CYCLIC SHEAR TEST OF A GEOSYNTHETIC CLAY LINER FOR A SECONDARY CONTAINMENT APPLICATION

The design of a large petrochemical facility in China has involved the evaluation of various secondary containment liner options. One of the options under consideration is Bentomat CL, a needlepunch-reinforced woven/nonwoven GCL with a thin polyethylene geofilm laminated to the nonwoven side. The liner cross-section includes (from bottom to top): a subgrade consisting of scree (i.e. loose stones or rocky debris), a 30 cm thick layer of compacted soil, Bentomat CL, and either a 50 cm thick compacted soil layer or a 20 cm thick concrete slab. Following the large (7.9 magnitude) earthquake that struck the Sichuan province in May 2008, local design engineers were concerned about the ability of the GCL to withstand seismic loads. To address this concern, a cyclic shear test was performed to assess the potential for damage to the GCL.

A cyclic shear test of the sand/GCL/sand liner system was performed using a large dynamic direct shear machine capable of applying static and dynamic loads to soil and geosynthetic specimens. The liner system specimen was placed under a normal stress of 100 kPa, and subjected to 25 cycles of displacement-controlled sinusoidal shearing with a displacement amplitude of 20 mm and a frequency of 1 Hz.

Shearing occurred at the sand/geofilm interface, and the GCL sustained no visible damage, even after 25 cycles of cyclic shearing. The interface friction angle was initially 28.6 degrees, and decreased to a final value of 16.7 degrees after 25 cycles. Material property tests performed on pre-cyclic and post-cyclic GCL samples provided additional evidence that the GCL specimen did not sustain damage due to cyclic loading.

References:

Athanassopoulos, C., Fox, P. J. & Ross, J. D. (2010). Cyclic shear test of a geosynthetic clay liner for a secondary containment application. Geosynthetics International, 17, No. 2, 107–111.

Technical Note

Cyclic shear test of a geosynthetic clay liner for a secondary containment application

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ABSTRACT: This note presents the results of a cyclic shear test of a secondary containment liner system composed of sand/GCL/sand. The GCL was a needle-punch-reinforced woven/nonwoven product with a thin geomembrane laminated to the nonwoven side. Under a normal stress of 100 kPa, shearing occurred at the sand/geomembrane interface and the GCL sustained no visible damage after 25 cycles of loading with a displacement amplitude of 20 mm and a frequency of 1 Hz. Material property tests performed on pre-cyclic and post-cyclic GCL samples provided additional evidence that the GCL specimen did not sustain damage due to cyclic loading. Analysis of the cyclic loading data indicates hysteretic stress-displacement behavior that is broadly similar to natural soils and displays strength and stiffness degradation as well as reduction in damping ratio with continued cycling.

KEYWORDS: Geosynthetics, Geosynthetic clay liner, Sand, Interface, Damage, Cyclic shear, Direct shear

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1. INTRODUCTION

The design of a large petrochemical facility in China has involved the evaluation of various secondary containment liner options. One of the options under consideration is a geosynthetic clay liner (GCL) with a thin polyethylene geomembrane laminated to one side. GCLs are commonly used as alternatives to compacted clay liners in waste and liquid containment applications, because of their low hydraulic conductivity and ease of installation. A geomembrane-laminated GCL is often specified in secondary containment applications, for improved hydraulic performance and chemical compatibility. In this application the secondary containment liner is needed for the majority of the petrochemical plant footprint to maximize capture of potential hydrocarbon leaks from tanks, piping and process equipment. The liner cross-section includes (from bottom to top): a subgrade consisting of scree (i.e. loose stones or rocky debris), a 30 cm thick layer of compacted soil, a geomembrane-laminated GCL, and either a 50 cm thick compacted soil layer or a 20 cm thick concrete slab. In retrospect of the large (7.9 magnitude) earthquake that struck the Sichuan province in May 2008, local design engineers were concerned about the ability of the GCL to withstand seismic loads. To address this concern, a cyclic shear test was performed on the liner system to assess the potential for damage to the GCL. The work was conducted using a large dynamic direct shear machine capable of applying static and dynamic loads to soil and geosynthetic specimens, including sections of entire liner systems. Further description of the machine is provided by Fox *et al.* (2006) and Nye and Fox (2007).

