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Characterization of Glyben for Seismic Applications

ABSTRACT: Glyben is artificial clay that is prepared by mixing sodium bentonite powder and glycerin. It is used for laboratory tests and scale modeling for geotechnical applications. The mechanical properties of glyben depend on the bentonite and glycerin mix proportions. The shear strength, dynamic shear modulus, damping ratio, and Poisson's ratio were evaluated for glyben samples prepared with different glycerin/bentonite ratios. Vane shear tests, T-bar tests, hammer tests, and resonant column tests were conducted on glyben specimens and the shear strength and dynamic properties were evaluated considering a wide range of strain values and confining pressure. The measured glyben properties were compared with properties of natural cohesive soils to verify the range of applicability of glyben as a test bed material. It was found that glyben has the same range of strength and dynamic properties as soft to medium stiff clay. The trend of variation of the shear modulus and damping ratios of glyben is similar to that of natural clays. It is noted, however, that the damping ratio of glyben is higher than that of natural clays for shear strains below 0.01%. It was concluded that glyben can reasonably model the nonlinear behavior of natural soil under strong dynamic excitation.

KEYWORDS: glyben clay, shear strength, shear modulus, damping ratio, resonant column

Introduction

The measurement of dynamic soil properties is a crucial task in the analysis of geotechnical earthquake engineering problems. Soil properties that influence wave propagation and other low strain phenomena include shear modulus, damping ratio, Poisson's ratio, and density. The stiffness and damping characteristics of cyclically loaded soils are critical to the evaluation of seismic geotechnical problems. Because soils display strong nonlinear behaviour, both stiffness and damping characteristics have to be evaluated for strain values covering a range from low to high strains.

The dynamic properties of soft soils subjected to strong seismic shaking were the focus of several studies. Tiers and Seed (1968) studied the effect of strain and load cycles on the parameters of the hyperbola model with San Francisco Bay mud. Based on a large number of tests, Hardin and Drnevich (1972a,b) presented some empirical equations to evaluate the dynamic modulus and damping ratio of soft clay. Vucetic and Dobry (1991) proposed that the plasticity index (PI) is the key factor influencing the dynamic modulus and damping ratio of both normally consolidated and over consolidated soils. They concluded that the normalized dynamic modulus increased and the damping ratio decreased with the increase of PI. Lanzo et al. (1997) studied the trend of the dynamic shear modulus and damping ratio under small strains through cyclic simple shear tests. Assimaki et al. (2000) proposed a four-parameter model for estimating the dynamic modulus and damping ratio for granular soils in which the input parameters were confining pressure and density.

The artificial clay known as "glyben" is a mixture of sodium bentonite powder and glycerin. By varying the mix proportions, the shear strength of glyben varies between 5 and 60 kPa, which is sufficiently low to allow compaction by hand or a compactor. Mayfield (1963) conducted undrained triaxial tests on glyben which showed constant shear strength behavior. Kenny and Andrawes (1997) carried out undrained triaxial and vane shear tests on glyben and demonstrated that it behaves generally as a $\phi_u = 0$ material under quick undrained loading. Its advantages as a laboratory material include: different strength can be obtained by varying the proportions of bentonite and glycerin; it is completely insensitive to handling; it has a short preparation time; and there is negligible evaporation of glycerin at room temperature. However, pore-water pressure measurements are precluded and glyben samples cannot be consolidated from slurry and must be formed by compaction.

Artificial-soil materials are increasingly used as a test bed for laboratory tests and scale modeling nowadays (e.g., Blaney and Mallow 1987; Iskander et al. 2002), and evaluating glyben's shear strength and dynamic stress-strain behavior, as a possible substitute for soft clay, is therefore needed. The main objectives of this paper are: to evaluate the shear strength and dynamic properties of glyben with different mix proportions considering different confining pressures over a wide range of strain, and to compare the properties of glyben with those of natural soft clays to verify its validity as a testing material to model cohesive soils.

