CURRENT RESEARCH ON DYNAMIC SHEAR BEHAVIOR OF GEOSYNTHETIC CLAY LINERS

Geosynthetic clay liners (GCLs) have seen increasing usage in civil engineering applications. However, little is known about their response to dynamic stresses during seismic events. There is a concern over the internal shear strength of GCLs and interface shear strength of GCLs with adjacent materials under these conditions.

A new type of shear box capable of applying seismic ground motions has been constructed at Ohio State University. The shear box can test rectangular GCL specimens measuring 0.3 × 1.1 m (12 × 42 in.). The device has a maximum shear displacement of 254 mm (10 in.), a maximum normal stress of 2,400 kPa (50,000 psf), a maximum shear stress of 750 kPa (15,700 psf). In the case of sinusoidal shearing, the maximum frequency corresponding to a displacement amplitude of 25 mm (1.0 in.) is 5 Hz. This paper, presented at the GRI-19 Conference, describes the objectives of the research program, the equipment, initial dynamic shear testing results, and further dynamic shear tests planned within the next two years.

The testing program began by evaluating the internal strength of hydrated Bentomat SDN under dynamic loadings. Four displacement-controlled cyclic loading tests were performed at a normal stress of 85 kPa, a frequency of 1 Hz, and displacement amplitudes of 10, 15, 20, and 25 mm. For comparison, a fifth static shear test was conducted without prior cyclic loading. In each of the cyclic tests, the GCL experienced strain-softening (reduction in shear stress over time) and volumetric contraction. Post-cyclic static shear strengths were observed to decrease with increasing displacement amplitude. When 50 cycles of ±10 mm displacement were applied, the post-cyclic shear strength was unaffected. When 50 cycles of ±25 mm displacement were applied, the post-cyclic shear strength was nearly reduced to the residual friction value of 5.4º. In addition, with higher displacement, fewer displacement cycles were needed to reach failure. Residual strengths (measured at large shear displacements) were similar for each test.

Additional testing is planned to help obtain a better understanding of GCL dynamic shear strength. The one-of-a-kind shear box is also available for project-specific testing applications. In fact, the shear box can be programmed to recreate ground motions from historical earthquake data as a means to more accurately model geosynthetic liner system performance.

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CURRENT RESEARCH ON DYNAMIC SHEAR BEHAVIOR OF NEEDLE-PUNCHED GEOSYNTHETIC CLAY LINERS

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ABSTRACT

Current research on the dynamic shear behavior of needle-punched geosynthetic clay liners (GCLs) is described. A state-of-the-art, large-scale, dynamic direct shear machine has recently been constructed that can test rectangular GCL specimens measuring 305 × 1067 mm (12 × 42 in.). The device has a maximum shear displacement of 254 mm (10 in.), a maximum normal stress of 2,000 kPa (42,000 psf), a maximum shear stress of 750 kPa (15,700 psf), and the capability for general dynamic loading. The maximum frequency for sinusoidal loading with a displacement amplitude of 25 mm (1.0 in.) is 5 Hz. This paper describes the objectives of the research program, the equipment, and the first dynamic shear data ever obtained for a needle-punched GCL.

INTRODUCTION

Characterization of the shear behavior of geosynthetic liner systems under dynamic loading conditions is important for the assessment of long-term performance of landfills in seismic regions. Since the peak dynamic friction angle is only slightly higher than the peak static friction angle in most cases (Yegian and Lahlaf 1992, De and Zimmie 1998), static shear strengths are often used for dynamic analyses, as in the calculation of yield accelerations (USEPA 1995). However, important information such as cyclic stress ratio vs. number of cycles to failure and post-earthquake static shear strengths are not given by static shear data. Dynamic shear tests are needed to provide this information.

Most studies of the dynamic shear behavior of geosynthetic liner systems have been conducted using shake tables for low normal stress conditions, often 15 kPa or less (Yegian and Lahlaf 1992, De and Zimmie 1998, Yegian and Kadakal 1998, Lo Grasso et al. 2002). De and Zimmie conducted shake table tests using a geotechnical centrifuge and were able to increase the normal stress level to 84 kPa. Cyclic direct shear (De and Zimmie 1998) and simple shear devices (Lai et al. 1998) have also been used to investigate the dynamic response of geosynthetic liner materials. Despite these efforts, relatively little data are available for shear strength of geosynthetics and geosynthetic interfaces under dynamic loading conditions, especially for high normal stresses. For example, the only information available on the dynamic behavior of geosynthetic clay liners (GCLs) is from Lai et al. (1998) and Lo Grasso et al. (2002). Lai et al.

tested small specimens (diameter = 80 mm) of an unreinforced geomembrane-supported GCL in a direct simple shear device. These specimens were subjected to sinusoidal excitations and sheared to small displacements for a normal stress range of 23 – 113 kPa. Lo Grasso et al. conducted shake table tests on GCL/geomembrane interfaces at a normal stress of 0.82 kPa using both sinusoidal and seismic loading conditions. Information on the type of GCL and the hydration/consolidation conditions used in the study was not provided.

