MULTI-SCALE ASSESSMENT OF GEOTEXTILE-
GEOMEMBRANE INTERACTION

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MULTI-SCALE ASSESSMENT OF GEOTEXTILE-GEOMEMBRANE INTERACTION

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To My Mother
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SUMMARY

The interface strength between geotextiles and geomembranes is typically a critical factor governing the stability of slopes that incorporate geosynthetics since the double layer lining system was legislated as the national specification for landfills in the United States in the mid 1980s. Previous researchers have focused on the large-scale interaction of fiber-texture interfaces while the micromechanical behavior of the internal geotextile structure has received limited attention. Characterizing the variation in the arrangement and distribution of filaments and/or voids is essential to understanding the micro-scale mechanisms of nonwoven fabrics interacting with textured counterface materials. This thesis presents the results from a study that examined the micromechanical mechanisms involved at needle-punched nonwoven geotextile-textured HDPE geomembrane interfaces and relates the results to the observed macro-scale response.

A large displacement direct interface shear device was developed and used in this study to reduce the system errors that often occur with conventional shear devices and to allow internal geotextile strains to occur during shear. Complimentary numerical modeling was undertaken to study the interface response. The effects of boundary conditions and materials properties on the interface response were quantified. An advanced image analysis technique was used to allow the evolution of the filament microstructure under various boundary and load conditions to be quantified. The different phases within the geosynthetic interface zone were detected from images captured using high-resolution optical microscopy. The changes of geotextile internal structure were
statistically quantified in terms of inter-filament distances as well as the local void ratio and inscribing void size distributions. The tensile response of single filaments was measured using a helium neon deflectometer and these measurements were used to evaluate the shear induced filament strain.

It was found that the geotextile strain critically affected the geotextile-geomembrane interface shear response as well as the variation in the internal filament structure. The three orthogonal viewing planes and the serially sectioned surface images in the vertical direction revealed localized filament concentrations around texture elements. The locations of concentrations were consistent with the shear direction and texture geometry. Shearing resulted in significant variation of the geotextile filament structure due to localized stretching of filaments and surface degradation of geotextile near the interface. The inter-filament distance changes as well as the local void ratio distribution reflected the significant response of the geotextile to the normal and shear stress states. The sizes of voids enclosed by adjacent filaments were measured using optical image analysis and expressed in terms of the largest inscribing opening size (LIOS). LIOS was particularly useful for quantifying the structure of horizontal surfaces at different depths with the geotextile specimen, where the filament network consisted of long curved features. The interface shearing of a geotextile against a textured geomembrane resulted in a distinct reduction of the filament diameter distribution reflecting the tensile force effects on the individual filaments. The minimum filament diameter was observed at peak shear. The test results showed the impact of the concentrated normal stress and micromechanical interlocking between the geomembrane textures and geotextile filaments during interface shearing. This study provides micro-
mechanical insight into the combined role of geomembrane surface topography and geotextile filament structure on macro-scale geosynthetic interface response.
CHAPTER I

INTRODUCTION

1.1 Motivation for Study

The contact behavior and interaction between various materials is an important issue for engineers in many disciplines. With terminology focusing on geometry, geomaterials can be divided into three categories: continua, particulates, and fibrous materials. Each category of material can lead to different interactions under different load conditions.

Over the past few decades, fiber-texture interaction has become a key issue in geosynthetic engineering, with the introduction of new materials such as geotextiles and geomembranes. Previous researchers have focused on the large-scale interaction at fiber-texture interfaces while the micromechanical behavior of the internal geotextile structure has received limited attention. This dissertation seeks to study the fundamental mechanisms involved in the interaction between geotextile filaments and geomembrane surface textures at the micro-scale and to relate this to the observed large-scale behavior.

1.2 Texture-Fiber Interfaces in Geotechnical Engineering

Geotextiles and geomembranes have been the most widely used geosynthetics, due to their unique advantages in drainage, separation, filtration, protection, and reinforcement applications. These two materials are typically used as a composite system rather than as a stand-alone solution because of their complementary properties of
hydraulic conductivity. In double layer lining systems, which have been legislated as the national specification for landfills in the United States since 1986, the interface strength between geotextiles and geomembranes is typically a critical factor governing the stability of slopes that incorporate geosynthetics (Mitchell and Seed, 1990; Seed and Mitchell, 1990). Similar composite installations of geosynthetics are also used in diverse construction activities such as tunnels, dams, and pile installations (Giroud, 1984; Frobel, 1988; Girard et al., 1989).

Geotextiles are porous/fibrous materials consisting of irregularly oriented long filaments which vary in terms of spatial distribution, curvature, orientation, size, and mass density. Geomembranes are continuum materials that depend on properties such as tensile strength, hardness, surface roughness, and chemical constitution. The methods currently used to determine the interface characteristics of composite geosynthetic systems include mechanical experimental devices such as direct interface shear tests, ring shear tests, or pullout resistance tests. The complex surface topography of textured geomembranes and the fibrous nature of nonwoven geotextiles render conventional models for interface friction of continuum-continuum and continuum-particulate systems inadequate (Frost et al., 2001). While the properties of textile fabric and continuous polymer sheets have been studied separately, detailed studies into the interaction between filaments and texture elements that are part of these sheets, particularly at the microscopic scale under varying external loading conditions, are required.
1.3 Scope of Thesis

This thesis presents the results and findings of studies into the response of fabric-continuum interfaces. The scope of the thesis is divided into four sections: (1) review of previous studies and current knowledge about the textile internal structure and membrane surface texture; (2) development of image analysis techniques and experimental program; (3) large scale behavior of interfaces and their study using both physical experiments and numerical modeling; (4) microscale investigation and quantification of void/filament structure. This thesis is organized into eight chapters in the following manner:

Chapter 2: provides a review of previous work on methodologies to quantify the internal structure of fabrics and the surface geometry of continua. The current understanding of the shear response of fabric-continuum interfaces is also presented.

Chapter 3: describes the laboratory program undertaken to assess the properties and interaction of materials. Physical properties of the selected materials are described, followed by a detailed description of the newly designed and constructed interface shear device that was used in this study. This chapter also presents the measurement procedures used to observe the macro- and micro-scale contact behavior of the test materials. The sample preparation procedures and digital image analysis methods are described. This chapter also introduces the experimental system for estimating the tensile properties of single geotextile filaments, which are subsequently used in Chapter 7 to
analyze the micro-scale change of filament diameter near geotextile-geomembrane interfaces.

Chapter 4: presents macro-scale results from a series of interface shear resistance tests. The effects of geotextile strain on the interface resistance against smooth and textured geomembrane surfaces is studied. The role of overburden soil is introduced to further investigate the effects of boundary conditions on the interface shear evolution.

Chapter 5: presents the results of geotextile-geomembrane interface modeling using a finite difference method code. The interfaces are simulated in terms of equivalent shear bands. The strain softening is modeled to quantitatively characterize the stress-strain envelope of the interface shear and the model results are compared with the experimental test results.

Chapter 6: introduces stereological concepts used to evaluate the void structure of geotextiles. The void structures are evaluated in terms of two void-based descriptors for various external loading as well as boundary conditions. The deformation of geomembrane surface texture features and the role of filament elongation in the geotextile during interface shear are also discussed. Statistical studies on the image analysis data are presented.

Chapter 7: presents the results of the image analysis studies from the viewpoint of the geotextile filaments. The deformed geotextile microstructure is quantitatively described in terms of the filament size distribution and the nearest neighbor distance distribution (NNDD) of the geotextile filament phase. The results of
image analysis are compared with simulated data acquired from modeled lattice structures.

Chapter 8: presents the final conclusions of this dissertation with comments regarding the proposed direction of future studies into the topic.

References and appendices with supplementary information are presented at the end of the thesis.
CHAPTER 2

CHARACTERIZATION OF FABRIC-CONTINUUM INTERFACES: CURRENT UNDERSTANDING

2.1 Introduction

Geosynthetics, being man-made polymeric materials, have different engineering properties compared to natural geomaterials. As such, different methods may be required to characterize their properties. For geotextiles, tracking the variation in arrangement and distribution of fibers is considered essential to understanding the micro-scale mechanisms that govern how nonwoven fabrics interact with textured counterface materials.

Efforts to develop a theoretical solution to describe nonwoven fabric structures have been undertaken by many researchers (Komori and Makishima, 1978; Advani and Tucker, 1985; Lombard et al., 1989; Pourdeyhimi, 1999). Numerical functions describing the non-linear compression of non-woven geotextiles have been developed in terms of average number of fiber-to-fiber contacts per unit volume of fiber assemblies (Komori and Makishima, 1977), average pore size changes (Giroud, 1981), and energy loss (Kothari and Das, 1992). However, such theories are somewhat limited due to simplifying assumptions concerning filament structure, and they have not been validated due to experimental observation difficulties. Detailed study has not been made yet on the orientation rearrangement or spatial redistribution of geotextile filaments as a function of the surface topography of adjacent materials under a range of normal stress states.

This chapter is divided into three sections. The first two sections present previous approaches used to quantify the microstructure of nonwoven fabrics and micro-scale topography of polymer sheet materials, respectively. The third section includes a
summary of past work on the interface shear resistance between fabrics and continuum materials.

### 2.2 Evaluation of Nonwoven Fabric Structure

Nonwoven geotextiles can be divided into four types based on the manufacturing technique used: heat bonded, resin bonded, spun bonded, and needle punched. During the past decade, needle punched nonwoven (NPNW) geotextiles have become the most widely used type in field applications. The needle punching process improves the engineering properties of the geotextile such as tensile strength and interface resistances by enhancing the integrity of the filament elements structure.

Several techniques to describe fabric structure have been devised by previous researchers. The primary objective in these studies was to evaluate the hydraulic properties of geotextiles including drainage capacity and clogging effects. Five experimental methods to quantify fabric structure are reviewed in this chapter including: sieve analysis, mercury intrusion porosimetry, in-plane water flow, capillary flow, and optical image analysis techniques.

#### 2.2.1 Sieve Analysis: dry and hydrodynamic sieving

Determining the apparent opening size (AOS) is a general method to evaluate the pore size distribution of geotextiles (ASTM D 4751). In this mechanical test, a series of glass beads of different sizes are consecutively sieved from small to large sizes. The percentage of glass beads retained through a geotextile filament layer is recorded for each step. The AOS is defined as the diameter of glass bead where 95% are retained in the specimen. For both the dry and hydrodynamic sieving, five parameters of the particles
must be considered: chemical nature, relative density, shape, size distribution, and quantity of particles (Rigo et al. 1990).

The filtration opening size (FOS) is measured through a hydrodynamic sieving. In this method, well-graded soils are sieved through a geotextile by the cyclic motion of a basket in a water tank. The soil diameter corresponding to the 95% passing is defined as the FOS. In addition to natural soils, different types of particles have been used, such as artificial sand, silica materials, and glass beads. Therefore, particle properties must be verified when applying this method.

Lombard et al. (1989) proposed an analytical solution (equation 2.1) to calculate the opening size distribution of geotextiles using the Poisson polyhedral concept.

\[
F_j(d) = 1 - \left[ \left( 4\mu d / (\pi T_g D_j \rho_j) + 1 \right)^{T_g/D_j} \exp(-4\mu d / (\pi D_j^2 \rho_j)) \right] \tag{2.1}
\]

where \( F_j(d) \) is the distribution frequency of filter pore diameters, \( \mu \) is the mass per unit area of geotextile (g/m²), \( T_g \) is the geotextile thickness (mm), \( \rho_j \) is the mass per unit volume of the polymer (kg/m³), and, \( d \) and \( D_j \) are the pore and fiber diameters (μm), respectively.

Heat-bonded geotextiles were used to compare the theory with the experimental results acquired by the AOS and FOS methods. The test results showed that the mechanical shaking of the AOS method produced a deformation in the geotextile structure, resulting in overestimation of the local opening sizes. Such an effect varied as a function of the initial density, structure, and the surface treatment method of the fabric. In the same way, it was found that the hydrodynamic drawing force of the FOS methods accelerated the
penetration of the particles through the geotextiles with regard to the thickness of the fabrics.

2.2.2 Mercury Intrusion Porosimetry

The mercury intrusion porosimetry technique has been used to determine the pore volume and pore volume distribution of soils and rocks. In this method, mercury is forced into the pores by external pressure. Smaller pores require higher pressures to be intruded with mercury. Based on the assumption of a cylindrical pore model, the pore size corresponding to each level of external pressure is calculated as shown in Equation 2.2:

\[ d = \frac{-4\gamma \cos \theta}{P} \]  

(2.2)

where \( d \) is the pore diameter, \( \gamma \) is the surface tension of the mercury, \( \theta \) is the contact angle between the mercury and the pore wall, and \( P \) is the absolute pressure causing the intrusion.

Mercury is used because its high surface tension enables it to be non-wetting when in contact with most materials (Rebenfeld and Miller, 1995). This method can discern pore sizes ranging in terms of equivalent diameter from 2.5 nm (0.025 \( \mu m \)) to 100 \( \mu m \) (ASTM D 4404).

Prapaharan et al. (1989) applied this technique to estimate the pore size distribution of nonwoven geotextile fabrics. They reported that this method was applicable to evaluate the apparent opening size and permeability of geotextiles, by comparing their test results with those obtained using the dry sieving method and permeability tests. However, similar to the sieving tests, this method has limitations in
being directly applied to fabrics because the high pressure, which is used for mercury intrusion, may alter the initial fabric structure.

2.2.3 In-plane Water Flow Method

Rebenfeld and Miller (1995) estimated the pore volume distribution of glass fibers using an experimental setup which consisted of a cylindrical cell and a porous medium. A water-saturated fabric was seated on a micro porous membrane in a closed chamber and then step-wise gas pressure was applied to force out the water that had been soaked inside the fiber pores. By measuring the amount of water drained at different level of pressure, the percent pore-size distribution of fibers could be estimated. The decrease of pore size and the change of pore size distribution of the fabric due to compression were monitored from in-plane flow analysis. The radial flow of water through the fabric was videotaped and the resulting surface image of the liquid flow was used to evaluate the degree of heterogeneity of the fabric structure. This method has an advantage of using water, which has relatively low viscosity, however control of the water flow to ensure equal saturation throughout the specimen is difficult. Moreover the observation is limited to the surface and quantitative measurement of the microscale water flow through the textile inner pores are not obtained.

2.2.4 Capillary Flow Test (Bubble Point Method)

This method is an ASTM specialized method for geotextiles that uses gas pressure (ASTM D 6767; D 316) to measure the pore size distribution. In contrast to the in-plane water flow method, the gas flow rates through a wet and dry geotextile under a range of pressures are measured and compared. At each step in air pressure, the percentage of the airflow passing through the filter pores larger than or equal to the specified size is
calculated from ideal data of the system based on the pressure-size relationship. This method is applicable to pore sizes in the range of about 1 to 200 $\mu m$. An advantage of this technique is its rapid speed of measurement, which allows real-time evaluation in the field (Christopher, 2003).

Another variation of this technique is called the bubble point method. The pressure required to blow the first continuous bubble detectable at the opposite side of a specimen by increasing the air pressure applied on one face of a saturated fabric is called the bubble point and is used to calculate the maximum pore size (ASTM F 316). However in this method, pore sizes tend to be underestimated because the measured value is determined by the narrowest diameter of each pore conduit in the fabric (Bhatia and Smith, 1994).

2.2.5 Image Analysis

The initial anisotropy of nonwoven fabrics is determined by the position of the filaments during manufacturing which produces geotextiles in four different categories: parallel-laid, cross-laid, random-laid, and composite. Hearle and Stevenson (1963) studied the anisotropic characteristics of nonwoven fabrics by observing their surface images. Their results were used to explain the anisotropic tensile modulus of the fabric with regard to the test directions.

Studies to directly observe the microscopic inner-structure of fabrics have been performed by several researchers (e.g., Faure et al., 1990; Long et al., 1990; and Mlynarek et al., 1990). Mlynarek et al. (1990) observed a soil-geotextile drainage system using an optical microscope to investigate the filtration and clogging mechanisms. Filtration tests were conducted using a geotextile and two types of soils. After testing, the
samples were encapsulated in epoxy resin. The epoxy-cured specimens were cut and the cross sections were observed under a microscope. Long and Lau (1990) impregnated nonwoven geotextiles with various chemicals such as polyester, epoxy, and methyl methacrylate. Through similar procedures of sample preparation used by Mlynarek et al. (1990), three polished surfaces of specimens having mutually perpendicular orientations were observed under a microscope. The horizontal and vertical angle of fibers were measured based on their elliptical cross sectional shape. It was experimentally confirmed that the second and fourth order orientation tensor notations suitably described the three dimensional fiber orientations, which were noted by previous researchers (Advani and Tucker, 1987; Tucker, 1988).

2.3 Quantification of Surface Geometry

In general, a surface profile can be divided into two components: roughness and waviness. Roughness is the local irregularities of the surface texture from a reference line, which usually result from the manufacturing process. Waviness indicates the more widely spaced curvature of the surface, which results from various factors: machine or workpiece deflections, vibration and chatter as shown in Figure 2.1 (ASME B46.1-1995). Various parameters have been developed to quantitatively describe the surface roughness of different types of materials. Table 2.1 shows the most widely used surface roughness parameters.

Gokhale and Underwood (1990) proposed a method to calculate the fracture surface roughness \( R_s \) from two-dimensional measurements of the fracture profile \( R_L \). where \( R_s \) is defines as Equation (2.3):
Table 2.1 Summary of Geomembrane-Geotextile Interface Resistance.

<table>
<thead>
<tr>
<th>Author</th>
<th>Geomembrane</th>
<th>Geotextile</th>
<th>Friction Angle</th>
<th>Test Method</th>
<th>Geotextile Size (inch)</th>
<th>Normal Stress Range (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Martin et al. (1984)</td>
<td>CSPE</td>
<td>CZ 600 / Typar</td>
<td>15° / 21°</td>
<td>Direct Shear</td>
<td>4 x 4</td>
<td>4.8 to 48</td>
</tr>
<tr>
<td>[3] Mitchell and Seed (1990)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>CSPE</td>
<td>HB / NP</td>
<td>26° / 28°</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[6] Stark et al. (1996)</td>
<td>HDPE</td>
<td>Polyfelt</td>
<td>32°</td>
<td>Ring Shear</td>
<td>1.57 ID; 3.94 OD</td>
<td>50 to 480</td>
</tr>
<tr>
<td></td>
<td>PP, HDPE (C)</td>
<td></td>
<td>21.0 to 22.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.2 to 17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.1 to 18.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[8] Lee (1999)</td>
<td>HDPE</td>
<td>Trevira / Amoco</td>
<td>10.6° to 20°</td>
<td>Direct Shear</td>
<td>4 x 4</td>
<td>50, 100, 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.6° to 12°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^1)HB: Heat Bonded Nonwoven; ^2)NP: Needle Punched Nonwoven; ^3)PE: Polyester; ^4)PP: Polypropylene; I: Impingement; C: Coextruded
Figure 2.1 Schematic Diagram of Surface Characteristics (ASME B46.1-1995).

\[ R_s = \frac{R_L \cdot \psi}{\psi} \]  

(2.3)

\[ R_s = \frac{\text{Fractuer surface area}(S_o)}{\text{Apparent projected area}(A)} \]  

(2.4)

where \( \psi \) is the profile structure factor, and \( R_L \) can be experimentally measured from digital image analysis:

\[ R_L = \frac{\text{profile length} (\lambda_o)}{\text{projected length} (L)} \]  

(2.5)

The profile structure factor \( \psi (\phi_p) \) is determined by the profile orientation distribution function \( f(\alpha, \phi_p) \), where \( \alpha \) is the angle between a tangent to a line element of profile on vertical section and a reference axes.
Table 2.2 Conventional Surface Roughness parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average roughness</td>
<td>$R_a = \frac{1}{L} \int_0^L</td>
<td>Z(x)</td>
</tr>
<tr>
<td>Root mean square roughness</td>
<td>$R_q = \left( \frac{1}{L} \int_0^L \left( \frac{Z(x)}{x} \right)^2 , dx \right)^{1/2}$</td>
<td>ASME B46.1-1985</td>
</tr>
<tr>
<td>Average slope</td>
<td>$\Delta a = \frac{1}{L} \int_0^L \left</td>
<td>\frac{dZ}{dx} \right</td>
</tr>
<tr>
<td>Root mean square slope</td>
<td>$\Delta q = \left[ \frac{1}{L} \int_0^L \left( \frac{dZ}{dx} \right)^2 , dx \right]^{1/2}$</td>
<td>ASME B46.1-1995</td>
</tr>
<tr>
<td>Average wave length</td>
<td>$\lambda_a = 2\pi \frac{R_a}{\tan(\Delta a)}$</td>
<td>ASME B46.1-1995</td>
</tr>
<tr>
<td>Root mean square wavelength</td>
<td>$\lambda_q = 2\pi \frac{R_a}{\tan(\Delta q)}$</td>
<td>Thomas (1982)</td>
</tr>
<tr>
<td>Maximum peak to valley roughness</td>
<td>Largest single peak to valley height</td>
<td>ASME B46.1-1995</td>
</tr>
<tr>
<td>Normalized roughness parameters</td>
<td>$R_n = \frac{R_{\text{max}}}{D_{50}}$</td>
<td>ASME B46.1-1995</td>
</tr>
<tr>
<td>Profile roughness parameters</td>
<td>$R_L = \frac{L_o}{L}$</td>
<td>Gokhale and Underwood (1990)</td>
</tr>
</tbody>
</table>

$$
\psi(\phi_p) = \int_0^\pi \left[ \sin \alpha + (\pi / 2 - \alpha) \cos \alpha \right] f(\alpha, \phi_p) \cdot d\alpha
$$

(2.6)

Dove and Frost (1996) developed a method to quantitatively measure the roughness of geomembranes using optical profilometry. Two and three dimensional surface roughness parameters of geomembranes were calculated from the images on three vertical sectioning planes having mutual orientations of 120° based on the theoretical
developments of Gokhale and Drury (1994). The experimentally measured fracture surface roughness ($R_s$) of the different types of geomembranes using the general solution of equation (2.3) to (2.4) showed good agreement with the semi-empirical expression for surface roughness (equation 2.7), proposed by Underwood and Banerji (1987), where equation (2.7) and (2.8) are for the partially oriented and randomly oriented surfaces, respectively.

\[ R_s = \frac{\pi}{4} (R_L - 1) + 1 \]  

(2.7)

\[ R_s = \frac{\pi}{4} R_L \]  

(2.8)

Extensive studies have been conducted at the Georgia Institute of Technology over the past decade to evaluate the surface properties of different types of geomembranes (e.g., Dove et al., 1996; Dove and Frost, 1996; Zettler et al., 2000; Frost and Lee, 2001).

In order to be able to examine the large range of surface roughness values of geomembranes, Dove and Frost (1996) used different approaches as a function of topography scale. The microstructure of surfaces at scales less than 10 microns was observed using an atomic force microscope. Images covering 100 $\mu m^2$ in plane area were collected, and used to compute various parameters for surface property characterization including: real surface area, fractal dimension, and surface roughness parameters (Dove et al., 1996). For texture ranges greater than 10 microns, cross sectional images were captured using a CCD camera for image analysis. Three vertical cross sections were made along sectioning lines mutually oriented at 120 degrees. The
specimens were embedded in a Plaster of Paris mixture. After curing of the plaster and careful polishing of the cross sections, the surface images were captured using a CCD camera. The digital images were converted into outlined features, and surface roughness parameters were determined (Dove and Frost, 1996). Based on the experimental data for different types of geomembranes, it was concluded that the general method requires profiling lengths of at least 14 mm for smooth geomembranes and 35 mm for textured geomembranes. Furthermore, a classification method for geomembranes was proposed in terms of the surface roughness parameter (R_s) as follows:

a) Smooth: 1.00 to 1.10  
b) Slightly textured: 1.10 to 1.35  
c) Moderately textured: 1.35 to 1.60  
d) Heavily textured: Greater than 1.60

Zettler et al. (2000) investigated the shear-induced change of surface topography for smooth high-density polyethylene (HDPE) geomembranes. The changes in the surface roughness profile as a result of shearing against particles with various sizes and angularities were detected using a stylus profilometer.

Frost and Lee (2001) investigated the role of topography on the interface shear mechanism at geomembrane-geotextile interfaces. For textured geomembranes, the peak interface strength was dependent on the micro texture of the geomembrane. The post shear surface resulted in a dramatically lower peak strength when sheared repeatedly. The macro scale texture of geomembranes was found as the primary source of residual strength and generated pulling and breakage of the geotextile filaments.
Since introduced by Mandelbrot (1967), fractal analysis has been applied in various fields in order to evaluate the characteristics of irregular and complex profiles in nature (Kaye, 1978; Carr and Warriner; 1989; Carr et al., 1989; Carr and Warriner, 1989; Miller et al., 1990; Turcotte, 1992; McWilliams et al., 1993; Vallejo, 1995). The length of a complex profile can be expressed in an exponential form in terms of segment length \( r \), and fractal dimension \( D \) as shown equation (2.9).

\[
L = (C)(r)^{(1-D)}
\]  

(2.9)

where \( C \) is a constant, \( r \) is the segment length, and \( D \) is the fractal dimension.

Fractal dimension is used for quantitative evaluation of the degree of roughness of profiles, and the larger fractal dimension indicates the more complex profile. Equation (2.9) can be reduced in terms of the number of segments \( N \), and the corresponding segment length \( r \).

\[
L = (N)(r)
\]  

(2.10)

From equation (2.9) and (2.10),

\[
N = (C)(r)^{-D}
\]  

(2.11)

If the relationships between \( N \) and \( r \) are plotted linearly on an equivalently scaled log-log graph, the absolute value of the slope \( (D) \) represents the fractal dimension of the profile. Vallejo and Zhou (1995) applied the fractal concept to evaluate the surface...
roughness of four commercial geomembranes. Using different lengths of segments and corresponding number of segments, the fractal dimension $D$ was calculated.

2.4 Interface Shear Resistance

Geotextiles and geomembranes are frequently installed adjacent to each other in field applications due to their complementary properties and functions. The roles of geotextiles in composite lining systems as described by Martin et al. (1984), and Giroud (1986) are summarized below.

Geotextile liners are used in combination with geomembranes for the following purposes:

- Cover geomembranes on slopes to improve the lining systems.
- Reduce tensile stresses transmitted to geomembranes from overburden materials through load spreading.
- Protect geomembranes from puncture and tear caused by angular materials.
- Minimize the local burst failures of geomembranes brought by cavities, cracks, and local subsidence of ground beneath the geomembrane layer.
- Act as lateral transmitters of water and gas, preventing the excess tension of geomembranes due to inefficient drainage.
- Protect geomembranes from ozone and ultraviolet attack before covering with soil.

An extensive range of methodologies to measure fiber friction has been published in textile engineering:

- One point contact of two single fibers: Mercer and Makinson, 1947; Olofsson and Gralen, 1947; Howell, 1951; Pascoe and Taylor, 1955; and Bartlett et al., 1953.
- Twist method using two single fibers: Lindberg and Gralen, 1948; Hood, 1953; and Van der Vegt and Schuringa, 1956.