Index Properties

A series of Atterberg and compaction tests were conducted on glyben to determine its index properties. It should be noted that these indices were obtained based on glycerin contents. General characteristics of glyben samples are summarized in Table 1. The optimum glycerin content obtained was about 39 % glycerin and the maximum dry density was 1770 Kg/m^3. It is noted that glyben properties listed in Table 1 lie within the range for soft clay soil

TABLE 1—*Index properties of glyben samples.*

Liquid Limit	Plastic Limit	Plasticity Index	Specific Gravity	Dry Density (Kg/m^3)	Glycerin Content (%)	Void Ratio
50	39.5	10.5	2.73	1770	39	0.94

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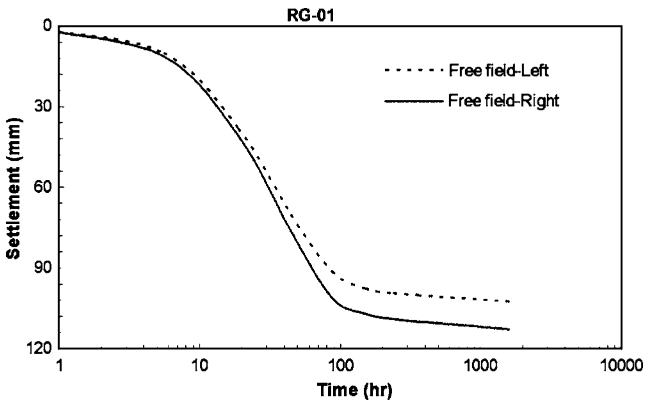

FIG. 1—*Settlement curves of glyben soil from 1 to 80 g in prototype scale.*

(however, based on glycerin not water content). For example, plasticity index, PI=10.5 %, maximum dry density, $\rho_d=1770\ \text{Kg/m}^3$ and void's ratio, $e=0.94$. The void ratio of the glyben was estimated using the specific gravity of glycerin (1.26) and dry density of glyben.

Shear Strength

Seismic site response and soil-structure interaction behavior are primarily a function of the strain level and the soil shear strength. During seismic events, the ground and structure loadings are dynamic and are applied over a short period of time. Thus, the model clay soils for shake table tests (either large scale laboratory or centrifuge models) are subjected to dynamic loading, which constitutes undrained loading conditions. Hence, these soil beds would display undrained stress-strain behavior and it is necessary to evaluate their undrained shear strength.

Both vane shear and T-bar tests were conducted in a centrifuge container with dimensions 737 by 380 by 375 mm. For each soil model, glycerin and bentonite were mixed at a desired ratio using a mechanical mixer. The models were prepared by tamping the soil in layers in the centrifuge container. Sample preparation time for this size container was about half a day, which represents significant time saving in comparison with time required for preparation of reconstituted natural clay. Three different glyben mixture ratios were considered: 40 % glycerin, 42.5 % glycerin, and 45 % glycerin. The homogeneity of each clay layer was checked by conducting vane shear tests at intervals of 50 mm in depth.

The settlement of glyben was measured in flight using LVDTs as the model swung from 1 to 80 g (which was completed in about 10 min in model scale), and at 80 g until testing started. Figure 1 shows the settlement of model RG-1 plotted versus log time. The total settlement ranged between 100 and 112 mm for the different models, which is similar to those recorded for natural soft clays (e.g., Fox et al. 2005). However, the vast majority of settlement occurred as the model swung up from 1 to 80 g (the first 300 h prototype scale in Fig. 1). This initial (almost immediate) settlement is attributed to compaction of glyben. The settlement measured as the model spun at 80 g until testing started was negligible and was attributed to consolidation. The rate of consolidation, however, was much smaller than for natural and artificial clays (e.g., Bransby et al. 2001) such that consolidation during testing was negligible and the stress-strain behavior was considered to be undrained. This represents significant savings of centrifuge time as it eliminates the consolidation time required for natural clays.

TABLE 2—*Shear strength properties of glyben with different mixture ratio.*

Sample	Bentonite (%)	Glycerin (%)	S_u Before Flight (kPa)	S_u After Flight (kPa)
GLY 40	60	40	60	66
GLY 42.5	57.5	42.5	47	54
GLY 45	55	45	29.5	33
GLY 47.5	52.5	47.5	18.5	…[a]
GLY 50	50	50	8	…[a]

[a]Was not tested in flight.

Vane Shear Tests

A large number of vane shear tests were conducted on glyben soil to establish its strength properties. The vane shear tests were performed in accordance with ASTM D 2573 (2001) using a vane 108 mm 4 (1/4 in.) tall and 85.7 mm 3 (3/8 in.) in diameter, rotated at 6 deg/min. The shear strength of glyben was estimated using the following equation:

$$\tau = M/\pi D^2 H/2 \times (1 + D/3H) \qquad (1)$$

where M is the torque to shear the soil (MN.m), D is the overall diameter of vane (mm), and H is the height of vane (mm). Table 2 shows the measured shear strength of glyben with different mixture ratio.