GCLs offer many advantages over compacted clay liners, not the least of which is lower cost for many applications. As such, GCLs are now commonly specified in the design of waste disposal facilities and other facilities requiring hydraulic barriers. Internal and interface shear strengths continue to be a chief concern for designers because of the very low shear strength of hydrated bentonite. Many quality studies have been published on GCL static shear strength (see Fox and Stark (2004) for review). Test data is currently needed on the shear behavior of GCLs and GCL interfaces during dynamic loading and on post-dynamic static shear strengths.

OBJECTIVES

In response to the above need, a research program is underway at Ohio State University to investigate the shear strength behavior of GCL liner systems under dynamic loading conditions. This research is funded in part by CETCO of Arlington Heights, Illinois, USA. Dynamic shear tests will be conducted for GCLs and GCL interfaces (e.g., with geomembranes), as well as multi-interface specimens representing sections of GCL liner systems, using a new dynamic direct shear machine that has recently been constructed for the project. This paper presents an overview of the capabilities of this new device and the first cyclic shear data ever obtained for a needle-punched GCL.

DYNAMIC DIRECT SHEAR MACHINE

A large-scale, state-of-the-art dynamic direct shear machine has been constructed to obtain internal and interface shear strengths of GCLs under a wide range of normal stresses. The dynamic direct shear machine is a freestanding apparatus that measures 3.8 m long, 1.0 m wide and 1.2 m tall. The basic design of the machine is similar to the static shear device described by Fox et al. (1997) with the exception that the shearing system is capable of applying bidirectional (*i.e.,* back-and-forth) dynamic loading to a test specimen. A photograph of the machine is shown in Fig. 1 and scale drawings are provided in Fig. 2, which shows plan and profile views along with a detailed view of the test chamber. The test chamber measures 305 × 1067 mm (12 × 42 in.) in plan and can accommodate specimens up to 254 mm (10 in.) in thickness. A specimen is placed in the test chamber and sheared by a hydraulic actuator positioned horizontally in front of the specimen. The maximum shear displacement is 254 mm (10 in.) which allows for the measurement of residual or near-residual shear strengths in most cases (Fox et al. 1998, Triplett and Fox 2001).

Figure 1. Dynamic direct shear machine - nearly completed.

Shearing System

Shear force is applied to the specimen using a hydraulic actuator (model no. 244.31) manufactured by MTS Systems Corporation of Eden Prairie, Minnesota, USA. The actuator has a capacity of 245 kN (55,000 lb.), which corresponds to a maximum applied shear stress of 750 kPa. An axial load cell designed for cyclic loading is incorporated into the piston to measure applied shear forces on the test specimen. The actuator is driven by a 340 liter/min. (90 gal./min.) hydraulic pump and a hydraulic manifold that includes 19 liters of accumulation to better allow the actuator to achieve peak response. Piston motion is controlled by a three-stage servo-hydraulic valve and a MTS FlexTest SE digital controller such that essentially any displacement-controlled or stress-controlled time-history, including monotonic loading, is possible. For static shear tests, the system is capable of shear displacement rates as slow as 0.01 mm/min. This is ten times slower than the maximum displacement rate recommended by Fox et al. (2004) for internal shear of hydrated GCLs. Although the dynamic capabilities of the system have yet to be fully investigated, the system was designed to have sufficient capacity to accommodate sinusoidal shearing with a displacement amplitude of 25 mm (1.0 in.) at a frequency of 5 Hz. Smaller displacement amplitudes will allow higher frequencies to be investigated.

Shear forces are transferred to the test specimen through an aluminum pullout plate measuring 1500 × 305 × 22 mm. The pullout plate is coated for corrosion resistance and is bolted to the actuator at the front of the test chamber. This plate is lighter and thicker than the Fox et al. (1997) counterpart so that it has less effect on dynamic response and more resistance to buckling under compressive loads. The pullout plate is 433 mm longer than the test chamber, 152 mm of which is required for attachment to the actuator. The remaining 281 mm allows the pullout plate to move into the rear of the test chamber to maintain a constant shearing surface area during testing. An aggressive gripping surface is attached to the bottom of the test chamber

