Shear-Induced Geomembrane Damage due to Gravel in Underlying Compacted Clay

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ABSTRACT: Lining systems for landfills and heap leach pads are often constructed with compacted clay liners (CCLs) containing significant amounts of gravel. Geomembranes placed against gravelly CCLs are vulnerable to damage due tohighoverburden stress andinterface shear displacement. This invited paper reports results from the first experimental investigation of shear-induced damage to geomembranes placed in contact with gravelly compacted clay. A series of large-scale direct shear tests was conducted for the interface between smoothHDPE geomembranes and CCLs with 20 percent gravel. The tests were performed for normal stress levels ranging from 72 to 1658 kPa to simulate overburden stresses associated with bottom liner systems. Replicate interface shear tests were also performed for normal stresses up to 4145 kPa with a geosynthetic clay liner (GCL) placed in between the geomembrane and the CCL to evaluate protection provided by the GCL. Results indicate that shear displacement between a geomembrane and a gravelly CCL under high normal stress conditions can cause severe damage to the geomembrane. The testing program also found that placing a GCL between a geomembrane and a gravellyCCL can essentially eliminate such damage.

1. INTRODUCTION

Lining systems for waste containment and mining applications often include composite liners consisting of a geomembrane underlain by a low-permeability soil layer. The low-permeability layer can be either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL). CCLs are typically constructed using locally-available clay-rich soils within a specific range of water content and dry unit weight to achieve a low hydraulic conductivity of 10^{-9} m/sec or less. In the northern USA, many clay-rich soils are glacially-deposited and can contain significant amounts of gravel-size particles. Research conducted by Shakoor and Cook (1990) and Shelley and Daniel (1993) indicated that the hydraulic conductivity of soil/gravel mixtures can be unaffected for gravel contents as high as 50 to 60 percent; however, these tests were conducted onuniform soil mixtures prepared in the laboratory. Considering that construction techniques are much more variable and uniform mixing cannot be expected in the field, current industry practice is to limit the gravel content in CCLs to approximately 20 percent. Project specifications also typically require that any stones protruding from the CCL surface be removed or pushed down with a smooth drum roller prior to the deployment of a geomembrane.

As a result, geomembranes are often placed against compacted clay liners having considerable gravel content, which can leave the geomembranes vulnerable to damage. Gravel particles can cause puncture damage during construction operations, in particular during placement of overlying cover soil (Giroud and Touze-Foltz 2003), or with increasing overburden stress as waste or ore is placed on the liner. Geomembranes may also be vulnerable to damage during shear displacement due to, for example, construction loads, seismic forces, slope movement, or waste settlement (Fox et al. 2011). Although intact geomembranes are virtually impermeable, tears or puncture holes will provide open pathways for leakage into the environment below. While considerable research has been conducted to evaluate potential geomembrane damage due to construction operations (Darilek et al. 1995, Reddy et al. 1996, Nosko and Touze-Foltz 2000) and sustained normal stress after installation (Wilson-Fahmy et al. 1996, Narejo et al. 1996, Koerneret al. 1996, Tognon et al. 2000, Dickinson and Brachman 2008), no studies have investigated shear-induced damage to geomembranes placed in contact with CCLs containing gravel.

GCLs are factory-manufactured hydraulic barrierscontaining sodium bentonite clay with a maximum hydraulic conductivity of 5 × 10^{-11} m/sec. GCLs are used in place of, or together with, CCLs as the low-permeability soil component under the geomembrane in composite liner systems (Bonaparte et al.2002). It has alsobeen established that GCLs can serve as effective cushions to minimizepuncture damage in overlying geomembranes (Heerten 1994, Narejo et al. 2007, Allen and Narejo 2010). Additionally, since the rate of leakage through defects in a composite liner system decreases with decreasing hydraulic conductivity of the underlying soil layer and increasing intimate contact with the geomembrane, GCL-based composite liner systems are expected to allow less leakage than soil-based composite liner systems should a puncture occur (Narejo et al. 2002).