- Methods using a rotating cylinder and a stationary yarn: Saxl, 1936; Mercer, 1945; Schlien, 1953; and Roder, 1955.

While several other methods have been developed in addition to those listed above, they are not suitable for evaluation of geosynthetic resistances. Furthermore, information about interface friction between nonwoven fabrics and planar surfaces was almost non-existent before the early 1980s.

Martin et al. (1984) measured the resistance of interfaces between geotextiles and geomembranes using a direct shear box measuring 10.2 cm by 10.2 cm. The results from tests involving rough-surface PVC geomembranes resulted in an almost doubling of the resistance compared to those for a smooth PVC sheared against the same geotextiles, indicating the significant role of surface texture on the evolution of interface resistance.

Williams and Houlihan (1986) evaluated the coefficients of friction between geomembranes and geotextiles through direct shear tests, and presented mechanisms for the different interface friction values in terms of sliding and dilation, which were affected by the surface roughness of materials. A brief summary of this work is given below.

- For the same nonwoven geotextiles contacting with different flexible smooth membrane liners, the highest interface friction angles were measured against Chlorosulfonated Polyethylene (Hypalone, 21°) showing the highest dilation, followed by Polyvinyl Chloride (PVC, 18°), Linear Low Density Polyethylene (LLDPE, 11°) and High Density Polyethylene (HDPE, 10°).
- The work required for dilation is a function of the applied normal stress and the stiffness of the geotextiles.

- The major component of friction for rough membranes is dilation at the interface. In the case of relatively stiff and smooth types of geomembrane, the major source of friction is sliding.

- Contacting with the same type of geotextile, softer geomembranes showed higher adhesion at the interface.

The strain corresponding to the peak frictional resistance at the geotextile-geomembrane interface is affected by the texture geometry of the geomembrane and the mass density of the geotextile. Jones and Dixon (1998) studied the shear behavior between different types of geotextiles and geomembranes by performing direct shear and ring shear tests. The peak interface shear stress for smooth geomembranes was mobilized at very low displacements (less than 2 mm), resulting in the relatively low level of stress softening. For textured geomembranes, the peak stresses occurred at larger displacements of 5 to 10 mm and showed a significant decrease of shear stress as displacement increased. Similar results can be found from other studies (Stark et al., 1996; Lee and Frost, 1998; Hillman and Stark, 2001; and Frost and Lee, 2001). Geotextiles with a higher mass per unit area exhibited a higher shear strength and larger displacements to peak strength (Lee and Frost, 1998; Frost and Lee, 2001). Table 2.2 provides a summary of previous research into geotextile-geomembrane interface shear resistances.

A merit of using the ring shear device is that the travel length of the materials is not limited by the length of the equipment. Accordingly, any range of residual or large-displacement friction can be evaluated without stopping the test. However, the tensile properties of nonwoven fabrics vary with the orientation of the measurements (Hearle
and Stevenson, 1963). Furthermore, the frictional resistance of fabrics is affected by the structure of the fabrics, especially fiber orientation. The ring shear device is not designed to consider the constantly changing surface profile and structure of the materials during shear. Most engineering materials have non-isotropic geometries, and thus the ring shear device can cause a significantly biased measurement. Examples of variation in measurements between ring shear and direct shear devices can be found in Hillman and Stark (2001).

Using textured geomembranes that have been sprayed with HDPE particles, Ojeshina (1991) conducted interface friction tests between geomembrane and various counterface materials. The friction angle increased as the area portion of HDPE-sprayed surface increased, and then reached a constant value when the sprayed area covered about 70 % of the smooth geomembrane surfaces. A comparable result can be found for tests with sand and steel, indicating the existence of a critical roughness \( R_n \approx 70 \) above which no more frictional resistance increases result from increasing the surface roughness of the counterface material (DeJong et al., 2002).

Due to the excessive stretching and thinning of the materials, the frictional resistance measured using pullout test devices is known to be lower than those measured in direct shear devices. Further, the interface friction parameters measured using a conventional direct shear device are lower than field data due to the small size of the specimens (Williams and Houlihan, 1986).

When a nonwoven geotextile contacts with a geomembrane surface, in particular, a textured geomembrane, the filaments of the geotextile tend to be attached on the geomembrane surface without external or internal force by a “Velcro” effect. This
bonding force was first noticed by Swiss engineer, de Mestral in 1948, when observing that burrs clung to animal fur under a microscope. This mechanical bonding force is quantified according to ASTM D 5169-98, dynamic shear strength of hook and loop. Such contact behavior is different from the conventional concept of interlocking during shear of continuum or particulate materials. However, this hook-and-loop effect tends to be neglected, even though it may significantly affect the initial seating of geotextile fibers on the geomembrane surfaces during installation, and subsequently the actual interaction between the materials.

Han et al. (1992) analyzed the mechanism of the interlocking and failure of an artificial Velcro. A numerical solution was provided and then compared with the experimental tests results, showing approximate agreement. However, such a solution is not applicable to geotextiles and geomembranes directly because of the anisotropic and irregular orientation of geotextile filaments and the topography of geomembrane surfaces.

Hebeler et al. (2004) studied the hook and loop interaction using an HDPE geomembrane and NPNW fabrics in laboratory tests. The magnitude of hook and loop interaction was found to be determined by the characteristics of the geomembrane texture. A coextruded geomembrane showed limited response to ASTM hook and loop testing while a structured geomembrane resulted in no measurable response in combination with all tested loop materials.

In this study, the hook-and-loop mechanism of fibers under low normal forces was observed through interface shear tests and image analysis. The results are described in Chapter 4, 6 and 7.
2.5 Summary and Conclusions

The complicated internal structure of fabrics has rendered the direct application of theories which impose assumptions made for simplification of the models inapplicable. Surface topography causes different contact behavior against counter surfaces with different structures. This chapter has reviewed the methods used to date for characterization of fabric structure and surface geometry at the microscopic scale. The contact mechanisms at the interfaces of fabric-surface and particle-surface systems were also reviewed.

A series of attempts to evaluate the pore size distribution of geotextiles using different methods was performed at Syracuse University (Bhatia et al., 1993; Bhatia and Smith, 1994; Bhatia et al., 1996). Each method showed significantly different results for the same nonwoven geotextile. For example, the mercury intrusion method indicated that the 50% passing diameter of the fabric pores was 4 to 5 times greater than the results obtained with the bubble point method. Such differences are due to the disturbance of the delicate fabric microstructure and the imposed boundary conditions of each test method. The surface image analysis of fabrics has limitations in that it is not able to evaluate the complex inner structure of fabrics.

The quantitative assessment of interface resistance between fibers and texture elements demands micro scale evaluation of both fiber structures and texture surface profiles. In this dissertation, an advance image analysis process was adopted for this purpose and the details are described in Chapter 3. When compared with other methods, image analysis techniques have advantages in that detailed information about the microscopic structure can be collected by selecting the measurement surfaces, and
controlling the magnitude and resolution of the images. For this purpose, careful sample preparation and polishing techniques are essential. Furthermore, advanced thresholding techniques for digital image processing and quantitative evaluations are required for characterization of the microstructures.
CHAPTER 3
EXPERIMENTAL METHODS

3.1 Introduction

The previous chapter reviewed characterization methods used by others in the study of fabric structure and surface geometry. A brief review of the behavior of fabric-continuum interfaces was also included. This chapter describes the test program conducted to study the interaction of materials with different geometries. First, the properties of the test specimens are described, and the experimental setup and details on the test program are presented. Methods to quantitatively evaluate the geomembrane surface roughness profiles and single-fiber tensile properties are summarized. These tests are required to permit further analysis of the micro-scale interaction at fiber-texture interfaces. The image analysis techniques adopted to quantitatively evaluate the microstructure evolution of fiber-texture interfaces are also described.

3.2 Materials Tested

To investigate fiber-texture interaction, several materials currently used in practice were used in this study. The materials included four nonwoven geotextiles as well as smooth and textured HDPE geomembranes.

3.2.1 Geotextiles

Nonwoven fibers can be classified according to the bonding type between fibers as follows (DIN 61210, 1982):

- Frictional bonding by shrinking, pressing and pulling
- Frictional bonding and interlocking by needling / looping / swirling
- Adhesive bonding with liquid or solid bonding agent
- Cohesive bonding by part dissolving / welding
- Multiple bonding (combination of two or more of the above methods)

The needle-punched nonwoven type is the most widely used geotextile since its engineering properties fulfill the requirements for permeability, filtration, tensile properties, and frictional resistance. Such advantages of the needle-punched fibers are generated through the fiber-fiber bonding process and the resulting spatial arrangement of filaments. Descriptions of the geotextiles used in this study, that have different polymer types and mass per unit weights follow:

- Geotextile A (GSE NW 8): Polypropylene, staple fiber, needle punched nonwoven fabric with a mass per unit area of 8 oz/yd², manufactured by GSE Lining Technology, Inc.
- Geotextile B (GSE NW12): Polypropylene, staple fiber, needle-punched nonwoven fabric with a mass per unit area of 12 oz/yd², manufactured by GSE Lining Technology Co.
- Geotextile C (AMOCO 4510): Polypropylene, staple fiber, needle-punched nonwoven fabric with a mass per unit area of 10 oz/yd², manufactured by Amoco Fabrics & Fibers Co.
- Geotextile D (Trevira 011/280): Polyester, continuous filaments, needle-punched nonwoven fabric with a mass per unit area of 8 oz/yd², manufactured by Hoechst-Celanese Corp.

Detailed information regarding the properties of these tested geotextiles is provided in Table 3.1. The two GSE products were selected to investigate the role of thickness, mass density, and tensile strength of fibers on the evolution of interface resistance. Amoco 4510, which has an intermediate mass per unit area was used to study
the effective thickness of the fabrics on shear. Trevira 011/280 was chosen to study the role of different tensile properties of individual filaments during shear evolution.

Table 3.1 Summary of geotextile properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Fiber type</th>
<th>Test Methoda</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPb</td>
<td>Staple</td>
<td>D 5216</td>
</tr>
<tr>
<td>PP</td>
<td>Staple</td>
<td>D 4632</td>
</tr>
<tr>
<td>PP</td>
<td>Staple</td>
<td>D 4632</td>
</tr>
<tr>
<td>PEc</td>
<td>Continuous</td>
<td>D 4833</td>
</tr>
<tr>
<td>Mass per Unit Area, g/m²</td>
<td>270</td>
<td>405</td>
</tr>
<tr>
<td>Grab Tensile Strength, N</td>
<td>955</td>
<td>1,420</td>
</tr>
<tr>
<td>Grab Elongation, %</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Puncture Strength, N</td>
<td>525</td>
<td>835</td>
</tr>
<tr>
<td>Trapezoidal Tear Strength, N</td>
<td>420</td>
<td>555</td>
</tr>
<tr>
<td>Apparent Opening Size, mm</td>
<td>0.180</td>
<td>0.150</td>
</tr>
<tr>
<td>Permittivity, sec⁻¹</td>
<td>1.50</td>
<td>0.80</td>
</tr>
<tr>
<td>Permeability, cm/sec</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>Water Flow Rate, l/min/m²</td>
<td>4,480</td>
<td>2,440</td>
</tr>
</tbody>
</table>

Note: aASTM; bPP: Polypropylene; cPE: Polyethylene.

3.2.2 Geomembranes

High-density polyethylene (HDPE) is currently the most widely used geomembrane material due to its high tensile properties at low strain levels. Others commonly used include Very Flexible Polyethylene (VFPE), and Polyvinyl Chloride (PVC).

GSE HD is a smooth type geomembrane produced from formulated polyethylene resin. This product is designed for flexible geomembrane applications and contains 97.5% polyethylene and 2.5% carbon black. Compared with other products having similar thickness and tensile strength, this product exhibits a large elongation of about 700% after yield before reaching break point.
GSE HD Textured has upper and lower coextruded-textured surfaces. This product was designed to allow projects with steep slopes to satisfy specification GRI GM13 (GRI, 2003). Figure 3.1 shows typical surface images of smooth and textured geomembranes manufactured by GSE. The surface profiles of the geomembranes measured using a stylus profilometer are illustrated in Figure 3.2. The relative size of a 35 \( \mu m \) diameter filament is indicated for comparison purposes along with the profile of the textured geomembrane (Figure 3.2b). The engineering properties of the analyzed geomembranes are summarized in Table 3.2. More detailed information about texturing techniques of geomembranes is found in Donaldson (1994) and Lee (2000).

![Figure 3.1 Plan Images of Geomembrane Samples](image)

Figure 3.1 Plan Images of Geomembrane Samples: (a) GSE Textured (Single Sided Moderately Textured); (b) GSE HD Smooth: (GSE Lining Technology, Inc., 15.7 cm. x 11.8 cm).
3.2.3 Particulate Materials

In addition to geotextiles and geomembranes, particulate materials were used to observe the effect of overburden particles on the behavior of the geotextile-geomembrane interfaces. The selected particles included Ottawa 20/30, blasting sand, and two types of glass beads.

The blasting sand grains are angular and the Ottawa 20/30 sand grains are classified as poorly graded round to subrounded and composed primarily of silicon dioxide (US. Silica Company, 1997; Evans, 2005). Typical images of the sand specimen

Figure 3.2 Typical Surface Roughness Profiles of Geomembranes: (a) Smooth; (b) Textured.
particles are shown in Figure 3.3. The glass beads are borosilicate materials having high scratch resistance with Knoop hardness of 418 gf. The glass bead A has uniform size of 5 mm in diameter and glass bead B has an equivalent size to Ottawa 20/30 ($D_{50} = 0.72$ mm).

Figure 3.4 illustrates the grain size distribution of the selected materials. The index properties of the particles are given in Table 3.3.

Table 3.2 Properties of the Analyzed Geomembranes.

<table>
<thead>
<tr>
<th>Property</th>
<th>Smooth</th>
<th>Textured</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>1.4 nominal</td>
<td>1.4 nominal</td>
<td>ASTM D 5199</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>0.94</td>
<td>0.94</td>
<td>ASTM D 1505</td>
</tr>
<tr>
<td>Carbon black (%)</td>
<td>2.0</td>
<td>2.0</td>
<td>ASTM D 1603</td>
</tr>
<tr>
<td>Tensile Properties</td>
<td></td>
<td></td>
<td>ASTM D 6693</td>
</tr>
<tr>
<td>Strength at Break (N/mm-width)</td>
<td>43</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Strength at Yield (N/mm-width)</td>
<td>23</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>700</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Elongation at Yield (%)</td>
<td>13</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Tear Resistance (N)</td>
<td>187</td>
<td>187</td>
<td>ASTM D 1004</td>
</tr>
<tr>
<td>Puncture Resistance (N)</td>
<td>530</td>
<td>480</td>
<td>ASTM D 4833</td>
</tr>
</tbody>
</table>

Note: Source-GSE Lining Technology, Inc., product literature.

Table 3.3 Index Properties of the Particulate Materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>$D_{50}$ (mm)</th>
<th>$C_u^{a}$</th>
<th>$C_c^{b}$</th>
<th>$G_s^{c}$(g/m³)</th>
<th>$\varepsilon_{\text{max}}^{d}$</th>
<th>$\varepsilon_{\text{min}}^{e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa 20/30</td>
<td>0.67</td>
<td>1.46</td>
<td>0.96</td>
<td>2.65</td>
<td>0.732</td>
<td>0.501</td>
</tr>
<tr>
<td>Atlanta Blasting</td>
<td>0.74</td>
<td>1.48</td>
<td>0.96</td>
<td>2.65</td>
<td>1.07</td>
<td>0.734</td>
</tr>
<tr>
<td>Glass Beads φ 5mm (A)</td>
<td>5.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.48</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Glass Beads 20/30 (B)</td>
<td>0.71</td>
<td>1.18</td>
<td>0.93</td>
<td>2.48</td>
<td>0.73</td>
<td>0.581</td>
</tr>
</tbody>
</table>

Note: $^aC_u=D_{60}/D_{10}$; $^bC_c=D_{60}/(D_{10}xD_{90})$; $^c$AASHTO T133; $^d$ASTM D4254-91, Method B; $^e$ASTM D4253-93, Method 2A
Figure 3.3 Typical images of particles: (a) blasting sand; (b) Ottawa 20/30 sand (5.0 mm x 3.7 mm).

Figure 3.4 Grain Size Distribution of the Tested Materials.
3.3 Interface Shear Measurements

3.3.1 Previous Testing Devices

In geotechnical engineering, the shear resistance of soils has been measured using a variety of methods such as conventional direct shear, triaxial shear, simple shear, bi-axial shear, pullout resistance, and others. The direct shear device, or modifications thereof, have been commonly used to measure the interface resistance between combinations of materials including particulates, planar surfaces, fibers and composite materials. However, the conventional direct shear device has several limitations: 1) contact between the upper and the lower test box may cause overestimation of the resistance, 2) the net measurement area can vary with shear displacement, and 3) fine soils tend to leak at the gap between shear boxes or between the plane specimens and the edge of the inner surface of the shear box. For fabric-planar surface or fabric-particle interfaces, gluing or bolting the fibrous material to the testing platform may change the initial structures or surface properties. Furthermore, the unstable sliding of the shear box on a rough counter surface can cause significant errors.

As a solution to the problems mentioned above, researchers have often used pullout resistance devices in geosynthetic testing (Alobaidi et al., 1997; Bakeer et al., 1998; Perkins and Cuelho, 1999). Many researches have also applied various methods to explain their pullout test results: finite element method (Yogarajah and Yeo, 1994; Alobaide et al. 1997), and finite difference method (Gurung et al. 1999). However, the resistances measured by pullout tests tend to be underestimated due to the excessive stretching and thinning of the tested materials at or near the grab point. Another alternative method to reduce such system errors is the ring shear test (Stark et al., 1996).
This method has merit in that it can measure the large displacement residual stress of an interface without changing the net measurement area of the specimens. However, many engineering materials have anisotropic surface properties (e.g., most textured geomembranes have different surface relief in the machine and cross-machine directions due to the anisotropic extrusion coating or blown coextrusion process), so caution is required to avoid errors caused by the circular testing configuration.

3.3.2 Development of New Device

A large displacement direct interface shear device was designed and developed to reduce the system errors that often occur with conventional shear devices (Figure 3.5). The new device can be used to measure the interface resistances between different combination of materials: 1) two adjacent planar surfaces, 2) planar surfaces and particles, 3) planar surfaces and fabrics, and 4) planar surfaces and fabrics overlain by particulate materials. A platform on which a geomembrane specimen is fastened travels along a set of linear bearings (Thomson SPB-16 and ASB-16) that produce negligible system friction in the range of 0.1 to 0.2 % of the normal stress under the range of vertical test load of 680 kg.

Four threaded shafts are installed on the rigid walls mounted on either side of the sliding plate in order to robustly suspend the shear frame above the interface during specimen preparation and conditioning. The position of the shear frame is carefully adjusted using the four-screw system to ensure that it is horizontal. This minimizes system error caused by contact between the shear box and geomembrane specimen. The geotextile is folded around wedge-shaped plates on the leading edge of the shear box and secured by pressure fastening the wedges to a reaction wall. This allows shear induced
deformation and fabric strain to occur without the influences caused by gluing or screwing the geotextile to a rigid element.

Figure 3.5 Schematic Diagram of the Interface Shear Device (Kim and Frost, 2005).

The shear frame has a hollow half-cube shape, measuring 10.2 cm wide, 10.2 cm long, and 5.1 cm high. The four corners of the platen, as well as the inside of the frame, through which the vertical load is applied, were rounded to reduce any edge effects. When a fabric is used for the upper specimen on a planar sample, bonding the thin fiber to the bottom of the load plate, which is a technique used by previous researchers during sample preparation, can cause errors in the test results because such gluing may interfere with the movement and reorientation of the geotextile filaments during the tests. With the modified test equipment, the fabric is rolled up around the wedge-type plates and then fastened by squeezing the two adjacent wedges to the reaction wall with four threaded bolts. In this manner shear induced deformation and fabric extension is permitted.
A load cell and two LVDTs are installed on top of the platen which remains horizontally fixed during shearing. The shear resistance and corresponding lateral displacement are monitored with a horizontally mounted load cell and a LVDT, respectively. The LVDTs are DC-DC, which have non-linearity less than 0.5 percent, and the load cells have 1,000-pound capacity (SM Series, Interface Company) and nonlinearity nominally less than 0.03 percent of full scale. The complete experimental apparatus is shown in Figure 3.6.

3.3.3 Procedure for Sample Preparation

The geomembrane specimens were mounted on the testing platform measuring 20.3 mm (8 inches) wide and 27.9 cm (11 inches) in length. The geomembrane specimen size is 200 mm wide by 290 mm long, and is positioned with the manufacturing machine direction parallel to the shear direction. Three aluminum clamps were used to fasten the specimens to the platform. A geotextile specimen, approximately 10.2 cm (4 inch) wide by 25.4 cm (10 inch) long was fastened to the upper part of the system. The textile was rolled around the two adjacent wedges and then fastened by pushing wedges with four screw bolts to the supporting wall.

As previously noted, the geotextile fastened at the upper part of the equipment was supported by four shafts and the remaining portion of the geotextile was placed on the geomembrane surface, permitting strain during shear. The upper system was delicately adjusted using four sets of threaded bolts to ensure it was level. The platen has two openings on the bottom, which are connected to the cylindrical channel where two tubes are connected for the epoxy impregnation.
Figure 3.6 Experimental Setup for Interface Shear: (a) Rear View; (b) Side View.
3.3.4 Data Acquisition

The signals transmitted from load cells and LVDTs were collected by a data acquisition system (Module 34970A, Agilent Technology Company). The data acquisition setup consists three parts: a Data Acquisition/Switch Unit, a 16-Channel Multiplexer Module, and a USB/GRIB Interface. The Multiplexer module had a maximum scanning rate of 250 channels per second, so that the theoretical maximum frequency of data collection was 50 times per second from each of the five channels. This module had a resolution of 6.5 digits (22 bits) and a 50k reading nonvolatile memory including timestamp. External wiring was minimized, so that the resultant potential for noise to enter the system was reduced. The shear rate was controlled at 1.0 mm (~0.04 inch) per minute, and signals were collected once every ten seconds for each channel. The real time data were monitored by HP BenchLink Software installed at the Switch Unit.

3.3.5 Interface Shear Test Program

Table 3.4 provides details of the various test series conducted in this study. A total of six series of interface shear tests involving 132 cases were conducted with the normal stresses of 10, 50, 100, 200, 300, and 400 kPa. Series I was designed to investigate the role of strain and mass density of geotextile on the shear response against a smooth geomembrane. Series II were modeled to find the effect of geomembrane surface roughness on the interface shear resistance. Series III was designed to observe the effects of geotextile strain confinement on shear stress. Series IV was conducted to compare the geotextile inner structure at different level of shear strain. The compression and recovery behavior of the geotextile were monitored in Series V to VIII.
Table 3.4 Details of the Tests and Sample Preparation.

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Test Description</th>
<th>Specimen</th>
<th>Specimen Symbol</th>
<th>Test Number - Normal Stress (kPa)(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Residual/Smooth</td>
<td>GSE S / NW 8</td>
<td>S-R</td>
<td>21-10 20-50 07-100 08-200 09-300 19-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE S / NW 12</td>
<td>12S-R</td>
<td>24-10 23-50 10-100 11-200 12-300 22-400</td>
</tr>
<tr>
<td>II</td>
<td>Residual/Textured</td>
<td>GSE T / NW 8</td>
<td>8T-R</td>
<td>15-10 14-50 01-100 02-200 03-300 13-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 12</td>
<td>12T-R</td>
<td>18-10 17-50 04-100 05-200 06-300 16-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / AM</td>
<td>AM-T-R</td>
<td>315-10 314-50 301-100 302-200 303-300 313-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / TR</td>
<td>TR-T-R</td>
<td>215-10 214-50 201-100 202-200 203-300 213-400</td>
</tr>
<tr>
<td>III</td>
<td>Residual/Textured/Constrained</td>
<td>GSE T / NW 8</td>
<td>8T-R-C</td>
<td>415-10 414-50 401-100 402-200 403-300 413-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / AM</td>
<td>AM-T-R-C</td>
<td>515-10 514-50 501-100 502-200 503-300 513-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / TR</td>
<td>TR-T-R-C</td>
<td>615-10 614-50 601-100 602-200 603-300 613-400</td>
</tr>
<tr>
<td>IV</td>
<td>Peak/Textured</td>
<td>GSE T / NW 8</td>
<td>8T-P</td>
<td>33-10 32-50 25-100 26-200 27-300 31-400</td>
</tr>
<tr>
<td>V</td>
<td>Compression</td>
<td>GSE S / NW 8</td>
<td>8S-Com</td>
<td>57-10 56-50 43-100 44-200 45-300 55-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE S / NW 12</td>
<td>12S-Com</td>
<td>60-10 59-50 46-100 47-200 48-300 58-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 8</td>
<td>8T-Com</td>
<td>51-10 50-50 37-100 38-200 39-300 49-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 12</td>
<td>12T-Com</td>
<td>54-10 53-50 40-100 41-200 42-300 52-400</td>
</tr>
<tr>
<td>VI</td>
<td>Unloading from 50, 100, 200, 300, and 400 kPa to 10 kPa</td>
<td>GSE S / NW 8</td>
<td>8S-L-U</td>
<td>- 79-50 66-100 67-200 68-300 78-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE S / NW 12</td>
<td>12S-L-U</td>
<td>- 72-50 69-100 70-200 71-300 81-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 8</td>
<td>8T-L-U</td>
<td>- 73-50 60-100 61-200 62-300 72-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 12</td>
<td>12T-L-U</td>
<td>- 76-50 63-100 64-200 65-300 75-400</td>
</tr>
<tr>
<td>VII</td>
<td>Unloading from 200, 300, and 400 kPa to 100 kPa</td>
<td>GSE S / NW 8</td>
<td>8S-L-U-100</td>
<td>- - - 87-200 88-300 93-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE S / NW 12</td>
<td>12S-L-U-100</td>
<td>- - - 89-200 90-300 94-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 8</td>
<td>8T-L-U-100</td>
<td>- - - 83-200 84-300 91-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 12</td>
<td>12T-L-U-100</td>
<td>- - - 85-200 86-300 92-400</td>
</tr>
<tr>
<td>VIII</td>
<td>Unloading from 300, and 400 kPa to 200 kPa</td>
<td>GSE S / NW 8</td>
<td>8S-L-U-200</td>
<td>- - - 97-300 101-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE S / NW 12</td>
<td>12S-L-U-200</td>
<td>- - - 98-300 102-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 8</td>
<td>8T-L-U-200</td>
<td>- - - 95-300 99-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSE T / NW 12</td>
<td>12T-L-U-200</td>
<td>- - - 96-300 100-400</td>
</tr>
</tbody>
</table>

(a) Weight per unit area (oz./yd²) of GSE
(b) Test No. - Maximum Normal Stress (kPa)
T: Textured Geomembrane; S: Smooth Geomembrane;
R: Specimen Curing at Residual Stress; P: Specimen Curing at Peak;
C: Compression only; L-U: Loading-Unloading
NW: GSE nonwoven geotextile; AM: Amoco 4510; TR: Trevira 011/280

The relatively low normal stress of 10 kPa was used to observe the hook and loop interfaces within the fabric-texture surfaces, and 400 kPa was applied to check the linearity of stress-strain relationships under high pressure.
Detailed analysis of the geotextile-geomembrane shear response will be discussed in this chapter, which will cover the following subjects of the macro-scale analysis:

- Shear stress-strain relationship
- Effect of surface texture on interface resistance
- Effect of geotextile strain on interface resistance
- Relationship between normal stress-peak strain
- Effect of hook and loop on resistance evaluation
- Determination of geotextile-geomembrane installed slope stability
- Impact of geotextile strain on the shear-induced geomembrane surface degradation

3.4 Characterization of Surface Roughness

The surface topographies of geomembranes were measured using an integrated strain profilometer (Taylor-Hobson Form Talysurf Series 2) to quantify their surface characteristics. The schematic diagram of the device is given in Figure 3.7. The stylus tip was moved at a speed of 0.5 mm/sec and the total profile length was 50 mm. The gauge range for the relief was set at 2.1 mm and the data were acquired with a resolution of 32 nm in the vertical direction. For the textured geomembranes, measurements were conducted in shear direction. For the smooth geomembranes, the tri-sector sampling method proposed by Gokhale and Drury (1994) was adopted to obtain representative surface profiles. In order to remove the waviness component of the surfaces, a Gaussian roughness filter was used with a 2.5 mm cutoff and 8 μm low pass cutoff for both the smooth and textured geomembranes. The results were quantified using various surface roughness parameters as shown in Table 2.1.
Figure 3.7 The Integrated Strain Profilometer Apparatus: (a) Configuration of Geomembrane Surface Topography using Profilometer; (b) Side view; Adopted from Zettler, 2000.
3.5 Sample Preparation and Image Analysis Technique

3.5.1 Sample Preparation

In order to observe the internal microstructure near the geotextile-geomembrane interface, an epoxy impregnation method was adopted to encapsulate the compressed and/or sheared specimen under different boundary conditions. The platen had two inlet holes that are connected to epoxy impregnation tubes. Low-viscosity epoxy resin was impregnated into the specimen using air pressure of up to 8 kPa. Once fully impregnated, the specimens were allowed to cure for 12 hours. All specimen preparation and testing was conducted at ambient room temperature (~ 18 °C). Further details on the selection of epoxy resin and development of the impregnation techniques are found in Jang et al. (1999).