2. MATERIALS

The GCL evaluated in this study was Bentomat CL, manufactured by CETCO in Suzhou, China. This GCL is a needle-punch-reinforced woven/nonwoven product containing 3.6 kg/m^2 of sodium bentonite, with a thin polyethylene geomembrane (90 g/m^2) laminated to the nonwoven side. A light brown, medium-grained sand was selected to represent both the cover and subgrade soils, as it was not practical to obtain soil from the actual project site. The particle size distribution curve is shown in Figure 1, and the standard Proctor compaction curve is shown in Figure 2. The sand contained 7% gravel and essentially no fines, and is classified as SP, poorly graded sand, according to the Unified Soil Classification System. The compaction curve indicates an optimum moisture content of 11% and a maximum dry unit weight of 19.1 kN/m^3. Based on the work of Dickinson and Brachman (2006, 2008), such material would provide excellent protection to the GCL.

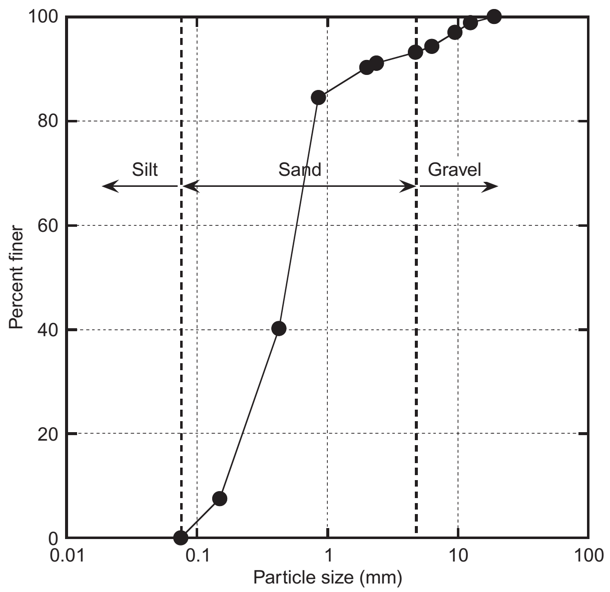

Figure 1. Soil particle size distribution curve

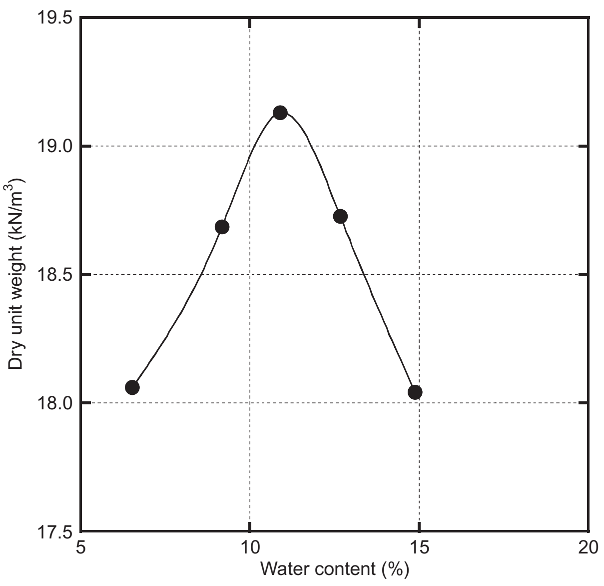

Figure 2. Soil standard Proctor compaction curve

3. CYCLIC SHEAR TEST

A cyclic shear test was conducted using the large dynamic direct shear machine shown in Figure 3. The test chamber measures 305 mm × 1067 mm in plan and 254 mm in depth. The specimen was sheared using a hydraulic actuator connected to a rigid pullout plate that was covered with an aggressive gripping surface (truss plates). The shear test was performed on the following cross-section (from top to bottom):

- compacted sand,
- geomembrane-laminated GCL, placed with the geomembrane facing up; and
- compacted sand.