Five vane tests were conducted for each glyben mix (i.e., bentonite/glycerin ratio), and their average reading was recorded in Table 2. The standard deviations of test data were about ±10%. The average shear strength varied from about 8 kPa for samples with 50 % glycerin to about 60 kPa for a 40 % glycerin mixture ratio. The samples were completely insensitive to handling and gave excellent repeatability during testing. Three series of vane tests were also conducted on glyben clay after flight. The results indicated a slight increase in shear strength (about 10 %), which could be due to the compaction of glyben during centrifuge flight.

T-bar Tests

The T-bar tests were performed in clay models prepared in a centrifuge container at 80 g to determine the continuous undrained shear strength profile S_u of glyben. The T-bar testing was done in-flight at 80 g. The T-bar was 31-mm wide and had a diameter of 7.9 mm. It was inserted in the soil at a rate of approximately 3 mm/s to a depth near the bottom of each clay layer. Another set of T-bar tests with a penetrating rate of 0.1 mm/s were conducted on the same soil and showed shear strength values approximately 10–20 % less than that measured for the penetration rate of 3 mm/s (Rayhani 2007). To save centrifuge time, it was then decided to perform all remaining T-bar tests at a penetration rate of 3 mm/s.

Four T-bar soundings were performed in the model container in order to establish a continuous soil strength profile at various stages during the test program. Also, a series of vane shear tests were conducted in the model container at 1 g before and after the centrifuge flight to compare with T-bar results. Figure 2 shows the T-bar results in the centrifuge container at 80 g and the average shear vane test results at 1 g before the centrifuge test and after flight.

The T-bar results were interpreted using the plasticity solution for the limiting pressure acting on a cylinder moving laterally

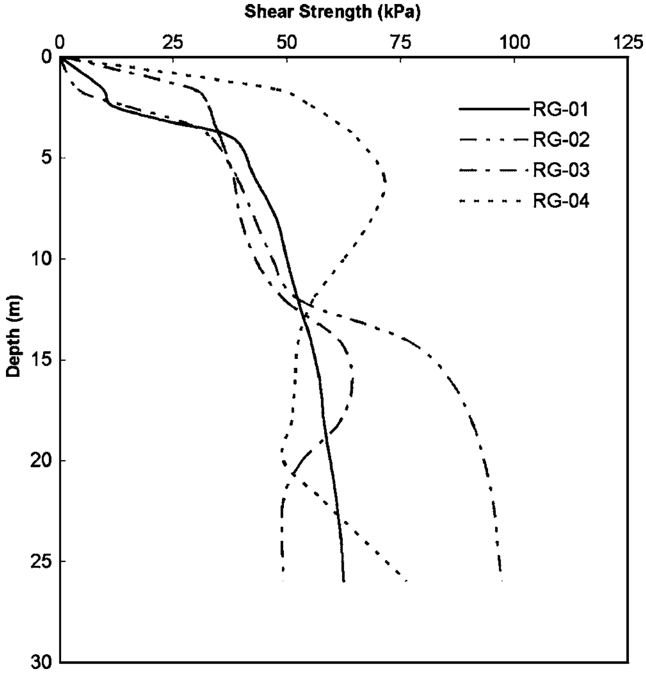

FIG. 2—*T-bar shear strength profile of glyben with 42.5 and 45 % glycerin at 80 g.*

through purely cohesive soil (Randolph and Houlsby 1984). The analysis assumes full closure of the soil behind the cylinder, such that a gap does not occur. The solution expresses the limiting force acting on an infinitely long cylinder as:

$$S_u = P/N_b d \quad (2)$$

where S_u is the undrained shear strength, P is the force per unit length acting on the cylinder, d is the diameter of cylinder, and N_b is the bar factor. The N_b factor of the T-bar penetrometer is dependent on the surface roughness of the cylinder (Stewart and Randolph 1991). The upper and lower bounds of the plasticity solution coincide at approximately twelve for a fully rough bar and diverge slightly at N_b of about nine for a smooth bar. Randolph and Houlsby (1984) recommended an intermediate value of 10.5 for general use, which has been used to interpret the results. The possible range of N_b is relatively small, and the upper and lower limits correspond to errors of less than ±13 % of the adopted value.

The undrained shear strength evaluated using the T-bar bearing resistance data varied between 40 and 60 kPa for glyben with 45 % glycerin (RG-01). For model RG-02, the shear strength varied between 40–50 kPa for the upper layer (with 45 % glycerin) and 85–95 kPa for the lower layer (with 40 % glycerin). For model RG-03, the shear strength varied between 40–50 kPa and 60–65 kPa for glyben with 45 % and 42.5 % glycerin, respectively. For model RG-04, the shear strength varied between 50–55 kPa and 65–75 kPa for glyben with 45 % and 42.5 % glycerin, respectively. The shear strength increased slightly with depth (i.e., with confining pressure) in all layers.

