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DYNAMIC PROPERTIES OF MODIFIED GLYBEN AS ARTIFICIAL CLAY FOR SEISMIC APPLICATIONS

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ABSTRACT

Modified glyben is an artificial clay comprising bentonite mixed with glycerin and water. Its dynamic properties were investigated in this paper for use in scaled physical model studies. The modified glyben has the potential to provide a better alternative for the traditional glyben (bentonite and glycerin) since the latter has a damping ratio about 3 times that of natural soils at low and intermediate strain levels. This paper presents the results of lab shear vane tests, cyclic triaxial tests, resonant column tests and bender element tests undertaken to evaluate the dynamic properties of modified glyben. The results show that the modulus ratio of modified glyben decreases and damping ratio increases with increasing shear strain amplitude similar to that observed for natural clays. In addition, there are significant thixotropic changes in the properties of modified glyben after mixing bentonite with glycerin and water, it does not consolidate significantly with time after the application of confining stresses and its dynamic properties are not affected by number of cycles.

Keywords: Geotechnical models, Soil dynamics, Synthetic clays, Cyclic tests.

INTRODUCTION

Obtaining a model soil that can simulate the seismic response of prototype soils in scaled soil-structure interaction model studies is one of the biggest challenges faced in this type of research. A significant number of model soils have been proposed and used successfully (e.g. Seed and Clough 1963, Meymand 1998, Moss et al. 1998, Rayhani and El Naggar 2006). However, these researchers faced some typical challenges including: sensitivity of the properties to consolidation caused by gravity effects in centrifuge tests, difficulties related to preparation and placement of soil into a laminar shear box and desiccation and drying of the model soil. Thus, there is a need for an artificial soil that avoids the challenges of conventional model soils.

This paper describes an artificial soil called modified glyben that appears to overcome some of the limitations of other artificial soils. Glyben is a synthetic clay mixture comprising bentonite and glycerin, which has been studied previously by Mayfield (1963), Kenny and Andrawes (1997), Rayhani and El Naggar (2006) and Turan et al. (2006). Some favorable features of glyben that make it preferable to other synthetic soils are that the dynamic properties of glyben can easily altered by

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changing the percentage of glycerin by mass (g/c) in the mixture, it does not consolidate significantly during short term tests of less than 1 week duration and its properties are not affected from drying and desiccation (Rayhani and El Naggar 2006, Turan et al. 2006). In spite of these favorable features, it was found that the dynamic properties of glyben show time dependant changes (thixotropy), they are sensitive to temperature changes and most importantly, the damping ratio of glyben is significantly higher than that of natural soils at low and intermediate shear strain amplitudes (Rayhani and El Naggar 2006, Turan et al. 2006). Consequently, a new artificial clay mixture composed of bentonite, glycerin and water (modified glyben) was examined using a series of compaction, lab shear vane, cyclic triaxial and resonant column tests to characterize its behavior. The results, which are presented below, show that modified glyben has a damping ratio similar to natural soils while retaining the preferable features of glyben. The authors are currently using modified glyben in a series of 1-G shake table tests employing a laminar shear box to study soil-structure interaction of structures embedded in clay. Thus, the results of this study are considered to be of interest to other researchers conducting similar 1-G or scaled physical model tests in the centrifuge.

METHODOLOGY

Compaction, lab vane shear, cyclic triaxial and resonant column tests were performed to investigate the mechanical properties of modified glyben. Details of these tests and the procedures are given in the following sections. Turan et al. (2006) provides details regarding the interpretation of cyclic triaxial and resonant column test results. As described below, all of the cyclic triaxial and resonant column tests performed in this study were conducted seven days after preparation of the glyben specimens to avoid variability of the measured dynamic properties due to thixotropy. In the modified glyben mixture used in this study, the percent glycerin-water solution in the mixture by mass (gw/c) was 42.5 % and the percent water in the glycerin-water solution (w/gw) was 25 %. For each specimen, glycerin and water were mixed first using a mixer, and then bentonite was added slowly with the glycerin-water solution into a geotechnical mixer.