Prior to testing, the GCL specimen was fully hydrated (i.e. with free access to water) under a normal stress of 10 kPa for two days and then consolidated under 100 kPa for an additional two days. The consolidation stress was applied gradually over a 24 h period to avoid lateral squeezing of the hydrated bentonite (Fox *et al.* 2000; Fox and Stark 2004). This specimen preparation procedure was intended to simulate the most conservative field conditions (i.e. full hydration under low normal stress after installation, followed by GCL consolidation over time due to the added weight of vehicles, structures, raw materials storage, tanks and process equipment). Each soil layer was compacted as a single lift at the optimum moisture content (11%) using a hand tamper, and was approximately 50 mm thick after compaction.

After hydration and consolidation, the liner system was subjected to 25 cycles of displacement-controlled sinusoidal shearing for a normal stress of 100 kPa, displacement amplitude of 20 mm and frequency of 1 Hz (i.e. 1 cycle/s). Thus the total distance travelled for each cycle (peak to peak) was 40 mm. The amplitude was selected based on a

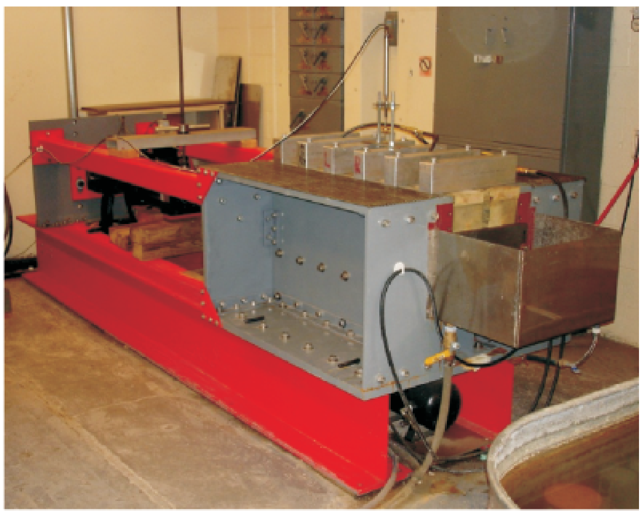

Figure 3. Large dynamic direct shear machine

review of data from the 2008 Sichuan earthquake, which showed a ground surface wave amplitude of 15 mm at a distance of 20.3 km (USGS 2009). Although the period for this ground motion was substantially larger than 1 s, Nye and Fox (2007) found that excitation frequencies ranging from 0.5 to 3 Hz had no significant effect on the internal cyclic shear behavior of a hydrated woven/non-woven GCL for a normal stress of 141 kPa. After the cyclic test was completed, the specimen was immediately removed from the machine for inspection, and final water contents of the GCL and soil were measured. To further evaluate the GCL for damage, pre-cyclic and post-cyclic samples of the material were sent for comparison testing to TRI Environmental, an independent third-party laboratory in Austin, Texas. The pre-cyclic sample was taken from the same roll as the GCL specimen, and was not hydrated, consolidated or sheared. The post-cyclic sample was taken directly from the GCL specimen after shearing.

4. RESULTS

Shear failure of the GCL liner system occurred between the laminated geomembrane and the cover soil layer. A photograph of the failure surface (i.e. laminated side of GCL) after shearing is shown in Figure 4. Final GCL water contents (two measurements) were 118% and 130%, and the final soil-water content near the sliding surface was 11.8%. Final inspection of the GCL specimen indicated no tearing, necking, ruptured reinforcement or other visible damage. The small wrinkles observed in Figure 4 were present in the GCL material prior to shearing. Thus no damage to the GCL specimen was observed as a result of cyclic shear. These findings demonstrate that, even though the shear strength of hydrated bentonite is low, the needle-punch reinforcement of the GCL was sufficiently strong at this normal stress level to force failure along an adjacent interface rather than through the hydrated bentonite.