Assessment of geomembrane damage under interface shear conditions could be especially important for heap leach pad liners, where the combination of high normal stress, potentially steep slopes, gravelly subgrades, and gravelly overliner soils pose a real threat to geomembrane integrity (Athanassopoulos et al. 2009). However, despite this combination of challenges, cushioning materials are rarely used in leach pad applications due to cost and stability considerations (Thiel and Smith 2003).

This invited paper presents an experimental study of damage to geomembranes placed on gravelly CCLs and then subjected to static pressure and large displacement interface shear. Large-scale shear tests were conducted to assess potential geomembrane damage from gravel in the CCL, both with and without an underlying GCL. Results are presented for varying normal stress levels up to 4145 kPa and the findings are discussed with regard to geomembrane performance for each loading condition.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The experimental program was conducted using two common geosynthetic products. The geomembrane (GM) was GSE HD Textured, a single-sided HDPE textured product manufactured by GSE Lining Technology, LLC (Houston, Texas, USA). The GM specimens had a thickness of 1.5 mm (60 mils) and coextruded texturing on one side. The GCL was Bentomat DN, a nonwoven/nonwoven (NW/NW) needle-punched (NP) product with no thermal bonding manufactured by CETCO (Hoffman Estates, Illinois, USA). This GCL is composed of granular bentonite held between two NW NP polypropylene geotextiles (200 g/m^2). The bentonite has a nominal minimum dry mass/area of 3.7 kg/m^2. To provide reinforcement, polypropylene fibers from the cover geotextile are needle-punched through the bentonite and the carrier geotextile. The average peel strength of the GCL, as obtained from 5 specimens using the wide-width method (ASTM D6496), was 2231 N/m and the coefficient of variation (standard deviation/mean) of peel strength was 8.5%.

Soil for the CCL specimens was obtained from a landfill site near Santa Barbara, California. The soil was passed through a US No. 4 sieve (4.76 mm) and then mixed with gravel from a different source to produce the final particle size distribution shown in Figure 1. The gravel fraction consisted of subangular to angular crushed rock with a maximum size of 19 mm. The CCL soil had gravel content = 20%, sand content = 26%, fines content = 54%, liquid limit = 56, plastic limit = 29, and a Unified Soil Classification of CH, Sandy Fat Clay with Gravel.

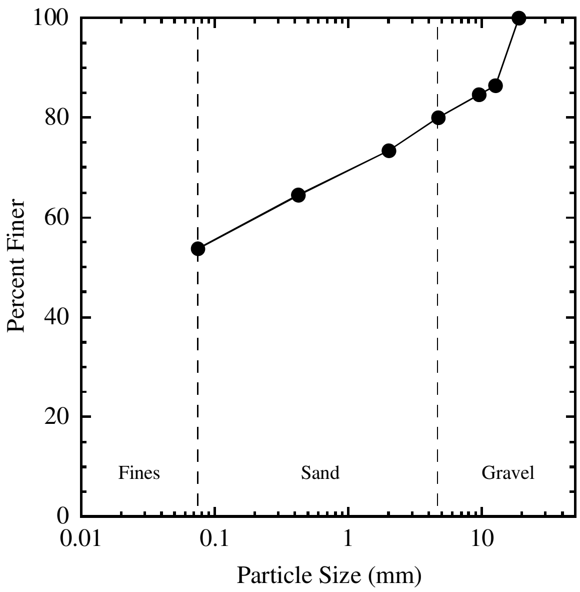

Figure 1 Particle size distribution for CCL material

2.2 Procedures

Static pressure and large-displacement shear tests were conducted on multi-interface specimens using the large dynamic direct shear machine described by Fox et al. (2006). The test chamber measures 305 × 1067 mm in plan and provides a shearing surface area of 0.325 m^2. Specimens were sheared between a rigid pullout plate and the floor of the test chamber, each of which was covered with an aggressive gripping surface. The pullout plate was connected to a 245 kN hydraulic actuator with a maximum stroke of 254 mm. The actuator was used to conduct static shear tests at constant displacement rate for the current study. For normal stress $\sigma_n \leq$ 1658 kPa, the shearing area for specimens was identical to the test chamber (305 × 1067 mm). For $\sigma_n \geq$ 2146 kPa, a new pullout plate was machined with a narrower shearing surface on the underside, which concentrated the applied force over a smaller area. Using this plate, the size of the test specimens was 152 × 1067 mm and normal stress levels as high as 4145 kPa could be achieved.