The epoxy-cured specimen of geomembrane-geotextile was removed from the equipment and a coupon of area 10.2 cm (4 inch) by 10.2 cm (4 inch) over which the footing was placed was extracted for secondary epoxy impregnation and curing. The difference in hardness of the layered or mixed materials usually causes difficulties in sectioning and polishing and makes getting high quality surfaces acceptable for image processing difficult. Cast acrylic plates were chosen as dummy layers to place at the top and bottom of the impregnated coupons because their hardness (Rockwell M 94) is close to that of the selected epoxy resin (Shore D Hardness 81). The layered specimens with the dummy plates were embedded in an epoxy resin bath and cured overnight to produce a larger coupon of sufficient thickness for sectioning.

After the secondary phase of resin curing, the specimens were dissected using a high precision saw as shown in Figure 3.8a (Isomet 1000 Precision Saw, Buhler, Ltd) to
enable the inner structure to be observed. The trisector method (Gokhale and Drury 1994) was selected to yield representative coupon surfaces from the specimens that incorporated smooth surfaced geomembranes under various normal stresses (Figure 3.9a). In this method, the sample images were gathered from three vertical sections, which had mutual orientation of 120 degrees. This method is known to be applicable to both isotropic and anisotropic materials and results in parameter estimation errors of less than about 5 percent. In contrast, the sheared specimens were cut to expose three orthogonal viewing planes, including the machine-direction, the cross-machine direction, and planar surfaces parallel to the geomembrane surface (Figure 3.9b). Then, the specimens were polished using a polishing machine (MultiPrep Polishing System, Allied Co.) as shown in
Figure 3.8b. Delicate polishing is critical in the preparation of surfaces to produce images of high quality for subsequent quantitative observations of the microscale interfaces of the texture-fiber. Three stages were used for the grinding and polishing as shown in Table 3.5.

Table 3.5 Procedures for Digital Image Analysis for Geomembrane-Geotextile Interfaces.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sampling and mounting</td>
<td>Selection of representative samples and setup for loading</td>
</tr>
<tr>
<td>2 Load application</td>
<td>Initial seating/compression/cyclic loading-unloading/shear</td>
</tr>
<tr>
<td>3 Epoxy impregnation/curing/cutting</td>
<td>Specimen sealing/epoxy flowing into geotextile pores - Cutting net specimen of the epoxy-cured layered specimen</td>
</tr>
<tr>
<td>4 Secondary curing</td>
<td>Addition of dummy thickness with acrylic plates to obtain required thickness for cutting and polishing - Epoxy saturation/curing</td>
</tr>
<tr>
<td>5 Cutting and Polishing</td>
<td>Trisector sampling in vertical sections for compressed specimens - Three orthogonal viewing planes/serial polishing in plane for sheared specimens</td>
</tr>
<tr>
<td>6 Image capture</td>
<td>Magnification control for appropriate resolution of the 640 x 480 pixel images - Serial capture of adjacent images</td>
</tr>
<tr>
<td>7 Image stitching</td>
<td>Image mosaic and blending - Obtain images covering the full region of interest having high resolution</td>
</tr>
<tr>
<td>8 Capture of image region in interest</td>
<td>Selection of image regions of interest</td>
</tr>
<tr>
<td>9 Feature detect/editing/binarization</td>
<td>Control of configuration of the images to obtain high contrast - Detection of feature in interest/binarization</td>
</tr>
<tr>
<td>10 Parameter collection and analysis</td>
<td>Collection of geometry and parameters of the feature in interest/analysis - Application of computer algorithm for operator-independent measurement</td>
</tr>
</tbody>
</table>
3.5.2 Process of Image Analysis

Once polished, images were captured from the various surfaces using a high-resolution digital microscope (Leica DM 4000). Each image contained a region 1.25 mm (width) by 0.94 mm (height) at 100x magnification. Adjacent images were stitched together to create larger mosaic images.
Table 3.6 Surface Preparation Method (Sources: Allied High Tech Products, Inc.)

<table>
<thead>
<tr>
<th></th>
<th>Wheel Surface</th>
<th>Lubrication Extender</th>
<th>Lubrication Description</th>
<th>Abrasive Type</th>
<th>Abrasive Description</th>
<th>Speed, rpm</th>
<th>Process time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8&quot; Silicon Carbide Disc</td>
<td>Distilled Water</td>
<td>-</td>
<td>600 Grit Adhesive Back</td>
<td>-</td>
<td>120</td>
<td>Until flat</td>
</tr>
<tr>
<td>2</td>
<td>8&quot; Silicon Carbide Disc</td>
<td>6 mm Polycrystalline Diamond Suspension</td>
<td>Glyco lubricant mixed with water.</td>
<td>GOLD LABEL (8&quot; Adhesive Back)</td>
<td>Woven durable, nap-free nylon with plastic backing used with diamond (15-3 micron) and any extender</td>
<td>120</td>
<td>13 min</td>
</tr>
<tr>
<td>3</td>
<td>8&quot; Silicon Carbide Disc</td>
<td>1 mm polycrystalline Diamond Suspension</td>
<td>Glyco lubricant mixed with water.</td>
<td>VEL-CLOTH (8&quot; Adhesive Back)</td>
<td>Low-napped, synthetic velvet with plastic barrier used with diamond (1-0.25 micron) or alumina</td>
<td>120</td>
<td>Minimum 10 minute or until getting desired quality of image</td>
</tr>
</tbody>
</table>
The various phases of the geosynthetic system were detected through a sequence of image processing functions. Figure 3.10 shows a portion of a mosaic image in the machine direction consisting of 5 columns by 3 rows of images. The underlying geomembrane as well as the individual geotextile filaments embedded in the epoxy resin can be readily seen. The initial gray scale image was binarized to allow the geotextile filaments and geomembrane profiles to be detected and analyzed (Figure 3.11). Procedures for sample preparation and image analysis are summarized in Table 3.6

Figure 3.10 Typical Mosaic Images from Geotextile-Geomembrane Interface Specimen: Gray Scale Image.
3.6 Characterization of Tensile Properties of Geotextile Filaments

3.6.1 Tensile Properties of Single Filaments

Most previous studies into the interaction between geotextiles and geomembranes have been limited to mechanical responses from large-scale perspectives. For example, Frost and Lee (2001) investigated the role of geomembrane textures on the evolution of interface friction against NPNW geotextiles, and quantified the degree of wear of
geomembrane surface textures in terms of surface roughness parameters. Similarly, while Hebeler et al. (2005) studied geotextile-geomembrane behavior in terms of “hook and loop” interaction, their experimental efforts focused on global rather than filament level response. It is obvious that the interface resistance is determined by the combined response of textures and filaments, however the sensitive unbonded nature of the filaments in nonwoven geotextiles have rendered the direct measurement of shear induced changes in their structure impractical to date.

The sample preparation and image analysis techniques used in this study enable the internal structure at geotextile-geomembrane interfaces to be observed (Kim and Frost, 2005; 2006). In order to quantitatively analyze the localized interlocking between geotextile filaments and geomembrane texture elements, the ability to characterize the tensile properties of single filaments is necessary.

Various techniques have been developed to characterize the tensile properties of single fibers. Typical test methods can be categorized into two types: (1) constant-rate-of-elongation (CRE) tests (Hindman, 1948); (2) constant-rate-of-loading (CRL) testes (Krais, 1928; de Meulemeester and Nicoloff, 1936). Due to creep effects, the two methods are known to provide differences if the stress-strain responses are non-linear. It is known that the CRE method shows higher strength values at low strain and lower values at large strain because of the greater amount of cumulative creep (Morton and Hearle, 1993). Specific test procedures and analysis methods are described in ASTM D 3822 and D 3379.

Even for natural fibers with low homogeneity and isotropy, fiber diameter or fineness, is known to be an important parameter that influences various physical
properties of fibers and textiles including stiffness, torsional rigidity, reflection of light, absorption of liquids, vapors, cohesion, and twist (Morton and Hearle, 1962; 1993). One of the most popular and traditional methods of measuring a fiber diameter is to use the projected surface image under a microscope. If the fiber has an oval cross-sectional shape, this method is achieved by dispersing a fiber 0.8 mm long in a suitable mounting medium and then observing the specimen in random directions. Other methods include the gravimetric (ASTM, 1954), air-flow (Lord, 1955), and vibroscope methods (Gonsalves, 1947).

3.6.2 Experimental Setup and Test Method

Tensile properties of single geotextile filaments were measured using an experimental device (Solids Analyzer Model RSA III, Rheometric Scientific Co.) for measuring and recording the stress-strain response of filaments. The device had a force resolution of 0.0002 grams, maximum force of $35N$ (3500 grams), and displacement resolution of $1 \times 10^{-6}mm$. A single fiber is centerline mounted using glue on a paper tab that has a slot at the center. Figure 3.12a presents a schematic diagram of a mounted specimen. The filament-mounted tab is gripped with a set of stationary jaws (Figure 3.12b) and then strained until the specimen is exposed to a small load less than one tenth of gram (Figure 3.12c). The tab is initially pulled using careful control of the tensile force to verify the axial alignment of the filament. After movement of the grips to ensure that the specimen is aligned straight, the paper tab is cut gently at the middle points of either side, ensuring that the force applied to the filament does not exceed the allowable variation range. The gage length (net measurement length of the filament) is 25 mm, and the extension rate is controlled to a constant value of 0.1 mm/sec. Data are collected at
the rate of 10 points per second (100 points per 1 mm extension). All other sample preparation and measurements protocols were conducted based on the procedures described in ASTM D 3379.

Figure 3.12 Specimen mounting method of a single filament: (a) tab and filament, (b) tab and filament in grip; (c) testing configuration.

Observing the change of filament diameter under tensile strain is necessary in order to be able to quantify the subsequent shear-induced change of filament sizes. Observing the surface image of a filament under a microscope is a widely used method to acquire the nominal diameter in practice. However, maintaining the required focus on the surface of a filament during tension testing is very difficult. This is because an optical microscope usually does not satisfy the two requirements for focusing at the same time: (a) a large range of measurement depth; (b) sufficient reflection of the light from the
filament surface into the eyepiece of the microscope. Precise focusing is essential to quantitatively and accurately measure the changing diameter of a filament in space and has technical limitations with conventional methods.

To overcome such measurement difficulties, the diameters \( d \) of single filaments were monitored at various strain levels using a helium neon gas laser beam. This device and associated method is based on the diffraction of light as shown in equation 3.1 (Park, 2006).

\[
d = \frac{m \lambda D}{\Delta y}
\]

(3.1)

where, \( \lambda \) is the wavelength of the laser beam, \( D \) is the distance between the filament and the image wall that the deflected lights reach, \( \Delta y \) is the interval of the reflected light element in which the center and \( n \)th bright zone of the reflected light image are measured, and \( m \) is a constant determined by the interval of the bright span of the reflected image.

Figure 3.13 shows a schematic diagram of the experimental setup that includes a laser projector and tensile strength facilities. For example, if the nearest bright point from the center image is selected among the detected points then \( m \) is set as 0.5. Similarly, \( m \) is 1.0 and 1.5 for the second and third points of bright zone. Helium neon gas which has a wavelength of 632.8 nm is used for the test. An important advantage of this method, particularly in this study, was that the measurements could be conducted during the tensile straining of filaments by recording the reflected beam images on the wall with a video camera.
Figure 3.13 Schematic Diagram of Filament Property Measurement: (a) Experimental Setup (Side View); (b) Light Diffraction (Plan View).

3.6.3 Measurement Parameters

The tensile behavior of single fibers can be expressed using various quantitative descriptors. The definitions and terminology illustrated in ASTM are summarized below.
(ASTM D 123, D3822, D3379), where tex is a unit of linear density that is equal to the mass in grams of a 1,000 meter long fiber. Denier (den) is another unit of linear density that is equal to the mass in grams of a 9,000 meter long fiber. Other definitions include:

- Breaking force, \( BF \) (\( mN \) or \( gf \)): maximum force applied to a fiber to carry the fiber rupture.
- Breaking tenacity, \( BT \) (gf/den): tenacity at breaking force.
- Breaking toughness, \( BTO \) (joule/den): energy absorbed to a specimen until rupture.
- Chord modulus, \( CM \) (cN/tex or gf/den): ratio of the change in stress to the change in strain between two specified points on a stress-strain curve.
- Elongation at peak, \( EP \).
- Initial modulus, \( IM \) (cN/tex or gf/den): ratio of the change in stress to the change in strain of the initial straight portion of the stress-strain curve.
- Linear density, \( LD \) (tex or denier): mass per unit length.
- Tangent modulus, \( TM \) (cN/tex or gf/den): the ratio of change in stress to change in strain derived from the tangent to any point on the stress-strain curve of a tensile test.
- Tenacity (specific stress), \( TN \) (gf/den): tensile stress expressed as force per unit linear density of the unstrained specimen.
- Tensile stress at specific elongation, \( TSSE \).
- Toughness, \( TO \) (work per unit volume; work per unit mass; work of rupture): capacity of a material to absorb energy required to a strain.
- Yield point, \( YP \): the point beyond which work is not completely recoverable and permanent deformation takes places.
3.7 Characterization of Tensile Properties of Geotextiles

3.7.1 Tensile Properties of Geotextiles

Tensile strength testing has been a widely used method to evaluate the engineering properties of various geosynthetics. This is attributed to the fact that many geosynthetics are designed to complement the relatively low tensile capacity of soils. Sliding failure at geotextile-geomembrane interfaces is known to accompany tension of geotextiles (Mitchell and Seed, 1990).

Leakage of leachate through damaged geomembranes is a hazard that geotechnical engineers often face in installed geomembranes. In order to avoid the degradation of geomembranes due to puncturing, tearing, or excessive tension, highly-flexible geomembranes have been developed. The highly-flexible geomembranes however, may cause excess strains which may result in low interface resistance as well as difficulties in handling in fields. In this study, geomembranes with relatively high rigidities were selected to quantify the effects of geotextile strain on the shear behavior, thereby limiting the effect of geomembrane strains. The tensile properties of geotextiles were characterized by laboratory testing.

3.7.2 Experimental Setup and Test Method

Wide-width tensile strength test is a popular method to evaluate the tensile properties of various geosynthetics (ASTM D 4595). Various studies have been conducted by many researchers about the effect of sample preparation on the test results (Myles and Carswell, 1986; Koerner, 1997; Jones, 2000; Mueller-Rochholz and Recker, 2000; Koerner, 2000). However, it is known that there is no universal relationship between specimen sizes and material properties (Koerner, 1998). In this study, 100 mm
wide by 200 mm long specimens were chosen in order to satisfy the ASTM recommendation and to match the specimen size used for the interface shear resistance tests conducted in this study. Figure 3.14 shows the typical experimental setup. One reason that the wide-width specimens are recommended is that geotextiles, particularly nonwovens tend to have a high Poisson’s ratio and the “rope-up” at high strain provides high values (Koerner, 1998). This problem was monitored and investigated during the experimental tests in this study.

Figure 3.14 Experimental Setup for Measuring Wide-Width Tensile Properties of a Geotextile (ASTM 4595); (a) Initial; (b) After Testing; (c) Side View.

- Equipment: Technology, Inc.
- Net Specimen Size: 4 in. (W) x 8 in. (H)
- Specimen: Polypropylene, staple fiber, NPNW
3.7.3 Measurement Parameters

Tensile properties of a geotextile can be expressed in terms of tensile strength, elongation, and various moduli. The definitions and terminology illustrated in ASTM are summarized below (ASTM D 4595).

- Tensile strength, $\alpha_f$ (N/m): maximum force per unit width at the textile rupture
- Initial tensile modulus, $J_i$ (N/m): the slope of the linear tangent line to the first straight portion of the force-elongation portion
- Offset tensile modulus, $J_o$ (N/m): slope of the linear tangent line between the tangent point and the zero-force axis
- Secant tensile modulus, $J_s$ (N/m): slope of the linear line between the zero-elongation and 10% or a certain elongation
- Breaking toughness, $T_u$ ($J / m^2$ or $in \cdot lbf / in^2$): often called work-to-break per unit surface area and calculated from the area of elongation-force relation

3.8 Summary

In this chapter, the details of the experimental tests and image analysis techniques used in this study were described.

A new interface shear device which allows the geotextile to strain during interface shearing against solid counterfaces was developed and used. The device was designed to analyze the response of textile-texture interfaces under various sequences of load-unload as well as interface shear with and without overburden materials. An advanced method of sample preparation and image analysis was implemented to investigate the microstructure evolution at the interfaces under various loading conditions.
Tensile strength tests for single filaments as well as wide-width geotextile tensile tests were undertaken to evaluate the change in microstructure of a NPNW geotextile and used to provide insight into compression and shear responses. The procedures followed during test setup, shear measurement, coupon preparation, and image analysis were summarized. The results and analysis of the experimental program will be discussed in Chapters 4 through 7.
CHAPTER 4
MECHANICAL INTERACTION BETWEEN GEOTEXTILES AND GEOMEMBRANES

4.1 Introduction

Failure at geotextile-geomembrane interfaces in field applications may involve a complex set of mechanisms involving both materials at the interface and may include tension and surface degradation near the interface. Previous researchers have used various methods when installing geotextiles in their laboratory test devices for measuring the geotextile-geomembrane interface shear resistances. Commonly used methods include gluing, bolting, overlapping around the footing, and confining with a dead load or cover soil. Field-installed geotextiles covering a geomembrane are often exposed to a high tensile stress due to the drag forces from overburden loads and construction equipment forces. Such phenomena are apparent in landfill sites where construction equipment moves on the landfill slopes to spread the waste over the covered area (Figure 4.1). In such cases, the stability of the interface is mostly dominated by the geotextile while the geomembrane is less subject to failure due to the relatively high rigidity and protection provided by the overlying geotextiles (Villard and Feki, 1999).

The failure modes of geosynthetics-installed slopes may be considered in three categories: 1) subsoil weakening/failure due to drainage through damaged geomembrane, 2) internal failure in geosynthetics; and 3) excess settlement or sliding of cover soil. Localized thinning, puncture, joint failure, and degradation by ultra violet are most common sources of geomembrane malfunction, while excessive stretching, surface
degradation, and clogging have been widely encountered problems threatening the geotextile installed geosynthetic slopes. The mechanisms associated with different boundary conditions and how they influence the strain within a geotextile or geomembrane have not been completely identified to date.

Figure 4.1 Tensile Mode of Geosynthetics in Field: Construction Equipment Placing Cover Soil on Slopes Containing Geosynthetics (Koerner and Daniel, 1997).

Lee (1999) reported the effect of geomembrane surface roughness or texture on stress-displacement mobilization at geotextile-geomembrane interfaces by performing shear tests with geotextiles against various geomembranes having different surface roughness characteristics. The impact of reusing geomembranes, which were exposed to wear by preceding shear tests, was quantified in terms of surface roughness parameters. General parameters that affect shear strength mobilization include the following:

- Geotextile: the tensile properties of both the textile sheet as well as single filaments, mass density, and the internal interlocking between filaments.

- Geomembrane: the hardness, tensile properties, texturing process and the resulting surface roughness characteristics
In this chapter, shear modes at geotextile-geomembrane interfaces will be studied by analyzing the results from shear tests including peak and residual shear resistances, displacement at peak, shear stress reduction at residual states, variation of coefficient of friction with confining stresses, and vertical displacement during shear. Such information will also be analyzed in terms of factors such as the geomembrane surface characteristics and the geotextile strain. The effects of test methods used to determine interface shear parameters will be discussed through calculation of factor of safety for a general case of a geosynthetic-reinforced slope. Results from this chapter based on global or engineering scale consideration will be discussed further in Chapter 5 where the results of numerical modeling are presented. Also, the results will be related to changes in the micro-mechanical geotextile filament structure as well as the geomembrane surface texture using microscopic observations and optical image analysis.

4.2 Effects of Geotextile Boundary Conditions on Stress-Displacement Curve

4.2.1 Resistance of Geotextile on a Smooth Geomembrane Surface

Textured, as opposed to smooth, geomembranes are typically used in landfill slopes in order to increase interface resistance. Various texturing techniques have been developed including coextrusion, impingement, lamination, and structuring (Hebeler, 2005). At the same time, smooth geomembranes are still widely used in various construction fields for functions such as waterproofing and separation. Comparison of the interface shear resistances of smooth and textured geomembranes against the same geotextiles can provide global scale insight into how texture elements and filaments interact and how they effect the resistance in engineering terms.
For interface shear tests, four geotextile sheets which were manufactured through needle-punching processes, were selected. The major difference between these materials are their mass density (mass per unit area) or thickness as well as the material from which the filaments are made. Detailed engineering properties of the materials were listed in Table 3.1. Four series of interface shear tests were conducted using the newly developed shear device (Table 3.4). The effects of geotextile strain during interface shear against a smooth and a textured geomembrane were observed. The constrained geotextile specimens were prepared by gluing the geotextile specimen on a surface of 0.5 cm thick dummy plates made of acrylic plates with 10 cm by 10 cm square shape, The geotextiles were overlapped around the dummy plates to avoid peeling of the specimen during interface shearing. The unconstrained geotextile specimens were prepared by fastening the geotextile around a set of wedge shape fastener (Figure 3.4). Detailed information about the sample preparation and test series were provided in Chapter 3.3.

Figure 4.2 presents the stress-displacement responses between a smooth HDPE geomembrane (GSE HD) and the two NPNW geotextiles under normal stresses ranging from 10 to 400 kPa. It is noted that the GSE NW8 (Figure 4.2a and c) resulted in higher resistances for both the unconstrained and constrained conditions even though GSE NW12 had higher mass per unit area and higher tensile stiffness.

Using the description of sliding friction suggested by Leonardo da Vinci in the fifteenth century, the following laws were republished by Amonton (1699) and have been known as the basic theory of friction (Bhushan, 1999)

- Friction force is proportional to the normal load
- Friction force is independent of the contact area
Figure 4.2 Shear Stress-Displacement Curve for NPNW Geotextile/Smooth Geomembrane: (a) Unconstrained Geotextile (A: 270 g/m²); (b) Unconstrained Geotextile (B: 405 g/m²); (c) Constrained Geotextile (A: 270 g/m²); and (d) Constrained Geotextile (B: 405 g/m²).
According to this theory, the coefficient of friction (the normalized friction), which is the ratio between resistance \( F \) and the normal force \( W \), may result in a constant. Most materials obey Amonton’s laws well, but polymers often show a change in coefficient of friction as the normal load increases as shown in Figure 4.3 (Archard, 1957).

\[
F = \mu \cdot W
\]  

(4.1)

Figure 4.3 Inconstant Coefficient of Friction of Polymethylmethacrylate (PMMA): (a) Lathe Turned, and (b) Polished (Archard, 1957).
The variation of coefficient of friction was relatively small as shown in Figure 4.4, compared to the textured geomembrane cases, which will be discussed in the next section. In general, the coefficient of friction decreased as normal stress increased at low normal stress levels, consistent with Hertzian contact theory, before becoming constant or
increasing slightly with further increases in normal stress. The peak resistances of the interfaces occurred at very low displacement levels (within about 2 mm as shown in Figure 4.2). Visual observation revealed that the strain of geotextile was very small throughout the test to pseudo-residual displacement of 80 mm for both the strain constrained and unconstrained cases. It is noted that greater displacement is required under higher normal stress to reach the peak resistance with a light geotextile (Figure 4.5a) while the thick geotextile resulted in small variation in the normal stress range of 50 to 400 kPa (Figure 4.5b). The result of the light geotextile (GSE NW8) shows a general feature of sliding friction (Bowden and Taylor, 1950). The greater interactions between filaments were found to be the dominant source of the low tensile strength geotextiles’ higher resistance. Strain confinement caused a resistance increase of 13 to 30 percent at peak and 14 to 50 percent at residual in the normal stress range of 100 to 400 kPa (Figure 4.6).

Figure 4.5 Effect of Geotextile Confinement on Mobilization of Displacement at Peak Resistance: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).
Figure 4.6 Effect of Geotextile Strain on Peak and Residual Resistances: Constrained/Unconstrained: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).

Strain softening, or the decrease of resistance after peak displacement is a common phenomenon in the interface shear response in most engineering materials, and the characteristics of post peak behavior varies with materials. The ratio of peak stress ($\tau_{\text{peak}}$) to pseudo-residual stress ($\tau_{\text{residual}}$) is called sensitivity.

$$\text{Sensitivity, } S_r = \frac{\tau_{\text{peak}}}{\tau_{\text{residual}}} \quad (4.2)$$

The variations in sensitivity throughout the range of normal stress used in this study (10 to 400 kPa) are similar for the unconstrained and constrained specimens. Constrained specimens (Figure 4.7).