A plot of shear displacement against time for the GCL liner system is shown in Figure 5. The specified displacement amplitude of 20 mm was achieved for all 25 cycles

Figure 4. Laminated side of GCL after cyclic shear test (note: scale in inches)

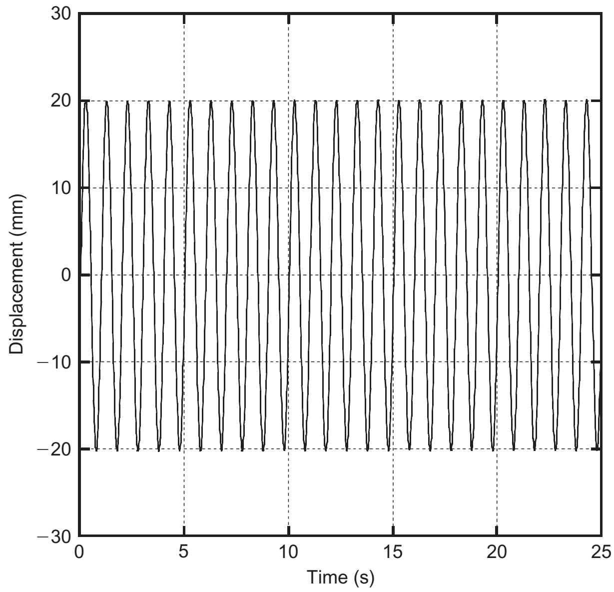

Figure 5. Shear displacement against time for cyclic shear test of a GCL liner specimen

of loading. Figure 6 shows the corresponding plot of shear stress against time. The maximum shear stress for each cycle decreased nonlinearly from a peak value of 54.5 kPa during the first cycle to approximately 30 kPa during the final cycles. These values yield an initial secant friction angle of 28.6° and a final value of 16.7° for the interface. The plot of shear stress against shear displacement is shown in Figure 7. The GCL/soil interface yielded repeating hysteresis loops that are broadly similar to those observed for natural soils and indicate progressive strength degradation during cyclic loading. Stress–displacement data from each loop were analyzed using the methods of Nye and Fox (2007) to obtain values of secant shear stiffness (shear stress/displacement) and damping ratio,

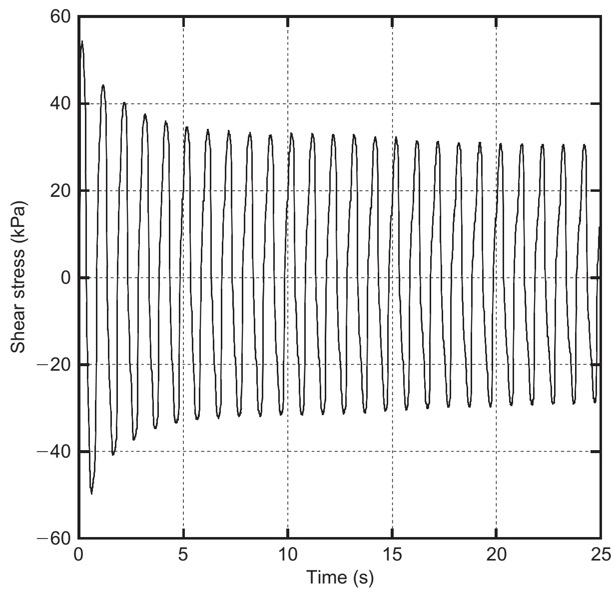

Figure 6. Shear stress against time for cyclic shear test of a GCL liner specimen

