The Role of Geomembrane Surface Roughness on Interface Behavior

Second Year Progress Report: Project CMS-9700186

OVERVIEW

The overall objective of this research program is to develop an improved understanding of the role of geomembrane surface roughness on interface behavior. Through a comprehensive experimental program using both the recently developed Optical Profile Microscopy technique as well as more traditional stylus profilometry methods to provide quantitative measures of geomembrane surface roughness, it is expected to provide a more rational basis for selecting design parameters and predicting the long-term behavior of composite systems with geomembrane interfaces.

There is now considerable interest within the geotechnical community to use surface roughness measurements when assessing interface strength characteristics as well as for manufacturing quality control and construction quality assurance. A number of researchers have qualitatively shown that the interface strength between soils and geosynthetics, as well as between layers of geosynthetic materials is a function of surface roughness however lack of a viable method to quantify the roughness has resulted in the use of qualitative descriptors for membranes such as "smooth" or "heavily textured" to reflect the different expected behaviors. Accordingly, the introduction of a quantitative measure of roughness to replace these qualitative descriptors can lead to significant advances not only in the fundamental understanding of the behavior of geomembrane interfaces but also in practice in the manufacture, design and construction of systems which include geomembranes.

The research program has been designed to study, in a global sense, the relationship between geomembrane roughness and interface strength for soil - geomembrane and geotextile - geomembrane interfaces and from a more localized perspective, how geomembrane roughness impacts local behavioral phenomena. The tasks include comparison of roughness measurements made using Optical Profile Microscopy with the results of interface strength tests performed in a custom interface shear apparatus which has been fabricated as part of the study. Other tests are focussing on measuring local conditions at geomembrane interfaces as a range of boundary conditions are simulated. For example, measurements of the distribution of local void ratio in the interface region using a recently developed resin impregnation - image analysis procedure have been used to provide insight into fabric and porosity evolution during shearing.

The experimental studies are being complemented with analytical studies. The quantitative measures of geomembrane surface roughness and local void ratio distribution in the interface region will permit the interface strength behavior to be examined within the context of state. Within this unifying framework of understanding, it is expected that small changes in initial state as well as changes in state as shearing progresses can be related to the physical characteristics of the geomembrane surface. Numerical simulations will be performed to study a range of interface conditions and explore optimal roughness designs for mobilizing interface shear.

PERSONNEL

A number of students have participated to varying degrees in the research work over the past year. These include a Ph.D. candidate, Mr. Seok-Won Lee, who graduated in December, 1998. The abstract and table of contents of his dissertation are included in this report (Attachment #1). A number of papers summarizing his work are currently in preparation for submission to journals. An M.S. student, Ms. Tamara Zettler is continuing to work on the project. The focus of her work has been how surface roughness changes under operational conditions. Ms. Zettler is expected to graduate in August, 1999. Another doctoral student is scheduled to begin working on the project this Fall and will focus on the computational aspects of the study. An undergraduate research assistant, Ms. Sentho Kagbo has also been participating on the project. The focus of her work has been a comparison of the roughness values obtained with the optical profile microscopy and stylus profilometer methods. Ms. Kagbo will continue to participate in the project for the next year with support from a recently awarded REU supplement to the project. All research assistants routinely participate in weekly meetings and thus have the opportunity to truly see the value of an interactive research environment and not just focus on their own component of the research.

ACCOMPLISHMENTS

Research efforts during the second year of this project have focussed on several experimental components of the program and have yielded significant new insight into interface mechanisms. These studies have included:

- Interface shear tests have been performed to different displacement levels for a range of sand – geomembrane interfaces. When the tests are stopped at a predetermined displacement, the specimen structure is fixed by impregnating it with an epoxy resin. Sections cut from these specimens are then placed on the stage of an optical microscope and images captured using a CCD camera are analyzed using a digital image analysis system to quantify structure evolution characteristics. Using the results of the geomembrane roughness, the sand – geomembrane interface strength tests and the imaging based structure quantification studies, studies of how the structure of the soil adjacent to the interface varies have been conducted. A paper on this topic is to be presented at the Geosynthetics ' 99 conference to be held in Boston from April 28 to 30, 1999 (Attachment #2). Factors varied during these tests include geomembrane roughness, particle angularity and normal load.
- A series of experimental measurements are being conducted to investigate how surface roughness changes under operational conditions such as during shearing where scarring of the surface may be caused by plowing of the sand particles into the geomembrane. A draft paper describing aspects of this work is included with this report (Attachment #3). Other factors being investigated include operational strain induced changes in surface roughness. To facilitate the study of these factors, a number of significant changes have been made to the large diaplacement shear apparatus being used. These changes will permit tests to be performed over a larger range of strain rates and under higher normal loads.
- The various experimental phases in this project as well as work being conducted by others have relied on a variety of different techniques to measure the surface roughness. While the measurements made with any particular device are internally consistent, there can be differences from device to device. Measurements being conducted a part of this study are

being used to investigate the role of scale on this variability. An interim summary report of the activities in this area is included in this report (Attachment #4).

SCHEDULED ACTIVITIES

Activities planned for the next year of the project will follow those outlined in the original proposal. A significant level of effort will be devoted during this final phase to perform the computational phase of the project wherein computer simulations of the interface interactions will be conducted and evaluated. Other experimental tasks will investigate how the surface roughness changes as a function of strain in the geomembrane. Recognizing that textured geomembranes can be subjected to significant operational strains, it is possible that the surface roughness will change and thus the interface strength could also be expected to change. Based on the results from the various tasks performed throughout the duration of the project, a unified framework of understanding of the role of geomembrane surface roughness on interface behavior will be identified.

ATTACHMENT #1

Influence of Surface Topography on Interface Strength

and Counterface Soil Structure

A Thesis
Presented to
The Academic Faculty

by

Seok-Won Lee

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in Civil and Environmental Engineering

Georgia Institute of Technology
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EXECUTIVE SUMMARY

Title: Influence of Surface Topography on Interface Strength and Counterface Soil Structure

Numerous man-made construction materials such as geomembranes, geotextiles, and geogrids, are being routinely used in conjunction with soils and rocks in geotechnical engineering applications. For economic and technical reasons, the demand for these composite soil-synthetic material systems is continuously increasing. The placement of these materials adjacent to one another creates interfaces which can have relatively weak shear strengths compared to the shear strength of the soil and thus slippage or relative movement may occur. Accordingly, design involving such materials is often controlled by the shear strength of the interface.

This thesis presents the results of investigations into the behavior of geomembranes in contact with geotextiles as well as granular soils to study the shear mechanisms as a function of geomembrane surface roughness. Accordingly, the goals of this research were to: (1) enhance an existing method to characterize the topography of geomaterial interfaces; (2) study the interface shear behavior between geomembranes and geotextiles; (3) study the interface shear mechanisms between granular materials and geomembranes; and (4) provide recommendations for design in the context of the materials used in this study. This study involved characterizing the surface roughness of geomembranes using the Optical Profile Microscopy (OPM) method. The shear behaviors between both granular soils and geomembranes as well as geotextiles and geomembranes were examined by conducting tests with geomembranes of varying roughness in a large displacement interface shear device.

It was found that surface roughness had a first-order effect on the shear behavior of geomembrane/geotextile interfaces. It was considered that the sliding of the geotextile was the main mechanism for the smooth geomembrane surfaces, however pulling out and tearing of the filaments from the geotextile and the removal of texture at asperities from the geomembranes were key mechanisms for textured geomembrane surfaces.

It was also found that the shear mechanism for granular soil/geomembrane interfaces was dramatically changed by the geomembrane surface roughness. Quantitative analysis of the evolution of the sand structure was performed using image analysis. For the smooth geomembranes, the shear strength was developed by sliding and plowing of sand particles, while for the textured geomembranes, the strength resulted from the interlocking and dilation of sand particles. The angularity of sand particles induced higher plowing effects on the smooth geomembrane resulting in higher residual friction angles than rounded to subrounded sand.

ATTACHMENT #2

THE EVOLUTION OF SAND STRUCTURE ADJACENT TO GEOMEMBRANES

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ABSTRACT

This paper summarizes the results of a study which has quantified the evolution of the structure of sands adjacent to geomembranes of varying roughness at different stages of shearing. The results show that the structure evolution and hence shear mechanisms for sub-rounded uniform sands adjacent to geomembranes are directly influenced by the surface roughness of the geomembranes. For smooth geomembranes, the shear mechanism predominantly involves sliding of sand particles and only affects the sand structure within two particle diameters of the geomembrane. For slightly textured geomembranes, the effects of interlocking and dilation of sand particles extends the zone of evolution to four particles diameters from the interface. For the moderately/heavily textured geomembranes, the interlocking and dilation of sand particles is fully developed and results in large dilation in the interfacial zone which extends up to six particle diameters from the interface. The results of this study can be used to provide a framework that can lead to a significantly improved basis for identifying alternative geomembrane roughening procedures and patterns and interface strengthening techniques.