Compaction and Lab Vane Test

A compaction test was conducted in accordance with ASTM D-698 on a sample with (gw/c) of 42.5 %. Maximum dry density of this mixture was found to be 1669 kg/m^3. Lab vane tests were performed to provide preliminary characterization of time dependent changes in the mechanical properties of the modified glyben. Lab vane tests were performed according to ASTM D-2573 to measure the shear vane strength. Tests were carried out on modified glyben samples with (gw/c) of 42.5% and (w/gw) of 25 %. Shear strength measurements were taken for 15 days.

Cyclic Triaxial Test

The dynamic properties of modified glyben at high shear strain amplitudes were studied using a Wykeham Farrance Cyclic Triaxial apparatus at the Geotechnical Research Centre of The University of Western Ontario. The triaxial apparatus is a digitally controlled, servo pneumatic, closed loop system, which controls three parameters: axial stress, confining pressure and back pressure. Axial load is applied by a double acting digitally controlled 5 kN pneumatic actuator and a co-axially mounted displacement transducer provides an accurate feed back signal to the control system for precise displacement control and data acquisition. In this study, strain controlled testing was used in accordance with ASTM D-3999 (Method B). Cyclic triaxial tests were performed on modified glyben specimens with (gw/c) of 42.5 % and (w/wg) of 25 %. The mixtures were then covered using an airtight material and stored at room temperature (21 ^0C) for 7 days. After 7 days, 70 mm diameter by 140 mm high triaxial specimens were prepared for testing by compacting the modified glyben into a split mold to achieve 95 % of the maximum density determined in accordance with ASTM D-698. Triaxial specimen was then placed on the triaxial pedestal with a top cap. A latex membrane was placed over the specimen using o-rings to seal the membrane against the top cap and base pedestal. Finally the triaxial cell was filled with water, the top cap was connected to the actuator and the cell water was pressurized to the desired cell pressure, σ_c. No backpressure was applied during the tests (i.e. backpressure valve was open to air).

Cyclic triaxial tests were carried out at cell pressures, σ_c, of 37, 100, 200 and 300 kPa and sinusoidal peak-to-peak axial strain amplitudes of 0.1%, 0.2%, 0.4%, 1%, 2%, 4% and 8%. A select number of tests were undertaken using more strain cycles to investigate the effect of cyclic stress history. Interpretation of dynamic shear modulus, G, and damping ratio, ξ, from test data was performed in accordance with Turan et al. (2006).

Resonant Column Test

The resonant column is widely used to measure the small-strain dynamic properties of soils. A description of the apparatus and procedures can be found in Drnevich et al. (1978) and Morris and Delphia (1992). Resonant column tests were performed on modified glyben specimens with (gw/c) of 42.5% and (w/gw) of 25 % according to ASTM D-4015 using torsional loading. Modified glyben specimens were prepared and allowed to sit for seven days to avoid thixotropic effects on the measured dynamic properties. Then 70mm diameter and 145mm high specimens were prepared by compacting modified glyben into a split mould to achieve 95% of the maximum density. The specimen was assembled in the resonant column, a latex membrane was placed over the specimen and sealed with o-rings and cell pressures, σ_c, of 37, 100, 200 and 300 kPa were applied to the specimens during testing. From the resonant column test, the fundamental angular frequency, ω_n, is measured and the shear wave velocity, V_s, is calculated from ω_n in accordance with the formulation given in Turan et al. (2006).

Bender Elements Test

Bender elements (see Viggiani and Atkinson 1995, Jovicic et al. 1996, Lee and Santamarina 2005) were used to measure the Poisson's ratio of modified glyben. The Bender element system used in this study (manufactured by IPC Global) is capable of generating square, sinusoidal and user defined compression-waves and shear-waves (p- and s-waves). In this test program, sinusoidal p-waves and s-waves were generated at frequencies ranging from 0.33 to 5 kHz and wavelengths equal to about half the sample thickness. Bender element tests were performed on a modified glyben specimen with (gw/c) of 42.5% and (w/gw) of 25 %. 100mm diameter and 100mm thick cylindrical specimens were prepared by compacting modified glyben into a split mould to achieve 95% of the maximum density. Modified glyben samples were tested under zero confinement.

