results, the small strain nonlinearity of cemented clay can be represented by the following equations:

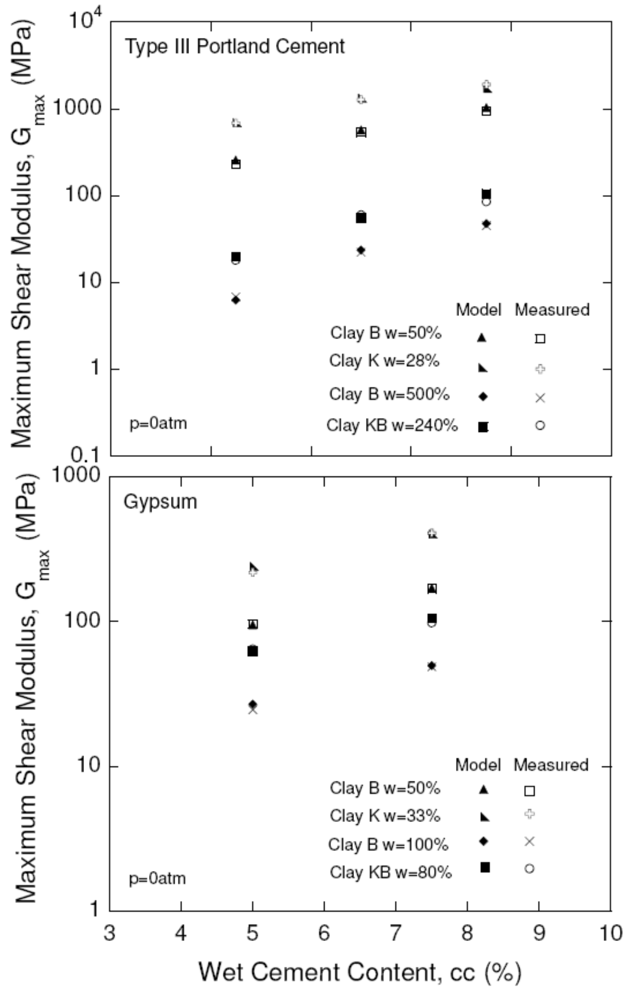

Figure 3. Predicted and measured maximum shear modulus

$$\frac{G_{tan}}{G_{max}} = \frac{1}{1+\omega_c\zeta_s^{0.75}+\omega_c\zeta_s+\omega_a^2\zeta_s^2} \quad [2]$$

$$\omega_c = \omega_s + e\sqrt{a_{cc}CC^2} \quad [3]$$

$$\zeta_s = \|\eta - \eta_{rev}\| \quad [4]$$

where G_{tan} is the tangent shear modulus (i.e., the slope of the shear stress vs strain amplitude curve at a certain shear strain level). Material parameters ω_s and ω_a describe the nonlinearity of the modulus degradation versus shear strain curves where ω_a controls the intermediate to large strain behavior; ω_s controls the small to intermediate strain behavior; η is the stress ratio; and η_{rev} is the stress ratio at the most recent stress reversal point. The symbol ζ_s represents a dimensionless stress measure and equals the dot product of η and η_{rev}. Reversal is defined by the strain direction. The stress reversal point is set at the transition between loading and unloading, and the loading/unloading condition is based on the vector product of the accumulated strain from the last reversal point χ and the incremental strain $\hat{\chi}$ (Pestana and Salvati 2006):

$$\chi:\hat{\chi} = \begin{cases} \geq 0 \ loading \\ < 0 \ unloading \end{cases} \quad [5]$$

For one-dimensional (1D) site response analysis, a simplified version of ζ_s is given below:

$$\zeta_s = \frac{\sqrt{2}\frac{\tau}{p_{at}}}{\frac{\sigma}{p_{at}}+a_{cc}CC^2} - \frac{\sqrt{2}\frac{\tau_{rev}}{p_{at}}}{\frac{\sigma_{rev}}{p_{at}}+a_{cc}CC^2} \quad [6]$$

Material parameters ω_s and ω_a, describing the nonlinearity for different clays, can be determined with uncemented clays ($CC = 0$) as shown in Figure 4a through Figure 4c. The value of ω_s and ω_a for Clay K, Clay KB, and Clay B are listed in Table 3.