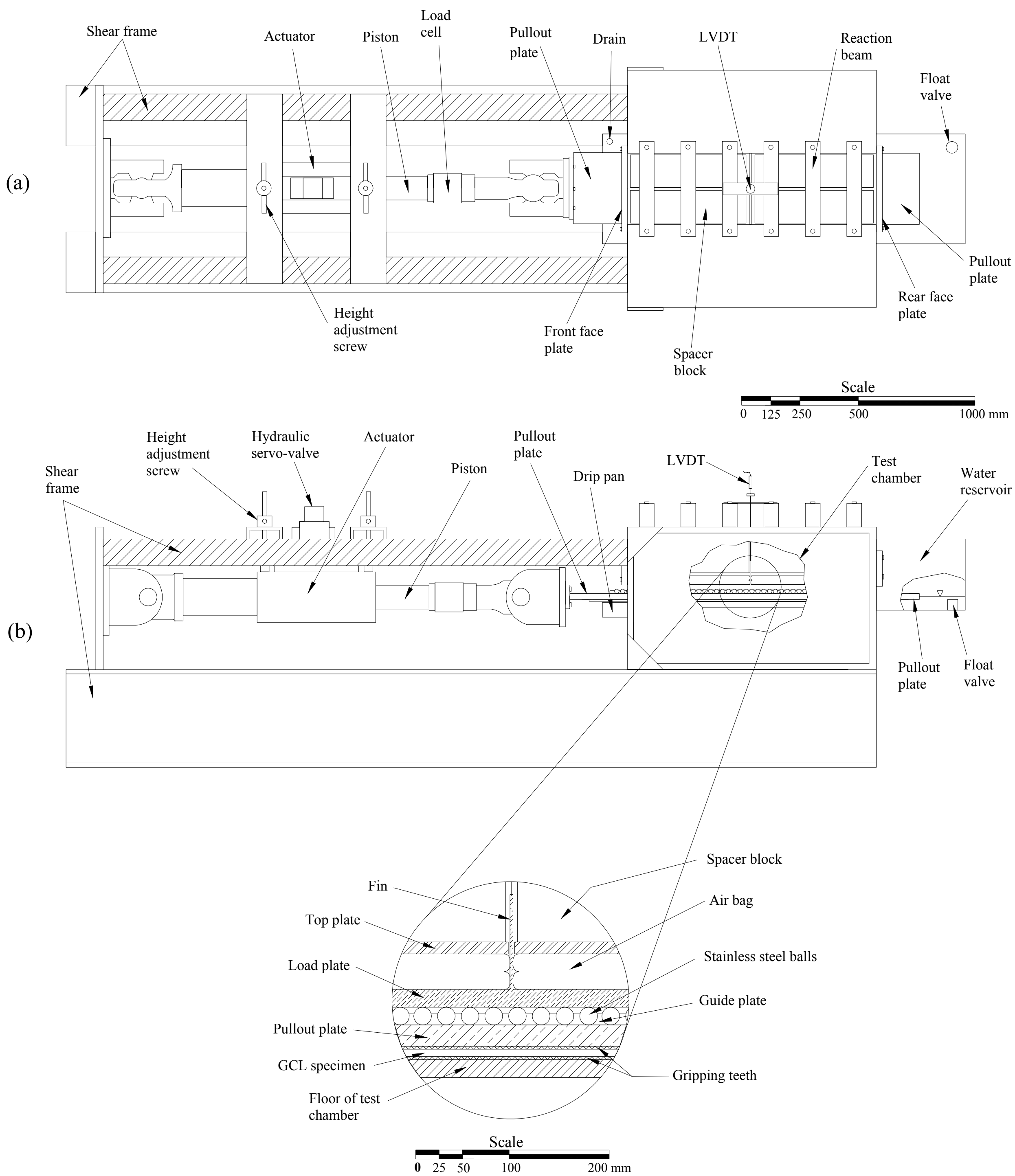

Figure 2. Dynamic direct shear machine: (a) plan view, and (b) profile view.

and the underside of the pullout plate, with the test specimen placed in between. This surface consists of modified metal connector plates (i.e., truss plates) that are used for wood truss construction (Fox et al. 1997). The teeth on the truss plates have been cut so that they are 1-2 mm tall and have a flat (i.e., rectangular) profile to allow for gripping in both directions during dynamic loading. This gripping surface is sufficiently rough that end-clamping of the geosynthetics is not needed, which allows a specimen to fail along the weakest surface and avoids possible progressive failure effects during shear (Fox and Stark 2004).

To maintain alignment of the piston with the pullout plate, the actuator is bolted to the rear of the machine frame through slotted holes, which in conjunction with two height-adjustment screws, allow for 0.13 m of vertical travel of the actuator assembly. This system eliminates eccentric loading on the piston that would interfere with shear forces recorded by the load cell.