INTRODUCTION

Geomembranes are commonly designed to be in contact with soils or other geosynthetics. A textured geomembrane with roughened top and/or bottom surfaces is used to increase the shear resistance mobilized with soils or other geosynthetics as compared to the shear resistance mobilized with interfaces involving smooth geomembranes. However, selection of a particular type of geomembrane is presently made on the basis of experience or/and through a design stage testing program of candidate materials.

Quantitative measurements of surface roughness have shown it to be a controlling parameter in the measured strength of interfaces (Kishida and Uesugi, 1987; Paikowsky et al., 1995; Dove and Frost, 1996; Dove et al., 1997; Lee et al., 1998). The load deformation response has been shown to be a function of the fundamental properties of both of the materials at the interface (sand particle size, distribution, shape, and angularity and planar surface hardness and roughness) and the state of the sand at the interface (density, and normal stress). This paper presents the results of a study which complements the findings of these earlier investigations by providing quantitative evidence of the evolution of the structure of sands of varying angularity adjacent to geomembranes with different surface topography.

EXPERIMENTAL PROGRAM

A series of direct shear interface tests were performed, in which the structure of specimens sheared to different stages along a predefined stress - horizontal displacement curve were preserved using epoxy impregnation. Coupons sectioned from the specimens were ground and polished so that facets of the soil structure could be accurately quantified from digital images captured using brightfield microscopy methods.

Soil Properties

The majority of the tests reported in this paper were conducted using Ottawa 20/30 sand. A few additional tests were performed using a commercial blasting sand produced by Rollo Silica of Georgia to study the effects of angularity. The Ottawa 20/30 sand particles were rounded to subrounded whereas the blasting sand particles were composed of angular crushed quartz particles. Table 1 summarizes the index properties of both materials.

Table 1. Soil Index Properties

Soil	D_{50} (mm)	C_u	C_c	G_s	e_{max} (mm)	e_{min} (mm)
Ottawa 20/30	0.72	1.19	0.98	2.65	0.742	0.502
Blasting sand	0.74	1.83	0.84	2.65	0.951	0.698

The sand particle shapes were also measured using image analysis. For the analysis, images of complete cross sections of sand particles were captured by placing the sand particles on a transparent flat surface on a microscope specimen stage. Table 2 presents the sand particle shapes measured using image analysis where the Roundness and Aspect Ratio are defined as:

$$\text{Roundness} = (\text{Perimeter}^2) / (4*\pi * \text{Area}) \tag{1}$$

$$\text{Aspect Ratio} = (\text{Length}) / (\text{Width}) \tag{2}$$

Table 2. Soil Particle Shape Parameters

Soil	Average Length (mm)	Average Width (mm)	Average Roundness	Average Aspect Ratio
Ottawa 20/30	1.06	0.83	1.08	1.28
Blasting Sand	1.17	0.81	1.24	1.47

Geomembrane Characteristics

One smooth and two textured HDPE geomembranes, considered to be representative of the range of textures currently used in practice, were utilized in this study. The samples included National Seal Co. Dura Seal HD, which is a smooth surfaced geomembrane, GSE Lining Technology, Inc. Friction Flex which has a slightly textured surface, and Poly-Flex Inc. Textured HDPE, which has a moderately/heavily textured surface.

The average and standard deviation of surface roughness values (R_S) determined using the Optical Profile Microscopy (OPM) method (Dove and Frost, 1996) for these geomembranes are summarized in Table 3. The last column of Table 3 gives the corresponding texture descriptor proposed by Dove and Frost (1996) and is based on the average value of R_S.

Table 3. Results of Surface Roughness Determinations

Geomembrane	Average R_S	Standard Deviation	Texture Descriptor
NSC Dura Seal	1.09	0.01	Smooth
GSE Friction Flex	1.25	0.03	Slightly Textured
Poly-Flex Textured	1.68	0.12	Moderately/Heavily Textured

Interface Shear Test Equipment

Interface shear tests were performed using a large displacement direct shear device (Figure 1). This device was used to permit large displacements and hence quasi-residual conditions to be achieved in the tests. The shear tests were conducted at a constant displacement rate of 0.01 inch per minute or less. Normal stresses of 100 and 300 kPa were applied.

The geomembrane specimens, measuring approximately 220 mm (8.7 inches) wide by 300 mm (11.8 inches) long, were placed on the testing platform of the interface shear apparatus, with the machine direction of the geomembrane parallel to the shear direction (Figure 1). The geomembrane was secured by fastening 25 mm (1 inch) wide metal brackets along the rear and two side edges of the specimen. The shear box was constructed out of a 102 mm (4 inch) square block of teflon. The diameter of the soil specimen was 63.5 mm (2.5 inches) and the nominal height of the soil specimen was 38.1 mm (1.5 inches). Normal load was applied using dead weights attached to an aluminum yoke. A LabView data acquisition system connected to the load cell, the horizontal displacement transducer and the two vertical displacement transducers recorded global test variables.

Air pluviation was used in this study to create uniform sand specimens. Using a pre-selected combination of discs (different number of holes and hole diameters) and fall height, the target relative density was consistently obtained.