Equations [1] through [6], the maximum shear modulus and the shear modulus variation with the shear strain constitute model Simsoil-CC: the new shear stiffness model for cemented clay.

Table 3. Model Parameters ω_s and ω_a

Properties	Clay K	Clay KB	Clay B
ω_s	2.0	1.5	1.2
ω_a	4.0	1.0	1.0

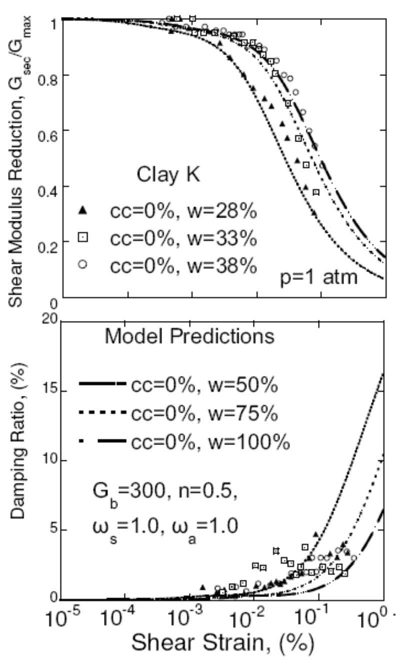

Figure 4a. Determination of Model Parameters ω_s and ω_a for Clay K

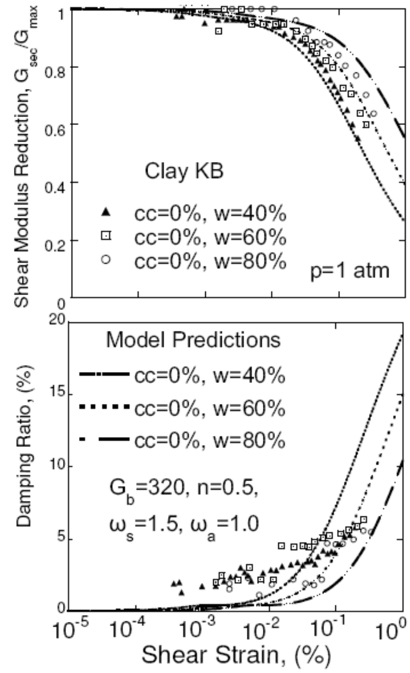

Figure 4b. Determination of Model Parameters ω_s and ω_a for Clay KB

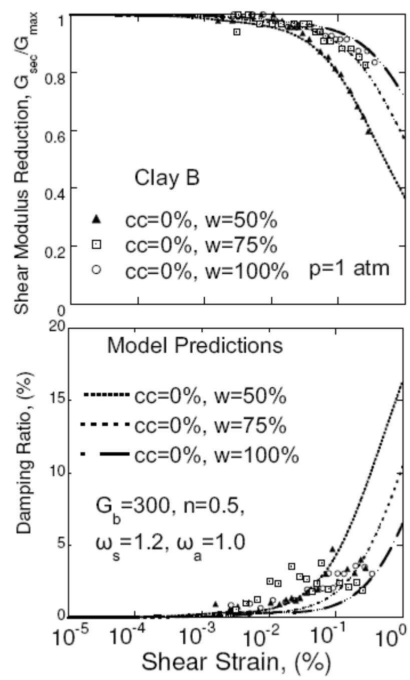

Figure 4c. Determination of Model Parameters ω_s and ω_a for Clay B

The shear modulus reduction and damping increase with increasing shear strain of cemented clay predicted by model Simsoil-CC are shown in Figures 5 through 7. Void ratio is an important factor controlling the shape of the modulus reduction curve as indicated in Figure 5. The shear modulus of cemented clay with a higher void ratio reduces more gradually than cemented clay with a lower void ratio. Cement content and cement type also influence the small strain nonlinearity of cemented clay. Confining pressure has minimal effect on the shear modulus reduction and damping curves of cemented clay, as shown in Figure 6.