Normal Stress and Vertical Displacement System

The dynamic direct shear machine is capable of accommodating a maximum normal stress of 2,000 kPa (42,000 psf) which will allow it to produce performance shear data for landfills approaching 150 m in depth. Normal stress is applied using two air bags that rest on a rigid load plate. Between the load plate and the pullout plate, a layer of 517 free-rolling stainless steel balls reduce the frictional resistance to 2% of the applied normal force. The air bags are bellowed so they can expand without tensioning the rubber, which would reduce the applied normal stress. Each bag reacts against a top plate, which in turn reacts against three aluminum reaction beams that transversely span the top of the test chamber. Depending on the thickness of the test specimen, wooden spacer blocks of various sizes are used to fill the void space between the top plates and the reaction beams. The air bags are enclosed laterally by front and rear face plates and a transverse fin that spans the middle of the load plate. Vertical displacement of the load plate due to test specimen volume change is continuously monitored during hydration, consolidation, and shearing using a linear variable displacement transformer (LVDT). The LVDT is mounted above the reaction beams and senses the motion of the load plate through a brass rod that rests at the midpoint of the top surface of the fin.

Proper control of air pressure for the dynamic direct shear machine is more challenging than for a static shear machine because of potentially rapid specimen volume changes that can occur during dynamic loading. Air pressure is generated using an air amplifier that increases the building air pressure by a factor of four to a maximum of 2500 kPa. The amplifier fills a pair of 18 liter air tanks that sit under the shear box. Air fills the primary tank and passes through a regulator to fill the secondary tank at the desired (lower) air pressure for testing. The secondary air tank is connected to the air bags through a large diameter flexible hose with minimal resistance. Thus, the air bags have direct access to a reserve of additional air under the same pressure. Air pressure in the bags and secondary tank is measured using a high-accuracy 35-2100 kPa digital test gage. The weight of components below the air bags adds an additional 2.5 kPa to the normal stress.

Hydration System

A water reservoir at the rear of the test chamber (not shown in Fig. 1) provides the specimen access to water throughout hydration, consolidation and shearing. The pullout plate has a series of longitudinal channels milled into the underside and each truss plate has holes across its surface to allow for water drainage. The pullout plate and truss plates are separated by a coarse wire mesh to minimize clogging of the water channels and further facilitate drainage. A similar system is used in the floor of the test chamber to provide drainage to the underside of the specimen. Water flow is collected at the front of the test chamber in a drip pan and channeled to a floor drain.

Data Acquisition

The dynamic shear machine uses a process control and data acquisition system developed by MTS for operation of the actuator. The system consists of a FlexTest SE digital controller that has inputs for the hydraulic pump unit, manifold, servo-hydraulic valve, load cell, LVDT, and PC interface. The controller allows for user interface through a personal computer, giving complete control of the testing system, including pump function, piston motion, and data sampling rates.

TESTING PROGRAM

The following testing program has been developed for GCLs and GCL interfaces, and is expected to be completed in the next two years. We have also applied for funding from the USEPA to extend the study for an additional two years to include other types of landfill liner components.

Static Loading Tests

Throughout the research program, static shear tests will be conducted to provide values of peak and residual static shear strength and to investigate failure mechanisms under static shear conditions. This information will be used to guide the dynamic shear testing program and to compare with the results of dynamic shear tests.

Cyclic Loading Tests

Cyclic loading tests will be performed to determine the fundamental dynamic shear behavior of GCLs and GCL interfaces. These tests will be conducted using both stress-controlled and displacement-controlled sinusoidal excitations. Variables for these tests will include:

- Specimen/interface type
- Normal stress
- Shear stress/shear displacement amplitude
- Loading frequency
- Number of cycles

The results of these tests will be used to determine relationships for:

- Cyclic stress ratio (shear stress amplitude/static peak strength) vs. number of cycles to failure vs. normal stress – for specimens that fail during cyclic loading,
- Permanent shear displacement vs. cyclic stress ratio vs. number of cycles vs. normal stress – for specimens that do not fail under cyclic loading,
- Post-cyclic static shear strength vs. cyclic stress ratio vs. number of cycles vs. normal stress – for specimens that do not fail under cyclic loading, and
- Relationships for equivalent shear modulus and damping for use in 1D ground response analyses (see Yegian et al. (1998) for discussion).

Seismic Loading Tests

These tests will subject GCLs and GCL interfaces to a suite of earthquake-type ground motions. Stress-controlled tests will be conducted for representative shear stress vs. time histories expected for landfill base liners and cover systems in seismic regions. Variables for these tests will include:

- Specimen/interface type
- Normal stress
- Ground motion record

The results of these tests will be used to determine relationships for:

- Failure or permanent shear displacement vs. normal stress vs. ground motion record – ground motion records will be characterized according to parameters for amplitude, frequency content, and duration, and
- Post-seismic static shear strength vs. normal stress vs. ground motion record – for specimens that do not fail under seismic loading.