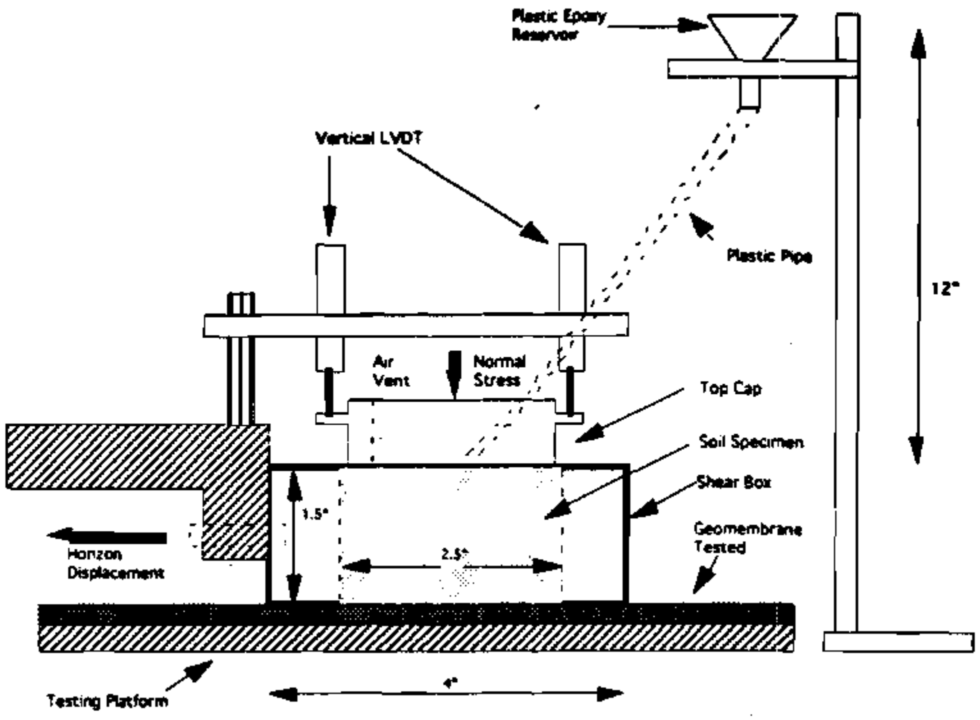

Figure 1. Schematic of Soil/Geomembrane Interface Shear Test System

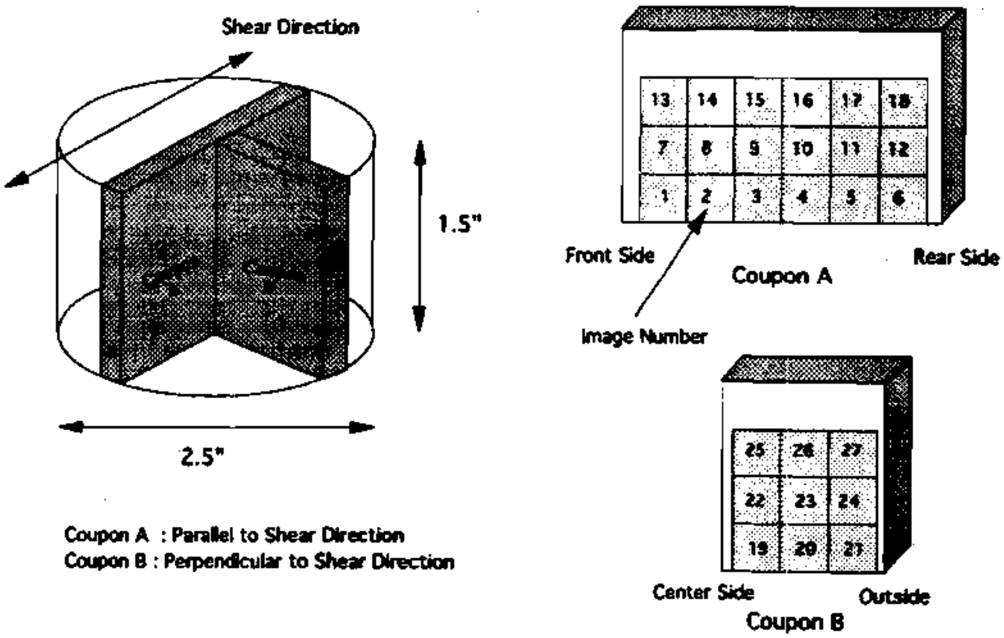

Figure 2. Typical Locations of Coupons and Images

Soil Specimen Preservation and Coupon Surface Preparation

After the sand specimens were sheared to their target displacement and stress states, they were impregnated with EPO-TEK 301 epoxy resin (Figure 1). Only elevation head was applied during impregnation of the sand specimen. Once the resin impregnated specimens had cured and were removed from the teflon shear box, coupons were cut using the pattern indicated in Figure 2. Coupon A was cut parallel to the shear direction, and coupon B was cut perpendicular to the shear direction. High image contrast between the sand particles and the epoxy matrix was achieved using a sequence of surface preparation steps referred to as the modified BUEHLER DIALOG method (Jang et al., 1998). For each specimen, 18 images, approximately 9.2 mm by 8.6 mm, were captured from coupon A and 9 images were captured from coupon B using a CCD camera mounted on a microscope (Figure 2). Each image included somewhere in the range of 110 sand particles.

INTERFACE STRENGTH TEST RESULTS

The interface shear test results performed as part of this study confirm the previously reported important effect that surface roughness has on the shear behavior of sand/geomembrane interfaces (e.g. Dove et al., 1997). For example, the results presented in Figure 3 for tests performed with various sand/geomembrane combinations under a normal stress of 300 kPa show that as the roughness increases, the peak and residual interface friction increases significantly with changes in roughness up to an R_s value of about 1.35. At higher roughness values, the interface friction remains approximately constant and equal to the soil friction angle reflecting the fact that failure is now occurring in the soil near the geomembrane.

The results also show the importance of particle angularity on the interface strength for sand-smooth geomembrane interfaces. While the peak friction angles mobilized with the blasting sand are very similar to those for Ottawa 20/30 sand in contact with the smooth geomembranes, the residual friction angles for blasting sand are significantly higher (3^0) than those for Ottawa 20/30. This is due to differences in the plowing effects resulting from the displacement of a harder material (sand) relative to a softer material (geomembrane) such that the harder material scratches and removes the soft material in its path. The angular soil particles indent the softer geomembrane more deeply making more scratches as described below. It is noted that the plowing effect is less significant for the textured geomembranes where other shear mechanisms dominate the shear strength as opposed to interfaces involving smooth geomembranes where sliding is the main shear mechanism.

This plowing effect on the smooth geomembranes is evident from the variations in surface roughness measured at various stages of shearing as shown in Figure 4. The interface shear tests were terminated at horizontal displacements of about 0.1, 10, 40 and 80 mm and the surface roughness perpendicular to the shear direction was measured using a stylus profilometer.

The roughness parameter, Ra, shown in Figure 4 is an arithmetic mean of the departures of the profile from the mean line. At peak, the roughness values for Ottawa 20/30 and blasting sand are similar although the Ottawa 20/30 shows marginally larger values. This is due to the difference of angularity of sand particles. Even though angular particles indent more deeply, rounded to subrounded Ottawa 20/30 initially indents a larger area than angular blasting sand. At residual state, the blasting sand produces much more scratches as reflected in the significantly higher roughness value. It is inferred that blasting sand starts to make the scratches on the geomembrane at the peak stress, and then continuously makes deeper scratches. This plowing effect also increases as the normal stress is increased.

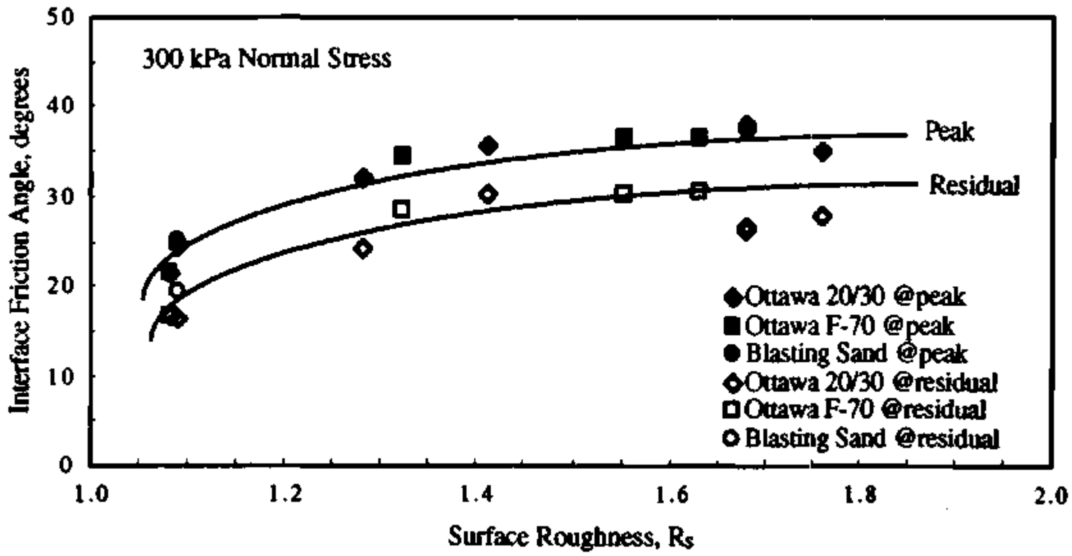

Figure 3. Peak and Residual Interface Friction Angles with Roughness

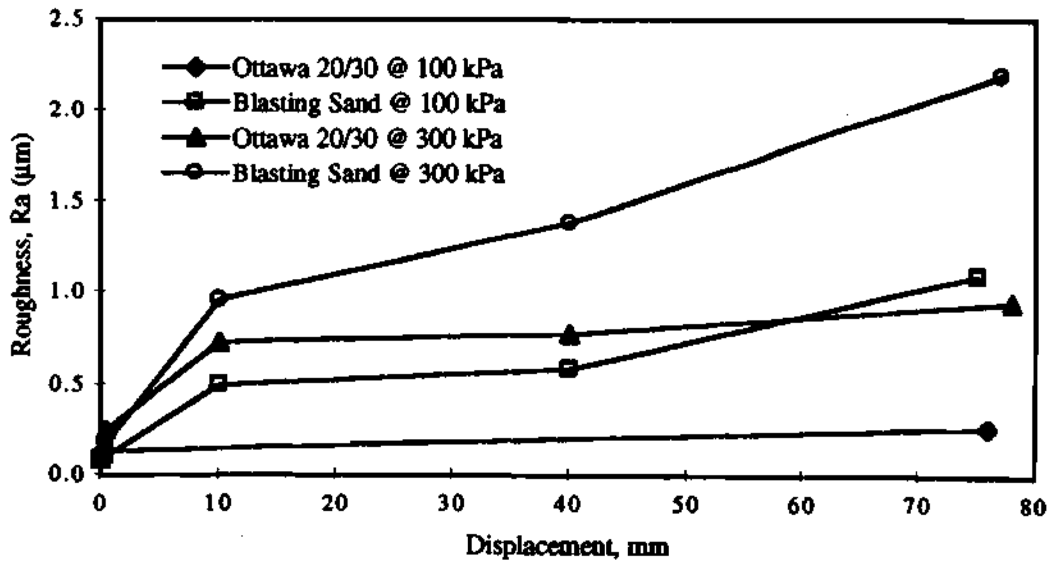

Figure 4. Increase in Surface Roughness Due to Plowing

EFFECT OF GEOMEMBRANE SURFACE ROUGHNESS ON THE EVOLUTION OF SAND STRUCTURE

To evaluate the effect of geomembrane surface roughness on the evolution of sand structure during shearing, an initial set of tests using geomembranes of various textures and Ottawa 20/30 sand were conducted. Specimens at different stages of shearing along the predefined stress-displacement curve were preserved using epoxy impregnation. The mean of the local void ratio distribution (Oda, 1976), and the void ratio as a function of distance from the interface were quantified using image analysis.