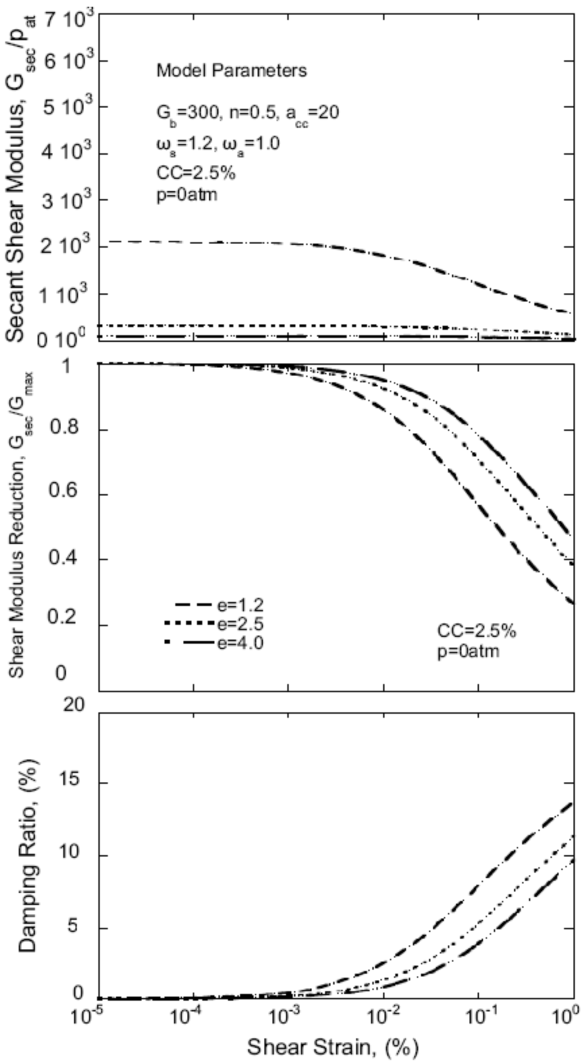

Figure 5. Model predictions for cemented clay with varying void ratio

3.3 Comparing Model Predictions with Test Results

The modulus reduction and damping curves from Fahoum (1996) are shown in Figure 8 and 9 and are compared with model predictions. Figure 8 shows the measured shear modulus reduction and damping for untreated sodium montmorillonite(SM), and 2%(SM+2L), 5%(SM+5L) and 8%(SM+8L) lime treated sodium montmorilloite. The sodium montmorillonite used in Fahoum (1996) was obtained from the American Colloid Company, and the PI of the soil is very high (PI=514). The