FIRST DATA

An initial dynamic shear testing program was completed on five specimens of hydrated Bentomat SDN, a light nonwoven/nonwoven (LNW/NW) needle-punched (NP) GCL with no thermal bonding manufactured by CETCO. Each specimen was hydrated under a shearing normal stress of 85 kPa using the 4-day, two-stage hydration procedure described by Fox et al. (1998). Displacement-controlled cyclic shear tests were then conducted for four displacement amplitudes of 10, 15, 20, and 25 mm at a frequency of 1 Hz for 50 sec. After cyclic loading, static shear tests were conducted at a shear displacement rate of 1 mm/min. to measure the post-cyclic static shear strength. A fifth static shear test was conducted without prior cyclic loading for comparison.

The first 6 sec of shear displacement for the ±10 mm cyclic shearing test is shown in Fig. 3. The actuator followed a sinusoidal wave with the required constant displacement amplitude and frequency. Measured shear stresses for the full duration of the same cyclic test are shown in Fig. 4. During the first cycle, shear stress reached a maximum amplitude of 54 kPa. Shear stress amplitude then decreased nonlinearly for subsequent cycles until it reached a near-steady value

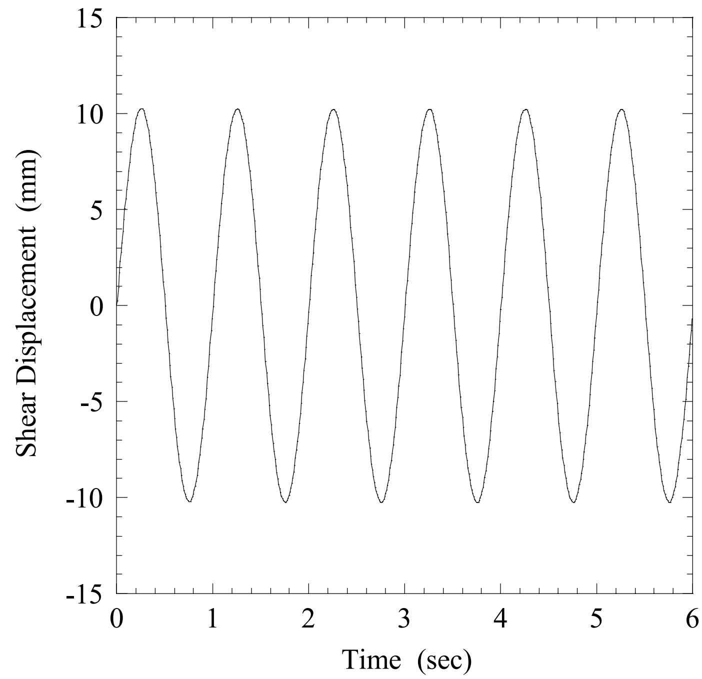

Figure 3. Shear displacement during the first 6 sec of a ±10 mm cyclic test of a LNW/NW NP GCL.

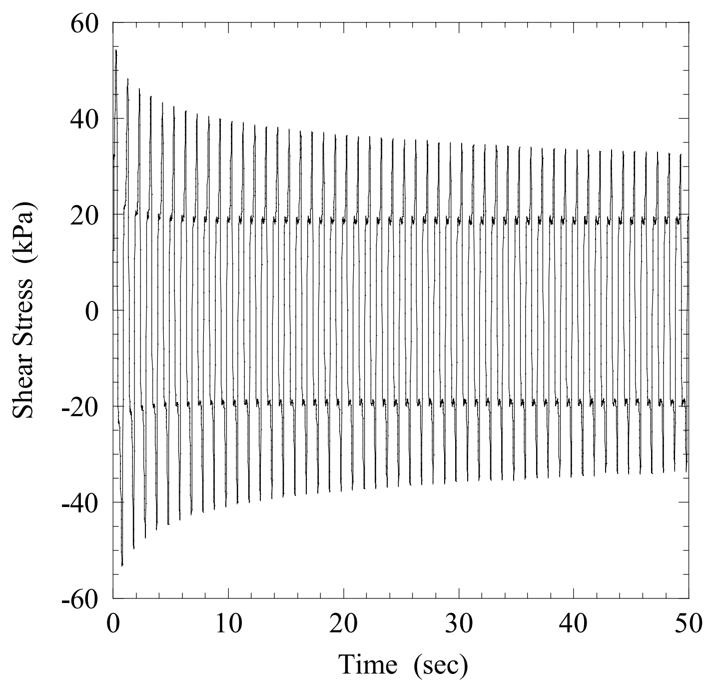

Figure 4. Shear stress for ±10 mm cyclic test of a LNW/NW NP GCL.

of 33 kPa during the 50th cycle. The shear stress vs. shear displacement diagram (Fig. 5) indicates the same progressive softening behavior during cyclic loading. The most notable difference between the cyclic response displayed in Fig. 5 and that of natural soils (e.g., Kramer 1996) is the increase of shear stress for each cycle as the maximum shear displacement is approached and the needle-punched reinforcement is engaged.