Smooth Geomembrane

To study the shear behavior of smooth geomembrane/Ottawa 20/30 sand interfaces, six specimens under normal stresses of 100 kPa were sheared along the same predefined stress-displacement curve. The shearing of these specimens was terminated at the stress and displacement states shown in Table 4 before the specimens were preserved by epoxy impregnation. Figure 5 presents the evolution of the mean of the local void ratio distributions for the complete specimen as well as for each layer. Figure 6 shows the evolution of the void ratio as a function of distance from the interface.

In the initial pre-shearing state, the air pluviation resulted in the bottom layer (lower 9 mm) being slightly denser than the middle and top layers, however in the immediate interfacial zone (within two particle diameters from the interface), the void ratio was slightly higher as would be expected at the interface between any particulate material and any planar surface. At pre-peak displacements, the void ratio in the interfacial zone remained relatively constant indicating no relative movement between particles. At peak stress displacements, sand particles in the interfacial zone start to move relative to each other. Even though the void ratio in the bottom layer is seen to increase at peak stress (resulting in a relatively higher void ratio compared to the middle and top layers), the sand structure collapses in the interfacial zone as sand particles fill the voids by sliding, and consequently, the void ratio in this zone decreases slightly to the average void ratio. As the shearing continues, the contraction started in the interfacial zone expands throughout the bottom layer. This trend continues throughout the whole shearing test. It should be noted that the void ratio changes described on the smooth geomembranes are relatively small compared to those measured with the textured geomembranes as discussed later.

From the above observations, the following mechanism is postulated. Shearing affects predominantly a zone two particle diameters from the interface, and no significant dilation or contraction is observed throughout the shear test on the smooth geomembrane. This means that the peak stress is induced by the initial sliding of the soil particles in the interfacial zone. Beyond the peak displacement, the shearing is mobilized by the sliding of soils and by the very slight plowing of particles into the geomembrane which produces the scratches on the

Table 4. Evolution of Specimens' Properties

Specimen	SMOT22	SMOT31	SMOT41	SMOT51	SMOT61	SMOT71
Initial Void Ratio, e_i	0.550	0.551	0.551	0.550	0.549	0.552
Final Void Ratio, e_f	0.544	0.546	0.548	0.545	0.543	0.552
Shear Stress, kPa	0.0	36.5	45.3	37	30.3	26.4
Displacement, mm	0.0	0.1	0.15	1.14	10.06	76

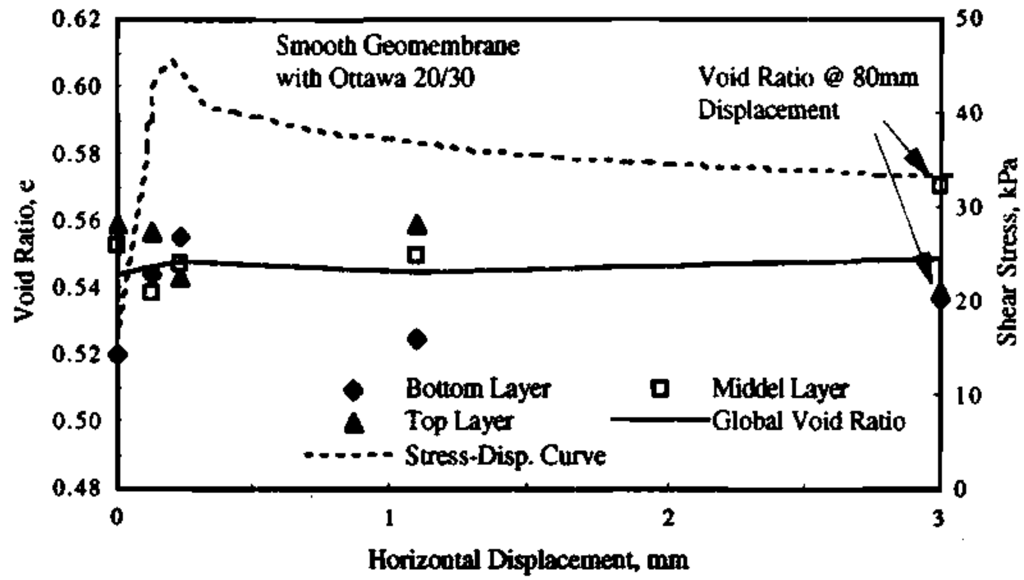

Figure 5. Evolution of the Mean of Local Void Ratio Distributions

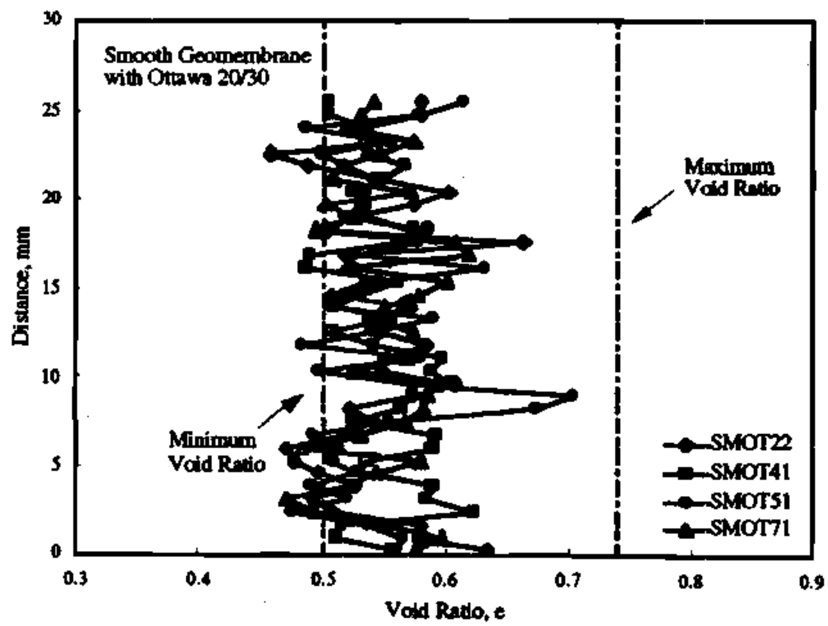

Figure 6. Evolution of Void Ratio as Function of Distance from Interface

surface. After the start of the residual state, the soil structure remains unchanged throughout the whole shear test.

Slightly Textured Geomembrane

GSE Friction Flex geomembrane was used to study the interaction between slightly textured geomembranes and Ottawa 20/30. Three specimens under normal stresses of 100 kPa were sheared along the same predefined stress-displacement curve (Table 5). Figure 7 shows the evolution of the mean of the local void ratio distributions for the complete specimen as well as for each layer while Figure 8 shows the evolution of the void ratio as a function of distance from the interface.

In the initial state, the same trend of a slightly denser bottom layer, but with a slightly looser interfacial zone within two particle diameters from the interface was observed. At peak stress, the soil particles started to move relative to each other in the interfacial zone. Unlike the smooth geomembrane tests where the sliding induced a decrease in void ratio in the interfacial zone, the void ratio in the interfacial zone increased slightly. This means that at peak stress, while some sliding of the soil particles on the geomembrane may occur, interlocking between the roughened surface of the geomembrane and the sand particles induces a higher void ratio in the interfacial zone. The shear zone is contained within a distance of about two particle diameters from the interface at the peak stress. As the shearing continues beyond peak displacement, the movement of the soil particles increase the porosity and extent of the interfacial zone, with dilation being observed at a distance of up to four particle diameters from the interface. The shearing zone remains about four particles wide even at large displacements.

Since the void ratio in the interfacial zone increases in the post-peak region, it is inferred that interlocking between the sand and the geomembrane is the principal shearing mechanism although some sliding of sand particles on the geomembrane surface may also be occurring. Moreover, at the start of the residual state, the effect of interlocking between the geomembrane and the sand and more importantly, particle dilation expands the shear zone and induces a higher void ratio in a zone equal to four particle diameters from the interface.

Moderately/Heavily Textured Geomembrane

Poly-Flex Textured geomembrane was used in a similar set of tests to represent the shearing between a moderately/heavily textured geomembrane and Ottawa 20/30. Six specimens under normal stresses of 100 kPa were sheared along the same predefined stress-displacement curve (Table 6). Figure 9 presents the evolution of the mean of the local void ratio distributions for the complete specimen as well as for each layer. Figure 10 shows the evolution of the void ratio as a function of distance from the interface.