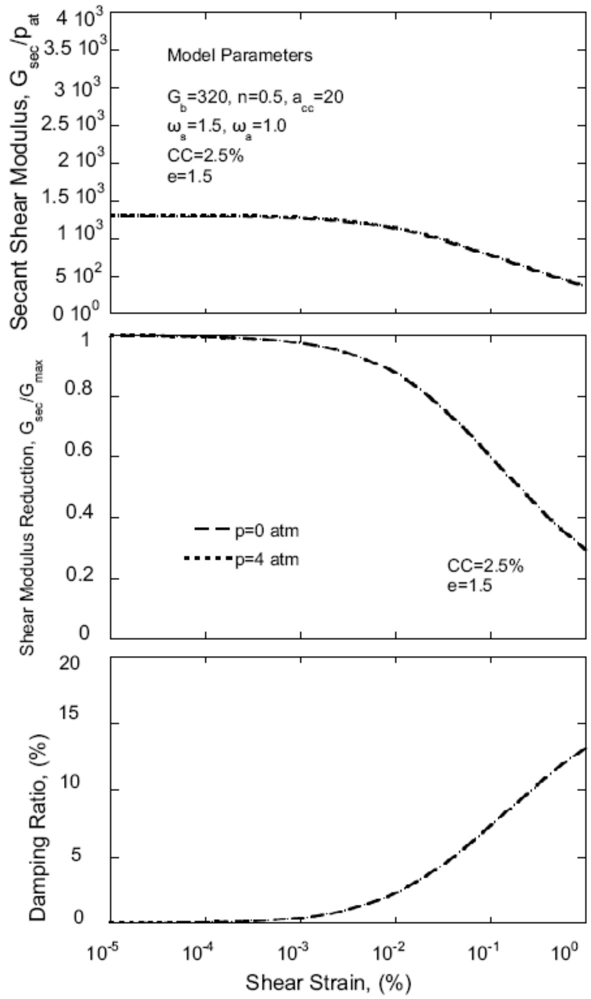

Figure 6. Model predictions for cemented clay with varying confining pressure

water content used in Fahoum's study was 30.5% for SM, 34% for SM+2L, 36.8% for SM+5L, and 32.9 % for SM+8L. By fitting the model with the reported maximum shear modulus, model parameters Gb, a_{cc}, and void ratio of untreated and treated soil are obtained. As seen from Figure 8, the model predictions match the measured shear modulus very well. The damping ratio of the untreated soil agreed with the model predictions, but the damping ratios of lime treated sodium montmorillonite are lower than predicted. In Figure 9, the modulus reduction and damping of untreated calcium montmorillonite(CM), 2%(CM+2L), 5%(CM+5L) and 8%(CM+8L) lime treated calcium montmorilloite are compared with model predictions. The water content is 41% for CM, 42% for CM+2L, 44.7% for CM+5L and 47 % for CM+8L. Calcium montmorillonite has a medium PI which is 35 (Fahoum 1996). The model predicted very well the modulus reduction curve with increasing shear strain for both untreated and treated clay. The model predictions of the damping ratios are higher than the measured results.

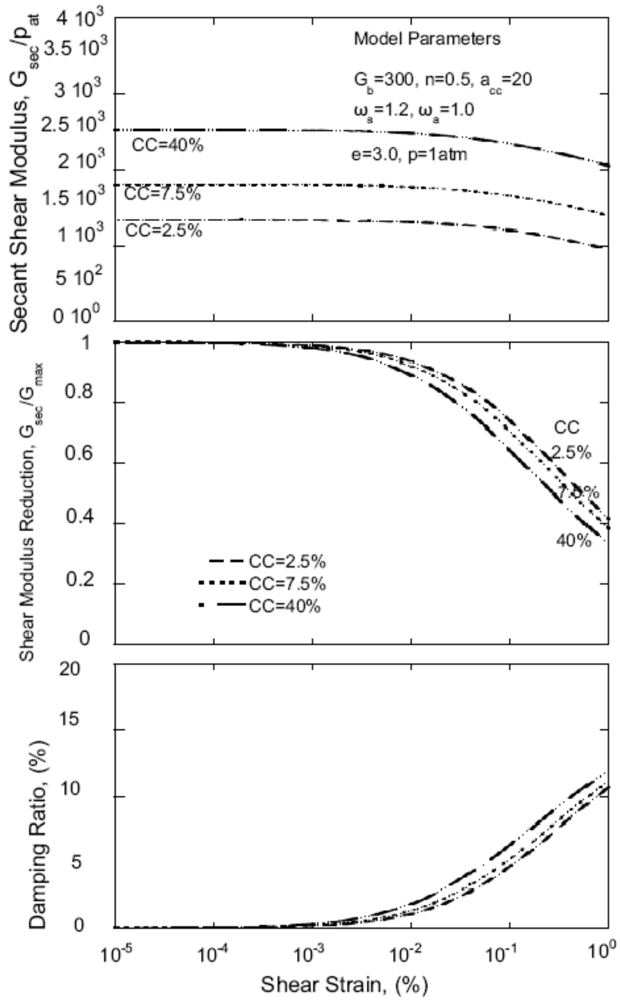

Figure 7. Model predictions for cemented clay with varying cement type and cement content