Two types of multi-interface specimens, GM/CCL and GM/GCL/CCL, were tested for the experimental program. From bottom to top, the GM/CCL specimens consisted of gravelly CCL, GM, and sand. The CCL subgrade was compacted in two lifts using a large hand tamper to a final thickness of approximately 75 mm. The target water content for compaction was 22%. New subgrade soil was used for each test. Figure 2 shows a typical view of the CCL subgradeimmediately after compaction in the test chamber. The gravel particles are lighter in color than the surrounding clay matrix and level with the clay surface (i.e., no protrusions). After compaction, the top of the CCL was sprayed with 100 mL of water to wet the shearing surface. The GM specimen was then placed on the CCL with the smooth side facing down to facilitate the observation of damage features (e.g., scratches, gouges, holes) and to ensure that failure occurred at the GM/CCL interface. Each GM specimen was cut longer than 1067 mm to allow additional material to enter the rear of the test chamber during shear and thus maintain constant shearing surface area. A layer of medium sand approximately 25 mm thick was placed on the GM and lightly tamped. The pullout plate was then placed on top of the sand and the normal stress was applied to the test specimen. No additional water was provided to the specimen after the application of normal stress. Preparation of specimens for the GM/GCL/CCL tests wasidentical to the GM/CCL tests with the exception that a hydrated GCL was placed between the CCL and the GM. GCLs were hydrated using the two-stage, controlled hydration procedure described by Fox et al. (1998) and Fox and Stark (2004) in which the hydration water content was varied according to the normal stress level and was equal to the final value expected after shearing (as obtained from previous tests).

A summary of the experimental program is provided in Table 1. Five GM/CCL tests were conducted for normal stress levels ranging from 72 to 1658 kPa. Six GM/GCL/CCL tests were conducted for normal stress levels ranging from 348 to 4145 kPa. Each test included a static pressure stage and a shearing stage. For the static pressure stage, the normal stress was released after 24 h, the precise position of the GM specimen on top of the CCL or GCL was marked, and the GM specimen was removed, photographed, and assessed for damage. For the shearing stage, the GM specimen was repositioned to its original location on top of the CCL and subjected to the same normal stress for an additional 24 h. The entire multi-interface specimen was then sheared to a final displacement of 150 mm at constant normal stress and a constant displacement rate of 1 mm/min. After shearing, the GM specimen was removed, photographed, and again assessed for damage. The CCL and GCL specimens were also photographed and inspected for damage after each testing stage.

Figure 2 Typical view of CCL after compaction in the test chamber

Table 1 Summary of Experimental Program

Normal Stress, σ_n (kPa)	GM/CCL	GM/GCL/CCL
72	1A	–
348	2A	2B
693	3A	3B
1176	4A	4B
1658	5A	5B
2146	–	6B
4145	–	7B

Damage assessment for the GM specimens was conducted by visual inspection, a bright light test, and direct measurement. Visual inspections and photographs focused on the number and condition of scratches, gouges, wrinkles, and holes in the GM specimens. For the bright light test, the GM specimen was held against a halogen lamp in a dark room. The number of holes was counted and the average dimension of each hole (i.e., average of long dimension and transverse dimension) was measured using a caliper. After the shearing stage was completed, the mode of failure was recorded for each specimen along with any indications of localized distress, such as tearing, necking or wrinkling of the GCLs.

3. RESULTS

Inspection of the geomembrane specimens following the initial 24-h static pressure stage showed relatively little damage. Minor to moderate dimpling was observed at some contacts with gravel particles for theGM/CCL tests, which generally increased with increasing normal stress. Substantially less geomembrane dimpling was observed for the GM/GCL/CCL tests than for the GM/CCL tests. No holes were observed following the static pressure stage for any of the tests conducted.