In the initial state, the void ratio distribution shows the same trend as with the other geomembranes. Below peak displacements, some

Table 5. Evolution of Specimens' Properties

Specimen	GDOT21	GDOT41	GDOT61
Initial Void Ratio, e_i	0.547	0.547	0.548
Final Void Ratio, e_f	0.542	0.545	0.567
Shear Stress, kPa	0.0	77.1	51.2
Horizontal Displacement, mm	0.0	1.09	10.1

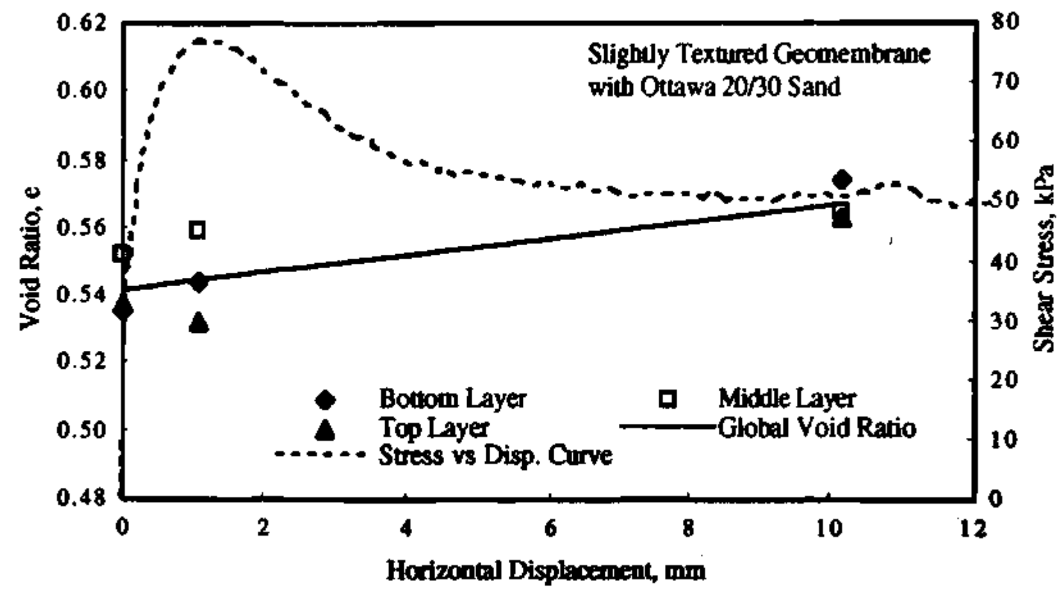

Figure 7. Evolution of the Mean of Local Void Ratio Distributions

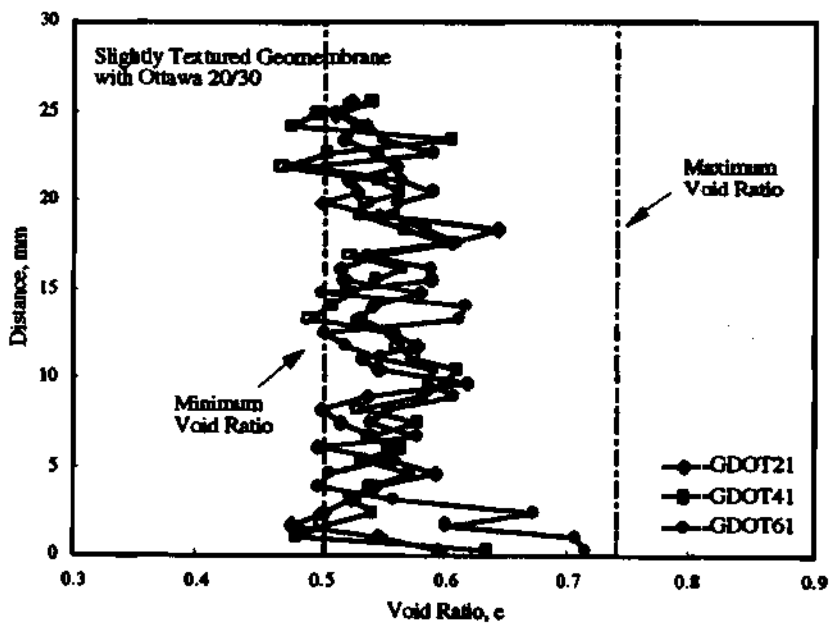

Figure 8. Evolution of Void Ratio as Function of Distance from Interface

minimal soil particle reorientation occurs. The results from specimens PFOT41 and PFOT42 which are for displacements just before and just after peak stress respectively, show large relative movement occurring near the peak stress. Just before the peak stress, the void ratio distribution in the interfacial zone, is similar with the initial state, however just after the peak stress, the void ratio is substantially increased. This indicates that at the peak stress, relative movements of soil particles is initiated. Soil particles start to slide on the geomembrane and interlock with the geomembrane textured surface. More importantly, dilation of soil particles occurs. As shearing continues, the interlocking and dilation progress further, and consequently, yield a higher void ratio in the interfacial zone which extends up to six particle diameters from the interface.

From the above observations, the following interface mechanism can be postulated for the moderately/heavily textured geomembrane and Ottawa 20/30. Below peak stress, the shearing induces minor reorientation in the bottom layer. At the peak stress, the sand particles near the interfacial zone start to slide, interlock with the geomembrane surface, and cause dilation between sand particles. Consequently, this yields a higher void ratio in the interfacial zone. The peak stress is principally developed by dilation of the soil itself. This means that for the moderately/heavily textured geomembrane, the shear strength is mobilized within the soil.

In conclusion, it is observed that the shear mechanism is significantly changed by the surface roughness of geomembrane. For the smooth geomembrane (R_s = 1.09), the shearing affect only two particle diameters from the interface, and the shear stress is developed by sliding and slight plowing of sand particles. For the slightly textured geomembrane (R_s = 1.25), the effect of interlocking between the sand particles and geomembrane result in dilation of sand particles along with some sliding, with the shearing affecting up to four particle diameters from the interface. For the moderately/heavily textured geomembrane (R_s = 1.68), the interlocking and dilation of sand particles is developed fully resulting in a large void ratio in the interfacial zone which extends six particle diameters from the interface.

EFFECT OF SAND PARTICLE ANGULARITY ON EVOLUTION OF STRUCTURE

The preceding discussion has shown how interface shear mechanisms vary as a function of geomembrane roughness for a sub-rounded uniform sand. To evaluate the effect of particle angularity on the evolution of sand structure, some additional tests were performed using angular blasting sand and smooth and moderately/heavily textured geomembranes. Specimens at different stages of shearing along a predefined stress-displacement curve were preserved using epoxy impregnation.

Smooth Geomembrane

Four specimens were sheared along the same predefined stress-displacement curve. At the initial state, the blasting sand showed a similar structure to that observed with Ottawa 20/30 (dense bottom layer

Table 6. Evolution of Specimens' Properties

Specimen	PFOT21	PFOT31	PFOT41	PFOT42	PFOT51	PFOT61
Initial Void Ratio, e_i	0.548	0.550	0.548	0.551	0.550	0.548
Final Void Ratio, e_f	0.540	0.551	0.559	0.563	0.566	0.571
Shear Stress, kPa	0.0	52.5	83.6	83.7	70.7	56.6
Displacement, mm	0.0	0.30	1.19	1.52	2.90	10.3