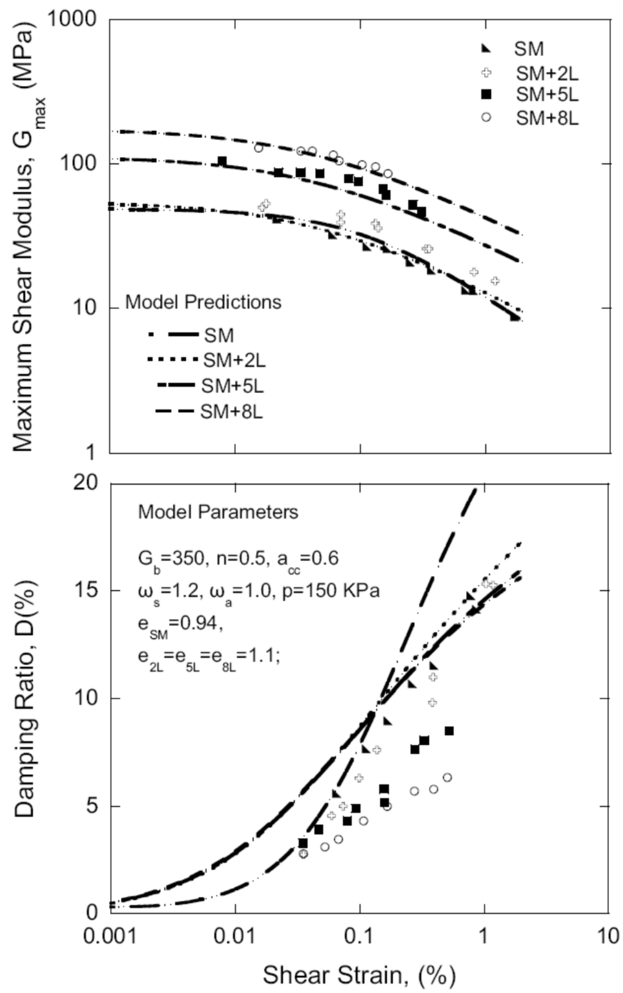

Figure 8. Model predictions with the test results of Fahoum 1996 study

In the study of Hoyos (2004) on the dynamic properties of chemically stabilized sulfate rich clay, Type V Cement was used as one of the stabilizers. Type V Cement is sulfate resistant and is recommended for construction in high-sulfate environments. The 7-day compressive strength of Type III Portland Cement is 50MPa, and the 7-day compressive strength of Type V Cement is 32MPa (Hoyos 2004). As the a_{cc} for Type III Portland Cement treated clay is 20, 15 was used as an estimate for Type V Cement treated clay. Other model parameters were obtained from fitting the model with the reported data. In Figure 10, the modulus reduction for 5% Type V cement-treated sulfate rich clay is compared with model predictions. The model predicted the measured results reasonable well for cemented clay with different void ratios. For 10% Type V cement-treated soil, model predictions for the 95% wet and 85% wet samples are higher than the reported data. This inconsistency might be caused by insufficient information for estimating the model parameters.

The proposed model for the small strain nonlinearity of cemented clay is compared with the laboratory test results of this study in Figures 11 through 13. In Figure 11, the model predictions matched most of the measured shear modulus and damping for both Type III Portland Cement and gypsum cemented clay samples. The model and test results showed the same effect of the void ratio on the modulus reduction and damping curves. In Figure 12, the measured shear modulus and damping cemented with different cement agents in different cement contents are compared with the model predictions. For gypsum cemented clay KB, the measured modulus is higher and measured damping is lower than the model predictions, but the difference between the test result and model predictions are within reasonable range. As indicated, with higher cement content, the shear modulus begin to decrease at a smaller strain. Comparing the influence of cement content and cement type with cemented sand, the influence is relatively small for cemented clay. The small strain nonlinearity of uncemented clay can be affected by the plasticity index of the clay; however, for cemented clay, this influence is negligible. As shown in Figure 13, when the void ratio is similar, the difference in the shear modulus of different clay samples treated with the same cement type and cemented content is small. Comparatively, for clay samples cemented with Type III Portland Cement, the difference between the modulus reduction curves of different clays are smaller than gypsum cemented samples.