Shearing of the smooth geomembrane specimens yielded the peak and large displacement failure envelopesshown in Figure 3. In general, shear strength increased with increasing normal stress for both the GM/CCL and GM/GCL/CCL tests. Shear strength for the GM/CCL interface was substantiallyhigher and more irregular than for the GM/GCL interface. Higher GM/CCL strengths are attributed, in part, to the ability of the geomembrane to more closely conform to the rough gravelly CCL subgrade without a hydrated GCL in between. While greater contact between the gravel particles and geomembrane is beneficial in terms of shear strength, it can cause severe damage to the geomembrane as well. Figure 3 also indicates that post-peak strength reduction was larger for the GM/GCL interface than for the GM/CCL interface ateach normal stress level.

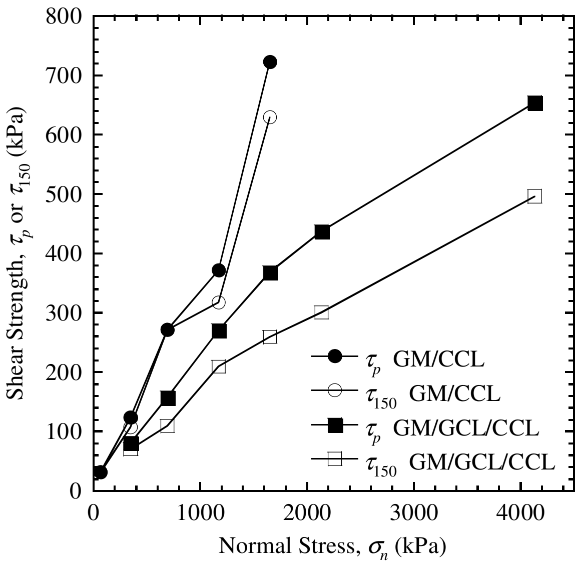

Figure 3 Peak and large displacement failure envelopes for GM/CCL and GM/GCL/CCL tests

At σ_n = 1658 kPa, Figure 3 shows a sharp increase in both peak and large displacement shear strengthsfor the GM/CCL interface, which gives the GM/CCL failure envelopes an irregular appearance. Such behavior is not typically observed (e.g., Triplett and Fox 2001) and occursin this case as the fine-grained CCLmatrix consolidates around each gravel particle. This consolidation causes the gravel to protrude more prominently above the surrounding clay surface and the geomembrane to conform more closely to these protrusions, which (1) increases the contact area between the gravel particles and geomembrane; (2) increases thefrictional resistance as the rougher gravel particles slide against the geomembrane; and (3) increases the shearing resistance due tomechanical interaction between the gravel and geomembrane.Other researchers have also reported interesting effects related to increased interface shear resistance due to local geomembrane deformation. Stark and Choi (2004) observed an increase in tangent friction angle for a smooth geomembrane/geonet interface under high normal stresses due to more extensive local deformations (i.e., dimpling) of the geomembrane. Similarly, Breitenbach and Swan (1999) reported significant increases in soil/geomembrane interface strengths with time due to local deformation of the geomembrane at the shear interface.

Post-shear visual inspections of the geomembrane specimens sheared directly against the gravelly CCL revealed minor to moderate damage (i.e., indentations, scratching) under low normal stress(σ_n ≤ 348 kPa) and severe damage (i.e., holes, gouges, tears) under higher normal stress (σ_n ≥693 kPa). Tests performed with a GCL in between the geomembrane and CCL resulted in far less damage to the geomembrane. Photographs comparing the post-shear condition of the geomembrane following the GM/CCL and GM/GCL/CCL tests at σ_n = 1658 kPa are shown in the Figure 5. The geomembrane from GM/CCL test 5A shows severe damage, with several deep scratches, gouges, and holes with anmaximum size of nearly 25 mm. The bottom photograph, from GM/GCL/CCL test 5B, shows no holes and only minor scratches and indentations on the geomembrane. The potential cushioning effect of the GCL was further evaluated by performing two additional GM/GCL/CCL tests at σ_n = 2146 and 4145 kPa. Figure 6 shows a photograph of geomembrane specimen 7Bat σ_n = 4145 kPa. Although some dimpling was noted, there were no holes in the geomembrane specimens for any of the GM/GCL/CCL tests, even for normal stresses as high as 4145 kPa.