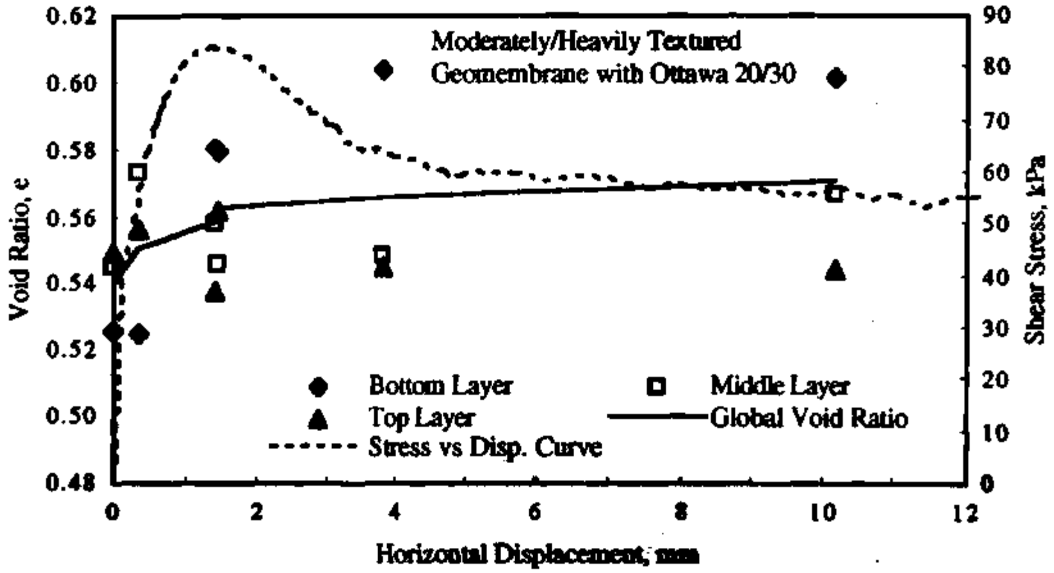

Figure 9. Evolution of the Mean of Local Void Ratio Distributions

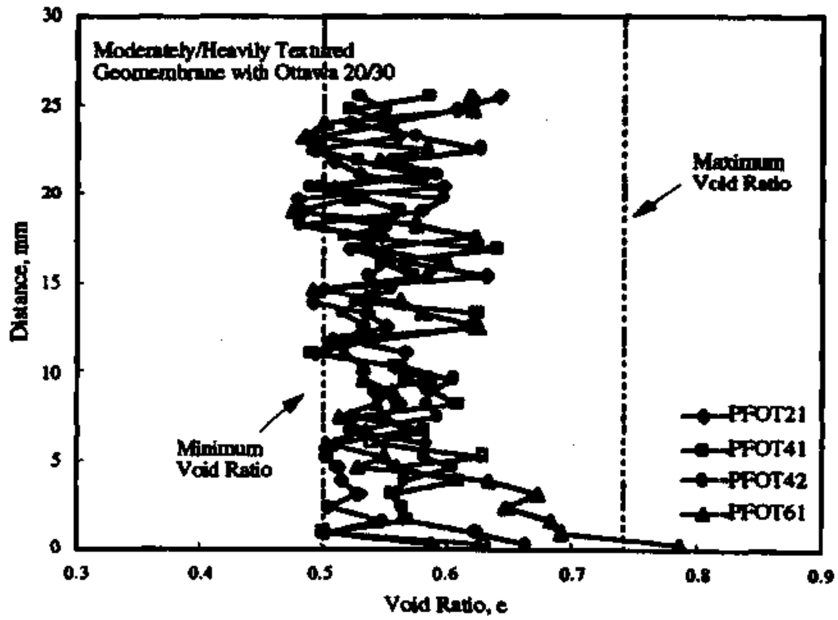

Figure 10 Evolution of Void Ratio as Function of Distance from Interface

and a loose interfacial zone within two particle diameters from the interface). At peak stress, when the soil particles started to move, a small increase of void ratio in the interfacial zone was observed which was in contrast to the observations from the tests on Ottawa 20/30 sand in contact with a smooth geomembrane. It was also found that the blasting sand showed a slightly higher interface strength than the Ottawa 20/30 on the smooth geomembrane. These differences between blasting sand and Ottawa 20/30 on the smooth geomembrane are consistent with the plowing effect described earlier.

From the above observations, the following mechanism can be postulated. The angular blasting sand induces more plowing on the smooth geomembrane than the rounded to sub-rounded Ottawa 20/30. Penetration of angular particles into the smooth geomembrane induces slight interlocking of sand particles near interface at the peak stress, resulting in a higher void ratio in the interfacial zone. This is in contrast to the Ottawa 20/30 test results which show the decrease in void ratio in the interfacial zone. By passing the peak stress, the particle movement in the interfacial zone resembles that of the Ottawa 20/30 sand where the void ratio was decreased to the average void ratio by sliding of the sand particles. However, the residual strength for angular blasting sand is higher since it results from deeper scratches.

Moderately/Heavily Textured Geomembrane

Poly-Flex Textured geomembrane was used to study the interaction between moderately/heavily textured geomembranes and angular blasting sand. Three specimens were sheared along the same predefined stress-displacement curve. In general, all the shearing process trends were very similar to those observed with Ottawa 20/30 with the moderately/heavily textured geomembrane. However, more dilation was observed for the blasting sand at both peak and residual states near the interfacial zone. This implies that even though the angular soil shows a similar trend to the Ottawa 20/30, it produces more dilation because of the angularity of soil particles.

In conclusion, it is observed that, for the smooth geomembrane, the angularity of sand particles induces larger plowing effects so that a higher void ratio is observed at peak stress in the interfacial zone. However, the angularity of the soil particles does not produce a significant effect on the moderately/heavily textured geomembrane, other than inducing more dilation throughout the shear test.

CONCLUSIONS

This paper has quantitatively illustrated the influence of geomembrane roughness and sand particle angularity on sand/geomembrane interface shear mechanisms. The results show that the shear mechanism is changed by the geomembrane surface roughness. The following conclusions are based on the data and interpretation presented in this paper:

1. For the smooth geomembrane (R_s = 1.09), shearing affects only two particles diameters from the interface, and the shear stress is developed by sliding and slight plowing of sand particles.

2. For the slightly textured geomembrane (R_s = 1.25), the effect of interlocking and dilation of sand particles is observed, where the shearing affects up to four particles diameters from the interface.
3. For the moderately/heavily textured geomembrane (R_s = 1.68), the interlocking and dilation of sand particles are fully developed resulting in the large void ratio at the interfacial zone. The shearing affects up to six particles diameters from the interface.
4. The angularity of sand particles induces higher plowing effects on the smooth geomembrane resulting in higher residual strengths than rounded to subrounded Ottawa 20/30 sand.
5. Soil particle angularity does not produce a significant effect on interfaces mechanisms for moderately/heavily textured geomembrane, with the exception that more dilation is induced throughout the shear test.

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ATTACHMENT #3

SURFICIAL SCARRING OF SMOOTH GEOMEMBRANES DURING SHEARING

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ABSTRACT

The behavior of any interface is a function of the properties of both counterface materials including surface roughness, material hardness, and particle angularity as well as interface state variables such as normal stress and density. This paper summarizes the results of a study which investigated the extent of surficial scarring induced on smooth geomembranes during shearing against granular soils. The results quantitatively identified the variations in geomembrane scarring resulting from changes in normal stress and soil particle angularity. At low normal stresses, the primary shearing mechanism involved sliding of the soil particles along the interface. At higher normal stresses, the shearing mechanisms transitioned to plowing of the geomembrane, whereby the granular soil scarred the geomembrane, significantly increasing the geomembrane's roughness. The transition to plowing as well as the amount of scarring was also dependent on the angularity of the soil particles. The results of this study provide a quantitative understanding of the wear mechanisms of the geomembrane during interface shearing. This understanding can provide useful information for the design and selection of counterface materials.

INTRODUCTION

The number of applications in which geomembranes are used to provide a relatively impermeable barrier continues to increase. However, the introduction of the synthetic material into a soil mass creates potential planes of weakness, where shearing and subsequent failure of the system can occur. The basic mechanisms controlling the behavior and strength of these interfaces are thus of significant interest.

Previous research (e.g. Yoshimi and Kishida, 1982; O'Rourke et al., 1990; Paikowsky et al., 1995) has shown that the strength of an interface is a function of the counterface material properties. For the case of geomembrane-sand interfaces, these include the geomembrane surface roughness and hardness and the soil particle angularity, hardness, and size, as well as the specimen density and the applied normal stress. For a relatively smooth surface, the shearing mechanism controlling interface shear strength results from particle sliding and/or plowing depending on the normal stress level among other factors (Shooter and Tabor, 1952; Dove, 1996; Lee, 1998; Dove and Frost, 1999).

Dove (1996) concluded that the total friction force could be defined as the sum of the friction forces resulting from sliding and plowing. For smooth HDPE geomembranes sheared against dense Ottawa sands under normal stresses lower than approximately 50 kPa, the primary mechanism was sliding with the adhesion between the particle contacts being the primary source of shear strength (Dove, 1996; Dove and Frost, 1999). At higher normal stress levels, the contact stresses between the sand particles and the geomembrane exceeds the yield stress of the geomembrane, and plowing contributes to the shearing mechanism. Figure 1 shows schematically how the amount of plowing and thus the friction coefficient is affected by the hardness of the counterface material and the particle angularity.

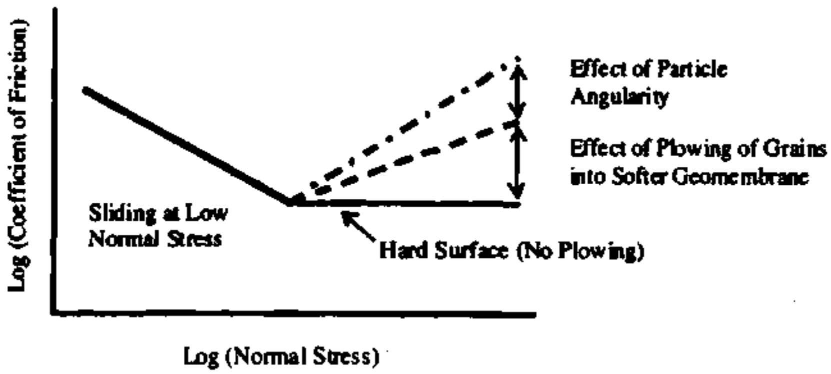


Figure 1. Schematic of Interface Shear Mechanisms

In addition to normal stress, the particle angularity significantly affects the degree of plowing that occurs, especially in the residual shear state. Lee (1998) found the peak friction angle of rounded to subrounded Ottawa 20/30 sands to be similar to that of angular blasting sands. In the residual state, however, the angular sands exhibited a friction angle approximately three degrees greater than the rounded sands. This difference is a result of the angular sand scarring the geomembrane more severely than the Ottawa 20/30 sand. Consequently, the roughness of the membrane sheared against the angular sand is greater than the roughness of the membrane sheared against Ottawa 20/30 sand. Previous research (Kishida and Uesugi, 1987; Dove and Frost, 1996; Lee et al., 1998) has firmly established that the roughness of a surface directly affects the shear strength. This paper quantitatively characterizes the increase in roughness of a smooth geomembrane as a function of normal stress and particle angularity during shearing with granular soils.