The variation in shear resistance with regard to normal stress is often expressed in terms of Mohr-Coulomb criteria as shown in equation (4.3).
\[ \tau_s = c_a + \sigma \cdot \tan(\delta') \]  

(4.3)

where \( c_a \) is apparent cohesion and \( \delta' \) is the peak interface friction angle.

The Mohr-Coulomb relationships for the resistances are presented in Figures 4.8 and 4.9 for various test configurations performed in this study. Figure 4.8 shows the regression lines of failure envelope for the constrained and unconstrained geotextile against a smooth geomembrane. The results showed negligible or even slightly negative values of apparent cohesion. This means the resistance of the smooth geomembrane is attributed to the sliding friction resulting in low coefficient of friction at relatively low normal stress. Similarly, the residual failure envelopes are presented in Figure 4.9. The effects of different methods to calculate the friction parameters will be discussed in Chapter 4.4.

![Figure 4.7 Interface Strength Sensitivity](image)

Figure 4.7 Interface Strength Sensitivity: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).
Figure 4.8 Peak Failure Envelope for NPNW Geotextile/Smooth Geomembrane Interface: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).

Figure 4.9 Residual Failure Envelope for NPNW Geotextile/Smooth Geomembrane Interface: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).
4.2.2 Resistance of Geotextile Against a Textured Geomembrane Surface

4.2.2.1 Unconstrained Geotextiles

Shear stress-displacement curves for the four geotextiles tested using unconstrained and constrained conditions against a textured geomembrane are presented in Figures 4.10 and 4.11, respectively. The unconstrained conditions resulted in lower resistances with relatively lower initial moduli and larger strains at peak (Figure 4.10). The constrained geotextiles exhibited higher peak resistances with smaller displacements to peak (Figure 4.11). For both the unconstrained and constrained cases, the light GSE geotextile (NW8) exhibited slightly higher values of resistance compared to those for the heavy geotextile (NW12) under relatively high normal stresses of 300 and 400 kPa while at normal stress levels less than 300 kPa the light geotextile resulted in higher resistances (Figure 4.10a and b; 4.11a and b). The differences are attributed to the difference in geotextile-geomembrane interlocking depths under different normal stresses. The coefficient of friction decreased as the normal stress increased through a range of 10 to 400 kPa (Figure 4.12), which does not obey Amonton’s first law. It is noted that the coefficient of friction is affected by the surface condition of the counterface material also rather than the geotextile only.

The peak resistance occurred at larger displacements of 8 to 23 mm as the normal stress increased (100 to 400 kPa: Figure 4.10 and 4.13). Consistent with the smooth geomembrane cases greater displacement was required under higher normal stress to reach the peak resistance.

In general, the sensitivity of the constrained test increased as the normal stress increased (Figure 4.14). For Trevira geotextile (Figure 4.14c), the low value of sensitivity
Figure 4.10 Shear Stress-Displacement Curves: Unconstrained NPNW Geotextiles/GSE Textured Geomembrane: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.11 Shear Stress-Displacement Curves: Constrained NPNW Geotextiles/GSE Textured Geomembrane: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.12 Variation of Coefficient of Friction with Normal Stress: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.13 Effect of Geotextile Confinement on Mobilization of Displacement at Peak Resistance: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.14 Interface Strength Sensitivity: Peak/Residual Resistance: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
of the unconstrained cases at small displacements is due to the relatively loose filament structure at the geotextile surfaces. In the normal stress range of 100 to 400 kPa, the geotextile confinement resulted in increase of sensitivity by 0.15 to 0.3. Even if there are some variations in the trend, it is interesting to note that the responses usually follow the same trend under different boundary conditions in the normal stress range of 100 to 400 kPa (Figure 4.15). It is also consistent to the trend of similar coefficients of frictions for different geotextiles as shown in Figure 4.16.

The failures at peak shear displacement are considered to be the results of the decrease in interlocking caused by geomembrane surface deformations and geotextile structure degradation. Moreover, from the low degradation of geomembrane surfaces observed after testing and the high displacement at peak resistance, the geotextile structure was found to be the major component of the unconstrained geotextile response against textured geomembrane. Such a failure mechanism results in a smooth peak and gradual transition of the stress-displacement curves (Figure 4.10a, b and d). At the pseudo-residual displacement of 80 mm, limited geomembrane debris, or surface degradation, was observed. Increased normal stresses might make the local geotextile filaments denser adjacent to the surface of the geomembrane, resulting in deeper penetrations of the geomembrane texture elements into the geotextile, greater deformation of geomembrane textures, and stronger interlocking of the two materials during compression and shearing.
Figure 4.15 Effect of Geotextile Confinement on Shear Stress: Constrained/Unconstrained Resistance: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.16 Effect of Geotextile Types on Coefficient of Friction: (a) Peak (Unconstrained), (b) Residual (Unconstrained), (c) Peak (Constrained), and (d) Residual (Constrained).
4.2.2.2 Constrained Geotextiles

The stress-displacement response curves of the constrained geotextiles against the textured geomembranes were shown in Figure 4.11. The strain confinement resulted in more fluctuations in data during interface shear, particularly under higher normal stress levels. These unstable conditions at the post peaks may be due to the friction between the geomembrane texture debris generated by shear failure and virgin rough geomembrane surfaces, or the interlocking between the geomembrane textures and the bonded geotextile filaments, which have higher stiffness due to constrained tension.

The disturbance of the geotextile structure is limited to relatively shallow depths at a given normal stress, which differs from the unconstrained cases. The strain confinement of Trevira geotextiles resulted in higher resistance without significant changes in peak displacement levels. The higher resistance may be the result of the higher friction between similar type specimens made from polyester (i.e., materials having similar hardness tend to generate higher resistance). It is noted that the governing components of shear evolution for the unconstrained and constrained geotextiles are the tensile properties of the geotextile and the strength of the geomembrane texture elements, respectively.

4.3 Effect of Geomembrane Texture

The impacts of geomembrane texture on peak and residual frictional resistance increase were represented as peak stress ratio ($PSR$) and residual stress ratio ($RSR$), respectively.
\[ PSR = \frac{\sigma_{p_{\text{textured}}}}{\sigma_{p_{\text{smooth}}}} \]  
\[ RSR = \frac{\sigma_{r_{\text{textured}}}}{\sigma_{r_{\text{smooth}}}} \]  

where,  
\( PSR \) = Peak stress ratio between textured and smooth geomembranes  
\( RSR \) = Residual stress ratio between textured and smooth geomembranes  
\( \sigma_{p_{\text{textured}}} \) = Peak stress of textured geomembrane  
\( \sigma_{p_{\text{smooth}}} \) = Peak stress of smooth geomembrane  
\( \sigma_{r_{\text{textured}}} \) = Residual stress of textured geomembrane  
\( \sigma_{r_{\text{smooth}}} \) = Residual stress of textured geomembrane  

The \( PSR \) decreased semi-linearly for both constrained and unconstrained cases as the confining stress increased (Figure 4.17). This decrease is primarily due to the geomembrane texture deformation and failure under higher levels of normal stress. The lower value of \( RSR \) for unconstrained geotextiles under 10 to 50 kPa normal stress is regarded as the consequence of hook and loop effect (Figure 4.17c and d). It is noted that the hook and loop effect occurs when a dense geotextile surface contacts a textured surface.  

The peak and residual resistances of the smooth geomembrane were lower than those of the textured over the range of normal stresses tested. However, it is noted that the greater resistances often occurred on smooth surfaces at low displacement level less than 1 mm, particularly at high normal stresses up to 400 kPa and constrained conditions. Such results are consistent with the concept that large displacement is required for
interlocking to develop between two materials as a result of local texture deformation and filament densification.

Figure 4.17 Effect of Geomembrane Texture on Resistance: (a) Peak Stress Ratio: GSE NW8; (b) Peak Stress Ratio: GSE NW12; (c) Residual Stress Ratio: GSE NW8; (d) Residual Stress Ratio: GSE NW12.
4.4 Determination of Friction Angle and Its Effect on Factor of Safety

Lee (1999) reported that surface roughness has a first-order effect on the geotextile-geomembrane interfaces. Many researchers, including Stark et al. (1996) have also reported this observation.

Confinement of geotextiles during laboratory shear testing increased the coefficient of friction for the range of normal stresses tested, resulting in global friction parameter increases in both apparent cohesions and friction angles. The coefficients of friction were high at a normal stress level of hook and loop (10 kPa) and showed a significantly decreased value as the normal stress decreased to 50 kPa. The coefficients of frictions at residual stresses converged to a relatively constant value for both test boundary conditions.

The peak failure envelope to calculate the friction parameters of apparent cohesion and friction angle are illustrated Figure 4.18 and 4.19, respectively. The results are from two methods to draw the regression lines with and without considering the apparent cohesion (y-intercept) from the envelopes, which may vary the slope of the regression lines (friction angle).

The results are plotted again in Figure 4.20 to verify the effects of regression methods on design. Figure 4.20 shows the portion of contribution of apparent cohesion to the total interface resistance measurements, as a function of normal stress. Apparent cohesion in geosynthetics is often ignored however, this is known to cause overly conservative designs for practical applications.

Qian and Koerner (2004) reported on the effect of apparent cohesion of waste liner materials on the landfill stability analysis. By using the “two-part wedge analysis,” it was
noted that simply ignoring the apparent cohesion seriously underestimated the value of the factor of safety (FS). Figure 4.21 shows an ideal landfill, material properties, and boundary conditions. Figure 4.22 shows the variation of the factor of safety calculated using parameters obtained from shear-displacement test results for the given ideal landfill condition. The data of case A were calculated from four data points at a normal stress range of 100 to 400 kPa, where the linear regression was drawn considering the apparent cohesion (y-intercept) from peak and residual failure envelopes illustrated in Figure 4.18 and 4.19. The data of case B were collected by the method of linear regression drawn from the origin on the graphs. Similarly, the cases C and D were generated in the normal stress range of 10 to 400 kPa with the methods of considering and not considering the apparent cohesion. For each of the boundary conditions, the FS values varied depending on the method of determining the friction parameters (A-D in Figure 4.22). The FS of the GSE geotextile installed slopes decreased by 15 to 40 % from the reference values, which are calculated for four data points at a normal stress range of 100 to 400 kPa, keeping in consideration for the apparent cohesions (y-intercepts). The Trevira and Amoco geotextiles showed more variation in a range of 40 to 15 % and 40 to 7%, respectively. Comparable results were found for the smooth geomembrane cases (Figure 4.23).

It is interesting that although the normalized frictions had similar values through 50 to 400 kPa of normal stresses, the portion of friction components under each normal stress were different (Figure 4.20). Again, the regression method of Mohr-Coulomb criteria must be carefully selected because a small change of combination of cohesion and friction angle (Figure 4.18 and 4.19) resulted in fairly significant changes in FS values (Figure 4.22).
Figure 4.18 Peak Failure Envelope for Textured Geotextile/Geomembrane Interface: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.19 Residual Failure Envelope for Textured Geotextile/Geomembrane Interface: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.20 Effects of Boundary Condition: Portion of Cohesion on Resistance: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.21 Forces Acting on a Waste Mass in A Landfill Slope and Its Ideal Conditions (X. Qian and R. M. Koerner, 2004).

4.5 Vertical Displacement and Shear Mode

Measuring vertical displacements or volume changes of specimens is essential for evaluation of geomaterial shear characteristics in experimental tests. However, such a measurement has historically not received much attention in geosynthetic interface studies regardless of its importance in understanding the mechanism of interface shear mobilization and failure.
Figures 4.24 and 4.25 show the vertical displacement of geotextile-textured geomembrane layers under unconstrained and constrained boundary conditions, respectively. It is interesting that the displacements, or thickness decrease in strain-

![Diagram](image)

**Figure 4.22 Effect of Boundary Conditions and Regression Methods on Factor of Safety:** Textured Geomembrane: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.

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**Determination of Friction Parameters**

- **A:** Stress range of 100 to 400 kPa; Apparent cohesion considered
- **B:** Stress range of 10 to 400 kPa; Apparent cohesion considered
- **C:** Stress range of 100 to 400 kPa; Apparent cohesion neglected
- **D:** Stress range of 10 to 400 kPa; Apparent cohesion neglected.
Figure 4.23 Effect of Boundary Conditions and Regression Methods on Factor of Safety: Smooth Geomembrane: (a) GSE NW8; (b) GSE NW12.

Constrained geotextiles are larger than the unconstrained displacements. In unconstrained interfaces, the stretching of geotextiles is found as the major contributor to thickness reduction, where geomembrane texture elements are deformed in the shear direction and the vertical displacement of the geotextile occurs during shearing. Higher normal stresses might cause more stress concentrations at the contact points and more deformation of both the geotextile structure and the geomembrane texture elements. The displacements at the maximum dilation points and peak resistance points are very similar, as seen in Figure 4.24 and 4.26. The denser geotextiles structures under higher normal stress required larger displacements to reach the peak resistance by tension-shear combination of geotextiles (Figure 4.26).
Figure 4.24 Vertical Displacement: Unconstrained: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Figure 4.25 Vertical Displacement: Constrained: (a) GSE NW8, (b) GSE NW12, (c) Trevira 011/250, and (d) Amoco 4510.
Generally, interface shear resistance increases with confining stress for most materials. However, resistances between nonwoven fabric and rough surfaces often generate much greater resistance than typical friction values, particularly under low confining stress. Such a phenomenon is called the hook and loop effect, and an evaluation...
method is available in ASTM standard (ASTM D 5169) to measure this effect. In this test program, such a phenomenon was observed by performing shear tests at 10 and 50 kPa. Figure 4.27 shows a typical feature of hook and loop effects following 80 mm displacement under 10 kPa loading.

![Figure 4.27 Hook and Loop Effect between NPNW Geotextile and Textured HDPE Geomembrane (10 kPa normal stress; Trevira 011/280 Geotextile; GSE Textured Geomembrane).](image)

The geotextiles tested against smooth geomembranes also resulted in vertical displacement during shearing (Figure 4.28). The vertical displacement decreased to a near constant value as the horizontal displacement reached the residual state for constrained tests on light weight geotextile (Figure 4.28a). In contrast to the results from tests on textured geomembranes, the strain confinement in shear direction increased the vertical displacement during shear (Figure 4.28b and d). It is noted that geotextile filaments are rearranged by interface shear against a smooth surface at low shear displacement. The resistance by sliding component of friction constrains the filaments adjacent to the interface while the other filaments are rearranged and this process last
until the resistance reaches the peak. The geotextile strain confinement increases the sliding component resulting in large values of peak shear displacement and vertical displacement. At the pseudo-residual state, a small amount of geotextile stretching was observed and the vertical displacements were regarded as the results of initial reorganization of geotextile filaments.

Figure 4.28 Vertical Displacement: (a) Unconstrained: GSE NW8; (b) Unconstrained: GSE NW12; (c) Constrained: GSE NW8; (d) Constrained: GSE NW12.
4.6 Effects of Overlaying Materials on Interface Shear

In field applications, geotextile-geomembrane lining systems are usually exposed to various loads by overlying materials and construction equipment during installation and normal operations. The cover materials may including soils, wastes, other geosynthetics, or multiple layers of such materials and may cause clogging, stress concentration, and resulting local deformation of the geosynthetics. The unconstrained boundary condition discussed above did not take the role of cover materials into account. The new interface shear device developed in this study was also designed to allow the role of overburden material properties on the shear evolution to be considered. In this section, the effects of cover soil on the geotextile-geomembrane interface resistance is investigated from interface shear tests using four particulate materials.

4.6.1 Materials and Testing Programs

The selected particulate materials included Blasting sand, Ottawa 20/30 sand, and two different glass beads. The two sand specimens were prepared to observe the effects of overlying particle shape on the geotextile-geomembrane interface resistance. The glass beads 20/30 has uniform size distribution similar to the sands and the glass bead with 5 mm diameter were selected to see the impact of particle size on the interface resistance. Index properties and more detailed information were illustrated in Table 3.3. A schematic diagram of the layer components of the interface shear tests are illustrated in Figure 4.29.

Two geotextiles (A and B) and both the smooth and textured geomembranes as shown in Table 3.1 and 3.2 were used in this phase of the study. A normal stress of 100 kPa was selected as a reference confining stress to evaluate the effects of cover materials and boundary conditions of the tests. The test conditions are summarized in Table 4.1.
Figure 4.29 Schematic Diagram of the Layer components of Interface Shear Tests with Overburden Materials.

Overburden materials:
- Blasting Sand
- Ottawa 20/30
- Glass Bead 20/30
- Glass Bead 5 mm dia.

Geotextile:
- GSE NW8 (A)
- GSE NW12 (B)

Geomembrane:
- GSE HDPE Smooth
- GSE HDPE Textured

Figure 4.30 Effects of Geotextile Strain Condition on the Interface Shear of a Smooth HDPE Geomembrane Against NPNW Geotextiles: (a) Geotextile A (270 g/m²); (b) Geotextile B (405 g/m²).
Table 4.1 Summary of Shear Testing with Various Cover Materials.

<table>
<thead>
<tr>
<th>Geotextile</th>
<th>Geomembrane</th>
<th>Cover material</th>
<th>$\tau_{\text{peak}}$ (kPa)</th>
<th>$\delta_{\text{peak}}$ (mm)</th>
<th>$\tau_{\text{residual}}$ (kPa)</th>
<th>Sensitivity</th>
<th>Geotextile strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (270 g/m²)</td>
<td>Coextruded</td>
<td>Blasting sand</td>
<td>78.6</td>
<td>5.6</td>
<td>42.2</td>
<td>0.54</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>A (270 g/m²)</td>
<td>Coextruded</td>
<td>Ottawa 20/30</td>
<td>78.1</td>
<td>7.6</td>
<td>48.0</td>
<td>0.61</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>A (270 g/m²)</td>
<td>Coextruded</td>
<td>Glass bead 5mm Dia.</td>
<td>62.9</td>
<td>20.3</td>
<td>44.9</td>
<td>0.71</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>A (270 g/m²)</td>
<td>Coextruded</td>
<td>Glass bead 20/30</td>
<td>64.9</td>
<td>34.5</td>
<td>34.3</td>
<td>0.53</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>B (405 g/m²)</td>
<td>Coextruded</td>
<td>Blasting sand</td>
<td>68.2</td>
<td>8.1</td>
<td>35.8</td>
<td>0.52</td>
<td>Unconstrained</td>
</tr>
<tr>
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<td>Coextruded</td>
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<td>45.1</td>
<td>8.4</td>
<td>27.8</td>
<td>0.62</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>B (405 g/m²)</td>
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<td>Glass bead 5mm Dia.</td>
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<td>11.9</td>
<td>33.4</td>
<td>0.60</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>B (405 g/m²)</td>
<td>Coextruded</td>
<td>Glass bead 20/30</td>
<td>66.3</td>
<td>13.1</td>
<td>38.2</td>
<td>0.58</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>A (270 g/m²)</td>
<td>Smooth</td>
<td>Acrylic plate block</td>
<td>22.2</td>
<td>0.5</td>
<td>16.3</td>
<td>0.73</td>
<td>Constrained</td>
</tr>
<tr>
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<td>Acrylic plate block</td>
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<td>0.3</td>
<td>11.0</td>
<td>0.61</td>
<td>Unconstrained</td>
</tr>
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<td>Blasting sand</td>
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<td>0.4</td>
<td>11.5</td>
<td>0.76</td>
<td>Unconstrained</td>
</tr>
<tr>
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<td>Glass bead 5mm Dia.</td>
<td>22.2</td>
<td>1.2</td>
<td>16.1</td>
<td>0.73</td>
<td>Unconstrained</td>
</tr>
<tr>
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<td>Acrylic plate block</td>
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<td>1.2</td>
<td>16.1</td>
<td>0.81</td>
<td>Constrained</td>
</tr>
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<td>Acrylic plate block</td>
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<td>11.4</td>
<td>0.69</td>
<td>Unconstrained</td>
</tr>
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<td>Smooth</td>
<td>Blasting sand</td>
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<td>14.2</td>
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<td>Unconstrained</td>
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<td>Glass bead 5mm Dia.</td>
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<td>0.6</td>
<td>16.7</td>
<td>0.77</td>
<td>Unconstrained</td>
</tr>
</tbody>
</table>

4.6.2 Smooth Geomembrane

The effects of the cover materials on the interface resistance of the unconstrained geotextile-geomembrane system were further studied by performing a series of tests with a smooth geomembrane. Results for tests with no cover materials are shown in Figure 4.30 for geotextiles having different mass per unit area. It is noted that constraining the top surface of the geotextile with gluing method has an effect of increasing the adhesion component of the sliding friction. The constrained geotextile shows increases in peak shear stress of 23 % and 21 % for geotextiles A and B, respectively.

The effects of cover materials are illustrated in Figure 4.31a and b. The conventional direct shear test result of the blasting sand, which was conducted to provide reference
data, showed coefficient of friction of 0.75 under a normal stress of 100 kPa and displacement at peak of 1.9 mm (Figure 4.31c). For both the light and heavy geotextiles, the large cover particles produced higher resistance than the blasting sands. Differences in resistance between the unconstrained geotextile and the geotextile covered with large particles show changes in the major component of shear from adhesion to deformation, caused by the particle size increase and its impact.

Figure 4.31 Effects of Cover Particles on the Interface Shear of a Smooth HDPE Geomembrane Against NPNW geotextiles: (a) Geotextile A (270 g/m²); (b) geotextile B (405 g/m²); (c) Reference Data of Direct Shear Test Results of Soils.
Figure 4.32 shows an example image of surface profiling that the large glass beads with 5 mm diameter induced through the thin geotextile during interface shearing. Such shear induced surface degradation is observed in microscopic scale as shown in Figure 4.33, which indicates that the sliding friction occurred by indentation of the individual geotextile filaments into the geomembrane surface by the high stress concentration from the overburden particles.

Figure 4.32 Shear-Induced Profiling Remained on a Smooth Geomembrane Surface through a Unconstrained Geotextile by Overlying Glass Beads of 5 mm Diameter — Image 13.4 cm x 9.97 cm.
Figure 4.33 Surface Degradation of Smooth Geomembrane by Interface Shear Against NPNW Geotextile Having Different Cover Particles: (a) Intact Surface; (b) Geotextile A (270 g/m²)-Blasting sand; (c) Geotextile B (405 g/m²)-5 mm Diameter Glass Beads; (d) Geotextile A (270 g/m²)-5 mm Diameter glass Beads — Image 1,254 µm x 941 µm.
4.6.3 Textured Geomembrane

The effects of geotextile strain condition and cover soils for textured geomembranes are presented in Figure 4.34. The stress-displacement response of the constrained geotextile shows a lower displacement to peak but high resistance for both the peak and pseudo-residual shear displacements (Figure 4.34a) than the unconstrained configuration. The geotextile covered by blasting sand (Figure 4.34b) exhibited similar results to those of the constrained specimen (Figure 4.34a), showing displacement of about 6 mm to peak.

Figure 4.34 Interface Shear results of a Coextruded HDPE Geomembrane Against NPNW Geotextile A (270 g/m²): (a) Smooth Cover Surface; (b) Cover Soil Overburden.

Figure 4.34b shows that the peak resistance of the geotextile-geomembrane occurred at 7 mm displacement with coefficient of friction of 0.78. Therefore, it is evident that the peak resistance occurred at the geotextile-geomembrane interface since this resistance is greater than that of the geotextile. The geotextile-geomembrane interface underlain by rounded sand particles (Ottawa 20/30) showed nearly the same peak resistance as the
blasting sand and higher residual stresses by 14% at large displacement. Comparable data were found at the interface with the thick geotextile having a mass per unit area of 405 g/m² against the same geomembrane as shown in Figure 4.35. The thick geotextile resulted in low resistance under the same test conditions with both the angular and rounded cover soils. Decrease of resistance due to such a geotextile difference was found to be about 13.2% for the blasting sand and 42.3% for Ottawa 20/30, respectively.

Figure 4.35 Interface Shear Results of a Coextruded HDPE Geomembrane Against NPNW Geotextile B (405 g/m²): (a) Smooth Cover Surface; (b) Cover Soil Overburden.

Figure 4.36 shows the results for tests performed with large size borosilicate balls. The light geotextile (A) with the mass per unit area of 270 g/m² shows a different shape of stress-strain envelope. The data was verified by repeating the test under the same condition. The shear-induced strained geotextile length at residual displacement was about 19 mm and matched with the displacement at peak resistance of the interface. The first yield point is considered as the result of the rearrangement of the large particles.
affected by the geomembrane texture relief through the thin geotextile layer, which was followed by the geotextile-geomembrane interface failure. The uniformly graded large glass beads having 5 mm diameter allowed the geotextile strain but still the stress concentration through the geotextile particles resulted in higher resistance at large displacement. The thick geotextile (B) with mass per unit area of 405 g/m² also showed a similar amount of stretching at residual displacement state to the displacement at peak resistance. The displacement between the first yield and the subsequent failure point of geotextile A is nearly the same as the displacement at peak for the geotextile B. The designed test device is considered to be appropriate for investigating the shear mechanism influences of overlying particle shape, relative particle size to the geomembrane texture relief in combination with the geotextile thickness and resulting stress dissipation effects.

Figure 4.36 Interface Shear Results of a Coextruded HDPE Geomembrane Against NPNW Geotextiles Covered with 5 mm Diameter Spherical Particles.
4.7 Summary and Conclusions

This chapter presented the results of an investigation into the role of geomembrane surface texture and geotextile strain on shear evolution. From experimental tests using a new interface shear device, the friction parameters determined for different boundary conditions and their effect on a slope design were quantitatively studied. The following conclusions are provided, based on the experimental test results in this chapter:

4.7.1 Smooth Geomembrane/NPNW Geotextile

- For interfaces with a smooth geomembrane, the unconstrained geotextiles resulted in slightly higher sensitivity over the same range of normal stresses. The results may be due to the interlocking and resistance of geotextile filaments near the interface, which are the major sources of the sliding friction on a smooth surface.

- The coefficients of friction were 0.16 to 0.20 for unconstrained geotextiles and 0.20 to 0.27 for constrained geotextiles, respectively.

4.7.2 Moderately Textured Geomembrane/NPNW Geotextile

- For interfaces with a textured geomembrane, the constrained geotextiles showed higher sensitivity over the range of 50 to 100 kPa normal stress. The results are due to the initial strong interlocking of texture-geotextile elements and the subsequent wear of textures at peak resistance.

- The moderately textured geomembrane resulted in a higher coefficient of friction than the smooth geomembrane with values in the range of 0.41 to 0.55 for the unconstrained geotextiles and 0.55 to 0.73 for the constrained.

- Stretching of the geotextile is found to be the major contributor to the thickness reduction during unconstrained interface shearing of geotextile-geomembrane systems, where the geomembrane texture elements are deformed in the shear direction and vertical displacement increases.
- The higher normal stresses cause greater stress concentrations at contact points, and also more deformation of both the geotextile structure and geomembrane texture elements.