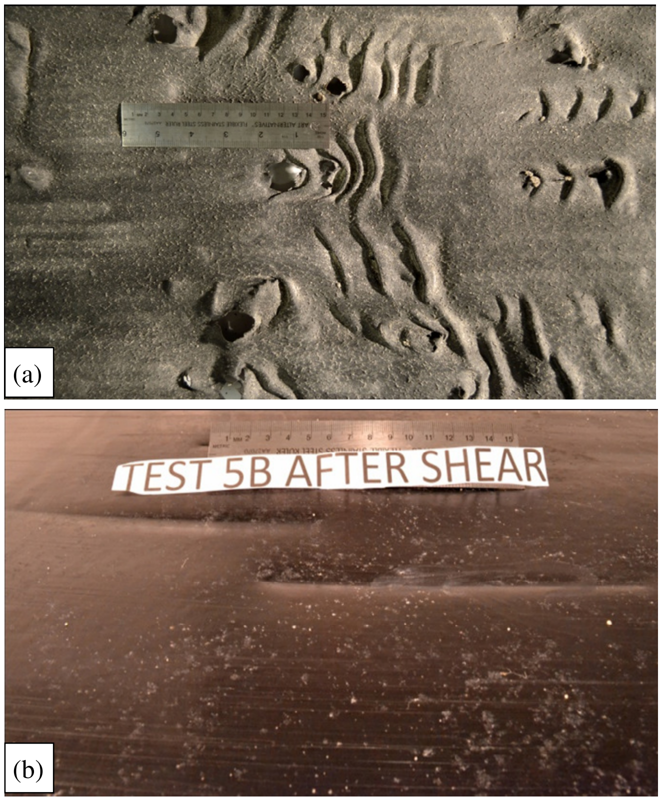

Figure 5 Photographs of geomembrane specimens 5A and 5B after shearing under σ_n = 1658 kPa for: (a) GM/CCL test, and GM/GCL/CCL test

Figure 7 presents the geomembrane damage measurements for the GM/CCL tests. The number of holes increased with increasing normal stress from zero holes measured at σ_n = 72 kPa and 348 kPa to 55 holes measured at σ_n = 1658 kPa. The maximum hole size also increased with normal stress up to 23.4 mm at σ_n = 1658 kPa.

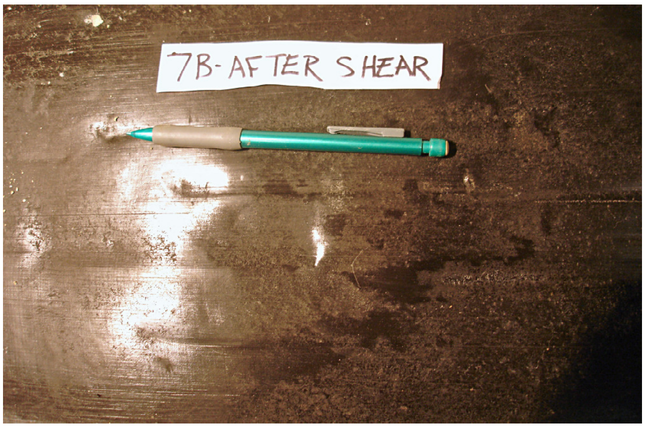

Figure 6 Photograph of geomembrane specimen7B after shearing under σ_n = 4145 kPa for GM/GCL/CCL test

For these tests, the transition from moderate to severe damage occurred data approximately 1176 kPa, which also corresponds to the sharp increase in measured shear strength shown in Figure 3 for the GM/CCL failure envelope. The trends in Figure 7 and Figure 3 support the conclusion that the irregular shape of the GM/CCL failure envelopes at high loads is due to increased shearing resistance as the gravel particles penetrate and interlock with the geomembrane.