EXPERIMENTAL PROGRAM

In this study, a series of direct interface shear tests between smooth geomembranes and granular soils were conducted in which the shearing process was terminated at predetermined locations along the shear-displacement curve. The roughness of the membrane was then quantitatively measured, perpendicular to the shearing direction, using a stylus profilometer.

Soil Properties

The granular soils used in this study were Ottawa 20/30 which has rounded to subrounded quartz particles and a commercial blasting sand which has angular crushed quartz particles. As seen in Table 1, these two granular materials have comparable index properties, thereby enabling a reasonable comparison of their shearing behavior.

Table 1. Soil Index Properties

Soil	D_{50} (mm)	C_u	C_c	G_s	e_{max} (mm)	e_{min} (mm)
Ottawa 20/30	0.72	1.19	0.98	2.65	0.742	0.502
Blasting Sand	0.74	1.83	0.84	2.65	0.951	0.698

Geomembrane Characteristics

All tests were conducted on smooth 1 mm HDPE Dura Seal HD geomembrane manufactured by the National Seal Company. The geomembrane specimens used for interface testing measured approximately 220 mm by 300 mm.

Interface Shear Equipment

A large interface displacement direct shear device was used to conduct the interface shear tests allowing measurements at quasi-residual conditions. Details of the apparatus were provided in Dove (1996) and Lee (1998). Tests were performed to horizontal displacements of 0.1, 10, 40, and 80 mm. Displacements of 0.1, 10, and 80 mm correspond to the peak, starting residual, and ultimate residual states, respectively.

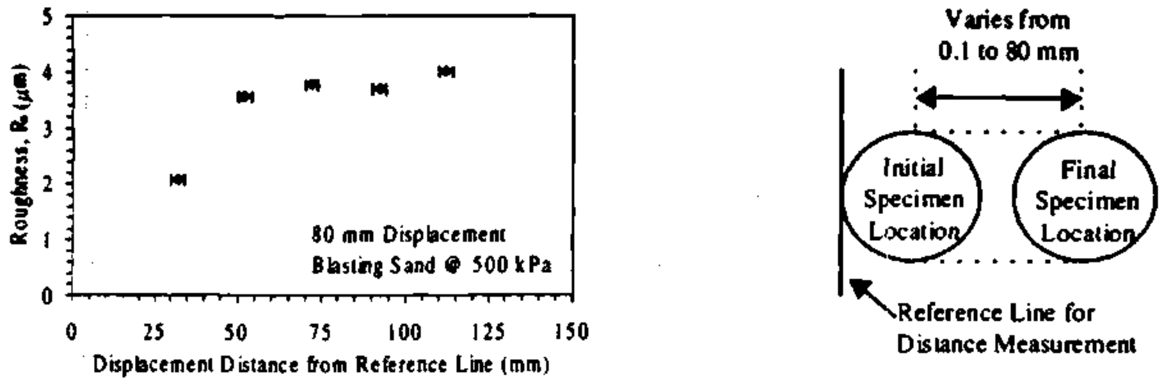
The tests were conducted at normal stress levels of 25, 50, 100, 300, and 500 kPa at a constant displacement rate of approximately 0.25 mm per minute. A target relative density of 80 percent (± 2 percent) was achieved for all soil specimens using an air pluviation system developed by Frost (1989).

The geomembranes were secured to the testing platform with three metal brackets to ensure no movement of the counterface material. All samples were sheared parallel to the geomembrane machine direction. A circular shear box was used for all tests, allowing soil specimens of 63.5 mm in diameter with a nominal height of 38.1 mm. A static normal load was applied using dead weights and two LVDTs were used to measure vertical changes in the soil specimen. A custom LabView data acquisition system recorded the shearing resistance, horizontal displacement, and vertical displacement.

Stylus Profilometer Measurements

The roughness of the geomembranes was measured with a Taylor-Hobson Form Talysurf Series 2 (50 mm traverse unit) stylus profilometer. The roughness is reported herein as R_a, the arithmetic mean of the departures of the profile from the mean line. R_a was determined from a 30 mm profile length using a Gaussian roughness filter (0.8 mm cutoff, 8 μm low-pass cutoff) to prevent the global waviness of the geomembrane from influencing R_a.

Figure 2a shows the typical variation in measured membrane roughness as a function of distance along the shearing path. Roughness measurements used for comparison purposes in this study were completed near the center of the shearing path length as shown in Figure 2b. The geomembrane roughness at the beginning of the test is less than the other values because only a portion of the soil specimen shears across that location and the plowing has not fully developed.



(a) (b)

Figure 2. a) Roughness, R_a versus Distance Sheared; b) Schematic of Sheared Membrane

TEST RESULTS

The results of the test program show how the degree of surficial scarring of smooth geomembranes is influenced by shearing distance, normal stress, and particle angularity. As evident in Figure 3, as the shearing distance increases there is a concurrent increase in roughness. At peak, the R_a measurements for the membranes in contact with Ottawa 20/30 and blasting sand are similar. At this stage, the particles have not experienced displacements large enough for surficial scarring to become evident.

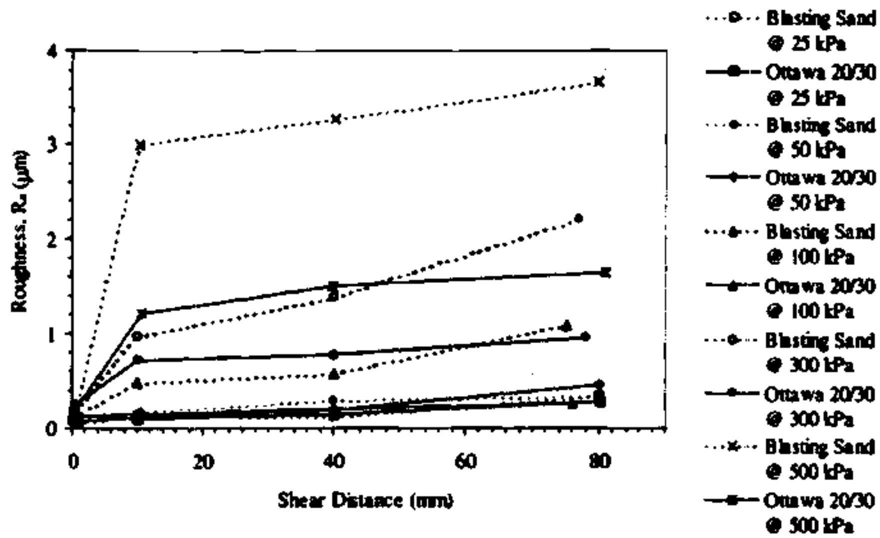
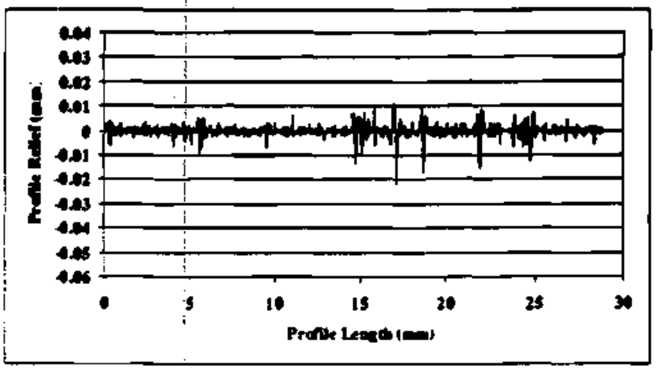