Comparing the measurements from the T-bar and shear vane tests shows that the T-bar has provided a good estimate of the undrained shear strength that is consistent with the values measured using the shear vane. The undrained shear strength obtained from the T-bar tests was higher than the shear vane results, which could be due to using different testing techniques, high penetration speed of 3 mm/s for the T-bar and the difference in the stress level between 1 g in vane tests and an 80 g level in T-bar tests, or both. It can also be concluded that the N_b factor of 10.5 for the T-bar was acceptable.

Dynamic Soil Properties

The measurement of dynamic soil properties is a crucial task in the analysis of geotechnical earthquake engineering problems. Soil properties that influence wave propagation and other low strain phenomena include stiffness, damping, Poisson's ratio, and density. The glyben dynamic properties were evaluated from resonant column tests at 1 g and hammer tests at 80 g.

Resonant Column Tests

Resonant column tests are used to measure the dynamic properties of soils for shear strains between 10^{-6} and 10^{-3} (ASTM 2000). The resonant column test is nondestructive; hence, the dynamic properties can be evaluated at different confining pressures for each soil specimen. A modified Stokoe resonant-torsional column device (Stokoe and Santamarina 2000) was used in this research. Resonant column tests were performed on specimens with a range of glycerin contents from 40–47.5 %.

Sample Preparation—The soil was mixed with glycerin using a mechanical mixer to ensure the uniformity of the sample. After mixing was completed, the mixture was covered with a plastic wrap and allowed to cure for about 2 h. It was observed that this curing process allowed a more even distribution of glycerin throughout the soil (in terms of color and consistency).

The specimens were prepared inside the resonant column device. A split mold with a rubber membrane stretched inside was set over the bottom platen of the resonant column and vacuum was applied to the mold. Specimens were prepared by tamping of the split mold to obtain the desired void ratio (90 % of maximum dry density). The full height of the specimen is achieved in three layers. O-rings were secured and vacuum was applied to the bottom of the specimen, and the split mold was removed and sample dimensions were noted with a digital caliper. Connections for the driving plate, LVDT, and accelerometers were made, and the pressure chamber was assembled. The specimen vacuum was gradually released while increasing cell pressure until the desired effective confining pressure was achieved. Initial confining pressures used in this study were about 30 kPa.

Test Procedure—The resonant column testing was done on each specimen with different values of isotropic confining pressures varying from 30 to 300 kPa. For each value of confining pressure applied to the specimen, the cell pressure was allowed to stabilize until no further movement in LVDT was observed. The sample was tested with broad band random noise excitation (100 Hz) to locate the resonance approximately. A narrow band random noise excitation (25 Hz) was then used to compute the resonant frequency and damping ratio. Resonant frequency and damping ratio were measured in real time using a dynamic signal analyzer (Cascante et al. 2003). The peak-to-peak response of the accelerometer was recorded from the digital oscilloscope and the transfer function was saved on a floppy disk for further processing. The same procedure was used to measure the dynamic soil properties at each confinement (σ_c=30, 60, 90, 150, and 300 kPa). After

TABLE 3—G_{max} *for different mixture ratio and confining pressure.*

Sample	Glycerin (%)	Bentonite (%)	Density (Kg/m^3)	G_{max} (MPa)				
				σ_c 30 kPa	σ_c 60 kPa	σ_c 90 kPa	σ_c 150 kPa	σ_c 300 kPa
GLY 40	40	60	1593	8.5	10	11.5	14	15
GLY 42.5	42.5	57.5	1584	5.7	6	6.5	7.2	8
GLY 45	45	55	1575	3	3.2	3.7	4.2	5
GLY 47.5	47.5	52.5	1557	2.3	2.6	3	3.2	3.5

performing low strain testing ($\gamma < 10^{-5}$) at the maximum confinement (300 kPa), each specimen was tested at larger shear strain levels ($10^{-5} < \gamma < 10^{-3}$) to evaluate the variation of dynamic properties with shear strain levels.

Data Processing and Analysis—After obtaining the fundamental frequency of glyben specimens, Eq 3 (Richart et al. 1970) was used to calculate v_s, i.e.,

$$\frac{I}{I_o} = \left(\frac{\omega_n h}{v_s}\right)\tan\left(\frac{\omega_n h}{v_s}\right). \quad (3)$$

where I is the mass polar moment of inertia of the specimen, I_o is the mass polar moment of inertia of mass attached to the top of the specimen, h is the height of the specimen, v_s is shear wave velocity, and ω_n is the fundamental angular frequency.