For bender elements test, the procedures regarding sample placement, testing and interpretation of data was used as detailed by Turan et al. (2006). From the arrival time of s-waves, T_S, and p-waves, T_P, and the distance, d, between the transmitter and receiver tips, s-wave velocity, V_S, p-wave velocity, V_P, and Poisson's ratio, ν was calculated (e.g. Viggiani and Atkinson 1995).

RESULTS

Consolidation Behavior

Although this study did not specifically focus on the consolidation behavior of the modified glyben, observations were made in the course of resonant column tests to confirm that modified glyben did not exhibit significant long-term time dependant compression after applying confining pressures. For example, Table 1 summarizes the maximum shear modulus, G_{max}, and damping ratio, ξ, of modified glyben specimen (gw/c = 42.5% and w/gw = 25 %) tested in a resonant column at a confining pressure of 300 kPa and a shear-strain amplitude of 0.0022%. The resonant column tests were performed on the same specimen: (i) 5min after application of the confining pressure and (ii) then later after 5-hours of a sustained confining pressure of 300 kPa. From Table 1, it can be seen that the maximum shear modulus and damping ratio of the modified glyben specimen were 6201.73 kPa and 0.0626 when the specimen was tested 5min after application of confining stress. Five hours after application of 300 kPa confining pressure, the maximum shear modulus increased by 0.9% to 6259.37 m/s and the damping ratio decreased by about 1.75 % to 0.06154. Thus, there were very minor changes in the small strain dynamic properties of glyben over a period of 5-hours at a confining stress of 300 kPa. However, a more detailed study on the consolidation behavior of modified glyben is needed.

Table 1. Changes in Dynamic Properties Due to Consolidation.

Time (Hours)	Shear Strain Amplitude	Damping Ratio	G_{max} (kPa)
0.08	0.0022	0.06262	6201.727
5	0.0022	0.06154	6259.367

Thixotropy

As discussed above, the thixotropic behavior of glyben was investigated using a series of lab shear vane tests. Figure 1 gives the variation of lab vane strength of modified glyben (gw/c = 42.5 %) with time. Figure 1 shows that modified glyben reached a steady-state vane shear strength in 7 days whereas the shear vane strength of the glyben was reported to stabilize in 5 days (Turan et al. 2006). The shear strength of modified glyben increased by 35 % 7 days after mixing (Figure 1). It was seen that there are significant thixotropic increases in the lab shear strength for modified glyben and that the modified glyben mixture, appears to be slightly more thixotropic than traditional glyben (Rayhani and El Naggar 2006, Turan et al. 2006). It is noted that, there is also a change in the shear modulus of modified glyben with time but also only during the first 7-days after mixing.