- The release of geotextile strain during interface sliding across textured geomembrane surfaces resulted in decreases of 25% to 53% of peak and 20% to 27% of residual resistance, respectively.

- The strains at the maximum dilation points and peak resistance points were very similar at the unconstrained geotextile against a textured geomembrane.
CHAPTER 5

MODELING OF GEOTEXTILE-GEOMEMBRANE INTERFACES

5.1 Introduction

In Chapter 4, the shear behavior of geotextile-geomembrane interfaces were experimentally studied in terms of boundary conditions including geomembrane surface roughness, geotextile strain, and the effect of overburden particle characteristics. In geotechnical engineering, numerical methods have been applied to investigate the response of soil systems under various boundary conditions using FEM (Finite Element Method), FDM (Finite Difference Method), or DEM (Discrete Element Method). Most studies have focused on the behavior of soil and rock systems with very limited study of the response of geosynthetic systems.

Numerous studies have been conducted to evaluate the geotextile-geomembrane shear responses (Martin et al., 1984; Williams and Houlihan, 1986; Koutourais and Sprague, 1991; Ojeshina, 1991; Stark et al., 1996; Jones and Dixon, 1998; Lee, 1999) however the interface shear mechanism was only expressed in terms of the friction parameters. Thus, quantitative descriptions to express the characteristics of interface are required.

In this chapter, the interfaces discussed in Chapter 4 are further studied using numerical modeling. The interface and its responses are modeled using FDM. By comparing the shear responses obtained from the laboratory tests and modeling results of the interface using Mohr-Coulomb criteria with strain softening, the geotextile-
geomembrane interfaces are characterized and the effects of material stiffness on the interface responses are discussed.

5.2 Constitutive Model

5.2.1 Simulation of Equivalent Shear Band

The large displacement shear at geotextile-geomembrane interfaces was simulated using the finite difference code of FLAC (Fast Lagrangian Analysis of Continua). The basic process of modeling involves various steps including: defining the grid boundaries, modeling the materials elements, generating the mesh based on the grid points, and defining the materials properties.

The model geometry was defined into three components including the geomembrane, the interface layer, and the geotextile. For convenience, each grid element of geomembrane and interface were divided into three regions in order to control the size, and number of mesh elements within and outside of the geotextile-geomembrane interface zones. Moreover by defining the mesh elements with symbols, the geometry, size and the density of grid elements could be easily controlled.

The Mohr-Coulomb model was used to simulate the interface resistance in the elastic region and strain-softening model was used to trace the post peak/plastic shear response.

To simplify and increase the calculation efficiency, the boundary conditions were specified for the geotextile, geomembrane and the interface, and the experimental devices were eliminated. The unconstrained boundary condition of the geotextile was considered by fixing the rear edge of the geotextile in the shear direction).
The interface was specified with the peak and residual friction angles, and the shear and normal stiffness. The shear resistance was measured at both the interface and the boundary of the geomembrane adjacent to the interface. The shear displacement was applied by a command of xvelocity which is applied at gridpoint at the bottom of geomembrane on the model boundary.

5.2.2 Simulation of Strain-Softening Behavior

5.2.2.1 Plastic Hardening/Softening Model

In FLAC, plastic shear strain is measured by the shear hardening parameter \( e^{pr} \) that is defined as Equation (5.1).

\[
\Delta e^{pr} = \left\{ \frac{1}{2} \left( \Delta e_i^{pr} - \Delta e_m^{pr} \right)^2 + \frac{1}{2} \left( \Delta e_m^{pr} \right)^2 + \frac{1}{2} \left( \Delta e_3^{pr} - \Delta e_m^{pr} \right)^2 \right\}^{1/2}
\]

\[
= \frac{1}{\sqrt{3}} \left[ \left( \Delta e_i^{pr} \right)^2 - \left( \Delta e_i^{pr} \Delta e_j^{pr} \right) + \left( \Delta e_j^{pr} \right)^2 \right]^{1/2}
\]

(5.1)

Where, \( \Delta e_j^{pr} = \frac{1}{3} \left( \Delta e_i^{pr} + \Delta e_3^{pr} \right) \) and \( \Delta e_j^{pr} , j = 1, 3 \) are the principal plastic shear strain increments. \( \Delta e_j^{pr} \) is the increments of plastic principal strain (Itasca, 1998).

The interface shear tests described in Chapter 4 involved large displacement. FLAC allows building user-defined functions for cohesion, friction, dilation and tensile strength.

The stress-strain curve is common in geomaterials that have a yield point and soften thereafter into residual strength as illustrated in Figure 5.1. The curve is assumed to be linear to the yield point where the strain is considered as elastic: \( e = e^e \). After yield, the total strain is composed of elastic and plastic components: \( e = e^e + e^p \). The user can
define the variation of parameters as a function of the plastic strain with regard to the softening/hardening model of the response.

Figure 5.1 Definition of Elastic and Plastic Shear Components from a Stress-Strain Curve (Itasca, 1998).

Figure 5.2 illustrates a methodology for estimating progressive mobilization of shear strength parameters with regard to the plastic strain (Stematiu et al., 1991; Popescu, 1993; Nobahar et al., 2001).

The shear stress corresponding to plastic displacements of $\delta_i$ are measured with various normal stress magnitudes (Figure 5.2a) and the results are plotted with regard to the normal stress in Figure 5.2b from the linear regression. The components of cohesion and friction angle are obtained about the plastic strain by mapping (Figure 5.2c). Finally, the mobilized shear strength parameters are expressed in terms of the plastic strain (Figure 5.2d).

In this study, the plastic portions of the shear-displacement curves were determined for the normal stress range of 50 to 400 kPa. Figure 5.3 shows the concept of mapping used in this study to model the post peak shear envelope in which the response before peak stress was assumed to be in the elastic range (Figure 5.3a and b). The
interface shear data obtained in this study showed an increase of the strain at peak with normal stress, particularly for the unconstrained geotextile (Figure 4.10 and 4.13). Therefore, the range of the shear curves for the mapping was selected with regard to the different strains at peak for each test (Figure 5.3b). The friction angle and apparent cohesion can be expressed linearly with plastic strain (Figure 5.3c and d).

![Diagram](image)

Figure 5.2 Estimation of Progressive Mobilization of Shear Strength Parameters from Direct Shear Test: (a) Direct Shear Test Results; (b) Estimation of Shear Strength Parameters at Different Displacement; (c) Shear Strength Parameters with Horizontal Displacement; (d) Variation of Parameters with Plastic Strain (After Nobahar et al. 2001).
Figure 5.3 Mapping of Plastic Behavior: (a) Separation of Elastic and Plastic Strains; (b) Plastic Portions of Shear Envelope; (c) Variation of Friction Angle with Plastic Displacement; (d) Variation of Apparent Cohesion with Plastic Displacement.

In FLAC, the interfaces can be characterized by Coulomb sliding or tensile separation (Itasca, 1998). An interface is considered as a combined form of a normal and shear stiffness ($k_n$) as shown Figure 5.4. The incremental relative displacement vector at the contact point is resolved into the normal and shear directions, and total normal and shear forces are determined by Equation (5.2).
\[
F_n^{(t+\Delta t)} = F_n^{(t)} - k_n \Delta u_n^{(t+1/2)\Delta t} L
\]

\[
F_S^{(t+\Delta t)} = F_S^{(t)} - k_s \Delta u_s^{(t+1/2)\Delta t} L
\]

(5.2)

where the stiffness, \(k_n\) and \(k_s\) have the unit of stress/displacement.

Figure 5.4 An Interface Connected by Shear (ks) and Normal (kn) Stiffness Springs (Itasca, 1998).

**5.2.2.2 Description of Input Data**

Figure 5.5 shows a schematic diagram of the generated grid mesh for the geotextile, geomembrane, and the subsurface. Normal stress is applied on the top of the geotextile. In order to avoid the shock effect, the shear rate was chosen as \(1.0 \times 10^{-5} /\text{time step}\).

The properties of the materials used for the simulation are summarized below and in Table 5.1. The bulk and shear modulus were calculated from general equation in terms of Young’s modulus and Poisson’s ratio, using the wide-width tensile test results.
where effective stress friction angle is $30^\circ$, residual friction angle is $20^\circ$, dilation angle at initial is $30^\circ$, and dilation angle at residual is $0^\circ$.

Table 5.1 Properties of the Materials Used for the Simulation.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Density ($kN/m^3$)</th>
<th>Shear modulus ($kN/m^2$)</th>
<th>Bulk modulus ($kN/m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotextile</td>
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<td>$7.5 \times 10^2$</td>
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<tr>
<td>Geomembrane</td>
<td>$9.22 \times 10^{-1}$</td>
<td>$1.54 \times 10^4$</td>
<td>$1.88 \times 10^2$</td>
</tr>
</tbody>
</table>
5.3 Parametric Studies of the Effects of Materials Properties

The post peak behavior of the interface resistance was modeled as a function shown in Figure 5.6 and Equation 5.3.

\[
\phi = (\phi_{ori} - \phi_{res}) e^{-be^p} + \phi_{ori}
\]  

(5.3)

From the strain at peak and the slope of the envelope to the peak strain, the corresponding shear stiffness \(k_s\) of the interface can be defined as Equation (5.4).

\[
k_s = \frac{\delta_{peak}}{\sigma_n \cdot \tan \phi'}
\]  

(5.4)

![Figure 5.6 Characterization of Post Peak Shear Envelope.](image)

For the test at normal stress of 100 kPa, the normal stiffness was set as 100 kN/m as a reference value and then the shear stiffness was determined as 10,000 kN/m from comparing the variation of resulting shear modulus with the experimental test result by trial and error methods. The simulation with these two stiffness values and the given materials properties generated a similar response to the experimental shear test results (Figure 5.7).

The unbalance force was checked at the stage of compression (Figure 5.8). The strain at peak is determined by the defined shear stiffness \(k_s\) of the interface. Also, the
slope of the shear stress-strain envelope varied with the properties of the geotextile and the geomembrane. Therefore, by examining the variation of the strain at peak or the slope of the shear stress-strain envelopes, the effect of materials properties on the shear interface can be analyzed.

![Shear Stress-Strain Plot](image)

Figure 5.7 Experimental and Model Responses of Shear Stress-Strain.

Figure 5.9 and 5.10 show the effect of geotextile strain on the interface shear evolution under the same load condition. The position marked as 1 in the figures represents the boundary at which the geotextile was constrained in the unconstrained case. The increased geotextile strain is observed in Figure 5.9b. The generated shear stress at the geomembrane layer along the interface is shown in Figure 5.10. The increased stress due to the geotextile constraint is readily seen in Figure 5.10b.

Figure 5.11 shows the effect of materials shear stiffness on the strain at peak in the interface shear tests. The differences between the constrained and the unconstrained cases were reduced as the materials stiffness increased. The strain at peak shear decreased
with the materials stiffness which indicates the increase of the shear stiffness at the interface.

![Figure 5.8 Check of Unbalanced Force at Compression.](image)

The ratio of peak strain for the unconstrained and the constrained tests are shown in Figure 5.12. The decrease in the ratio illustrates that the response of the interface is significantly affected by the geotextile shear stiffness, while the geotextile strain resulted in about 55% increase of the peak strain. In contrast, changes in the geomembrane stiffness had little effect.

Figure 5.13 shows the effect of the shear stiffness of the interface on the peak shear strain of the shear response. Significant change was observed at the low range of initial shear stiffness less than 2,000 kN/m (0.2 times to the reference value of 10,000
Figure 5.9 Relative Shear Displacement along Interface: (a) Constrained; (b) Unconstrained.
Figure 5.9 Relative Shear Displacement along Interface: (a) Constrained; (b) Unconstrained (Continued).
Figure 5.10 Shear Stress at Residual State: (a) Constrained; (b) Unconstrained.
Figure 5.10 Shear Stress at Residual State: (a) Constrained; (b) Unconstrained (Continued).
Figure 5.11 Effects of Material Shear Stiffness on the Strain at Peak: (a) Geotextiles; (b) Geomembranes.

Figure 5.12 Effects of Material Stiffness on the Strain at Peak – Unconstrained/Constrained: (a) Geotextiles; (b) Geomembranes.
Figure 5.13 Effect of Interface Shear Stiffness Magnitude on the Strain at Peak Shear.

Figure 5.14 Effect of Interface Shear Stiffness Magnitude on the Strain at Peak Shear: Unconstrained / Constrained.
Figure 5.15 Effect of Change of Materials Shear Stiffness on Interface Shear Stiffness: (a) Geotextile; (b) Geomembrane.

kN/m). The ratio of peak displacement between the unconstrained and constrained geotextiles is shown in Figure 5.14.

The effects of material shear stiffness on the interface shear stiffness is shown in Figure 5.15. The increase of geotextile shear stiffness resulted in a larger increase of shear stiffness at the interface than an increase in the geomembrane shear stiffness. The results indicate that the shear stiffness at the interface is affected by the material with the lower stiffness.

5.4 Summary

The characteristics of geotextile-geomembrane interface shear responses were further studied in this chapter by simulating the interface based on the laboratory shear test results. The material properties collected from preceding experimental tests were
applied. The finite different method was subsequently applied to simulate the interface allowing large displacement and detecting the post peak behavior using the FLAC program. The results illustrated significant change of interface shear stiffness with the changes of materials properties. The modeling results also showed the decrease of the interface shear stiffness by the geotextile strain against geomembrane surfaces. The output generated from this study is useful to use as reference data to simulate other geotextile-geomembrane layered system at different load and boundary conditions.
CHAPTER 6
EVOLUTION OF INTERNAL GEOTEXTILE VOID MICROSTRUCTURE UNDER EXTERNAL FORCES

6.1 Introduction

In Chapter 4, the interface shear resistances between four needle punched nonwoven geotextiles, and smooth and textured geomembranes were investigated. The interface shear response revealed a significant effect of the geotextile boundary conditions on shear evolution. Based on the experimental test results, shear modes of geotextile-geomembrane interfaces were hypothesized with regard to the role of geomembrane surface texture and geotextile strain.

As previously noted, efforts to develop a theoretical solution to describe the response of a nonwoven fabric structure have been undertaken by many researchers (Komori and Makishima, 1978; Advani and Tucker, 1985; Lombard et al., 1989; Pourdeyhimi, 1999). Numerical functions describing the non-linear compression of non-woven geotextiles have been developed in terms of average number of fiber-to-fiber contacts per unit volume of fiber assemblies (Komori and Makishima, 1977), average pore size changes (Giroud, 1981), and energy loss (Kothari and Das, 1992).

As noted in Chapter 2, such theories developed to evaluate the response of nonwoven fabric structures are limited due to their simplifying assumptions concerning filament structure, and they have not been validated due to difficulties in experimental observation. Several approaches to experimentally quantify the fabric structure have been undertaken by researchers including surface image observation techniques (Hearle and
Stevenson, 1963), sieve analysis (Rigo et al., 1990), mercury intrusion porosimetry (Bhatia and Smith, 1994), capillary flow (Bhatia and Smith, 1994), and in-plane water flow (Rebenfeld and Miller, 1995). The operating ranges of the different methods are summarized in Figure 6.1. Each method is known to provide significantly different results for the same nonwoven geotextile (e.g. Bhatia and Smith, 1994; Bhatia et al., 1996). Such differences are due to the disturbance of the delicate fabric microstructure and the imposed boundary conditions of each method. Optical and confocal microscopes have operating ranges that can achieve the required resolution for geotextile filament diameters and geomembrane surface profile measurements. However, observing only surface images of geotextiles also has inherent limitations for evaluating the complex inner structure of these materials. A key issue in geotextile structure quantification is to reduce the specimen disturbance during inner structure observation in order to obtain representative information. Further, while some microstructural properties of geotextiles and geomembranes have been evaluated separately, detailed studies into the interaction between filaments and texture elements of these two synthetic materials, in particular at the micro-scale under different external loading conditions, are required.

This chapter presents results from a study that used an optical based technique to provide quantitative insight into geotextile-geomembrane interfaces. The void structures were evaluated in terms of two void-based descriptors: local void ratio distribution and largest inscribing opening size distribution of the geotextile at different load and boundary conditions. The detailed underlying concepts of these two parameters and associated results are first introduced by comparing data acquired from an ideal lattice structure.
6.2 DIGITAL IMAGE ANALYSIS

6.2.1 Introduction

Geosynthetics, being polymeric materials, have significantly different engineering properties compared to natural geomaterials. As such, different methods are required to characterize their properties. Characterizing the variation in the arrangement and distribution of filaments and/or voids is essential to understand the micro-scale mechanisms governing how nonwoven fabrics interact with other counterface materials.
6.2.2 Filament Orientation

Tracking filament geometry and orientation has been an important issue in textile and fiber engineering fields. For yarns and woven textiles, general concepts of dynamics and mechanics are applied to mathematically express the deformation of textile structures and forces applied to each textile component. Nonwoven fabrics, particularly after needle punching, have filament structures that are variable and complex and have not been well characterized to date. Therefore, observing only the surfaces of needle-punched textiles may yield significant misinterpretations because of the three-dimensional array of the filaments.

![Figure 6.2 Coordinate System Used to Define Filament Orientations: (a) Spatial Coordinate Defined by Horizontal and Vertical Planes; (b) Tracing of Filament Orientation from Serial Surfaces (After Kim and Frost, 2006).](image)

The curved and woven filaments are often assumed to be straight and cylindrical. As such, the spatial orientation of the filaments can be expressed as a combination of two angles in horizontal and vertical planes (Figure 6.2). Efforts have been undertaken to compute the spatial information pertaining to the filaments from surface images and express them in tensor description (Advani and Tucker, 1985; Long and Lau, 1990).

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However, observing only cross-sections may not yield the actual spatial orientation of filaments.

Figure 6.3 presents the elliptical shapes of the filament cross-sections having different aspect ratios and orientations. For a linear filament in a space, the projected lengths in horizontal and vertical planes determine the filament orientation (Figure 6.2a). Filaments in different orientations (Figure 6.3a and 6.3b) produce different section shapes for a given reference plane (Figure 6.3c). It is intuitively found that the features on diagonal planes have identical figures (e.g., two phases marked a1 and a2 in Figure 6.3c). This situation is graphically illustrated in Figures 6.4a and 6.4b. The aspect ratio generated by the combination of plane and vertical angles of $\alpha$ and $\beta$ often overlaps (e.g., points marked x1 and x2 in Figure 6.4a) and the difference is too small to discern (Figure 6.4a). Moreover, features with an aspect ratio and with its reciprocal value can be confused since an aspect ratio is often expressed into either a number smaller or greater than 1 (Figure 6.4b).

An alternative method is to observe the serial planes with different thicknesses (Figure 6.2b). The spatial orientation in horizontal and vertical planes can be calculated by comparing the center of gravity of each filament feature on different planes, where the images can be obtained by serial polishing of a resin impregnated and cured specimen. Applying this method to a limited number of images is not appropriate for curved features such as geotextile filaments.

Due to the above problems, various alternative approaches were utilized in this study including: (a) detecting vertical distribution of geotextile features; (b) measuring the local void ratio; (c) measuring localized opening sizes; (d) tracing the distances of
Figure 6.3 Identification of Filament Orientation from Cross-Sections: (a) 2D Array of Straight Filaments; (b) 3D Array; (c) Cross Section of Filaments in 3D Array (After Kim and Frost, 2006).
Figure 6.4 Identification of Filament Orientation from Cross-Sections: (a) Use of Aspect Ratio and 2D Orientation Identification; (b) Actual Data Acquired from Aspect Ratio and 2D Angle (After Kim and Frost, 2006).
adjacent filaments or nth nearest neighbor distance; and (d) investigating change of filament diameters during interface shear. The first two methods are discussed in this chapter. Measurement errors were minimized by applying stereological concepts for specimen selection and using operator-independent computer algorithms to perform measurements.

6.2.3 Filament Distribution in Vertical Sections

A series of vertical load-unload tests were conducted on replicate specimens at normal stress levels of 10, 100, 200, and 300 kPa. The typical compression response of geotextile specimens as the normal load is sequentially increased and decreased is shown in Figure 6.5. The specimens were impregnated with low viscosity epoxy resin at various loading stage as marked A1, B1, D1 for compression and C1 and E1 for unloading. An example of load-induced change in filament distribution based on image analysis is shown in Figure 6.6.

Figure 6.5 Compression Behavior of Geotextile A.
It can be seen that as loading increases from 10 to 300 kPa, the geotextile is vertically compressed by about 50% from an initial thickness of about 2.0 mm into a region about 1.0 mm thick and when unloaded to 10 kPa rebounds to a height of about 1.5 mm. The plastic strain remaining was 56.3, 57.5, and 52.0 % of the total strain after unloading to 10 kPa from normal stresses of 100, 200, and 300 kPa, respectively. The nonlinear loading and unloading response was found to fit well with Equations 6.1 and 6.2 from among those proposed by Kothari and Das (1992) where, $T_o$ and $T_f$ are initial and final thickness, $P_o$ and $P_f$ are the initial and final normal stresses and $\alpha$ and $\beta$ are the compression and recovery parameters, respectively.

\[
\frac{T}{T_o} = 1 - \alpha \cdot \log_e \left( \frac{P}{P_o} \right) \quad (6.1)
\]
\[
\frac{T}{T_f} = \left( \frac{P}{P_f} \right)^{-\beta} \quad (6.2)
\]

The initial state of loading at 10 kPa showed a low variation in vertical distribution of filaments (Figure 6.6a) while the loading to 300 kPa resulted in dense population of filaments near the middle depth with a large variation (Figure 6.6d). The unloading stage from 300 to 10 kPa (from stage D1 to E1 in Figure 6.5) showed decreased variation (Figure 6.6e). Figures 6.6b and c shows the results obtained from loading to 100 kPa and recovery by unloading from 100 to 10 kPa, respectively.

The interface shear sliding showed in change of filament distribution resulting in high density near the interface at normal stress of 100 kPa (Figure 6.7a) while higher normal stress resulted in opposite results (Figure 6.7b). It is considered that the inner structure of geotextile under interface shear on a smooth surface is determined by combined modes: (1) reorganization of filaments near the interface; (2) constraint of geotextile filaments by normal stress. However, more quantitative descriptors are
required to understand the geotextile microstructure with regard to the load and boundary conditions.

Figure 6.6 Vertical Distribution of Geotextile Filaments at Different Stresses Conditions: Smooth Geomembrane-Geotextile A.
Figure 6.7 Vertical Distribution of Geotextile Filaments at Residual Shear State against a Smooth Geomembrane (Shear Surface: Face I): (a) Residual State under 100 kPa; (b) Residual State under 300 kPa.

6.3 Quantitative Microstructure Observation of Geotextile Pore Networks

6.3.1 Concept of Local Void Ratio

Local void ratio is a dimensionless descriptor that is used to quantify the microscale distribution of pores in a material. This concept was first proposed by Oda in 1972 to evaluate the frequency distribution of voids in a sand specimen from 2-D images. This descriptor requires the generation of polygon elements enclosed by straight lines, which connect the centers of gravity of the solid phases. The local void ratio is then calculated from the ratio of the void area to the total solid area enclosed by each polygon (Figure 6.8).

This technique has been modified and applied by many researchers to quantify sand structure and its evolution using different sample preparation methods and under different global strain levels (Bhatia and Soliman, 1990; Ibrahim and Kagawa, 1991; Kuo

Bhatia and Soliman (1990) noted that the calculated mean value of the void ratio \( e_{\text{mean}} \) in Equation 6.3 is not equal to the global void ratio \( e_s \) as defined in Equation 6.4 unless all polygon sizes are equal.

\[
e_{\text{mean}} = \frac{1}{k} (e_1 + e_2 + \ldots + e_k) = \frac{1}{k} \left( \frac{A_{s1}}{A_{s1}} + \frac{A_{s2}}{A_{s2}} + \ldots + \frac{A_{sk}}{A_{sk}} \right)
\]

(6.3)

Where, \( k \) is the number of polygons

\[
e_s = \frac{\text{Total area of voids in an image}}{\text{Total area of solids in an image}} = \frac{A_{s1} + A_{s2} + \ldots + A_{sk}}{A_{s1} + A_{s2} + \ldots + A_{sk}} = \frac{A_{v1}}{A_s}
\]

(6.4)

In order to overcome this problem, Frost and Kuo (1996) noted that the local void ratios weighted by the solid area \( (A_{si}) \) in each polygon would be more meaningful.

\[
e_w = \frac{1}{\sum_{i=1}^{k} A_{si}} \left( \sum_{i=1}^{k} A_{si} \cdot e_i \right)
\]

(6.5)

Substituting \( e_i = \frac{A_{vi}}{A_{si}} \) into Equation 6.5 yields
\[ e_w = \frac{A_s}{A_s} = e_s \]  

(6.6)

Finally, the mean value of the local void ratio weighted with solid area becomes equal to the general void ratio of the image. Detailed information about the unbiased calculation of local void ratio and its distribution are found in Park (1999).

The algorithm developed by Frost and Kuo (1996) was applied to automatically calculate the unbiased LVRD independent of operator judgment. Procedures for the automatic calculation of LVRD using a geotextile cross-section image are shown in Appendix B. First, the features of interests on the binarized image (B1) are eroded until the feature became unit size or unit width (B2). The image is inversed and the features are connected by cycles of segmentation of the images (B3) and (B4). The segmentation is conducted by connecting the adjacent features in vertical, horizontal, or diagonal lines in 45 degree in horizontal or vertical axes. The eroded features are removed to make completely enclosed polygons without disconnected line segments (B5). The segments of the disconnected lines are connected by extending the lines (B6) and the generated lines are used for calculation (B7). Theoretically, the lines have no width but in actual digital images they have unit width and its effect on the computed values was corrected automatically in the algorithm as described by Frost and Kuo (1996). Moreover, the effects of the incompletely straight lines enclosing polygons were compensated for by weighting the polygon size in the calculation of local void ratios. The errors caused by these two factors were shown to usually generate measurement errors less than 4 percent (Frost, and Kuo, 1996).
6.3.2 Concept of Largest Inscribing Opening Size

The opening or pore size of geotextiles and its distribution have been significant parameters related to engineering properties such as permeability, soil retention/clogging, damping, compressibility, tensile strength, and resulting long-term behavior during service periods. Thus, besides the LVRD, actual measurements of the pore sizes are of interest.

Lombard et al. (1989) proposed a theoretical method to calculate the opening size of a heat bonded nonwoven geotextile. The method was based on the Poisson polyhedron theory (Matheron, 1971). Their approach is summarized below.

In a Poisson line network, the radius distribution of the inscribing opening diameter is expressed in equation (6.7).

\[ G(r) = (\pi^2 \lambda^2 r^2 + 2\pi \lambda r + 1) \exp(-2\pi \lambda r) \]  

(6.7)

where, \( \lambda \) is the density of the Poisson line network, and \( r \) is the radius of the largest inscribing opening.