Maximum Shear Modulus and Damping Ratio

The shear modulus of the soil, G, generally decreases as the strain level increases. The shear modulus at very small strain ($\gamma \leq 10^{-5}$) is termed maximum shear modulus, G_{max}. Characterizing the stiffness of an element of soil requires the consideration of both G_{max} and the manner in which the modulus ratio G/G_{max} (G is shear modulus at a given strain level) varies with cyclic strain amplitude and other parameters.

The use of measured shear wave velocity is generally the most reliable means of evaluating the value of G_{max} for a particular soil. Since resonant column tests can induce shear strains lower than 3×10^{-6}, the shear wave velocities evaluated from the test results were used to compute G_{max} as:

$$G_{max} = \rho v_s^2 \quad (4)$$

As illustrated in Table 3, G_{max} increases with both the percentage of the bentonite in the glyben mix and the confining pressure.

Damping is an index representing the amount of energy dissipated during cyclic loading. As the soil particles slide upon adjacent particles under cyclic loading, the strain energy released during the unloading stage is less than the strain energy accumulated during the loading stage. Therefore, at higher strain levels more slippage and rearrangement of particles occurs and a higher damping ratio would be expected. This means the damping ratio of the soil, D, follows the opposite trend of the shear modulus; it increases with the strain level.

The maximum damping ratio, D_{max}, is determined at high strain levels ($\gamma > 10^{-2}$), after which the increase of D becomes slow. The damping ratio was obtained from the resonant column tests using the dynamic signal analyzer via Eq. 5 (Richart et al. 1970), i.e.,

$$\varepsilon = 1 \Bigg/ \sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + 4D^2\frac{\omega^2}{\omega_0^2}} \quad (5)$$

where ε is the dynamic amplification factor, ω is the frequency of the system, and ω_0 is natural frequency.

Effect of Confining Pressure on Shear Modulus and Damping Ratio—The stiffness of natural soil increases and its ability to dissipate energy decreases with an increase in the isotropic confining pressure. Figures 3 and 4 illustrate the variation of the measured shear modulus and damping ratio of glyben (both for small strain) as a function of confining pressure, respectively. It is noted from Fig. 3 that the shear modulus increased with an increase of the confining pressure, while Fig. 4 shows that D decreased as the confining pressure increased. This is attributed to the