Figure 3. Roughness, R_a versus Shearing Distance

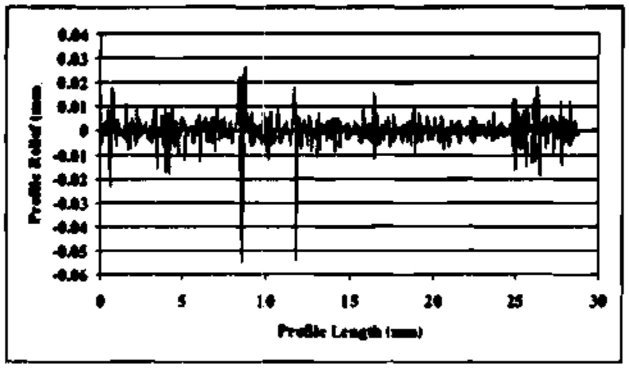
For Ottawa 20/30 sands at approximately 100 kPa and below and for blasting sands at approximately 50 kPa and below, there is not a significant increase in R_a with shearing distance. For these interfaces, contact stresses are not large enough to overcome the yield stress of the geomembrane and the particles are merely sliding along the surface of the geomembrane. At higher normal stresses (above about 50 kPa for Ottawa 20/30 and about 100 kPa for blasting sand), however, there is a notable increase in roughness with the majority of the increase occurring within the first 10 mm. For high normal stresses, the particles have begun to penetrate the membrane at displacements corresponding to peak stress and continue to do so during shearing to the residual state. This is concurrent with Dove's (1996) conclusion that a transition to plowing will occur at approximately the yield stress of the geomembrane. Plowing is the result of the displacement of a harder material (sand) relative to a softer material (membrane), causing the harder material to scratch and remove the softer material in its path (Dove and Frost, 1999; Frost et al., 1999). Within the first 10 mm, the particles are indenting a virgin membrane with minimal scarring. Thus, the wear on the membrane will exhibit a large increase over a short distance. At shearing distances greater than 10 mm, the relative increase in roughness with distance is not as large. In this region, as the particles are sheared across the membrane, they are no longer experiencing a smooth geomembrane. In effect, the particles are plowing into a membrane which has already been plowed by preceding particles.

The increase in R_a with displacement for blasting sand is greater than that of Ottawa 20/30. This is a function of the angularity of the soil particles. The amount the wear on the membrane will be a function of the projected area of indentation in the direction of shearing. The rounded to subrounded Ottawa 20/30 particles will have larger contact areas and thus lower contact stresses leading to a small increase in roughness. However, the angular blasting sand particles will indent the surface more severely with a variety of projected geometries creating more wear. Subsequently, the increase in roughness will continue over a greater distance.

The wear patterns discussed above are evident in Figure 4, which shows plots of two geomembranes that have been sheared to 80 mm at 500 kPa; the left plot has been sheared with Ottawa 20/30 (Figure 4a), while the right plot has been sheared with blasting sand (Figure 4b). In comparing the two plots, it can be seen that the rounded Ottawa 20/30 particles appear to slide along the membrane with minimal plowing making continuous shallow scratches. With the blasting sand, however, the membrane has many more scratches which appear deeper resulting from the sharp edges of the particle indenting the membrane.



(a)



(b)

Figure 4. a) Membrane Sheared with Ottawa 20/30; b) Membrane Sheared with Blasting Sand

The observations discussed above are also evident in Figure 5. For interfaces with Ottawa 20/30, the increase in roughness below about 100 kPa is minimal. Beyond 100 kPa, the increase is significant, but the increase with distance is relatively constant. The amount of wear is directly proportional to the normal stress. For blasting sand, the increase in roughness becomes significant at about 50 kPa. Beyond 50 kPa, the increase in roughness with distance is much greater than for Ottawa 20/30. This is a function of the angular soil particles having a greater tendency to plow into the membrane. Figure 5 clearly shows that membranes sheared with blasting sand have a significantly greater increase in roughness than with those sheared with Ottawa 20/30.

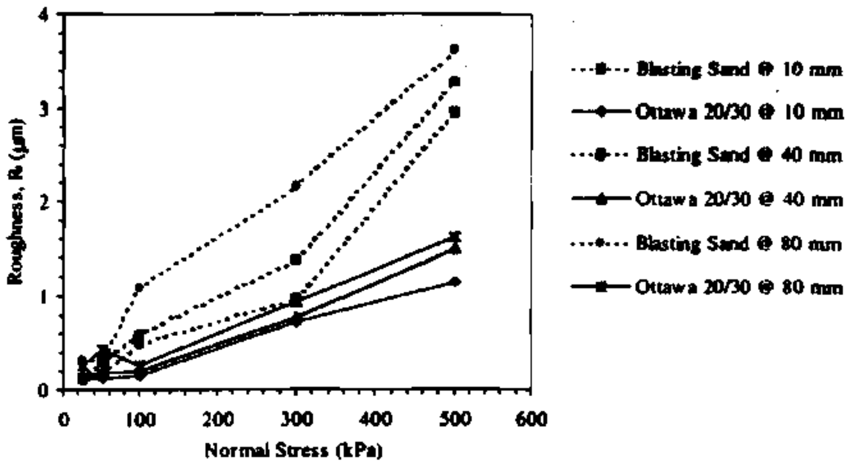


Figure 5. Roughness, R_a versus Normal Stress

CONCLUSIONS

This paper has quantified the increase in roughness of smooth geomembranes as a function of shear displacement, normal stress, and particle angularity. The following conclusions are based on the research presented in this paper:

- At peak stress (0.1 mm displacement), there is not a notable increase in roughness for any of the test specimens because the particles have not been displaced a sufficient distance relative to their initial contact positions.
- At normal stresses less than approximately 100 kPa for Ottawa 20/30 and approximately 50 kPa for blasting sand, there is minimal increase in roughness of the membranes with shearing. Above these normal stresses, the increase in roughness is notable, especially for interfaces sheared with blasting sand.
- The increase in roughness at higher normal stresses is a function the wear of the membrane caused by the particle contact stress exceeding the yield stress of the membrane thereby resulting in plowing of the particles into the membrane.
- The increase in roughness of the geomembranes is also a function of the geometry of the shear direction projected area of each particle contact. For the Ottawa 20-30 sand, the particles are rounded to sub-rounded. Therefore, all of the projected geometries will approximate a portion of a circle. For the angular blasting sand, the projected geometries are highly variable and angular. As the projected geometry becomes more angular and variable, the rate of increase in roughness with shearing direction also increases.
- The large initial increase in roughness for interfaces is due to the plowing of a virgin membrane with angular soil particles. Beyond the initial displacement, the particles are plowing into a previously scarred surface and the measured increase in roughness with displacement is less.

ACKNOWLEDGEMENTS

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ATTACHMENT #4

Comparison of Geomembrane Surface Roughness Values Between a Stylus Profilometer and Optical Profile Microscopy Methods

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March 9, 1999

Introduction:

Interface strength between construction materials and natural soils is a fundamental factor in the design of building construction applications and waste contaminant systems. The stability of structural foundations and the type of design and construction of total fill heights and perimeter slopes in landfills are determined by the interface strength of these geosynthetic materials and their contact with soil. By conducting various tests, such as direct shear tests and image analysis tests, on the interface between soils and construction materials, quantitative data can be obtained and analyzed to obtain more accurate surface roughness values of geomembranes used in structural foundations and landfills.

Research Objectives:

The objectives of this project are to determine and compare surface roughness, R_S, obtained from Optical Profile Microscopy (OPM) methods and from a Stylus Profilometer. Profile roughness parameters, R_L, and surface roughness parameters, R_S, were determined by conducting a series of image analysis tests using OPM at different magnifications of four given geomembranes varying in surface roughness. A continuation of last quarter's research on comparing R_S values, but at a much higher magnification was conducted to determine if there existed a similar trend as what was seen in the data obtained at lower magnifications.

Results:

Image analysis was performed on each trisector coupon of the four geomembranes varying in surface roughness at an increased magnification of 3.4 microns/pixel for 120X using OPM. R_L values, along with the x- and y-coordinates at every two pixels on the profile, were obtained and saved to a data file. The profile structure factor was first calculated by manipulating data saved to these particular files using a macro, and then used to determine Rs. It was further determined that a direct correlation existed between an increase in magnification from 27.8 to 3.4 microns/pixel and the resulting R_L values. However, between 7 and 3.4 microns/pixel, the data plots began to deviate exponentially, resulting in a much steeper slope of the plots.

The results obtained from the tests performed on the various geomembranes using the stylus profilometer also produced similar results at increased magnifications. However, because of the performance differences in obtaining data between the stylus profilometer and image analyzer, comparable R_L values were attainable by only 60%. One reason for the differences in these values could be attributed to the inability of the stylus profilometer to detect overlaps in the membranes while performing the tests.

Also, further analysis of OPM should be conducted to determine more accurate methods to obtain the angle from the vertical of line segments along the profile, given the x- and y-coordinate values for every 2 pixels.

Future Work:

Through development of a variable cone penetrometer with multiple friction sleeves of different surface roughness, interface strength between soil-construction materials can be determined. Research will be conducted to measure loads transmitted to multiple friction sleeves of increasing roughness assembled in series in the proposed variable interface cone penetrometer to show how superior estimates of the friction characteristics of soil-construction material interfaces can be obtained.

Sentho Kagbo

Dr. J. David Frost