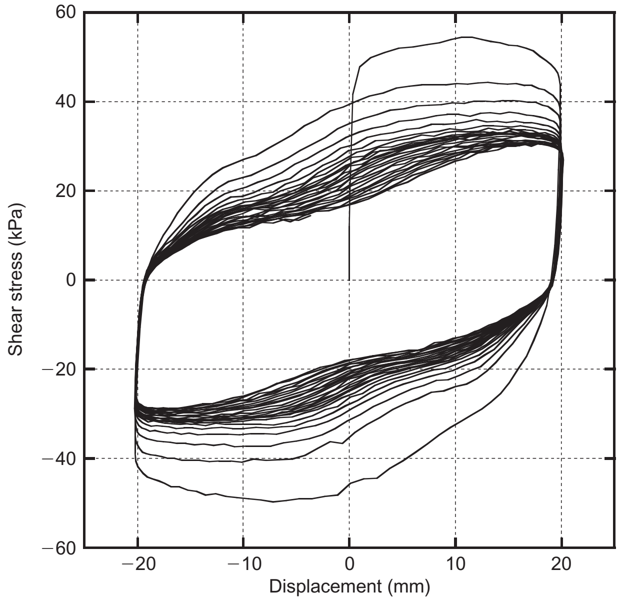

Figure 7. Shear stress against shear displacement for cyclic shear test of a GCL liner specimen

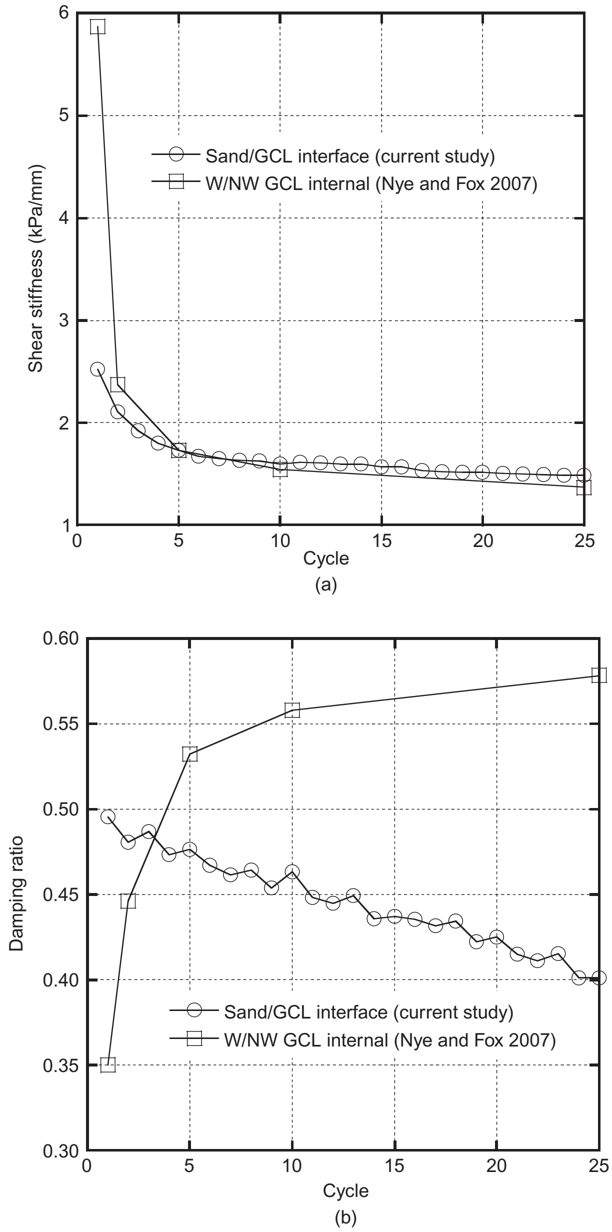

Figure 8. Results for internal and interface GCL cyclic shear tests: (a) shear stiffness; (b) damping ratio

shown against number of cycles in Figure 8. Both shear stiffness and damping ratio decreased during cyclic loading, with total reductions of 40% and 20%, respectively, after 25 cycles. Shear stiffness degradation occurred nonlinearly, with a rapid decrease during the first few cycles, whereas damping ratio decreased approximately linearly during the entire test.