The probability of the population of the openings being smaller than radius \( r \), \( F(r) \) is obtained from Equation 6.8.

\[ F(r) = 1 - G(r) \]  

(6.8)

The total length of lines per unit area of Poisson network, \( \sigma \) is expressed by Equation 6.9.

\[ \sigma = \pi \lambda \]  

(6.9)

Therefore,

\[ F(r) = 1 - [(\sigma^2 r^2 + 2\sigma r + 1) \exp(-2\sigma r)] \]  

(6.10)
For a web of filaments with diameter of $D_f$,

$$\sigma = \frac{8\mu}{(\pi T_g D_f \rho_f)}$$  \hspace{1cm} (6.11)

where, $\rho_f$ is the polymer density.

Finally, the Equation 6.12 expresses the cumulative probability that an inscribing pore diameter is equal to or smaller than $d$. The results obtained using this method are comparable to that of mechanical sieve analysis using glass beads (Rigo et al., 1990).

$$F(d) = 1 - \left[4\mu d / (\pi T_g D_f \rho_f) + 1\right]^2 \exp\left((-8\mu d) / (\pi T_g D_f \rho_f)\right)$$  \hspace{1cm} (6.12)

where, $F(d)$ is the frequency of filter pore diameters, $\mu$ is the mass per unit area of geotextile $(g/m^2)$, $T_g$ is the geotextile thickness $(mm)$, $\rho_f$ is the mass per unit volume of the polymer $(kg/m^3)$, and, $d$ and $D_f$ are the pore and fiber diameters $(\mu m)$, respectively.

In this study, the pore networks were quantified in terms of the largest inscribing opening size (LIOS) distribution from the 2-D images of representative specimen surfaces. The analysis was conducted using an automatic image analysis routine and compared with the theoretical estimates.

6.3.3 Parametric Study about Void Networks Description

Spatial array or distribution of micro-phases is often expressed as a lattice structure. The image analysis technique used in this study is based on two dimensional data and quantitative stereology permits the estimation of three-dimensional information regarding the geotextile microstructure (Underwood, 1969; 1970). The relationship between various descriptors applied in this study are discussed in this section using two
basic formations of simple cubic (SC) and face-centered cubic (FCC) lattices considering various strain conditions.

![2-D Lattice Diagrams](image)

Figure 6.9 Model of 2-D Lattice: (a) Simple Cubic; (b) Face Centered Cubic.

Figure 6.9 shows schematic diagrams of two ideal lattices, where each of the parameters is a constant value through the lattice regions. The solid and void parts are $\alpha$ and $\beta$ phases, respectively. The largest opening diameters inscribed by $\alpha$ phases can be calculated by the geometry of the adjacent four solid phases. For a SC lattice, the enclosed opening diameter or LIOS is the same as the net distance to the nearest neighbor phase. However, the actual value varies with the distribution of phases and became different from the ideal the lattice cases. Table 6.1 gives a summary of the parameters to be determined where, $l$ is lattice distance, $d$ is filament diameter, and $k$ is ratio of the two values, $l/d$. As mentioned, one of merits of using LIOS is that this descriptor gives a direct measurement of the local void sizes. However, it has a disadvantage that the
measurement can be ambiguous if the void portion is relatively high and the solid phases have small aspect ratio. In such cases, appropriate judgment is required to verify the adequate assignment of the center of the inscribing openings. The variation in parameters can be further expressed with regard to the changes of solid size, and strain types of the lattices including 2-D isotropic growing or shrinkage, 1-D stretch, and 2-D anisotropic strain with Poisson’s ratio, $\nu$.

Table 6.1 Calculation of Parameters of SC and FCC Lattices.

<table>
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<tr>
<th>Parameter</th>
<th>Simple Cubic</th>
<th>Face Center Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void Ratio</td>
<td>$e_t = \frac{4}{\pi} k^2 - 1$</td>
<td>$e_t = \frac{8}{\mu} k^2 - 1$</td>
</tr>
<tr>
<td>LIOD</td>
<td>$D = (k \sqrt{2} - 1) \cdot d$</td>
<td>$D = (2k - 1) \cdot d$</td>
</tr>
</tbody>
</table>

Variations of LVRD in ideal SC and FCC lattices with different types of strain are illustrated in Figure 6.10, where, the initial solid diameter, center-to-center distance, and Poisson’s ratio are set as 50, 100, and 0.2, respectively. The SC and FCC lattices show nonlinear relationships for the given conditions. Similarly, Figure 6.11 provides the change of the LIOS with variation of filament size and lattice strain. The effects of filament diameter change are the same for SC and FCC lattices and the other parameters give different rates of inscribing diameter change with the increase of lattice distances. The change of LIOS with various deformation patterns of lattices is summarized in Table 6.2. The study with the lattice structures can be used as a reference to characterize the distribution pattern of void/filaments such as uniformity or randomness.
Figure 6.10 Variation of LVRD in SC and FCC Lattices with Change of Different Parameters: (a) Filament Diameter; (b) 2-D Isotropic Deformation; (c) 1-D Deformation; (d) Anisotropic Deformation with Poisson’s Ratio.

Figure 6.11 Variation of LIOS in SC and FCC Lattices with the Changes of Different Parameters: (a) Filament Diameter; (b) 2-D Isotropic Deformation; (c) 1-D Deformation; (d) Anisotropic Deformation with Poisson’s Ratio.

Table 6.2 Change of LIOS with Various Deformation Patterns of Lattices.

<table>
<thead>
<tr>
<th>Variation</th>
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<th>Face Center Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament Diameter Decrease</td>
<td>$\sqrt{2l - d - \delta}$</td>
<td>$\sqrt{2l - d - \delta}$</td>
</tr>
<tr>
<td>2-D Isotropic Strain</td>
<td>$\sqrt{2(l + \Delta) - d}$</td>
<td>$2(l + \Delta) - d$</td>
</tr>
<tr>
<td>1-D Strain</td>
<td>$\sqrt{l^2 + (l + \Delta)^2} - d$</td>
<td>$2l - d$</td>
</tr>
<tr>
<td>Anisotropic Strain with Poisson’s ratio, $\nu$</td>
<td>$\sqrt{(l + \Delta)^2 + (l - \nu \cdot \Delta)^2} - d$</td>
<td>$\frac{4}{l} \cdot \sec \left( \frac{\pi}{2} - 2 \cdot l \cdot \tan \left( \frac{l}{2(l + \Delta)} \right) \right)$</td>
</tr>
</tbody>
</table>
6.4 Spatial Distribution of Local Void Ratio

6.4.1 Evolution of Local Void Ratio Distribution

Typical incremental and cumulative local void ratio distribution measurements for unsheared specimens under different normal stress conditions are shown in Figure 6.12. The cumulative percentage of the geotextile local void ratio less than 2 increased from about 15% at 10 kPa to about 83% at 400 kPa normal stress. The cumulative LVRD plots also show that about 20% and 8% of the local void ratios are still larger than 10 at normal stress of 10 and 100 kPa, respectively. The cumulative frequency of local void ratios less than 4 increased from 40% to 58% as the load increased from 10 to 100 kPa (Figure 6.12a and b). The unloading stage from 100 and 300 kPa to 10 kPa resulted in recovery to about 48% of cumulative frequency of local void ratio less than 4 (Figure 6.13c and d). The residual shear on a smooth geomembrane surface increased the frequency of small local void ratios (Figure 6.14). For example, the unsheared but compressed specimens have about 45% of local voids greater than 4 under 100 kPa (Figure 6.13a) while the sheared specimen resulted in about 30% on the same smooth geomembrane surface (Figure 6.14a). Similar results are found for the cases at normal stress of 200 kPa (Figure 6.13b and 6.14b). Such results are consistent to the proposed mode of interface shear between the smooth geomembrane and geotextiles discussed in Chapter 4, where the shear induced strain of a geotextile was negligible but the thickness reduction or settlement of the geotextile was apparent and considered to be the result of filament rearrangement and inter filament slippage.

Typical incremental and cumulative local void ratio measurements for geotextile specimens sheared against textured geomembranes at two different normal stresses are
Figure 6.12 Local Void Ratio Distribution at Various Normal Stresses: Smooth Geomembrane: (a) 10 kPa; (b) 100 kPa; (c) 200 kPa; (d) 300 kPa; (e) 400 kPa.
shown in Figure 6.15. The cumulative percentage of local void ratio less than 2 on the shear surface (Figure 3.8b) increased from 35% to 70% as the normal stress increased from 100 kPa to 300 kPa (Figure 6.11a and b). The LVRD plots also show that about 7% of the local void ratios are still larger than 10 at 100 kPa. The cross-shear surface (Figure 3.8b) under the same load conditions show that about 90% of the local void ratios are smaller than 4 and 2 at 100 kPa and 300 kPa, respectively (Figure 6.15c and d). The relatively low density of filaments in the shear surfaces is attributed to the geotextile strain and filament reorientation and/or rearrangement into the shear direction.
Figure 6.14 Local Void Ratio Distribution: Smooth Geomembrane; Shear Surface (Face I): (a) Residual Shear at 100 kPa; (b) Residual Shear at 300 kPa.

Figure 6.15 Local Void Ratio Measurement at Shear States: (a) Residual Shear at 100 kPa (Shear Surface: Face I); (b) Residual Shear at 300 kPa (Shear Surface: Face I); (c) Residual Shear at 100 kPa (Cross Shear Surface: Face II); (d) Residual Shear at 100 kPa (Cross Shear Surface: Face II).
For sheared specimens, the geomembrane textures and shear direction must be considered for quantitative measurements as illustrated in Figure 6.16a. The in-shear (face I), and cross shear (face II) surfaces as well as the in-plane surfaces parallel to the interfaces (face III) need to be observed to obtain the complete information for the sheared specimens. Figures 6.16b and 6.16c were captured from the specimens subjected to conditions corresponding to residual shear under 100 kPa normal stress. The relatively low density of filaments in the shear direction may be due to the geotextile strain and filament reorientation into the shear direction. In addition, a large void can be seen at the interface both in front of as well as behind the surface asperity. The larger number of filaments and lack of shear induced void regions in Figure 6.16c adjacent to the asperity show results consistent with the shear induced filament rearrangement and reorientation.

A horizontal surface parallel to the geomembrane surface was also polished serially (Figure 6.16a) to allow the spatial variation of geotextile and geomembrane phases at different heights above the geomembrane surface to be examined. The images shown in Figure 6.17 were captured from a specimen that had been sheared to a displacement of 80 mm before being impregnated with resin and analyzed.

The variation of the filament density with elevation from the interface sheared specimen is due to the geomembrane texture elements and the shear induced increase void region near geomembrane-geotextile interface as illustrated in Figure 6.16b. Significant variation of the filament density was also found from the specimen sheared under 10 kPa (Figure 6.18). Such variation is considered as the results of geotextile dilation on a textured geomembrane under low normal stress.
Figure 6.16 Effect of Shear on Geotextile-Geomembrane Structure: (a) Schematic Diagram of Sample Sectioning; (b) Surface of Shear Direction; (c) Surface of Cross-Shear Direction. 

Note: Residual State under 100 kPa Normal Stress 
Image Size: 3.992 mm (W) x 1.862 mm (H)
Figure 6.17 Micro-scale Images of Nonwoven Geotextile on a Textured Geomembrane at Different Depth: Residual Shear State under 100 kPa Normal Stress.
Figure 6.18 Micro-scale Images of Nonwoven Geotextile on a Textured Geomembrane at Different Depth: Residual Shear State under 10 kPa Normal Stress.
An example of shear-induced filament concentration near a geomembrane texture element is highlighted in Figure 6.19. The shear displacement resulted in localized filament concentration at geotextile-geomembrane interlocking points as well as localized high void ratio region while the compressed but not sheared specimen showed geomembrane texture elements surrounded by filaments without preferred orientation under the same normal stress (Figure 6.20).

Figure 6.19 Shear Induced Filament Concentration Near Texture Elements: Residual Shear State under 100 kPa Normal Stress.
The effect of shearing on filament-texture structures is further illustrated in Figure 6.21, in terms of void ratio distribution on serially analyzed planes. In contrast to the specimen that was compressed only as shown in Figure 6.21a and b, the sheared specimen in Figure 6.21c and d has a denser structure at higher elevations (further from geomembrane) and significantly looser structure at lower elevations, due to the filament concentration at filament-texture interlocking points, and shear induced surface degradation of the geotextile at the inter-contact points.

Figure 6.20 Filament Distribution Near Texture Elements: Compressed at Normal Stress 300 kPa.
6.4.2 Statistical Properties of Local Void Ratio Distribution

In the previous section, the changes of LVRD in geotextile microstructures were discussed with regard to the various boundary conditions. Associated statistical analyses based on these distributions are useful to model or characterize the distributions in terms of mean void ratio and boundary conditions.

Figure 6.22 shows an example of curve fitting to the actual data of cumulative local void ratio distribution. The goodness of curve fitting was evaluated using square
error criterion, and the results are summarized in Table 6.3 and 6.4 for vertical sections of specimens seated on smooth and textured geomembrane surfaces, respectively. The lognormal, k-Erlang, gamma and beta distribution models were found as the mostly appropriate fitting models for the LVRD data. The goodness of fit was also checked using Chi-square and Kolmogorov-Smirnov goodness-of-fit tests for parametric studies.

![Graphs showing statistical models of LVRD of geotextile vertical section](image)

Figure 6.22 Statistical Models of a LVRD of Geotextile Vertical Section: (a) Lognormal; (b) Erlang; (c) Gamma; and (d) Beta.
Table 6.3 Square Error of LVRD Estimated by Various Distribution Models-Smooth Geomembrane.

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<th>300 kPa compression</th>
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Table 6.4 Square Error of LVRD Estimated by Various Distribution Models-Smooth Geomembrane.

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Shear Surface

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</table>

Pearson’s probability distribution space categorizes regions of several probability distribution in the plane of kurtosis \( \beta_2 \) and square of skewness \( \beta_1^2 \), where the coefficient of skewness \( \beta_1 \) is used to express the degree of asymmetry of a distribution (Pearson and Hartly, 1972). The coefficient of kurtosis \( \beta_2 \) is an indicator that measures peakness of a distribution (Pearson, 1894). The standard deviation \( \sigma \) for the local void ratio weighted with solid area \( A_s \) is defined in Equation 6.13, where \( e \) is void ratio for each polygon, and \( \mu \) is the estimated mean value for the weighted distribution (Park, 1999).
\[ \sigma^2 = \frac{1}{A_s} \sum_{i=1}^{k} [A_{si}(e_i - \mu)^2] \]  

Equation 6.13

The skewness and kurtosis for local void ratio distribution are expressed in Equation 6.14 and 6.15.

\[ \beta_1 = \frac{1}{A_s} \sum_{i=1}^{k} \left[ A_{si} \frac{(e_i - \mu)^3}{\sigma^3} \right] \]  

Equation 6.14

\[ \beta_2 = \frac{1}{A_s} \sum_{i=1}^{k} \left[ A_{si} \frac{(e_i - \mu)^4}{\sigma^4} \right] \]  

Equation 6.15

It is found that the LVRD data are mostly distributed on the regions of gamma, and lognormal distribution at Pearson’s probability distribution (Figure 6.23).

The variation of the distribution data can be also evaluated in terms of entropy of the histogram, which quantifies the uniformity of a distribution (Equation 6.16).
\[ H = -\sum_{i=1}^{n} p_i \log_n (p_i) \]  

(6.16)

where, \( n \) is the number of bins in the histogram and \( p_i \) is the probability of the \( i^{th} \) bin.

Entropy indicates a measure of disorder in a discrete probability. This term can be calculated by appropriately modeling the distribution eliminating any bin having 0 probability. The entropy is 1 for distributions having same probability for each bin and 0 if all data are in a single bin (Park, 1999; Evans, 2006).

The entropy values calculated from gamma and lognormal distribution models are shown in Figure 6.24a and b, respectively. The entropy values ranged from about 0.42 to 0.79 for mean local void ratios of 0.6 to 2.7 with only a difference between the two distribution models. The data shows the high uniformity of the local void ratios at low normal stress and decreased uniformity at the range of mean void ratio smaller than 1.0 due to compression and/or shear.

**Figure 6.24 Variation of Entropy Value with Average Local Void Ratio: (a) Gamma Distribution; (b) Lognormal Distribution.**
6.5 Largest Inscribing Opening Size Distribution

6.5.1 Measurement of Largest Inscribing Opening Size

As illustrated, NPNW geotextiles have relatively large void sizes and often have more than 50% of the cumulative frequency of the local void ratio distribution greater than 10. For materials with such characteristics, another approach is to quantify the structure based primarily on the localized void size rather than the void and filament size as captured in the LVRD measurements.

The measurements of the LIOS were conducted using an automated image analysis routine. The gray-scale section images were binarized and then the temporary centers of the inscribing openings were identified through a series of image processing steps including erosion of solid (filament) phases, segmentation of the void area by connecting the eroded solid phases, final definition of the polygon boundaries, and detection of the centers of gravity of the generated polygons (see Appendix D for details). Such procedures are based on a routine originally developed by Frost and Kuo (1996) for calculating the local void ratio distribution in granular materials. The nearest distances from the center of each polygon to the adjacent geotextile features were then measured. By windowing (moving) the center point to the adjacent pixels, the procedure was repeated until the true center point of the largest inscribing circle was found. Detecting the openings was verified by checking that each circle touched at least three adjacent solid points.

Figure 6.25 shows a portion of an image resulting from the LIOS detection process, overlapped with the initial gray scale image. An example of the offset of the center point of the inscribing circle is shown in the enlarged view image in the figure.
The image was obtained from the middle depth within a specimen, which was subjected to a compression of 300 kPa on top of a smooth geomembrane surface. The broken shapes of linear features are due to the spatial lay down of the filaments during fabrication. Circular or linear phases with low aspect ratios found on the horizontal surfaces are considered to be mostly generated by reorientation of filaments through the needle-punch process following initial lay down of the filaments.

![Figure 6.25 Measurement of Largest Inscribing Opening Size of a Geotextile Section Image on A Planar Surface.](image)

*Note: 300 kPa compression; smooth geomembrane; planar surface at the middle depth of the specimen; image size: 2.654 mm (W) x 2.005 mm (H).*

6.5.1 Evolution of Geotextile Void Size

Results from analysis of images obtained from the vertical sections (see Figure 3.8) of specimens are shown in Figure 6.26. Theoretical opening diameters of an ideal filament network based on the method of Lombard et al. (1989) are illustrated in the Figure 6.26a, where the filament diameter was set as a constant of 35 µm, and the LIOS
was computed with regard to the thickness change of the specimen under normal stresses based on the results of the experimental load tests as shown in Figure 6.5. Symbol \( F_i \) defines herein a cumulative percent frequency of openings larger than \( i \, \mu m \) in diameter. Similarly, \( O_j \) indicates an opening diameter of a pore network corresponding to cumulative frequency of \( j \% \).

Figure 6.26b shows the effects of normal stress on the variation of geotextile pore networks in actual compression experiments conducted in this study. The opening diameter corresponding to the 50% cumulative frequency (\( O_{50} \)) decreased by about 45 \( \mu m \) as the load increased from 10 to 300 kPa and recovered to about 90% of its initial state on unloading back to 10 kPa.

Figure 6.26c presents the change of opening sizes due to shear against a smooth geomembrane at the same normal stress of 100 kPa. The increased number of small openings due to the combination of the geomembrane surface texture and the residual shear at a normal stress of 100 kPa is illustrated in Figure 6.26d. The cumulative frequencies of openings smaller than 50 \( \mu m \) increased by about 25 % in both compression and shear testing against textured geomembranes due to the stress and filament concentrations near the interfaces. The additional densification of the geotextile at residual shear was about 5 % for \( F_{50} \) on both the textured and smooth geomembrane surfaces as seen in both Figures 6.26c and 6.26d.

The shear-induced filament reorientation for a textured geomembrane interface and the resulting variation of the LIOS distribution of specimens are compared in Figures 6.26e and 6.26f. The surfaces in the shear direction (face II in Figure 3.8b) had similar
Figure 6.26 Results of LIOS Measurements from Vertical Sections with Various Boundary Conditions: (a) Theoretical Values by Lombard et al. (1989); (b) Normal Stress on a Smooth Geomembrane; (c) Effects of Residual Shear on a Smooth Geomembrane; (d) Effects of Residual Shear on A Textured Geomembrane Surface; (e) Residual Shear State at Different Normal Stress (Textured Geomembrane; Shear Surface, I); (f) Residual Shear at Different Normal Stress (Textured Geomembrane; Cross-Shear Surface, II).
values of $F_{50}$ and a decreased value of $F_{75}$ by about 4% at 300 kPa compared to the shear surface (face I in Figure 3.8b). Such results differ from the hypothesis that the surfaces in the shear direction (face II in Figure 3.8b) may have higher filament populations due to shear-induced filament reorientation. This was only observed for surfaces near the geotextile-geomembrane interlocking points and was not significant due to the deformation of the geomembrane textures in the shear direction resulting in an apparent smoothing of the textured geomembrane surface. The internal structure of the geotextile (face I in Figure 3.8b) had a reduced number of filaments. However, more features had a larger aspect ratio as a result of reorientation of the filaments in the shear direction. The filament phases with relatively high aspect ratios might reduce the net void sizes and change the pore network shapes, limiting the diameter of the inscribing openings. Moreover, the geotextile has a relatively high void ratio and so the effects of the increased number of filaments or decreased filament diameter is expected to have relatively small impacts on the LIOS distributions.

The theoretical lines in Figure 6.26a are for a network of filaments consisting of straight-line elements in space. A thin film of laid down geotextile may appear like a two-dimensional structure consisting of straight lines overlapping each other. However, microscopic observation of images from the sectioned specimens show the actual features as disconnected curved-line elements. Such differences between the theoretical and actual structures are considered the source of the high population of larger openings in the actual experimental results compared to the theoretical values.

Figure 6.27 presents the results from horizontal surfaces within the geotextile (face III in Figure 3.8b) at different elevations. Figure 6.27a shows the effect of normal
stress on the pore size distribution at mid-height within the specimen compressed against a smooth geomembrane surface. The cumulative distribution of voids smaller than 50 \( \mu m \) increased by about 25% as the normal stress increased from 100 to 300 kPa. It is noted that the horizontal sections parallel to the geotextile-geomembrane interface consisting of filament phases with large aspect ratios resulted in a high population of small void areas. For example, the geotextile on a smooth surface in vertical section (Figure 6.26c) has an \( F_{50} \) of 26% at a normal stress of 100 kPa while the horizontal surface near the middle of the specimen (Figure 6.27a) has a corresponding value of 49% at the same normal stress. Figure 6.27b shows the variation of opening sizes on horizontal surfaces of the same specimen at different elevations. The data were collected from geotextile sections sheared against a textured geomembrane. It shows consistently that the geotextile filaments are concentrated near the geomembrane texture features resulting in a high density of small openings at greater distances above the geomembrane-geotextile interface.

Figure 6.27 Results of LIOS Measurements from Planar Surfaces: (a) Effects of Normal Stress on A Smooth Geomembrane Surface (Middle Elevation); (b) Variation of LIOS at 100 kPa with Elevation.
6.5.2 Statistical Properties of Largest Inscribing Opening Size Distribution

The responses of geotextile opening size distribution to compression or residual shear against smooth or textured geomembrane surfaces are further studied in this section through a series of statistical analysis. Among the various curve fitting models, the beta distribution function was found as the best fitting curve by Pearson’s space method and

![Figure 6.28 Largest Inscribing Opening Size Distribution and Beta Distribution Model-NPNW Geotextile on a Smooth Geomembrane.](image-url)

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least square error method. The comparison of the measured cumulative frequency of pore size with the beta curve fitting results are presented in Figure 6.28 and 6.29 for the geotextile specimens placed on a smooth and a textured geomembrane, respectively.

Figure 6.29 Largest Inscribing Opening Size Distribution and Beta Distribution Model-NPNW Geotextile on a Textured Geomembrane: (a) Shear Surface (Face I); (b) Cross-Shear Surface (Face II).
The filaments on the smooth geomembrane showed linear relationship on the Pearson’s probability distribution space while the textured specimens resulted in variations with a large range (Figure 6.30). It is found that the LIOS data are mostly distributed on the regions of beta distribution at Pearson’s probability distribution. The standard deviation of the data showed semi-linear increase with the mean opening sizes (Figure 6.31). The textured geomembrane resulted in high value of coefficient of variation (slope of the graph) with low square error for the curve fitting. Such results of high variation at the textured geomembrane surface are consistent with the results of LVRD. The high normal stress and residual shear resulted in low entropy of the opening size distribution (Figure 6.32). The low value of entropy with mean opening size larger than 100 \( \mu m \) is considered as the result of hook and loop effect at low normal stress level of 10 kPa which results in dilation of specimen and geotextile filament disturbance near the geomembrane-geotextile interface.

Figure 6.30 Evaluation of Frequency Distribution Models using Space of Pearson’s Probability Distribution-Geotextile on Vertical Sections Placed on Geomembrane Surfaces: (a) Smooth Geomembrane; (b) Textured Geomembrane.
Figure 6.31 Relationship between Standard Deviation and Average Largest Inscribing Opening Size: (a) Smooth Geomembrane; (b) Textured Geomembrane.

Figure 6.32 Entropy Values of LIOS Distribution Based on Beta Distribution Model.
6.6 Conclusions

The sample preparation method and image analysis techniques described in this study made it possible to observe the inner structure of the geotextile-geomembrane interfaces under different external load conditions. The concentration of geotextile filaments as a function of distance from the geomembrane surface varied with increases/decreases in normal stress. The three orthogonal viewing planes and the serially sectioned surface images in vertical direction revealed localized filament concentrations near geomembrane texture elements. These results were consistent with the shear direction and texture geometry. Shearing resulted in significant variations of geotextile void structure due to the localized stretching and surface degradation near the interface.

The incremental and cumulative local void ratio distributions reflected the significant response of the geotextile to the normal stress states. The load history such as compression or interface shear against a textured geomembrane resulted in distinctive differences in the micro-scale pore network. LIOS has an advantage that it provides the actual scale of the pore size. LIOS was particularly useful for quantifying the horizontal surfaces of the geotextile specimen at different depths, where the networks consist of long curved features. The key factors governing the resistance of geotextiles are the deterioration of filament structure and the deformation of geomembrane textures.
CHAPTER 7
ASSESSMENT OF FILAMENT MICROSTRUCTURE UNDER EXTERNAL FORCES

7.1 Introduction

During the past few decades, various manufacturing methods have been developed to produce textiles for geotechnical engineering purposes. Needle punched nonwoven geotextiles (NWNP) are amongst the more common geotextiles used in various field applications. As previously noted, NPNW geotextiles consist of spatially curved filaments that are often assumed to be randomly oriented and isotropically distributed. In this chapter, the effects of interface shear on the geotextile microstructure are discussed in terms of stress-strain-diameter of filaments as a function of the boundary load conditions. First, the tensile properties single geotextile filaments wide-width geotextiles are investigated. The variation of filament sizes due to interface shear are discussed. The deformed geotextile microstructures are quantitatively described in terms of the nearest neighbor distance distribution (NNDD) of the geotextile filament phase.