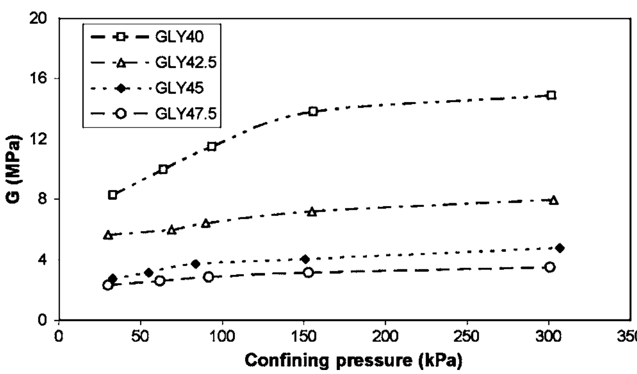

FIG. 3—*Variation of shear modulus of glyben with confining pressure.*

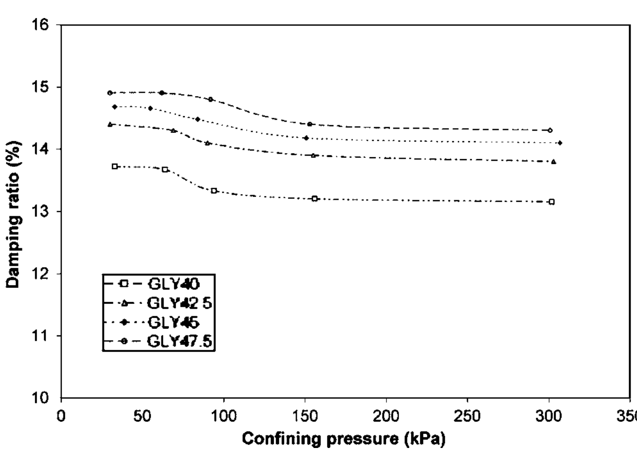

FIG. 4—*Variation of damping ratio of glyben with confining pressure.*

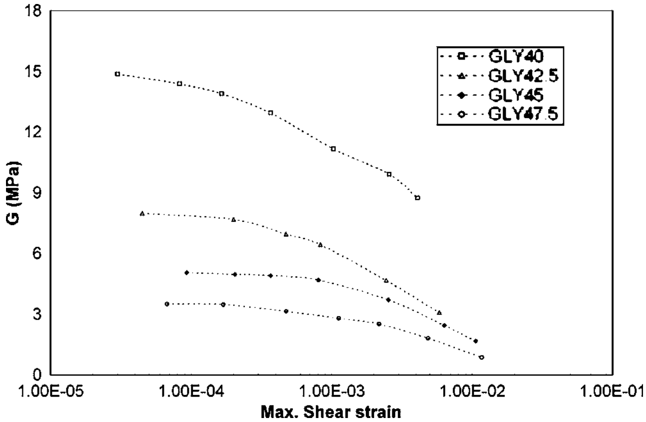

FIG. 5—*Effect of shear strain level on shear modulus of glyben.*

tighter contacts of adjacent particles in glyben samples under higher confinement, thus allowing more wave pathways and less energy dissipation, resulting in higher *G* and lower *D*.

Effect of Strain Level on Shear Modulus and Damping Ratio—The shear modulus and damping ratio of natural soils are known to be a function of the shear strain level. Figures 5 and 6 demonstrate the effects of strain level, γ, on the shear modulus (G) and the damping ratio (D) for four glycerin-mixing ratios. It is noted from the figures that glyben displayed the same behavior as natural soils, i.e., G decreased and D increased with an increase of γ. It is also noted from Fig. 5 that the initial dynamic shear modulus remained almost constant (G_{max}) for $\gamma \leq 10^{-4}$ and that G decreased as the strain level increased from 10^{-3} to 10^{-2}. The damping ratio, D, displayed a reverse trend as observed from Fig. 6. It increased rapidly for $10^{-3} \leq \gamma \leq 10^{-2}$ and remained almost constant (minimum value) for $\gamma \leq 10^{-4}$.

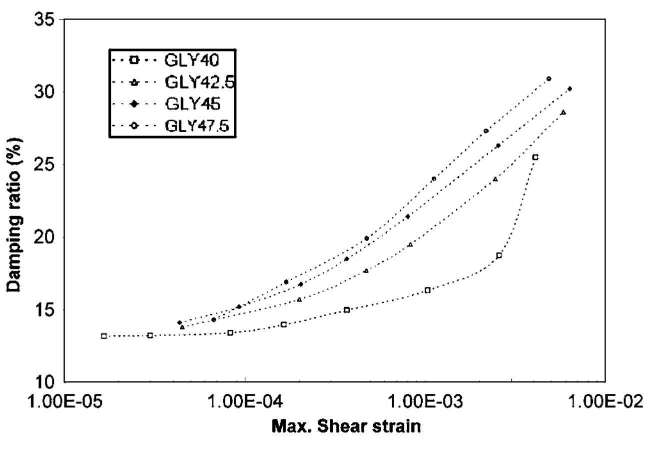

FIG. 6—*Effect of shear strain level on damping ratio of glyben.*

These observations give rise to the conclusion that glyben can reasonably model the nonlinear behavior of natural soil under strong dynamic excitation. However, it should be noted that D values for glyben at low strain levels are higher than that of natural soils.

The damping ratio for glyben evaluated at low strain range was about 13–15 %, whereas the damping ratio for natural clays at low strain is about 3–8 % (e.g., Ishibashi and Zhang 1993; Hardin and Drnevich 1972b). The glyben damping ratios at high strain levels are within the range of natural soils as will be shown later.

Determination of Poisson's Ratio and Elastic Modulus

The maximum dynamic elastic modulus can be obtained from the maximum shear modulus of soil (G_{max}) and Poisson's ratio (ν), i.e.,

$$E_{max} = 2G_{max}(1 + \nu) \tag{6}$$

Lambe and Whitman (1969)reported that ν has a relatively small effect on the dynamic shear modulus in most civil engineering projects. For fully-saturated soils, ν is 0.5, and for partially saturated soils, ν is about 0.35. Poisson's ratio of glyben soil was established using the measured v_p and v_s of the soil under the same conditions in the resonant column. The Poisson's ratio was evaluated from:

$$\nu = \left[0.5\left(\frac{v_p}{v_s}\right)^2 - 1\right] \Big/ \left[\left(\frac{v_p}{v_s}\right)^2 - 1\right] \tag{7}$$

where v_p is compression wave velocity. The Poisson's ratio of glyben determined from the resonant column tests varied from 0.417 to 0.435. It is therefore proposed to use Poisson's ratio of the glyben as 0.43 in further analysis. Table 4 shows E_{max} for the glyben soil specimens tested in this study.