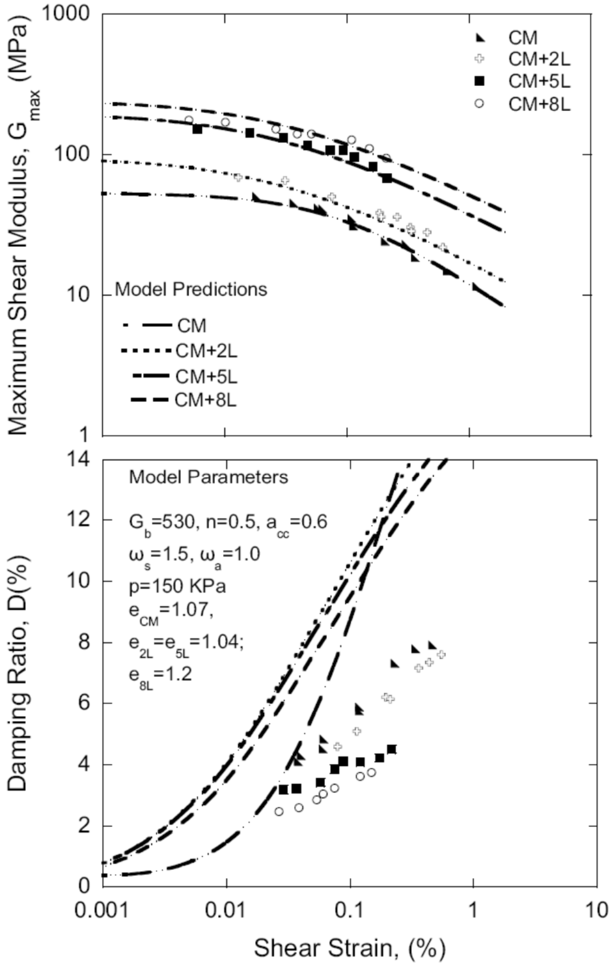

Figure 9. Model predictions with the test results of Fahoum 1996 study

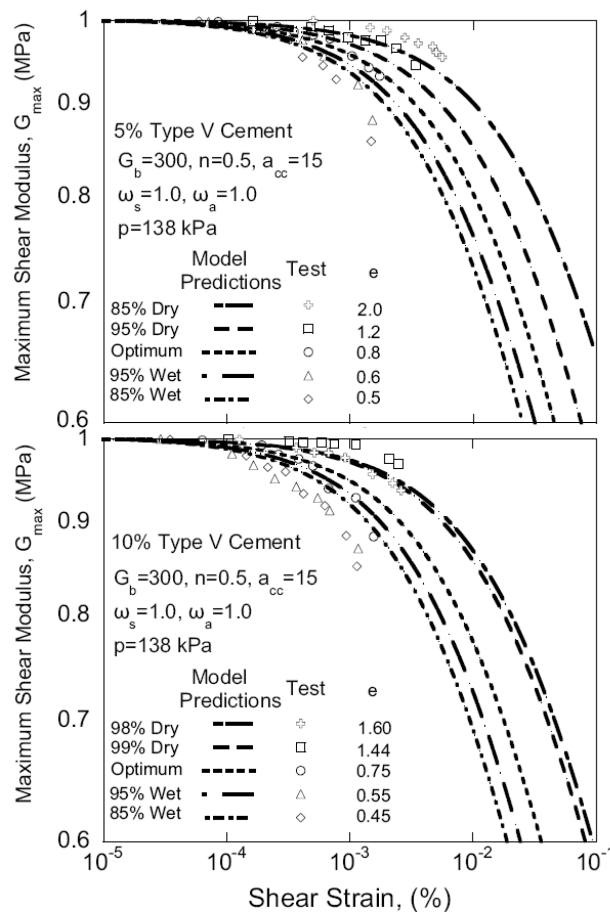

Figure 10. Model predictions with the test results of Hoyos (2004)

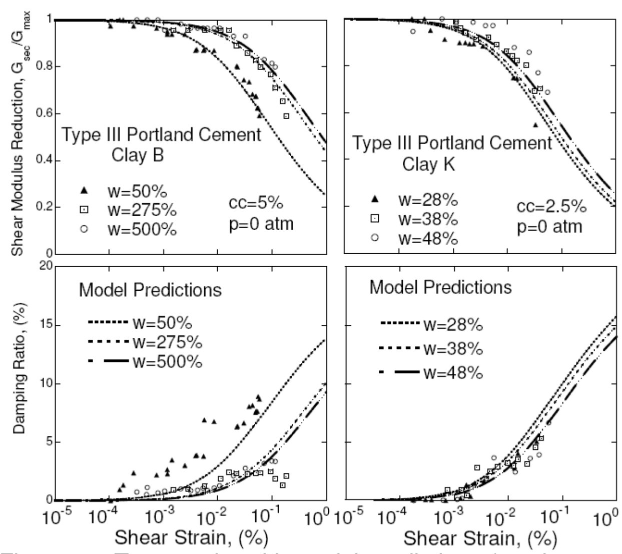

Figure 11. Test results with model predictions (varying Void Ratio)