7.2 Tensile Properties of Single Geotextile Filaments

7.2.1 Tensile Behavior of Geotextile Filaments

The typical tensile behavior of single geotextile filaments is shown in Figure 7.1. The tensile force versus displacement has a nonlinear elasto-perfect plastic form for filament from geotextile A and C, resulting in nearly constant resistances after peak until they reached rupture at elongations of 62% and 54%, respectively (Figure 7.1a). The
Figure 7.1 Tensile Properties of Single Filaments: (a) Tensile Force-Displacement: (b) Filament Diameter-Displacement.
change of filament diameter is shown as a function of tensile displacement (Figure 7.1b). The diameter of geotextile A decreased rapidly under initial tensile loading. The geotextile C resulted in a similar trend of stress-displacement response and constant decrease of diameter with tensile force. The geotextile D made from polyethylene demonstrated a different response. Its initial modulus was relatively high and then decreased at an elongation of about 0.5 mm. This specimen resulted in a constant increase of tensile force until the break point without yielding. Parameters obtained from the tests are summarized in Table 7.1. Geotextile A was selected for the further study using image analysis techniques since it had a relatively large filament thickness and showed a large and relatively constant rate of change of diameter with displacement.

Table 7.1 Tensile Properties of Single Filaments of NPNW Geotextiles.

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<thead>
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<th>Geotextile</th>
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<tr>
<td>Breaking force, $BF$ (gf)</td>
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<td>Chord modulus, $CM$ (gf/den-mm)</td>
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<td>Elongation at peak, $EP$ (%)</td>
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</tr>
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<td>Initial Diameter, $d$ ($\mu$m)</td>
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<tr>
<td>Initial modulus, $IM$ (gf/den-mm)</td>
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</tr>
<tr>
<td>Linear density, $LD$ (denier)</td>
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</tr>
<tr>
<td>Poisson’s Ratio</td>
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</tr>
<tr>
<td>Tangent modulus, $TM$ (gf/den-mm)</td>
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</tr>
<tr>
<td>Yield point, $YP$ (%)</td>
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7.2.2 Filament Size Distribution

As noted throughout the previous chapters, tensile strain of the geotextile sheet plays an important role in determining the interface shear response in geotextile-geomembrane layered systems. The initial shape of fiber networks is primarily determined by the degree of crimps of single filaments. Fabrics made from uncrimped
fibers usually have a higher initial tearing strength and exhibit more stretching behavior (Lunenschloss and Albrecht, 1985).

It is obvious that during tension the filaments constituting the geotextile are exposed to internal and external forces resulting in geotextile structure changes as well as single filaments strains. Synthetic fibers can have various cross section shapes such as three-lobal, three-sided, round and hollow. Other forms include four-, five-, or multi-lobal, and ribbon-shaped. In textile and fiber engineering fields, fibers with a certain cross section shape are often selected to obtain the required visual effect and performance. For example, hollow fibers are often used since they present more volume and increased stiffness compared to their mass per unit volume (Lunenschloss and Albrecht, 1985). Geotextile A which was selected for additional image analysis in this study has a semi-round cross-sectional shape (Figure 7.2) so that the filament size can be expressed in terms of the width orthogonal to the longest length of the sectioned filament features.

Figure 7.2 Typical Cross-Section Image of A Geotextile: Trevira 011/280 under 200 kPa Residual (Face I; 1.552 mm × 0.766 mm).
Typical results of interface shear resistance using geotextile A and the textured geomembrane are shown in Figure 7.3a. The corresponding vertical displacements that occurred during the initial compression and shear displacements are illustrated in Figure 7.3b. The specimen showed a dilation under a low normal stress of 10 kPa (A3 in Figure 7.3b) during shearing while the samples at 100 kPa and 300 kPa resulted in residual settlements after the peaks due to filament rearrangement and the localized filament-texture interactions.

![Figure 7.3 Interface shear response of the geotextile against a moderately textured geomembrane: (a) shear resistance; (b) vertical displacement.](image)

Results of the filament size distribution obtained from the vertical sections of the specimens are illustrated in Figure 7.4 and 7.5. Figure 7.4a shows an incremental filament size distribution of a geotextile compressed to 300 kPa on a smooth geomembrane surface. The data is also shown as a cumulative frequency form as well as a model graph of beta distribution which was used to compare the data obtained from different load and boundary conditions. The distribution of initial filament sizes at low normal stress of 10 kPa (A1 in Figure 7.3) is shown in Figure 7.5a. Theoretical curves
shifted by a decrease of mean filament size of 3 and 6 µm were also included where all the filament sizes are assumed to decrease in the same ratio. Symbol $F_i$ defines herein a cumulative percent frequency of filaments smaller than $i$ µm in diameter. Similarly, $D_j$ indicates a filament diameter corresponding to cumulative frequency of $j$%.

Figure 7.4 Filament Size Distribution: Compression to 300 kPa; GSE 8-Smooth Geomembrane: (a) Incremental Frequency; (b) Cumulative Frequency.

Figure 7.5b shows the effect of normal stress on filament size distribution. A slight decrease of about 1 µm is found for the diameter corresponding to the 50% cumulative frequency of filaments ($D_{50}$). Cumulative frequency of filaments smaller than 40 µm increased by 7% as the load increased from 10 to 300 kPa. Such a difference is considered as a result of slippage of inner filaments in the horizontal direction.

Figure 7.5c presents the change of filament size due to shear against the textured geomembrane. The data were obtained from the shear surface (face I in Figure 3.8b) under normal stress of 100 kPa. The filament size corresponding 50% frequency ($D_{50}$) decreased by about 6 µm at the peak stain. At pseudo residual displacement, the value of
Figure 7.5 Results of Filament Size Distribution Measured from Vertical Sections with Various Boundary Conditions: (a) Normal Stress on a Smooth Geomembrane with Theoretical Curves; (b) Effect of Normal Stress; (c) and (d) Effects of Shear on a Textured Geomembrane-Shear Surface (I); (e) and (f) Effects of Shear on a Textured Geomembrane: Cross-Shear Surface (II).
$D_{50}$ had recovered by $3 \, \mu m$, which is still smaller than the initial state at normal stress of 100 kPa by about $3 \, \mu m$. At both the peak and residual shear states, 90% of filaments remained smaller than $37 \, \mu m$. The filaments from specimens under 300 kPa normal stress had slightly smaller diameters compared to the specimens under 100 kPa (Figure 7.5d). Relatively small changes of filament diameter by about $1.5 \, \mu m$ were found after peak as the specimen was displaced to pseudo residual state of 80 mm. Such a low amount of recovery after peak shear is considered as a result of high confining stress at the interlocking points between the deformed geomembrane textures and by packed filaments.

The results from the counter shear surfaces (face II in Figure 3.8b) which is orthogonal to the shear direction are illustrated in Figure 7.5e and f. A low frequency of filaments smaller than $25 \, \mu m$ ($F_{25}$) was found at peak strain under 100 kPa normal stress compared to the result from the shear surface (face I). A small change was found after peak strain with the $D_{50}$ enlarging to $28 \, \mu m$. Similarly to the results from the shear surface in Figure 7.5d, the change of distribution after peak strain was small for specimens at high normal stress of 300 kPa (Figure 7.5f).

7.2.3 Efficiency of Single Filaments on Tensile Strength

The wide-width tensile strength test is a popular method to evaluate properties of various geosynthetics. In order to investigate the contribution of single filaments to the wide-width tensile stress-strain properties of the selected geotextiles tests were performed using the procedure described in ASTM D 4595. Figure 7.6 shows a result of tensile test using geotextile A. Various studies have been conducted by many researchers about the effects of sample preparation on the test results. However, it is known that there is no
universal relationship between specimen sizes and test results (Koerner, 1998). In this study, 100 mm width by 200 mm height was chosen for the specimen size in order to satisfy the ASTM recommendation and to subject the specimen to boundary conditions similar to the specimens used for the interface shear resistance tests conducted in this study.

![Graph](image)

Figure 7.6 Result of Wide-Width Tensile Strength Test: GSE8.

Geotextile A had tensile modulus of about 3,488 gf/mm for 10 cm width at an elongation measurement of 50 mm. The tensile strength corresponding to 12 mm elongation was about 41,856 gf. A single filament had nominal yield strength of 33 gf as shown in Figure 7.1. The average number of geotextile filament phases observed from the cross-section images is approximately 18,000 for a 10 cm width specimen. For 100% efficiency of tension, where all the filaments contribute completely to generate their yield tensile strength, the total tensile capacity of ideal wide-width geotextile specimen ($T_{C_{ideal}}$) will be 594,000 gf. It is noted that the geotextile has about 7.05% of its
efficiency on tensile strength generation compared with the $TC_{\text{ideal}}$ of the filaments. If the initial size distribution of filaments are considered, the actual capacity under 10 kPa ($TC_{\text{initial}}$) is about 207,218 gf, which is 34.9% of the $TC_{\text{ideal}}$ of the ideal case. If a filament size distribution is known, the tensile strength that can be generated additionally by geotextile stretch can be calculated from equation 7.1.

\[
T_g = \sum_{i=1}^{n} (\sigma_y - E_{f_i} \cdot \varepsilon_{f_i})
\]

(7.1)

where, $\sigma_y$ is yield strength, $E_{f_i}$ is Young’s modulus and $\varepsilon_{f_i}$ is strain of single filaments. 

The diameter and force at the filaments have a reciprocal relation as shown in Figure 7.1 so that the remaining tensile capacity of each filament can be calculated from the reduced diameters of each filament. For example, geotextiles under two different conditions may be comparable: 1) compressed on a smooth surface under 10 kPa; and 2) peak shear state on a textured surface under 100 kPa. The difference of tensile capacity is 165,347gf, which corresponds to 85.9% of the peak shear resistance under 100 kPa and 79.8% of tensile capacity at normal stress of 10 kPa ($TC_{\text{initial}}$).

### 7.3 Quantitative Filament Microstructure Observations

#### 7.3.1 Concept of Nearest Neighbor Distance

Nearest neighbor distance distribution is a descriptor used to quantitatively describe spatial arrangement of micro-structural phases in a material. This parameter is often used to relate feature distribution with the failure behavior of composite materials. This concept was derived from the Poisson point process and has been developed and
modified by many researchers for application to actual problems. The concepts are summarized below based on the works performed by Tewari and Gokhale (2004).

For a random population of points in a space, the probability that at least one point exists in an area \( dA \) that inscribe a point is equal to \( N_A dA \) where, \( N_A \) is number of features in unit area. The probability that the unit area, \( dA \) has exactly \( q \) number of points can be expressed in a Poisson distribution form as follows:

\[
P_r(q) = \frac{(N_A dA)^q}{q!} \exp(-N_A dA)
\] (7.2)

The \( n \) th nearest neighbor distance distribution can be expressed in terms of a probability density function \( \psi_n(r) \), which is the probability of finding nearest neighbor in the distance range \( r \) to \( (r + dr) \):

\[
\psi_n(r) = 2\pi r N_A \left( \frac{\pi r^2 N_A}{(n-1)!} \right)^{n-1} \exp(-\pi r^2 N_A)
\] (7.3)

For the uniform random distribution of points in space, the nearest neighbors in \( n \) th orders are expressed in equation 7.4 (Stoyan and Kendall 1987).

\[
\langle P_n \rangle = \frac{\Gamma\left(\frac{n+1}{2}\right)}{\sqrt{\pi(n-1)!}} N_A^{-1/2} = K_n N_A^{-1/2}
\] (7.4)

The numerical values of \( K_n \) defined by Equation (7.4) are shown in Table 7.2.

Table 7.2 Numerical value of \( K_n \) (Tewari and Gokhale, 2004).

<table>
<thead>
<tr>
<th>( n )</th>
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<td>( K_n )</td>
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<td>15/16</td>
<td>35/32</td>
<td>315/256</td>
<td>693/512</td>
</tr>
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</table>
The nearest neighbor may be expressed using different definitions (Figure 7.7):

1. $D_{center}$ which is the distance between centers of gravity of adjacent features,
2. $D_{net}$ which is net distance based on the centers of gravity, and
3. $D_{nearest}$ which is the shortest net distance considering the shape of the features. The distance by method (1) is measured by counting the number of pixels between the two phases in x-, and y-coordinate of the digitized image. For a distribution of ideal disks having the same size, the net distance, $D_{net}$ is the center-based length, $D_{center}$ minus the diameter. If the disk sizes are different, the net distance, $D_{net}$ can be calculated by subtracting the two radii from the measured total distance, $D_{net}$. For real materials, the two-dimensional images may have different shapes and random orientations (Figure 7.7b). Similar to the disk shape features, the center-based total and net distances can be calculated. The true nearest distances are equal or smaller than the center-based net distances.

![Figure 7.7 Definition of Nearest Neighbor Distance Measurement: (a) Disk Shape Feature; (b) Oriented Elliptical Feature.](image-url)
Effects of various definitions on the NND calculation are illustrated in Figure 7.8 which is acquired from a geotextile cross-section image. The difference of the data obtained from net and center based show the degree of variation in filament shape and orientation as well as uniformity in distribution. Figure 7.9 further illustrates the concept of NNDD using a set of fifteen disks. The dots are points on each disk for distance measurement. The nearest neighbor of disk # 2 and # 6 is disk # 5, but # 5’s nearest neighbor is # 1, and vice versa. Similarly, the second, third and the higher order nearest neighbors can be determined. In this study, a series of distance measurements were conducted using an automated image analysis algorithm.

7.3.2 Nearest Neighbor Distance Distribution

An image to describe the application of the nearest neighbor distances to an actual geotextile cross-section image is shown in Figure 7.10. The image was captured from the geotextile compressed under a normal stress of 300 kPa. The nearest and the fifth nearest neighbors detected are shown in Figure 7.10a, and 7.10b, respectively. In this phase of the study, representative information on the spatial distribution of filaments was obtained from the surfaces of three vertical sections cut from the specimens using the tri-sector sampling method.

The effects of vertical load of the filament structure are shown in terms of the incremental and cumulative frequencies of the nearest neighbor distance distribution (NNDD) in Figure 7.11. The frequency of geotextile features within 10 µm of the interface increased from 48 to 83% as the normal stress increased from 10 to 300 kPa. The unload cycle back to 10 kPa produced an irreversible change of about 7%. Similar changes in filament distributions can also be seen using the second nearest neighbor
analysis although the changes vary as a function of distance from the surface as seen in Figure 7.11b. It is interesting to note that the cumulative frequency distribution for the

![Graph](a)

![Graph](b)

![Graph](c)

![Graph](d)

![Graph](e)

Figure 7.8 Difference of NNDD with Definition (300 kPa Compressed Specimen).
initial and the unloading states are similar in spite of the apparent irreversible compression of the unloaded specimen (Figure 7.12). Such results are due to the lateral spreading of the specimen under compression, which resulted in irreversible strain in both vertical and lateral directions and a somewhat larger percent of the larger distances after unloading. The mean distances of the measured nearest distances in different orders are shown in Figure 7.13a. The decrease in the coefficient of variation (i.g., ratio of standard deviation to the mean value) of NNDD in Figure 7.13b indicates the usefulness of higher order NNDD to describe the filament microstructures with less variation.

Figure 7.9 Measurement of Nearest Neighbor Distance: 1st to 6th Orders.

Note: Dots on disks: starting points of the shortest distance measurement from the reference disks to the adjacent phases in nth order.
Figure 7.10 Measurement of Nearest Neighbor Distance: 1st to 6th Orders.

Note: Dots on disks: starting points of the shortest distance measurement from the reference disks to the adjacent phases in nth order.
Figure 7.11 NNDD Measurements for an Actual Geotextile: (a) Nearest; and (b) 5th Nearest Neighbors.
Figure 7.12 Cumulative Nearest Neighbor Distance Distribution of Geotextile Filaments: Nearest to Fifth Nearest Neighbors: (a) Initial at 10 kPa; (b) Loading to 300 kPa; (c) Unloading from 300 to 10 kPa.
Figure 7.13 Use of Different Order of NNDD: (a) Mean Distances of Randomly Distributed and Actual Filaments with Different Orders; (b) Change of Coefficient of Variation with Orders.

Among the three methods of NNDD description (Figure 7.7), the center-to-center distances obtained from centers of gravities of geotextile filaments may provide reliable data on the microstructure changes with regard to the textile strain and resulting filament distance changes since this method is not affected by the shape or orientation of geotextile filament phases. Such responses to normal and shear stresses as well as thegeomembrane surface profiles are illustrated in Figures 7.14 to 7.18.

Figure 7.14a shows the variation in the NNDD of geotextile filaments with normal stress in which 56 to 78 % of the filament features have distances smaller than 50 $\mu$m to nearest neighbors for tests with smooth geomembrane surfaces. The relatively high value of small distance population for 5th neighbor distances under loading to 300 kPa indicates dense packing of the filaments with low local variation through the specimen section (Figure 7.14b).
Figure 7.14 Results of NND Measurements from Vertical Sections: Effects of Normal Stress on a Smooth Geomembrane: (a) Nearest; (b) 5th Nearest.

The effect of shear against a smooth geomembrane surface is shown in Figure 7.15a. The population of nearest neighbor distance less than 50 \( \mu m \) slightly increased by shear to residual state. The cumulative frequency for the higher order distances increased, which might be from the filament redistribution by the inner slippage of the filaments (Figure 7.15e and f).

Figure 7.16 gives the effect of shear against a textured geomembrane on NNDD of filament phases. The sheared specimen shows a slightly lower frequency for the nearest value and nearly same value for the higher order distances compared to the case for a smooth geomembrane. This small difference is considered to be the result of compensation of geotextile strain and filament rearrangement with thickness change. The results are consistent with the data for LIOS as shown in Figure 6.26d.

The effects of normal stress on the geotextile filament structure under shear are shown in Figure 7.17. The combination of the normal stress and the shear-induced filament concentration resulted in an apparent change of the filament arrangement. The difference in the data between the 1st and 5th nearest data is considered to be caused by
various sources including normal stress, geomembrane texture deformation, geotextile strain and localized filament stretches.

Figure 7.15 Results of NND Measurements from Vertical Sections: Effects of Residual Shear-Smooth Geomembrane.
Apparent increase of filament density was found in face II (shear direction) of the specimens as shown in Figure 7.18. This is attributed by the filament reorientation in the shear direction which results in an increase of filaments with low aspect ratio in the cross

Figure 7.16 Results of NND Measurements from Vertical Sections: Effects of Residual Shear-Textured Geomembrane.
shear surface. The ratio of cumulative frequency between the face I and II are shown in Figure 7.19 for the specimens at residual states. The differences with orientation converge for third nearest neighbor distribution since the filament distance change due to shear is relatively small compared to the initial distance to the phases of higher order neighbor distance.
The tensile properties of filaments from needle-punched nonwoven geotextiles were measured through an experimental program and quantified in terms of the stress-strain-diameter response as well as other quantitative parameters. The experimental setup that used a helium neon deflectometer enabled tracing the complete tensile response of filaments as a function of strain. Using digital image analysis techniques, the change of filament size during interface shear testing was investigated. The interface shear against a textured geomembrane resulted in distinct reduction of filament size. The maximum change of filament diameter was observed at peak shear strain. The test results showed the impact of the concentrated normal stress and micromechanical interlocking between the geomembrane textures and geotextile filaments during interface shear.

Figure 7.19 Effects of Normal and Shear Stress State on NNDD.

**7.4 Summaries and Conclusions**

The tensile properties of filaments from needle-punched nonwoven geotextiles were measured through an experimental program and quantified in terms of the stress-strain-diameter response as well as other quantitative parameters. The experimental setup that used a helium neon deflectometer enabled tracing the complete tensile response of filaments as a function of strain. Using digital image analysis techniques, the change of filament size during interface shear testing was investigated. The interface shear against a textured geomembrane resulted in distinct reduction of filament size. The maximum change of filament diameter was observed at peak shear strain. The test results showed the impact of the concentrated normal stress and micromechanical interlocking between the geomembrane textures and geotextile filaments during interface shear.
The incremental and cumulative filament NNDD reflected the distinctive response of the geotextile to the normal stress states. Shearing resulted in significant variations of geotextile filament structure due to the localized stretching and surface degradation near the interface. The key factors governing the resistance of geotextiles are the deterioration of filament structure and the deformation of geomembrane textures.

Based on the global stress-strain curves and the internal micro-scale analyses in the machine direction, the following observations are made. The geotextile specimens are stretched in the shear direction and filament density decreases as the shear displacements increase. Geotextile strain and filament pullout occur during shear evolution. The resistance reaches a peak as the geotextile dilates over the geomembrane texture before decreasing to a residual state. The initial seating load and the penetration depth of the geomembrane texture into the geotextile are key factors that determine the shear modes which can range from geotextile surface degradation by filament pull-out and hook and loop interactions at low normal stresses to stretching of the geotextile and the resulting tension of the geotextile filaments.
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This dissertation has presented the results of study into geotextile-geomembrane interface contact mechanisms that is a critical issue in many geosynthetics field applications. Previous studies into geotextile-geomembrane interaction have focused on the large-scale behavior and the fundamental contact/shear mechanisms were not investigated. This chapter summarizes the results of the research and presents recommendations for further study. The approaches of this study may be classified into four categories: (1) design and development of a shear device and experimental setup; (2) laboratory investigation; (3) numerical modeling; and (4) analysis and discussion.

In order to investigate the micromechanical interaction between geotextile filaments and geomembrane texture elements at interfaces, a series of laboratory tests were performed.

- The role of geotextile strain and geomembrane surface roughness was investigated using a newly developed interface shear device. The device was designed to adequately measure the large displacement interface shear response of various geomaterials: continuum, particulate, and fibrous media. It overcomes the errors caused by boundary conditions in conventional shear devices by using modified systems: hollow shear frame, roll-type secure
system, a set of linear bearing guidance, and independently placed shear frame
supporting systems.

- The shear displacement was guided using a set of linear bearings that reduces
the system friction into the range of 0.1% to 0.2% of the applied normal
stress. The boundary condition allowing the geotextile to strain enabled the
specimen to be prepared for quantitative image analysis by an epoxy
impregnation method. Moreover, the vertical displacement of the layered
specimen could be monitored without interference throughout the shear
displacement phase of testing using the hollow shear frame and its robust
supporting systems.

- The sample preparation process for the digital image analysis was enhanced in
this study. The delicate geotextile specimen could be impregnated with low
viscosity epoxy resin at different load and boundary conditions.

- The secondary curing of the specimens with cast acrylic plates with a similar
hardness to the epoxy resin enabled thin-layered specimens to be prepared for
dissecting and polishing. Careful procedures for sample preparation and high-
resolution microscopic observation enabled the microstructure of geotextile
filaments to be readily seen. The current study extended the scope of optical
microscopic measurements in geomaterials to one tenth of the scales to the
previous studies in geotechnical image analysis fields, which are usually
focused on sand specimens.

- The tensile properties of single geotextile filaments were measured with a
force resolution of 0.0002 grams and strain resolution of $1 \times 10^{-6} \text{ mm}$. The
experimental setup using a helium neon gas laser beam projector enabled the
complete tensile response of the filaments with applied strain to be tracked.
The properties of the strain-stress-diameter relation of the filaments were
quantified in terms of various parameters.

The interface shear modes at geotextile-geomembrane interfaces were
termedized considering the boundary conditions through a series of laboratory tests.

- The coefficient of friction ranged from 0.16 to 0.20 with the unconstrained
  geotextiles and 0.20 to 0.27 with the constrained geotextiles against a smooth
  geomembrane in the normal stress range of 50 to 400 kPa, respectively. The
  measured geotextile strain at residual strain state was small but it is noted that
  the enhanced integration of geotextile filaments by strain confinement
  increases the sliding component of friction against a smooth surface.

- The release of geotextile strain resulted in increased sensitivity through the
  normal stress range of 10 to 400 kPa. This is considered to be due to the
  rearrangement of filaments after peak shear strain at small strain level. The
  initial large thickness loss and the residual vertical displacement provided
  consistent results.

- In textured geomembrane/NPNW geotextile interfaces, the constrained
  geotextiles resulted in higher sensitivity in the range of 1.25 to 1.9 under
  normal stress range of 50 to 400 kPa.
• Stretching of geotextiles was found to be the major contributor to thickness reduction where the geomembrane texture elements deform in the shear direction.

• The surface texture of the moderately textured geomembrane resulted in the peak and residual shear stress by 3.9 to 4.7 times for the constrained and 2.8 to 3.9 times for the unconstrained cases, respectively.

• The coefficient of friction decreased with normal stress in the range of 10 to 400 kPa, which is different from the basic concept that most engineering materials have constant coefficient of friction with confining stresses but polymers often show differences as noticed by Archard (1957).

• The methods of geotextile-geomembrane friction parameter determination and their effects on the calculation of slope stability were discussed.

• The constrained geotextile removed the dominant geomembrane texture elements resulting in residual vertical displacements while the unconstrained geotextile showed an unique shear mode with regard to the shear displacements: (1) initial seating where geomembrane textures deform; (2) secondary compression of the geotexile at a small shear strain due to filament rearrangement; (3) dilation of the specimen with shear displacement until the strain reaches the peak shear strain. The geotexile travels on the textured geomembrane where the peak shear strain occurred at the maximum dilation points. (4) After peak the geotextile settled by geotextile filament disturbance on the yielded geomembrane textures through the residual states.
Overlying particles with semi round or angular shapes increased the adhesion component of the sliding friction of a geotextile against a smooth geomembrane surface. The thick geotextile with high mass per unit areas resulted in low resistances at the same load and boundary conditions with both the angular- and round-shape cover soils.

The geotextile-geomembrane interface was simulated using the finite difference method. The results illustrated significant change of interface shear stiffness with the changes of materials properties as well as the boundary conditions.

The digital image analysis techniques enabled the microscale contact behavior of the filaments-textures to be quantified.

- The applicability of tracking filament orientation from a single surface image was discussed analytically.
- The filament distribution in vertical sections was monitored from the cross section images. The representative information of the geotextile filaments array and evolution was acquired using the tri-sector sampling method for the compressed specimens. Three orthogonal viewing planes were observed for the sheared specimens including shear, cross-shear, and in plane surfaces at different elevation from the interfaces.
- The geotextile filament microstructures were quantified using various parameters including local void ratio, largest inscribing opening size, filament size, and nearest neighbor distance of filaments with regard to the load and
boundary conditions. The variation of parameters were modeled with simple cubic packing and centered-cubic lattice structures and compared with actual data. Distributions of each parameter were also modeled statistically and characterized using Pearson’s probability distribution space as well as entropy.

- The descriptions of LVRD and LIOS distribution were useful to quantify the geotextile section images with relatively large aspect ratio and dense population of filaments that are usually found near geotextile-geomembrane interlocking points or in-plane surfaces at different elevations.

- The local void ratio and its distribution were useful as a non-dimensional parameter to characterize the void structures while the LIOS had an advantage that it provides the actual scale of pore size.