Relationship Between V_s and Undrained Shear Strength

Based on the measured undrained shear strength of glyben, S_u, and the measured shear wave velocity, v_s, the following empirical relationship could be proposed to correlate both parameters:

$$v_s = 7.09(S_u)^{0.551} \tag{8}$$

where v_s is in m/s and S_u is in kPa. This relationship, shown in Fig. 7, can be used to establish shear wave velocity for glyben soil from the measured undrained shear strength. However, this equation was

TABLE 4—E_{max} *for different mixture ratio and confining pressure.*

Sample	Glycerin (%)	Bentonite (%)	Density (Kg/m^3)	E_{max} (MPa)				
				σ_c 30 kPa	σ_c 60 kPa	σ_c 90 kPa	σ_c 150 kPa	σ_c 300 kPa
GLY 40	40	60	1593	24	28.5	33	40	43
GLY 42.5	42.5	57.5	1584	16	17	18.5	20.5	23
GLY 45	45	55	1575	8.5	9	10.5	12	14
GLY 47.5	47.5	52.5	1557	6.5	7.5	8.5	9	10

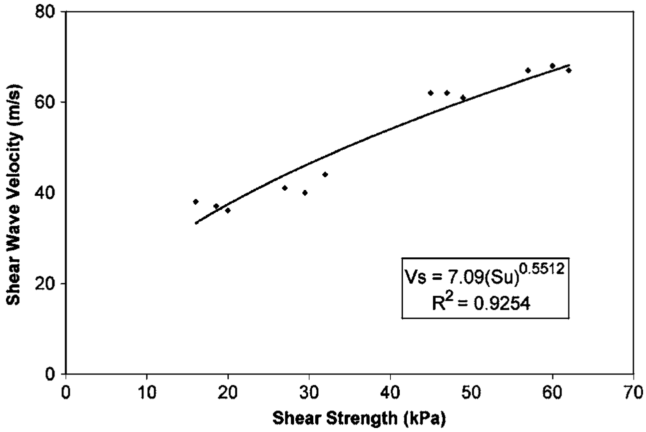

FIG. 7—*Variation of shear wave velocity with undrained shear strength of glyben.*

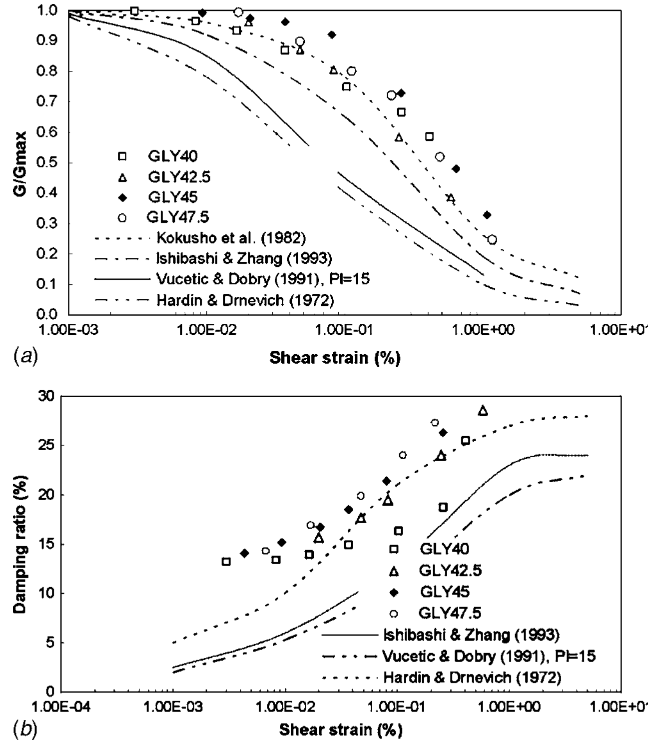

FIG. 8—*Shear modulus and damping ratio of glyben clay, PI=10.5, σ_c =300 kPa.*

developed based on limited data of glyben with glycerin content of 40–47.5 %, and would be more applicable for stress level less than 300 kPa.