Corresponding plots of shear stress vs. time and shear stress vs. shear displacement for the ±25 mm cyclic shearing test are shown in Figs. 6 and 7. In this case, the reinforcement is essentially ruptured in the first few cycles, leaving a near-residual dynamic shear strength of hydrated bentonite of approximately 18 kPa thereafter. Interestingly, this yields a residual dynamic friction angle of 12°, which is nearly three times the static value of 4-5° for GCLs (Fox et al. 1998). Considering that the average displacement rate for this test (50 mm/sec) is 30,000 times faster for that for the Fox et al. tests (0.1 mm/min.), this corresponds to a 20% gain in shear strength per log cycle of displacement rate.

GCL volume change data for the ±10 mm and ±25 mm tests is shown in Fig. 8. Both specimens experienced volumetric contraction during cyclic loading, the magnitude of which increased with increasing shear displacement amplitude. Post-cyclic static shear strengths are shown in Fig. 9. The application of 50 cycles of ±10 mm displacement had no effect on subsequent static peak shear strength. Larger shear displacement amplitudes resulted in progressively lower peak strengths. When 50 cycles of ±25 mm displacement were applied, the peak strength was nearly reduced to the residual value. Residual strengths measured at large shear displacement were similar for each test and yield a residual friction angle of 5.4°.

CONCLUSIONS

A research program is underway at Ohio State University to investigate the shear strength behavior of geosynthetic clay liners (GCLs) and GCL interfaces under dynamic loading conditions. A new dynamic direct shear machine has been constructed that tests GCL specimens measuring 305 × 1067 mm (12 × 42 in.). The machine has a maximum shear displacement of 254 mm (10 in.), a maximum normal stress of 2,000 kPa (42,000 psf), a maximum shear stress of 750 kPa (15,700 psf), and the capability for general dynamic loading. The maximum frequency for sinusoidal shearing with a displacement amplitude of 25 mm (1.0 in.) is 5 Hz.

This paper presents the first data ever obtained on the dynamic shear strength of a hydrated needle-punched GCL. Four displacement-controlled cyclic loading tests were performed at a normal stress of 85 kPa, a frequency of 1 Hz, and displacement amplitudes of 10, 15, 20, and 25 mm. In each case, the GCL experienced strain-softening and continuing volumetric contraction during cyclic loading. Dynamic shear response was similar to natural soils except that, for each cycle, the shear stress increased as the maximum displacement was approached and the needle-punched reinforcement was engaged. Post-cyclic static shear strengths progressively decreased with increasing displacement amplitude. When 50 cycles of ±10 mm displacement were applied, the post-cyclic static shear strength was unaffected. When 50 cycles of ±25 mm displacement were applied, the post-cyclic peak strength was nearly reduced to the residual value.

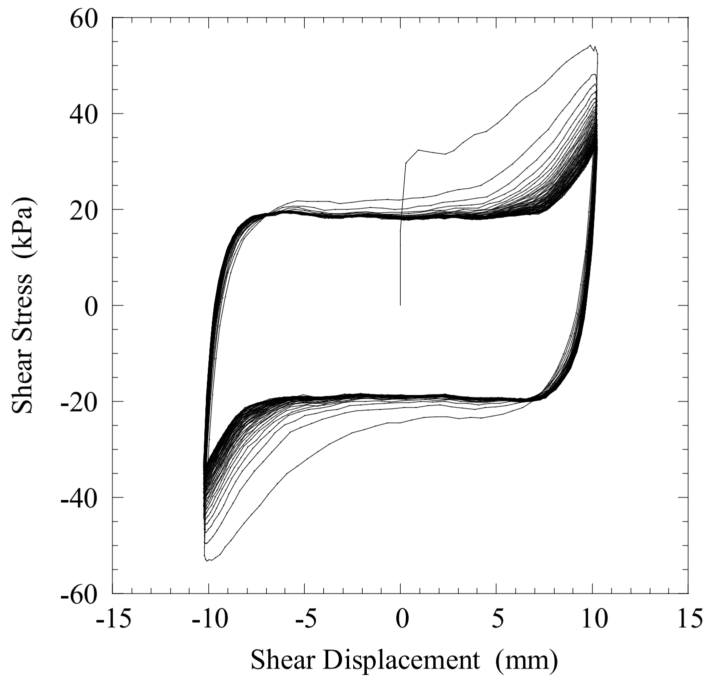

Figure 5. Shear stress vs. shear displacement for ±10 mm cyclic test of a LNW/NW NP GCL.