The only other relevant data for reinforced GCLs were published by Nye and Fox (2007), who conducted internal cyclic shear tests of a woven/nonwoven needle-punched GCL. Values of shear stiffness and damping ratio were obtained for a normal stress of 141 kPa, displacement amplitude of 20 mm and frequency of 1 Hz, and are also shown in Figure 8. The shear stiffness data of Nye and Fox (2007) are generally in close agreement with values from the current study. An important exception is the first data point, which represents internal shear failure for the GCL and indicates much higher stiffness. After the GCL specimen failed on the first cycle, shear stiffness values correspond to the hydrated unreinforced bentonite, and are significantly lower for subsequent cycles. Damping ratios from Nye and Fox (2007) display a wider range and an entirely different (increasing) trend than values from the current study. Although the Nye and Fox (2007) data correspond to internal GCL failure, and thus would not be expected to follow trends for the sand/GCL interface, the comparisons of Figure 8 are interesting, and indicate that there is much more to be learned regarding the dynamic shear behavior of these and other similar materials.

The results of pre-cyclic and post-cyclic tests of the GCL material are summarized in Table 1, and include bentonite mass/area, tensile strength, peel strength and hydraulic conductivity. The hydraulic conductivity tests were performed after the laminated geomembrane was removed from the specimens. The test results indicate no significant changes in material properties, and provide additional evidence that the GCL specimen did not sustain damage due to cyclic loading. Increases in GCL mass/area and peel strength for the post-cyclic specimens are probably due to material variability.

5. SUMMARY AND CONCLUSIONS

The design of a large petrochemical facility in China has involved the evaluation of various secondary containment liner options, including a liner system with a geomembrane-laminated needle-punch-reinforced woven/nonwoven GCL. Because of concerns over the ability of the GCL to withstand seismic loads, a cyclic shear test of a sand/GCL/sand liner system was performed using a large dynamic direct shear machine. Under a normal stress of 100 kPa, the liner system specimen was subjected to 25 cycles of displacement-controlled sinusoidal shearing with a displacement amplitude of 20 mm and a frequency of

Table 1. Summary of pre-cyclic and post-cyclic test results for GCL material.

Property	Pre-cyclic	Post-cyclic	Change
Bentonite mass/area	Mean = 3552 g/m^2 COV = 9.9%	Mean = 3759 g/m^2 COV = 3.4%	+5.8%
Tensile strength	Mean = 14.3 kN/m COV = 1.4%	Mean = 13.6 kN/m COV = 9.6%	−4.9%
Peel strength	Mean = 886 N/m COV = 15.5%	Mean = 937 N/m COV = 27.2%	+5.8%
Hydraulic conductivity (without geomembrane)	3.3×10^{-11} m/s	3.1×10^{-11} m/s	−6.1%

COV = coefficient of variation (standard deviation/mean).

1 Hz. Inspection of the failed specimen indicated that shearing occurred between the laminated geomembrane and the cover soil layer, and not through the GCL. Final inspection of the GCL indicated no tearing, necking, ruptured reinforcement or other visible damage. The interface friction angle was initially 28.6°, and decreased to a final value of 16.7° after 25 cycles. Hysteretic stress–displacement behavior of the failure surface was broadly similar to that observed for natural soils, and displayed strength and stiffness degradation as well as reduction in damping ratio with continued cycling. The results of pre-cyclic and post-cyclic tests of the GCL material indicated no significant changes in material properties, and provide additional evidence that the GCL specimen did not sustain damage due to cyclic loading.

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