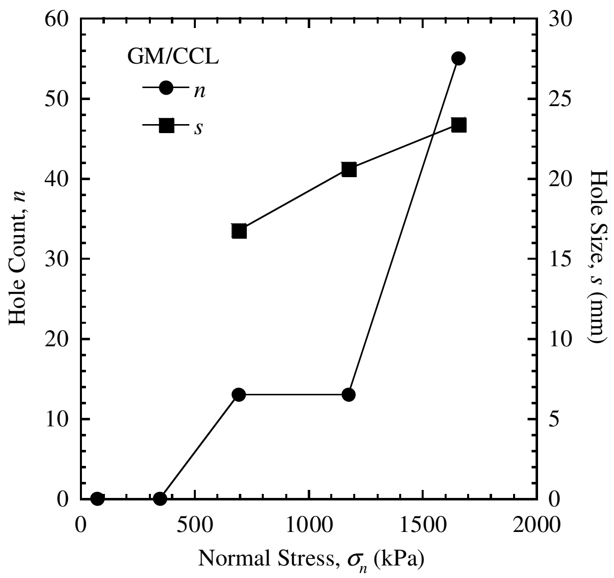

Figure 7 Geomembrane damage results for GM/CCL shear tests

4. CONCLUSION

Liner systems for waste containment and mining applications often consist of a geomembrane underlain bya low-permeability soil layer such as a geosynthetic clay liner (GCL) or a compacted clay liner (CCL). CCLs sometimes contain significant gravel content, which can pose a damage risk to an overlying geomembrane. A series of large-scale direct shear tests was conducted on smooth HDPE geomembranes in contact with compacted clay containing 20 percent gravel. Results of GM/CCL shear tests indicate that shear-induced damage to the geomembrane was minorat low normal stress ($\sigma_n \leq$348 kPa). However, the geomembrane experienced severe damage when shear occurred under higher normal stress ($\sigma_n \geq$693 kPa), with one geomembrane specimendeveloping more than 50 holes and a maximum hole size of nearly 25 mm. These results indicate that damage due to shear displacement over a coarse subgrade can be far greater than damage from static pressure alone. Results of corresponding GM/GCL/CCL shear tests found that a GCL placed in between the geomembrane and gravelly CCL can essentially eliminate such damage, even for normal stresses as high as 4145 kPa.

The GCL component of a GM/GCL/CCL composite liner may also possibly experience damage if interface shear displacements were to occur. Although not observed in the current testing program, such GCL damage could impact hydraulic performance of the composite. However, if the GCL is able to prevent puncture of the geomembrane, as has been demonstrated herein, the hydraulic performance of the overall composite liner system, consisting of an intact geomembraneover a damaged GCL, wouldlikely be superior to that of a punctured geomembraneover a CCL.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Allen, S., and Narejo, D. (2010) "Point strains in HDPE geomembranes with and without GCL protection layers," *Proceedings, 3rdInternational Symposium on Geosynthetic Clay Liners*, Würzburg, Germany. (CD-ROM)

ASTM D 6496*Standard test method for determining average bonding peel strength between the top and bottom layers of needle-punched geosynthetic clay liners*, ASTM International, West Conshohocken, PA.

Athanassopoulos, C., Kohlman, A., Henderson, M., and Kaul, J. (2009)"Evaluation of geomembrane puncture potential and hydraulic performance in mining applications," *Proceedings, Tailings and Mine Waste '0*8, Taylor & Francis Group, London, pp189-198.

Bonaparte, R., Daniel, D., and Koerner, R. (2002)*Assessment and Recommendations for Improving the Performance of Waste Containment Systems*.CR-821448-01-0, Environmental Protection Agency, Washington, DC, p1039.

Breitenbach, A.J., and Swan, R.H., Jr. (1999)"Influence of high load deformations on geomembrane liner interface strengths," *Proceedings, Geosynthetics '99*, Boston, MA, 1, pp517-529.

Darilek, G., Menzel, R., and Johnson, A. (1995) "Minimizing geomembrane liner damage while emplacing protective soil," *Proceedings, Geosynthetics '95*, Nashville, TN, 2, pp669-676.

Dickinson, S., and Brachman, R. W. I. (2008) "Assessment of alternative protection layers for a geomembrane–geosynthetic clay liner (GM–GCL) composite liner," *Canadian Geotechnical Journal*, 45 (11), pp1594-1610.