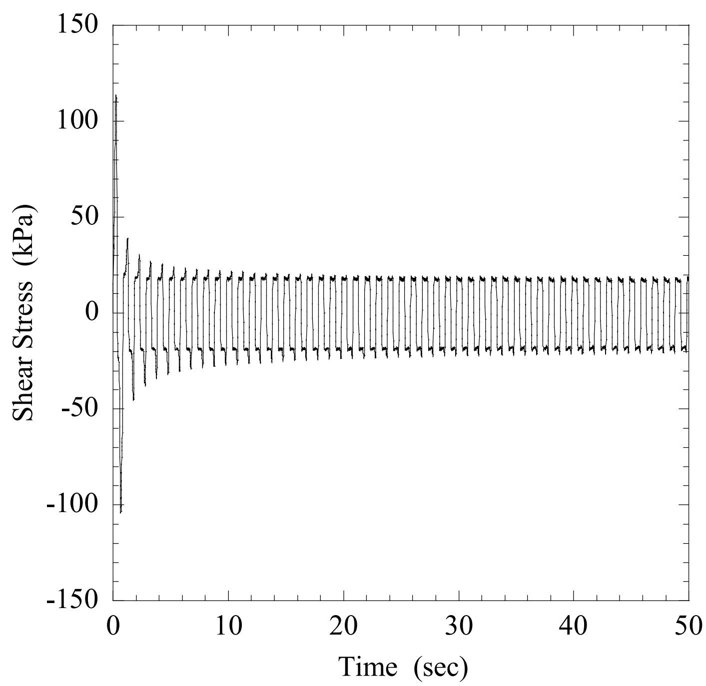

Figure 6. Shear stress for ±25 mm cyclic test of a LNW/NW NP GCL.

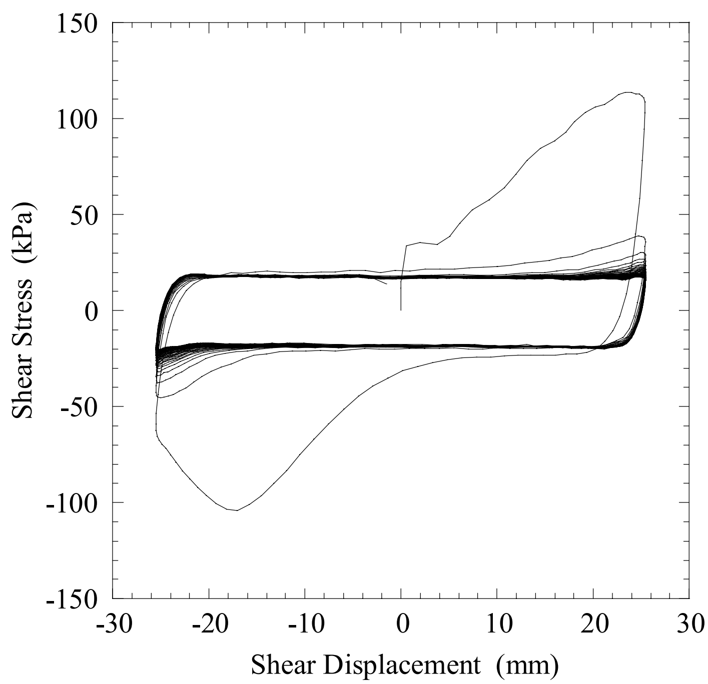

Figure 7. Shear stress vs. shear displacement for ±25 mm cyclic test of a LNW/NW NP GCL.

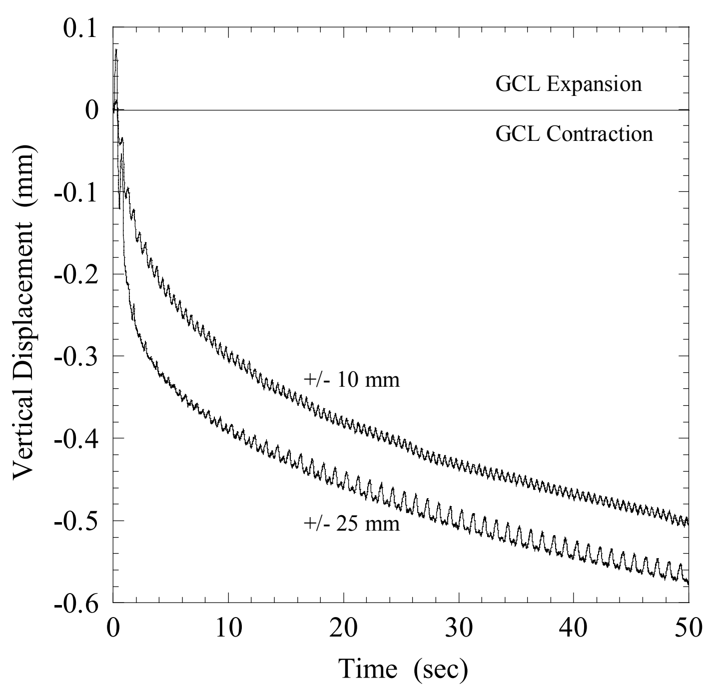

Figure 8. Volume change behavior for ±10 mm and ±25 mm cyclic tests of a LNW/NW NP GCL.