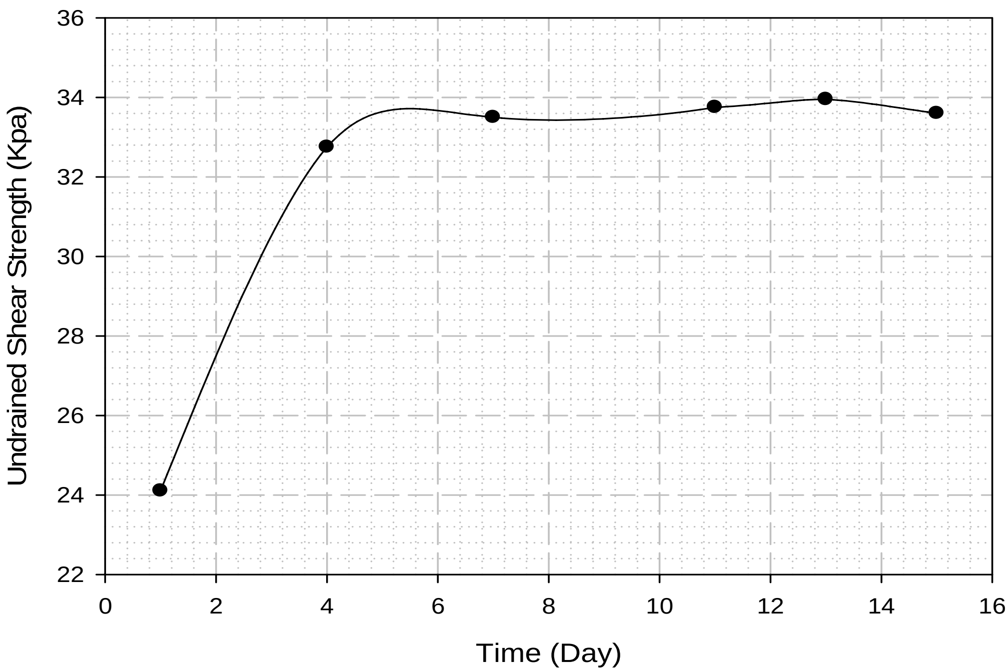

Figure 1. Time dependent variation of undrained shear strength of modified glyben.

Effect of Shear Strain Amplitude

Figure 2 compares the variation of the modulus ratio, G/G_{max}, versus shear strain amplitude for the modified glyben mixture with (gw/c) of 42.5 % and (w/gw) of 25 % with that of glyben (Turan et al. 2006). Figure 2 is separated into two ranges: low shear strain amplitudes for resonant column tests and high shear strain amplitudes for cyclic triaxial tests. Figure 2 shows significant trends with respect to the dynamic shear modulus of modified glyben for tests undertaken at a confining stress, σ_c, of 100kPa. First, at high shear strain (cyclic triaxial range) amplitudes, the measured modulus ratio, G/G_{max}, lies within the typical range for natural clays. Second, at low shear strain (resonant column range) amplitudes, the modulus ratio, G/G_{max}, lies just on the upper bound for natural clays. Third, there is a separation or gap in the modulus degradation data from the resonant column and cyclic triaxial measurements. This finding agrees with the results of Turan et al. (2006) for glyben and could be attributed to the different excitation frequencies and mode of loading in resonant column compared with the cyclic triaxial apparatus.

Figure 3 summarizes the damping ratio, ξ, versus shear strain amplitude for tests conducted at a confining pressure, σ_c = 100kPa. Again, the graph is divided into two strain ranges: high strain amplitude for cyclic triaxial tests and low strain amplitude for resonant column tests. Figure 3 shows that the damping ratio of modified glyben matches well with that of natural clays. At a shear strain amplitude of 0.02%, the damping ratio of traditional glyben is about 0.15 (Turan et al. 2006) whereas for modified glyben and natural clays the ratio is about 0.06 and 0.02 to 0.06, respectively. Thus, the results in Figure 3 show that modified glyben overcomes the major limitation of traditional glyben, which has a high damping ratio for small strain amplitudes (Rayhani and El Naggar 2006 and Turan et al. 2006).

In all calculations, Poisson's ratio was used as 0.4 as evaluated from P-wave and S-wave velocity measurements in bender element apparatus.