Hammer Tests

The shear wave velocity profile is a required input for site response analyses. One way to evaluate the shear wave velocity profile in a centrifuge model is using the hammer test. The hammer test was used to evaluate the shear wave velocity for each gravity level at a depth of 20 m in the centrifuge model. The test procedure consisted of striking the steel base plate of the soil container with a sledge hammer which generates compression waves that were detected by the horizontal arrays of accelerometers inside the soil column. Differential travel times were computed by identifying the compression wave arrival time at each accelerometer. The compression wave velocity, v_p, was computed once the accelerometer positions were known. Travel times were estimated using the first strong peak interpretation method. The shear wave velocity (v_s) is then estimated using the p-wave velocity (v_p) and glyben Poisson's ratio (ν), i.e.,

$$(v_p/v_s) = [(1-\nu)/(0.5-\nu)]^{0.5} \qquad (9)$$

Table 5 shows the shear wave velocity of glyben at a depth of 20 m for different centrifuge gravity levels. The equivalent confining pressure for each gravity level was estimated assuming $K_0=0.5$ (assuming normally consolidated soil) and octahedral confining stress. It is noted from Table 5, the shear wave velocity for glyben increased with increasing the octahedral confining pressure. It is also noted that the shear wave velocity measured in a centrifuge container in flight for low confining pressure agreed, in general, with that measured from resonant column tests. For high confining pressures, the in-flight shear wave velocity was higher than that measured in the resonant column, which might be due to the inaccuracy of the time arrival interpretation in hammer tests or changes in the soil Poisson's ratio.

TABLE 5—*Shear and compression wave velocity of glyben in centrifuge container.*

Model Gravity (g)	GLY 42.5			GLY 45		
	σ_c(kPa)	v_p(m/s)	v_s(m/s)	σ_c(kPa)	v_p(m/s)	v_s(m/s)
10	36	170	60	35	160	55
20	71	200	82	70	180	63
30	107	230	70	106	215	75
40	143	260	90	142	230	80
50	178	280	98	177	260	90
60	214	295	103	213	280	98
70	249	310	108	248	290	100
80	285	320	110	283	295	103

Comparison With Natural Soil Behavior

The measured shear modulus and damping ratio of glyben were compared with the published data for natural clays (e.g., Hardin and Drnevich 1972b; Ishibashi and Zhang 1993; Vucetic et al. 1991). The different models established by these researchers are compared with the glyben properties established in this study as shown in Fig. 8. Also included in Fig. 8 is the best fit curve of the data reported by Kokusho et al. (1982) from cyclic triaxial tests on undisturbed samples of soft clay.

It is noted from Fig. 8(*a*) that the shear modulus reduction curve of glyben displayed the trends and values similar to those to be expected of natural clays throughout the strain range considered. The shear modulus trend of glyben for all strain range was similar to that proposed by Kokusho et al. (1982). Figure 8(*b*) shows that the damping ratios of glyben for high shear stain ($\gamma < 10^{-4}$) lie within the same range and have a similar trend of the reference data presented in the figure. For the lower shear strain values ($\gamma < 10^{-4}$), however, the damping ratio of glyben is above the established curves for natural clay materials. At medium and large strain levels ($\gamma > 10^{-4}$) the damping ratio of glyben displayed the trends and values that would be expected as soft to medium clay. This trend is close to that proposed by Hardin and Drnevich (1972b) with some scatter for glyben with 40 and 47.5 % glycerin.

Conclusion

The strength and stiffness characteristics of glyben were evaluated using several laboratory and centrifuge tests including shear vane, resonant column, hammer and T-bar. The undrained shear strength, dynamic shear modulus, damping ratio, and Poisson's ratio were evaluated for glyben samples prepared with different glycerin/bentonite ratios. The shear strength and dynamic properties were evaluated considering a wide range of strain values and confining pressure. The measured glyben properties were compared with the existing database on cohesive soils to verify the range of applicability of glyben as a test bed material. The following conclusions may be drawn:

1. Glyben has the same range of shear strength and dynamic properties as soft to medium stiff clay. The undrained shear strength and the shear modulus increased and the damping ratio decreased as the percentage of bentonite in the mixture increased.
2. The trend of variation of the shear modulus and damping ratios of glyben with the important parameters is similar to that of natural clays. The shear modulus, G increased and the damping ratio, D, decreased with an increase in the confining pressure for the same strain level. When the shear strain increased, G decreased and D increased. It is noted, however, that the damping ratio of glyben is higher than that of natural clays for shear strains below 0.01 %.
3. The shear modulus reduction curves for glyben are similar to those available for natural clay soils.
4. Based on the experimental results, a formula was proposed to correlate the shear wave velocity and the undrained shear strength of glyben.

It may be concluded that glyben can reasonably model the nonlinear behavior of natural soil under strong dynamic excitation.

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