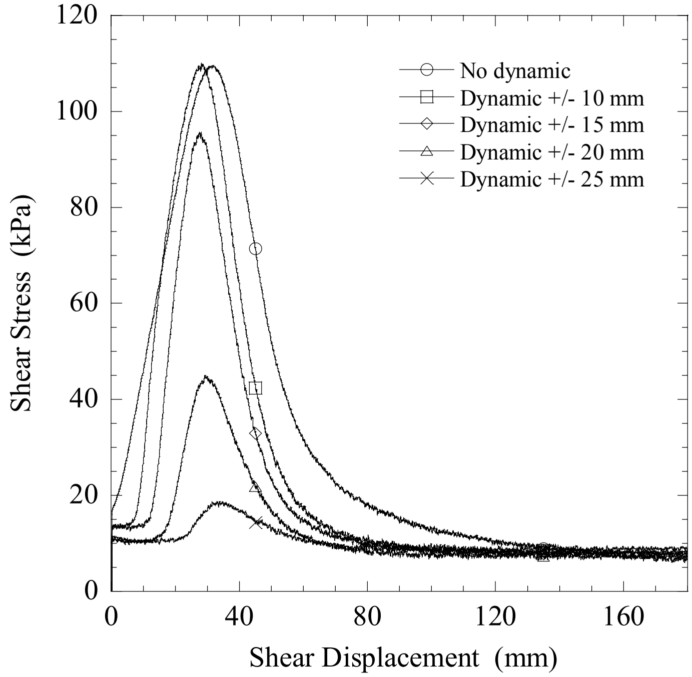

Figure 9. Post-cyclic static shear strengths for a LNW/NW NP GCL.

REFERENCES

De, A. and Zimmie, T. F. (1998). "Estimation of dynamic interfacial properties of geosynthetics," *Geosynthetics International*, 5(1-2), 17-39.

Fox, P. J., Rowland, M. G., Scheithe, J. R., Davis, K. L., Supple, M. R., and Crow, C. C. (1997). "Design and evaluation of a large direct shear machine for geosynthetic clay liners," *Geotechnical Testing Journal*, 20(3), 279-288.

Fox, P. J., Rowland, M. G., and Scheithe, J. R. (1998). "Internal shear strength of three geosynthetic clay liners," *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10), 933-944.

Fox, P. J. and Stark, T. D. (2004). "State-of-the-art report: GCL shear strength and its measurement," *Geosynthetics International*, 11(3), 117-151.

Fox, P. J., Stark, T. D., and Swan, Jr. R. H. (2004). "Laboratory measurement of GCL shear strength," *Advances in Geosynthetic Clay Liner Technology: 2nd Symposium*, STP 1456, R. E. Mackey and K. von Maubeuge, eds., ASTM International, 92-109.

Kramer, S. L. (1996). *Geotechnical Earthquake Engineering*, Prentice Hall, Inc., Upper Saddle River, New Jersey, 653 pp.

Lai, J., Daniel, D. E., and Wright, S. G. (1998). "Effects of cyclic loading on internal shear strength of unreinforced geosynthetic clay liner," *Journal of Geotechnical and Geoenvironmental Engineering*, 124(1), 45-52.

Lo Grasso, S. A., Massimino, M. R., and Maugeri, D. I. C. A. (2002). "Dynamic analysis of geosynthetic interfaces by shaking table tests," *Proceedings, 7th International Conference on Geosynthetics*, Nice, Vol. 4, 1335-1338.

Triplett, E. J. and Fox, P. J. (2000). "Shear strength of HDPE geomembrane/geosynthetic clay liner interfaces," *Journal of Geotechnical and Geoenvironmental Engineering*, 127(6), 543-552.

USEPA (1995). "RCRA Subtitle D (40 CFR 258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities," G. N. Richardson, E. Kavazanjian, Jr., and N. Matasovic, EPA/600/R-95/051, April.

Yegian, M. K. and Lahlaf, A. M. (1992). "Dynamic interface shear strength properties of geomembranes and geotextiles," *Journal of Geotechnical Engineering*, 118(5), 760-779.

Yegian, M. K. and Kadakal, U. (1998). "Geosynthetic interface behavior under dynamic loading," *Geosynthetics International*, 5(1-2), 1-16.

Yegian, M. K., Harb, J. N., and Kadakal, U. (1998). "Dynamic response analysis procedure for landfills with geosynthetic liners," *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10), 1027-1033.