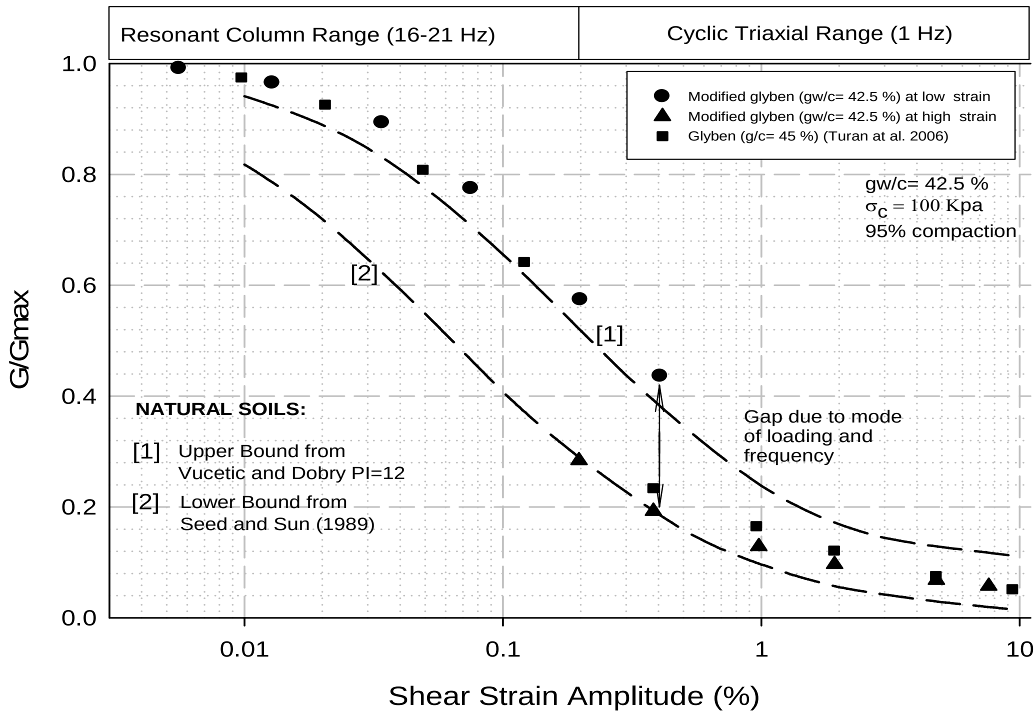

Figure 2. Normalized shear modulus versus shear strain amplitude.

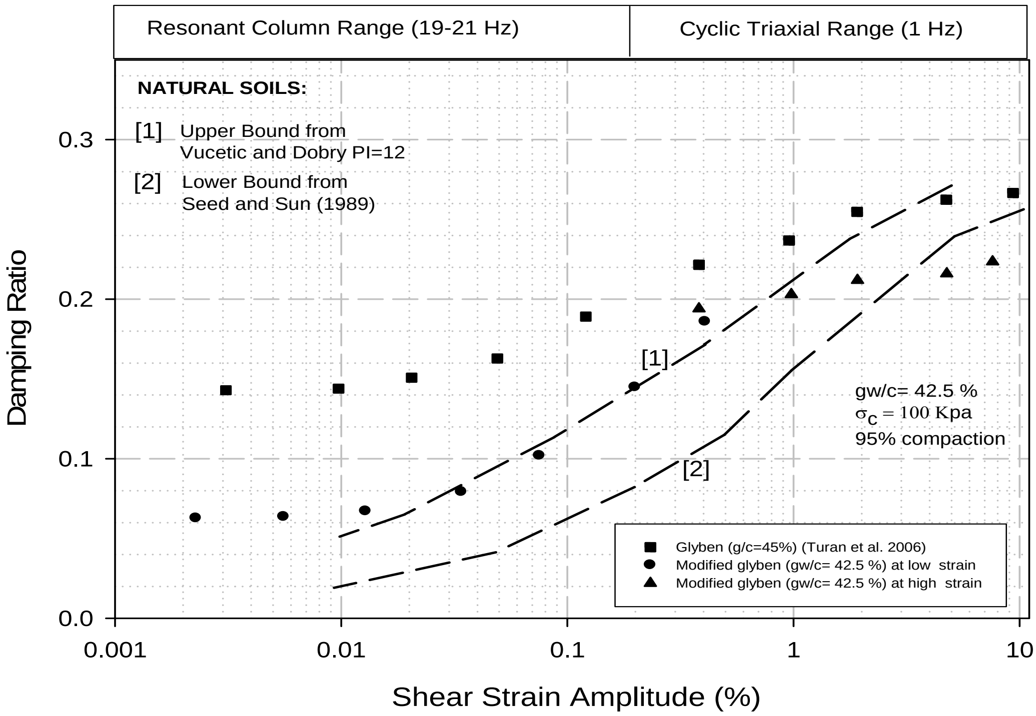

Figure 3. Relationship between damping ratio and shear strain.