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), pp933-944.

Fox, P. J., and Stark, T. D. (2004)"State-of-the-art report: GCL shear strength and its measurement," *Geosynthetics International*, 11 (3), pp117-151.

Fox, P. J., Nye, C. J., Morrison, T. C., Hunter, J. G., and Olsta, J. T. (2006)"Large dynamic direct shear machine for geosynthetic clay liners," *Geotechnical Testing Journal*, 29(5), pp392-400.

Fox, P.J., Ross, J.D., Sura, J. M., and Thiel, R. S. (2011) "Geomembrane damage due to static and cyclic shearing over compacted gravelly sand," *Geosynthetics International*, 18(5), pp272-279.

Giroud, J. P., and Touze-Foltz, N.(2003) "Geomembranes in landfills: discussion at the 7th International Conference on Geosynthetics," *Geosynthetics International*, 10(4), pp124-133.

Heerten, G. (1994)"Geotextile and/or GCL protection systems for geomembranes," *Geosynthetic Liner Systems: Innovations, Concerns and Designs*, Koerner, R. M., and Wilson-Fahmy, R. F., eds., IFAI, pp150-162.

Koerner, R. M., Wilson-Fahmy, R. F., and Narejo, D. (1996) "Puncture protection of geomembranes. Part III: Examples," *Geosynthetics International*, 3(5), pp655-675.

Narejo, D., Koerner, R. M., and Wilson-Fahmy, R. F. (1996) "Puncture protection of geomembranes, Part II: Experimental," *Geosynthetics International*, 3(5), pp605-627.

Narejo, D., Corcoran, G., and Zunker, R. (2002)"An evaluation of geosynthetic clay liners to minimize geomembrane leakage caused by protrusions in subgrades and compacted clay liners," *Clay Geosynthetic Barriers*, Zanzinger, H.,Koerner, R. M., and Gartung, E., eds.,Balkema, Rotterdam, pp61-69.

Narejo, D., Kavazanjian, E., and Erickson, R. (2007)"Maximum protrusion size under geomembrane/GCL composite liners," *Proceedings, Geosynthetics '07*, Washington, D.C. (CD-ROM)

Nosko, V., and Touze-Foltz, N. (2000) "Geomembrane liner failure: modeling of its influence on contaminant transfer," *Proceedings, Second European Conference on Geosynthetics*, Bologna, Italy, pp557-560

Reddy, K. R., Bandi, S. R., Rohr, J. J., Finy, M., and Siebken, J. (1996) "Field evaluation of protective covers for landfill geomembrane liners under construction loading," *Geosynthetics International*, 3(6), pp679-700.

Shakoor, A., and Cook, B.D. (1990) "The effect of stone content, size, and shape on the engineering properties of a compacted silty clay," *Bulletin of the Association of Engineering Geologists*, XXVII(2), pp245-253.

Shelley, T.L., and Daniel, D. E. (1993)"Effect of gravel on hydraulic conductivity of compacted soil liners," *Journal of Geotechnical Engineering*, 119(1), pp54-68.

Stark, T.D., and Choi, H. (2004) "Peak versus residual interface strengths for landfill liner and cover design," *Geosynthetics International*, 11(6), pp491-498.

Thiel, R., and Smith, M.E. (2003) "State of the practice review of heap leach pad design issues," *Proceedings, 17th GRI Conference, Hot Topics in Geosynthetics-IV*, Geosynthetics Institute, Folsom,PA, p17.

Tognon, A. R., Rowe, R.K., and Moore, I. D. (2000) "Geomembrane strain observed in large-scale testing of protection layers," *Journal of Geotechnical and Geoenvironmental Engineering*, 126(12), pp1194-1208.

Triplett, E. J., and Fox, P. J. (2001) "Shear strength of HDPE geomembrane/geosynthetic clay liner interfaces," *Journal of Geotechnical and Geoenvironmental Engineering*, 127(6), pp543-552.

Wilson-Fahmy, R. F., Narejo, D., and Koerner, R. M. (1996) "Puncture protection of geomembranes.Part I: Theory," *Geosynthetics International*, 3(5), pp605-628.