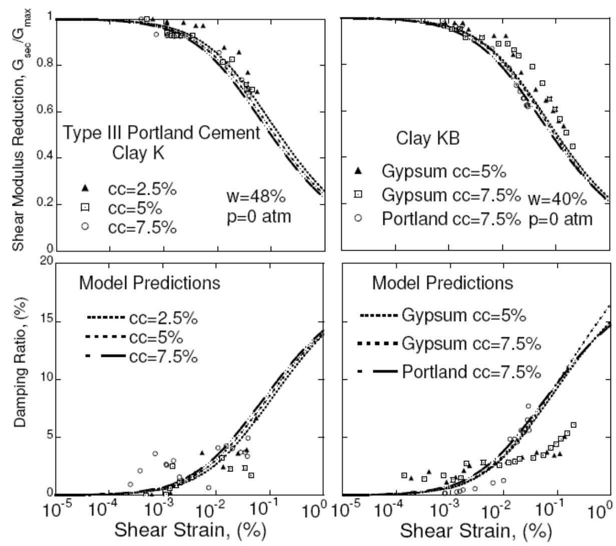

Figure 12. Test results with model predictions (varying Cement Content)

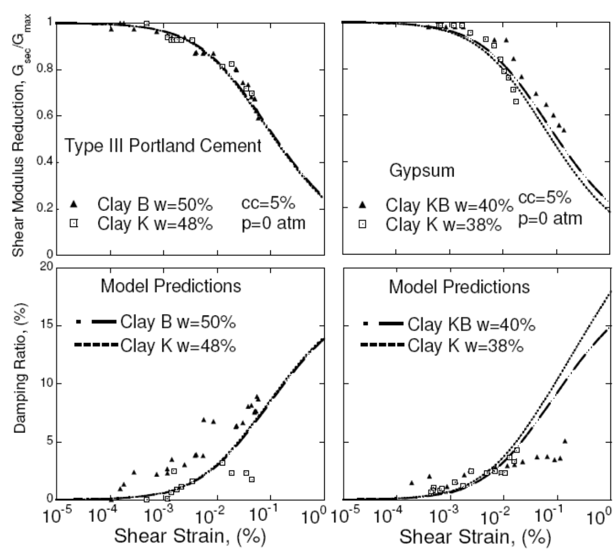

Figure 13. Test results with model predictions (varying Clay type)

4 CONCLUSIONS

Model SimSoil-CC was proposed for estimating the maximum shear modulus as well as the modulus and damping variation with the shear strain of cemented clay. The model predictions, which agree with the test measurements, indicate that the void ratio, cement content, and cement type are significant factors influencing the maximum shear modulus and the shear modulus nonlinearity of cemented clay. Comparatively, confining pressure and cement type have a much smaller effect. Besides the test results of this study, the model predictions matched reasonable well with other test data available in literature.

REFERENCES

ASTM D 1557. ASTM D 1557 standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3(2,700 kn-m/m3)).

Pestana, Juan M. and Salvati, Lynn A. 2006. Small strain behavior of granular soils. part 1. model for cemented and uncemented sands and gravels. *Journal of Geotechnical and Geoenvironmental Engineering.*, 132(8):1071–1081.

Fahoum, K. 1996. Dynamic properties of cohesive soils treated with lime. *J. of Geotechnical and Geoenvironmental Engineering*, ASCE, 122(5).

Hoyos, L.R. , Puppala, A.J. and Chainuwat, P. 2004. Dynamic properties of chemically stabilized sulfate rich clay. *Journal fo Geotecnical and Geoenvironmental Engineering*, ASCE.

Singh, M. and Garg, M 2005. Study on anhydrite plaster from waste phosphogypsum for use in polymerised flooring composition. *Construction and Building Materials*, 19(1).

Yang, L., 2008. Shear Stiffness Modeling of Cemented Sand and Cemented Clay, Dissertation, University of Notre Dame.