Effect of Confining Pressure

Resonant column tests were conducted on modified glyben specimens with gw/c = 42.5 % to investigate the effect of confining pressure on the dynamic properties. Figure 4 shows the dynamic shear modulus and damping ratio measured at confining pressures of 37, 100, 200, 300 and shear strain amplitudes ranging from 0.002 % to 0.4 %. From Figure 4, it can be seen that there is a clear increase in the dynamic shear modulus as the confining pressure increases. Conversely, the damping ratio decreases as the confining pressure increases. This type of behavior is commonly encountered in natural soils (e.g. Teachavorasinskun et al. 2002 and Cai and Liang 2004). Figure 4 also shows that with the confinement effect, the increase in shear modulus slows down for confining pressures higher than 100 kPa. The damping ratio decreases with increasing confining pressures up to 100 kPa then it remains almost unchanged with increasing confining pressures.

Influence of the Number of Cycles

Figure 5 summarizes the effect of the number of loading cycles on the dynamic shear modulus and damping ratio of the modified glyben. A cyclic triaxial test was performed at a confining pressure of 300 kPa, a frequency of 1 Hz and shear strain amplitude of 0.2 %. A relatively high shear strain amplitude was used because it was considered to be a severe test of the impact of loading cycles on the dynamic properties of glyben.

From Figure 5, it can be seen that the number of cycles has almost no impact on both the dynamic shear modulus and damping ratios for the conditions considered. The dynamic shear modulus was found to vary from 1600 kPa to 1650 kPa and the damping ratio varied from 0.155 to 0.145. These variations are relatively small and in the order of ±3 % and 6 % for the shear modulus and damping ratio, respectively. Consequently, the dynamic response of glyben does not appear to be strongly affected by the number of loading cycles for up to at least 500 cycles. Such behavior suggest that glyben is not structured like some natural soils (e.g. Leroueil and Vaughan 1990).

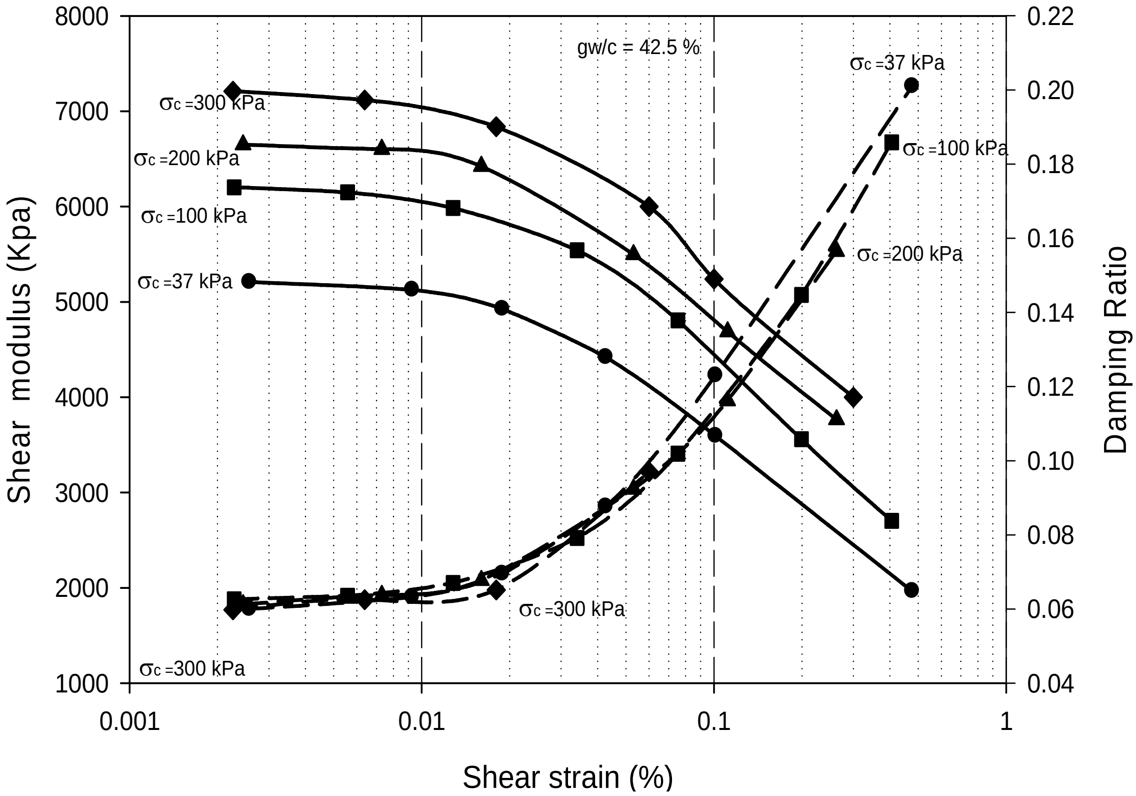

Figure 4. Variation of shear modulus and damping ratio with confining pressure at low strains.

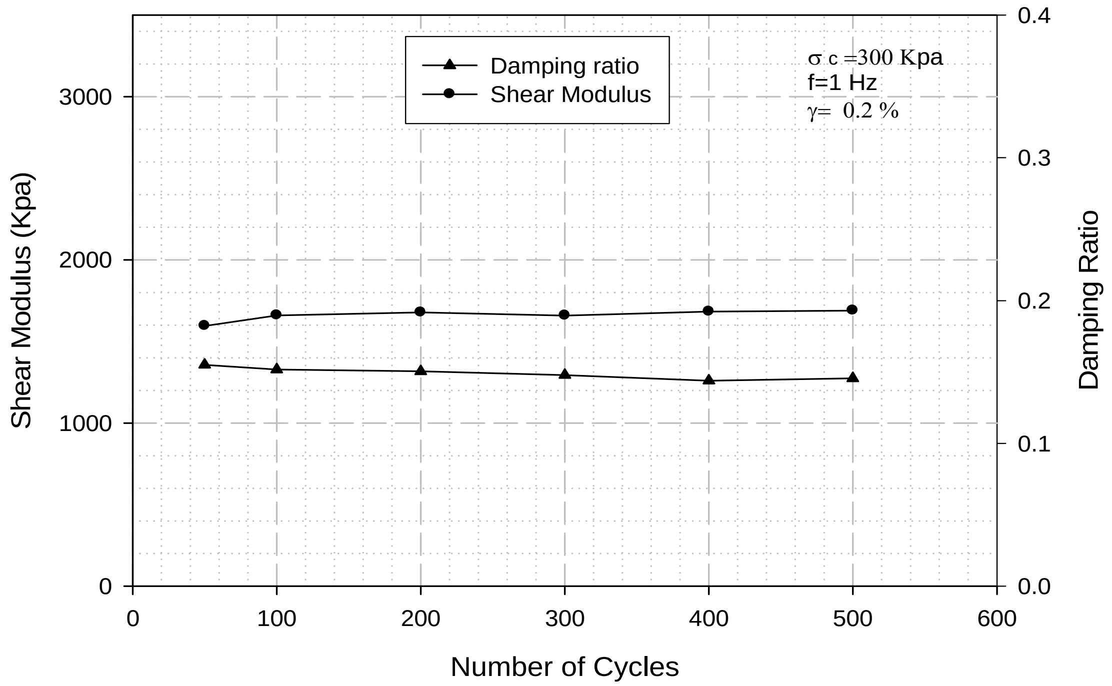

Figure 5. Variation of shear modulus and damping ratio with number of cycles.

CONCLUSIONS

This paper has presented an overview of an experimental investigation into the effect of time (or thixotropy), strain amplitude, confining pressure and cyclic stress history on the properties of modified glyben. The testing program comprised lab shear vane tests, compaction tests, cyclic triaxial tests, bender element tests and resonant column tests. Tentative results indicate that the dynamic properties of modified glyben are not significantly affected by consolidation or sustained application of confining stresses. This behavior could be beneficial for scaled physical model tests. For modified glyben, variation of the modulus ratio, G/G_{max}, versus shear strain amplitude is comparable to that of natural soils. Thus, it is concluded that the dynamic stiffness of most natural clays can be accounted for in scaled physical model tests over a large range of shear strain amplitudes. The damping ratio, ξ, of modified glyben is comparable to natural clays, especially in the strain ranges that are caused by earthquakes. Thus, modified glyben seem to overcome the major limitation of traditional glyben. Significant changes in the dynamic properties of glyben were observed within the first 7-days of mixing glycerin and bentonite. As such, scaled model tests should ideally be undertaken after allowing sufficient time for thixotropic changes to take place. Modified glyben is also an economical alternative to traditional glyben.

Frequency dependency of dynamic properties, consolidation behavior, effect of (gw/c), (w/wg), temperature, drying and desiccation and pore fluid viscosity on the dynamic properties are primary issues that need to be investigated in more detail. A standardized methodology for compaction and placement of modified glyben in a laminar shear box is also needed.

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REFERENCES

Cai, Y.Q., and Liang, X. “Dynamic properties of composite cemented clay.” Journal of Zhejiang University Science, 5(3), 309-316, 2004

Drnevich, V. P., Hardin, B. O., and Shippy, D. J. “Modulus and Damping of Soils by Resonant-Column Method.” Spec Tech Publ. 654, 91-125, ASTM, Symp on Dyn. Geotech. Test, Denver, CO,1977

Jovicic, V., Coop, R., and Simic, M. “Objective criteria for determining Gmax from bender element tests.” Geotechnique, 46(2), 357–362, 1996.

Kenny, M. J., and Andrawes, K. Z. “The bearing capacity of footings on a sand layer overlying soft clay.” Geotechnique, 47(2), 339–345, 1997.

Lee, J. S., and Santamarina, J. C. “Bender Elements: Performance and Signal Interpretation.” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 131(9), 1063–1070, 2005.

Leroueil, S., and Vaughan, P.R. “The general and congruent effects of structure in natural soils and weak rocks.” Geotechnique, 40(3), 467-488, 1990.

Meymand, P. J. “Shaking table scale model tests of nonlinear soil-pile-superstructure interaction in soft clay.” Ph.D. Dissertation, Univ. of California, Berkeley, CA, 1998.

Mayfield, B. “The performance of a rigid wheel moving in a circular path through clay.” Ph.D. Dissertation, University of Nottingham, UK, 1963.

Morris, D.V., and Delphia, J.C. “Resonant column testing of dynamic rock properties.” Proc., 9th Conference on Engineering Mechanics, ASCE, College Station, TX, 1105, 1992.

Moss, R., Rawlings, M., Caliendo, J., and Anderson, L. “Cyclic Lateral Loading of Model Pile

Groups in Clay Soil.” Proc., 3rd Conf. Geotechnical Earthquake Engineering and Soil Dynamics, ASCE, Seattle, WA, 494-505, 1998.
Rayhani, M. H. T., and El Naggar, M. H. “Characterization of Glyben for seismic applications” Report No. GEOT-3-06, The University of Western Ontario, London, ON, Canada, 2006.
Seed, H. B., and Clough, R. “Earthquake Resistance of Sloping Core Dams.” J. Soil Mechanics and Foundation Div., ASCE, 89(1), 209-242, 1963.
Seed, H. B., and Sun J. I. “Implications of site effects in the Mexico City earthquake of Sept. 19, 1985 for earthquake-resistant design criteria in the San Francisco Bay Area of California.” Report No. EERC 89-03, University of California, Berkeley, CA, 1989.
Teachavorasinskun, S., Thongchim, P., and Lukkunaprasit, P. “Shear modulus and damping of soft Bangkok clays.” Can. Geotech. J., 39, 1201–1208, 2002.
Turan, A., Hinchberger, S. D., and El Naggar, M. H. “Mechanical and thermal behavior of glycerin bentonite mixture” Report No. GEOT-2-06, The University of Western Ontario, London, ON, Canada, 2006.
Viggiani, G., and Atkinson, J. H. “Interpretation of bender element tests.” Geotechnique, 45(1), 149–154, 1995.
Vucetic, M., Dobry, R. “Effect of soil plasticity on cyclic response.” Journal of Geotechnical Engineering, ASCE, 117(1), 89-107, 1991.