- The interface shearing of a geotextile against a textured geomembrane resulted in distinctive reduction of filament size distribution. The maximum change of filament diameter was observed at peak shear.

- The contribution of single filaments to the interface shear resistance was calculated by taking wide-width tensile strength using a geotextile. The initial tensile capacity of geotextiles was calculated using the results of single filament tensile test and microscopic observation of geotextile cross sections. The shear induced stretching of geotextile filaments under unconstrained boundary conditions and the resulting decrease of tensile capacity of the geotextile was determined.
• The NNDD was useful to characterize the properties of filament distribution. This descriptor responded sensitively to the external load conditions and was found efficient to track the filament structure evolution.

• The quantitative parameters and automatic routines applied in this study to characterize the geotextile inner structures can be applied to images obtained from a broad range of fields with various scales. For example, the LVRD will be appropriate to be applied in the materials having relatively high local void ratio and LIOS will be suitable for the web-shaped images with curved or linear elements. The filament or phase size distribution as well as the NNDD would be suitable to quantify the size growing/shrinkage of imbedded materials or phase evolution with internal or external conditions.

• An interface shear mode between unconstrained geotextile and moderately textured geomembrane was proposed based on the experimental test results and microscopic observation. The proposed shear mechanism describes the geotextile-geomembrane shear mode into five stages considering the change of geotextile inner structure and geomembrane texture deformation with shear displacement.

8.2 Shear Mode of Geotextile-Geomembrane Interface

The shear evolution and failure modes of NPNW geotextiles against smooth and textured geomembrane surfaces are summarized in Figure 8.1 to 8.3, respectively. Against a smooth geomembrane surface as shown in Figure 8.1, the interface resistance is predominantly due to sliding. Initial shear displacement results from redistribution of
Figure 8.1 Typical Shear Mode of NPNW Geotextile/Smooth Geomembrane Interface.

geotextile filaments. Light geotextile with small thickness usually result in high resistance while thick geotextiles exhibit lower resistance with large vertical displacement as well as larger shear displacement to peak. The initial moduli are often greater than those obtained with a textured geomembrane at low displacements up to about 1.5 mm since the resistance against a textured surface generated by interlocking between the filaments and texture elements requires relatively large displacement to be mobilized. After peak strain, the friction decreases within a displacement of about 4 mm.
and goes to pseudo residual state. The light geotextile reaches nearly constant residual shear within a displacement of about 40 mm while the thick geotextile exhibits a constant increase in vertical displacement up to a displacement of 80 mm at the end of the test.

The geotextiles showed different responses against a textured geomembrane surface (Figure 8.2 and 8.3). In the case of a constrained geotextile (Figure 8.2), the filaments near the interface are rearranged and a high resistance occurs at relatively low shear displacement. The resistance increases until the interlocking between filaments and
texture elements fail by wear of the geomembrane textures. The geotextile surface near the interface is heavily disturbed after peak strain. The post peak response of the interface fluctuates due to the additional friction between the worn geomembrane texture elements and the disturbed geotextile.

Figure 8.3 illustrates the proposed shear mechanism for NPNW geotextile-textured geomembrane interfaces based on the results of the experimental tests and microscopic observations conducted in this study. At initial compression, the geomembrane texture elements deform (Stage 1). The unconstrained geotextile starts to stretch by interlocking with the geomembrane texture elements and vertical displacement occurs (Stage 2). The geotextile begins to dilate with shear displacement which is caused by the sliding of geotextile fibers over the geomembrane texture elements until the geomembrane texture elements begin to fail (Stage 3). At this stage, the geotextile filaments are rearranged and the shear stress concentrates at the interlocking points between the two materials. The interlocking between the geotextile and geomembrane texture elements are released by the loose geotextile inner structure and deformed geomembrane texture elements (Stage 4). As a result of the failure of the geomembrane texture elements, and the residual degradation of geotextile near the interface the geotextile is compressed until it reaches large displacement (Stage 5). A high normal stress may confine the geotextile dilation and result in large displacement at peak by the deep interlocking between geotextile and geomembrane textures as well as high resistance before release of the interlocking.
Figure 8.3 Interface Micromechanism of Geotextile-Geomembrane System: Unconstrained Geotextile-Moderately Textured Geomembrane.
8.3 Recommendations

The research conducted in this study was focused on the interaction between geotextiles and geomembranes to investigate the contact and shear evolution mechanisms. The followings are the recommendations provided for the future research based on the current study.

- The overburden particulate materials were found to affect the behavior of the interface through experimental tests. Additional study is required to characterize the micromechanical response of the interface through digital image analysis under the surcharge materials.

- Fine particle migration or clogging has been a critical issue in geotextile applications in the field. The delicate sample preparation and image analysis technique applied in this study is expected to enable phenomena to be quantitatively observed.

- The current study used a smooth and a textured geomembrane as reference counter surfaces against the NPNW geotextiles. Additional study is required with different geomembranes to generalize the micromechanical interface shear mechanisms proposed in this study. Numerous studies found in the literature describe the large-scale response of geotextile-geomembrane interfaces but very limited information about the effects of the pattern of geomembrane surface profiles is available. Microscopic observation and quantifying methods suggested in this study may contribute to find the optimal solution for filament-texture interfaces in geosynthetic fields.
• The NPNW geotextiles are known to be appropriate for geotechnical engineering purposes and widely used in practice. In addition to the NPNW geotextiles, studying the microscale properties of woven geotextile or fabrics with the proposed methods may extend knowledge about the engineering behavior of nonwoven textile materials.
APPENDIX A

Technical Drawing of Shear Apparatus
Figure A.1 Schematic diagram of the designed interface shear device.

Figure A.2 Top View.
Figure A.3 Details of the Upper Structure of the Interface Shear Device.
Figure A.4 Details of the Collar and Main Frame.

Figure A.5 Footing.
Figure A.6 End Wall.

Figure A.7 Roll Panel I.
Figure A.8 Roll Panel II.
Figure A.9 Roll Panels (Front View).

Figure A.10 Details of Roll Panels (Side View).
Figure A.11 Reaction Wall and Side Frame.
APPENDIX B

LVRD Estimation from a Geotextile Section Image
Figure B.1 Binarized Image.

Load: 300 kPa compression
Image size: 2.178 mm (w) x 1.227 mm (H)

Figure B.2 Erosion of Detected Feature.
Figure B.3 Image Inverse.

Figure B.4 Segmentation.
Figure B.5 Eroded Feature Removal.

Figure B.6 Polygon Generation.
Figure B.7 Binarized Image.
APPENDIX C

Calculation of Largest Inscribing Opening Size
Figure C.1 Flow Chart of LIOS Calculation.
Figure C.2 Tracking of Largest Inscribing Opening Size: (a) Initial Detecting of Nearest Neighbor Solid Phase by Windowing from the Center of Gravity of a Polygon; (b) Measurement of Distance between the Point of Initial Center of Gravity and the Detected Solid Phase; (c) Limit of Tracking Boundary into the x-, and y-Coordinate of the Detected Nearest Solid Phase; (d) Secondary Detecting of Adjacent Solid Phase from a New Reference Position within the Selected Boundary.
import java.util.*;
import java.io.*;
import java.awt.*;
import java.awt.image.*;
import javax.swing.*;

public class extends JFrame {
    String imageName = "test.jpg";
    double freedomOfMovement = 0.5;
    String centroidFileName = "centroid.txt";

    class Point {
        int x;
        int y;
        public Point(int _x, int _y) {x = _x; y = _y;}
        public String toString(){ return "[" + x + "," + y + "]";}
    }

    boolean doOptimal = true;
    int si = 10; // 0;
    int ei = 11; // resultsCenters.length;

    boolean img[ ][ ];
    Image image;
    int imgH;
    int imgW;
    Point centers[ ];
    Point boundaries[ ][ ];

    Point resultsCenters[ ];
    Point resultsNearestPoint[ ];
    int resultsBestDistance[ ];
    boolean timg1[ ][ ];

    int totalBoundaries = 150;

    void DoItNow() {
    }

    int dist2(int x1, int y1, int x2, int y2) {
        return (x1-x2)*(x1-x2)+(y1-y2)*(y1-y2);
    }

    void generateBoundaries() {
        boundaries = new Point[totalBoundaries+1][ ];
        int cx = totalBoundaries+1;
        int cy = totalBoundaries+1;
        boolean mp[ ][ ] = new boolean[2*totalBoundaries+3][2*totalBoundaries+3];
        boolean ch[ ][ ] = new boolean[2*totalBoundaries+3][2*totalBoundaries+3];
        for(int i=0;i<mp.length;i++) for(int j=0;j<mp[i].length;j++) {
            mp[i][j] = false;
            ch[i][j] = false;
        }
        for(int r=0;r<totalBoundaries;r++) {
            int r2 = r*r;
            //for(int y=0;y<ch.length;y++)
            //  for(int x=0;x<ch[i].length;x++)
            //      ch[i][j] = false;
            for(int y=0;y<mp.length;y++) {
                for(int x=0;x<mp[y].length;x++) {
                    int d2 = dist2(cx, cy, x, y);
                }
            }
        }
    }
}
if(d2<=r2) {
    if(!mp[y][x]) {
        mp[y][x] = true;
        ch[y][x] = true;
    }
}
}

LinkedList ll = new LinkedList();
for(int y=0;y<ch.length;y++)
    for(int x=0;x<ch[y].length;x++)
        if(ch[y][x]) {
            ll.add(new Point(x-cx, y-cy));
            ch[y][x] = false;
        }

boundaries[r] = new Point[ll.size()];
for(int i=0;i<ll.size();i++) {
    boundaries[r][i] = (Point)ll.get(i);
}

//System.out.println("total boundaries for r = " + r + " is: " + boundaries[r].length);
//System.out.println("(calculated: total boundaries for r = " + r + " is: " + (2*Math.PI*r));

void testBoundaries() {
    try {
        BufferedReader br = new BufferedReader(new InputStreamReader(System.in));
        while(true) {
            System.out.print("radius? ");
            int r = Integer.parseInt(br.readLine().trim());
            System.out.print("fillMode (t)? ");
            String fillMode = (br.readLine().trim());
            boolean fillNow = false;
            if(fillMode.equals("t")) fillNow = true;
            if(r<0||r>=boundaries.length) break;
            boolean timg[][] = new boolean[2*r+3][2*r+3];
            for(int y=0;y<timg.length;y++)
                for(int x=0;x<timg[y].length;x++)
                    timg[y][x] = false;

            int cx = r+1;
            int cy = r+1;
            if(fillNow) {
                for(int ri=0;ri<=r;ri++)
                    for(int i=0;i<boundaries[ri].length;i++) {
                        int tx = cx+boundaries[ri][i].x;
                        int ty = cy+boundaries[ri][i].y;
                        timg[ty][tx] = true;
                    }
            } else {
                for(int i=0;i<boundaries.length;i++) {
                    int tx = cx+boundaries[i].x;
                    int ty = cy+boundaries[i].y;
                    timg[ty][tx] = true;
                }
            }
            for(int y=0;y<timg.length;y++)
                for(int x=0;x<timg[y].length;x++)
                    System.out.print((timg[y][x]?".":" ")
            System.out.println();
        }
        System.out.println();
    }
}
void openTheImage() {
    image = new ImageIcon(imageName).getImage();
    imgW = image.getWidth(null);
    imgH = image.getHeight(null);
    img = new boolean[imgH][imgW];

    int pixels[] = new int[imgW*imgH];
    PixelGrabber pg = new PixelGrabber(image, 0, 0, imgW, imgH, pixels, 0, imgW);
    try {
        pg.grabPixels();
    } catch (InterruptedException e) {
        System.err.println("interrupted waiting for pixels!");
        e.printStackTrace();
        return;
    }

    int i = 0;
    int cnt = 0;
    int r, g, b;
    int clr;
    for(int y=0;y<imgH;y++) for(int x=0;x<imgW;x++) {
        clr = pixels[i];
        r = (clr&0xff);
        g = ((clr>>8)&0xff);
        b = ((clr>>16)&0xff);
        if(r+g+b<(3*128)) {
            img[y][x] = true;
        } /*
        img[y][x] = (pixels[i]==-1);
        if(img[y][x]) {
            cnt++;
        }*/
        i++;
    }
    System.out.println("total black pixels = " + cnt);
}

void readTheCenterInformation() {
    try {
        BufferedReader br = new BufferedReader(new FileReader(centroidFileName));
        LinkedList ll = new LinkedList();
        while(true) {
            String tstr = br.readLine();
            if(tstr==null) break;
            StringTokenizer st = new StringTokenizer(tstr);
            if(st.countTokens()!=3) break;
            int tv = Integer.parseInt(st.nextToken());
            double xd = Double.parseDouble(st.nextToken());
            double yd = Double.parseDouble(st.nextToken());
            xd += 0.5;
            yd += 0.5;
            ll.add(new Point((int)xd, (int)yd));
        }
        centers = new Point[ll.size()];
    }
}
for(int i=0;i<centers.length;i++) {
    centers[i] = (Point)ll.get(i);
}
} catch(Exception e) {
    System.out.println("error reading centroid.txt");
e.printStackTrace();
}

void calculateBestDistanceAndCenter(int ind) {
    for(int y=0;y<imgH;y++) for(int x=0;x<imgW;x++)
        timg1[y][x] = false;

    int cx = centers[ind].x;
    int cy = centers[ind].y;
    try {
        int nx = -1;
        int ny = -1;
        int r;
        for(r=0;r++;) {
            boolean bad = false;
            for(int i=0;i<boundaries[r].length;i++) {
                int tx = cx+boundaries[r][i].x;
                int ty = cy+boundaries[r][i].y;
                if(ty<0||tx<0||ty>=imgH||tx>=imgW) {
                    bad = true;
                }
                if(img[ty][tx]) {
                    bad = true;
                }
            }
            if(bad) break;
        }
        if(img[ty][tx]) {
            bad = true;
        }
        if(bad) break;
    }

    resultsBestDistance[ind] = r;
    resultsCenters[ind] = new Point(cx, cy);
    resultsNearestPoint[ind] = new Point(nx, ny);
    if(nx==-1&ny==-1) {
        System.out.println("obvious error, nx=-1,ny=-1");
    }
    if(doOptimal) {
        for(int tr=0;tr<r*freedomOfMovement;tr++) {
            for(int i=0;i<boundaries[tr].length;i++) {
                int tx = cx+boundaries[tr][i].x;
                int ty = cy+boundaries[tr][i].y;
                timg1[ty][tx] = true;
            }
        }
    }
    return;
}
*/

resultsBestDistance[ind] = r;
resultsCenters[ind] = new Point(cx, cy);
resultsNearestPoint[ind] = new Point(nx, ny);
if(nx==-1&&ny==-1) {
    System.out.println("obvious error, nx=-1,ny=-1");
}
if(doOptimal) {
    for(int tr=0;tr<r*freedomOfMovement;tr++) {
        for(int i=0;i<boundaries[tr].length;i++) {
            int tx = cx+boundaries[tr][i].x;
            int ty = cy+boundaries[tr][i].y;
            timg1[ty][tx] = true;
        }
    }
*/

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//now do all the checking for all the positions
for(int tcy=0;tcy<imgH;tcy++) for(int tcx=0;tcx<imgW;tcx++) {
    int tnx = -1;
    int tny = -1;
    int tr;
    for(tr=0;;tr++) {
        boolean bad = false;
        for(int i=0;i<boundaries[tr].length;i++) {
            int tx = tcx+boundaries[tr][i].x;
            int ty = tcy+boundaries[tr][i].y;
            if(ty<0||tx<0||ty>=imgH||tx>=imgW) {
                bad = true;
                if(ty<0) ty++;
                if(tx<0) tx++;
                if(ty=imgH) ty--;
                if(tx=imgW) tx--;
                tnx = tx;
                tny = ty;
                break;
            }
            if(img[ty][tx]) {
                bad = true;
                tnx = tx;
                tny = ty;
                break;
            }
        }
        if(bad) break;
        if(tr>resultsBestDistance[ind]) {
            resultsBestDistance[ind] = tr;
            resultsCenters[ind] = new Point(tcx, tcy);
            resultsNearestPoint[ind] = new Point(tnx, tny);
            if(tnx==-1&&tny==-1) {
                System.out.println("obvious error,
                tnx=-1,tny=-1");
            }
        }
    }
}
}//end doOptimal
} catch(Exception e) {
    System.out.println(e);
    e.printStackTrace();
}

void writeTheFile() {
    try {
        PrintWriter pw = new PrintWriter(new FileWriter("centroidResults.txt"));
        pw.println("(SNo)(BestDistance)(CenterX)(CenterY)(NearestX)(NearestY)");
        for(int i=0;i<resultsCenters.length;i++) {
            String str = " ";
            str += (i+1) + "t";
            str += resultsBestDistance[i] + "t";
            str += resultsCenters[i].x + "t";
            str += resultsCenters[i].y + "t";
            str += resultsNearestPoint[i].x + "t";
            str += resultsNearestPoint[i].y;
            pw.println(str);
        }
    }
}
pw.println(str);
pw.flush();
}
} catch(Exception e) {
    System.out.println("Error while writing centroidResults.txt file");
e.printStackTrace();
}
}

int offsetY = 40;

void displayGUI() {
    setSize(imgW+5, imgH+offsetY+5);
    setVisible(true);
}

public void paint(Graphics g) {
    g.drawImage(image, 0, offsetY, null);
    /*g.setColor(Color.WHITE);
    g.fillRect(0,0,imgW,imgH+offsetY);
    g.setColor(Color.BLACK);
    for(int y=0;y<imgH;y++) for(int x=0;x<imgW;x++) {
        if(img[y][x]) {
            g.drawLine(x,y+offsetY,x,y+offsetY);
        }
    }*/
    g.setColor(Color.BLACK);
    for(int i=si;i<ei;i++) {
        g.drawLine(
            resultsCenters[i].x, resultsCenters[i].y+offsetY,
            centers[i].x, centers[i].y+offsetY);
    }
    g.setColor(Color.GREEN);
    for(int i=si;i<ei;i++) {
        g.drawLine(
            resultsCenters[i].x, resultsCenters[i].y+offsetY,
            resultsNearestPoint[i].x, resultsNearestPoint[i].y+offsetY);
    }
    g.setColor(Color.RED);
    for(int i=si;i<ei;i++) {
        int rcx = resultsCenters[i].x;
        int rcy = resultsCenters[i].y+offsetY;
        int r = resultsBestDistance[i];
        int twor = 2*r-2;
        g.drawArc(rcx-r+1, rcy-r+1, twor, twor, 0, 360);
    }
    g.setColor(Color.BLUE);
    for(int i=si;i<ei;i++) {
        g.drawLine(centers[i].x-1, centers[i].y+offsetY-1, centers[i].x+1,
                    centers[i].y+offsetY+1);
        g.drawLine(centers[i].x+1, centers[i].y+offsetY-1, centers[i].x-1,
                    centers[i].y+offsetY+1);
    }
}

void doIt() {
    //generate the boundary information
    System.out.println("Generating boundaries");
}
generateBoundaries();
System.out.println("done generating boundaries");
//testBoundaries();
//open the image
System.out.println("opening image");
openTheImage();
System.out.println("done opening image");
//open the file
System.out.println("reading centers");
readTheCenterInformation();
System.out.println("done reading centers");

//do the calculations
resultsCenters = new Point[centers.length];
resultsNearestPoint = new Point[centers.length];
resultsBestDistance = new int[centers.length];
timg1 = new boolean[imgH][imgW];
System.out.println("calculating information");

si = 0;
ei = resultsCenters.length;
for(int i=si;i<ei;i++) {
    System.out.println("calculating for: " + i);
    calculateBestDistanceAndCenter(i);
    System.out.println(" results best " + resultsBestDistance[i]);
    System.out.println(" results orig center :" + centers[i]);
    System.out.println(" results best center :" + resultsCenters[i]);
    System.out.println(" results nearest point:" + resultsNearestPoint[i]);
}
System.out.println("done calculating information");

//write the file
System.out.println("writing results");
writeTheFile();
System.out.println("done writing results");

displayGUI();
}

public static void main(String args[]) {
    DoItNow din = new DoItNow();
din.doIt();
}
APPENDIX D

Estimation of Nearest Neighbor Distance
Figure D.1 Flow Chart of NND Calculation.
import java.util.*;
import java.io.*;
import java.awt.*;
import java.awt.image.*;
import javax.swing.*;

public class CenterToCenter extends JFrame {
    static final long serialVersionUID = 12345L;

    String imageName = "NND.gif"; //default: "Initial image.jpg"
    String centerFileName = "center.txt"; //default: "center.txt"
    String distancesFileName = "distancesCenterArea.txt"; //default: "distances.txt"

    int totalClosestParticles = 6; //default: 2
    boolean displayOneDistanceOnly = false; //default: false
    int displayDistance = 1; //default: 1
    int radiusOval = 3; //default: 3

    Color[] colors = {Color.RED, Color.GREEN, Color.BLUE, Color.YELLOW, Color.MAGENTA, Color.CYAN, Color.ORANGE, Color.GRAY};

    LinkedList<ParticleInformation> particleInformations;

    class Point implements Comparable {
        int x;
        int y;
        public Point(int _x, int _y) {x = _x; y = _y;}
        public Point(Point a) {x = a.x; y = a.y;}
        public String toString() { return "[Point: " + x + ", " + y + "]";}

        public int compareTo(Object o) {
            Point p = (Point) o;
            int diff = 0;
            if(x!=p.x) diff = x-p.x;
            else if(y!=p.y) diff = y-p.y;
            return diff;
        }
    }

    class ParticleInformation {
        int cx;
        int cy;
        int id;
        int area;
        DistanceCenterToCenter[] dps;
        int dpsInd;

        public ParticleInformation(int _id, int _cx, int _cy, int _area) {
            id = _id;
            cx = _cx;
            cy = _cy;
            area = _area;
        }

        public void initializeDps(int n) {
    }
dps = new DistanceCenterToCenter[n];
dpsInd = 0;
}

public void initializeNextDistancePoint(int id1, int id2, int d, int sx, int sy, int ex, int ey) {
    dps[dpsInd] = new DistanceCenterToCenter(id1, id2, d, sx, sy, ex, ey);
    dpsInd++;
}

int distance(int x1, int y1, int x2, int y2) {
    int dx = x1-x2;
    int dy = y1-y2;
    return dx*dx + dy*dy;
}

void defineEndPoints(int ss[ ], int es[ ], int x1, int y1, int x2, int y2) {
    int dx = x2-x1;
    int dy = y2-y1;

    ss[0] = x1;
    ss[1] = y1;
    es[0] = x2;
    es[1] = y2;

    //ss[0] += dx/10;
    //ss[1] += dy/10;
}

public void findDistance(ParticleInformation pi) {
    int ss[ ] = new int[2];
    int es[ ] = new int[2];

    int d = distance(cx, cy, pi.cx, pi.cy);

    defineEndPoints(ss, es, cx, cy, pi.cx, pi.cy);
    //ss[0] = cx; ss[1] = cy;
    //es[0] = pi.cx; es[1] = pi.cy;

    initializeNextDistancePoint(id, pi.id, d, ss[0], ss[1], es[0], es[1]);
    pi.initializeNextDistancePoint(pi.id, id, d, es[0], es[1], ss[0], ss[1]);
}

class DistanceCenterToCenter implements Comparable {
    int sx, sy;
    int ex, ey;
    int id1;
    int id2;
    int d;

    public DistanceCenterToCenter(int _id1, int _id2, int _d,
                                  int _sx, int _sy, int _ex, int _ey) {
        sx = _sx;
        sy = _sy;
        ex = _ex;
        ey = _ey;
        id1 = _id1;
        id2 = _id2;
        d = _d;
    }
}
public String toString() {
    return "[" + id1 + "," + id2 + ":" + d + ":(" + sx + "," + sy + ")" + ":(" + ex + "," + ey + ")];
}

public int compareTo(Object o) {
    DistanceCenterToCenter dp = (DistanceCenterToCenter) o;
    int diff = 0;
    if(d!=dp.d) diff = d - dp.d;
    else if(id1!=dp.id1) diff = id1 - dp.id1;
    else if(id2!=dp.id2) diff = id2 - dp.id2;
    return diff;
}

boolean img[ ][ ];
Image image;
int imgH;
int imgW;

void openTheImage() {
    image = new ImageIcon(imageName).getImage();
    imgW = image.getWidth(null);
    imgH = image.getHeight(null);
    img = new boolean[imgH][imgW];
    int pixels[ ] = new int[imgW*imgH];
    PixelGrabber pg = new PixelGrabber(image, 0, 0, imgW, imgH, pixels, 0, imgW);
    try {
        pg.grabPixels();
    } catch (InterruptedException e) {
        System.err.println("interrupted waiting for pixels!");
        e.printStackTrace();
        return;
    }
    int i = 0;
    int cnt = 0;
    int r, g, b;
    int clr;
    for(int y=0;y<imgH;y++) for(int x=0;x<imgW;x++) {
        clr = pixels[i];
        r = (clr&0xff);
        g = ((clr>>8)&0xff);
        b = ((clr>>16)&0xff);
        if(r+g+b<(3*128)) {
            img[y][x] = true;
        }/*
        img[y][x] = (pixels[i]==-1);
        if(img[y][x]) {
            cnt++;
        }*/
        i++;
    }
    System.out.println("total black pixels = " + cnt);
}
int offsetY = 40;

void displayGUI() {
    setSize(imgW+5, imgH+offsetY+5);
    setVisible(true);
}

int visitNow(int id, int x, int y, boolean vis[][], boolean img[][], int cs[]) {
    LinkedList<Point> q = new LinkedList<Point>();
    q.add(new Point(x, y));
    vis[y][x] = true;

    int qc = 0;

    int h = vis.length;
    int w = vis[0].length;

    while(qc<q.size()) {
        Point p = q.get(qc); qc++;

        int dx, dy;
        for(dx=-1;dx<=1;dx++) for(dy=-1;dy<=1;dy++) {
            int cx = p.x + dx;
            int cy = p.y + dy;
            if(cx>=0 && cx<w && cy>=0 && cy<h) {
                if(img[cy][cx] && !vis[cy][cx]) {
                    vis[cy][cx] = true;
                    q.add(new Point(cx, cy));
                }
            }
        }
    }

    int dxs[] = { 1, 0,-1, 0};
    int dys[] = { 0, 1, 0,-1};

    double div = 1.0/q.size();
    double cx = 0;
    double cy = 0;

    for(int i=0;i<q.size();i++) {
        Point p = q.get(i);
        cx += p.x*div;
        cy += p.y*div;
    }

    //System.out.printf("For id=%d, q.size()=%d\n", id, q.size());
    cs[0] = (int)Math.round(cx);
    cs[1] = (int)Math.round(cy);

    int area = q.size();
    q.clear();
    return area;
}

void generateParticleBoundaries() {
    int i, j, k;
    boolean vis[][ ] = new boolean[img.length][img[0].length];

    for(i=0;i<vis.length;i++) for(j=0;j<vis[i].length;j++) {
        vis[i][j] = false;
    }

}
```java
particleInformations = new LinkedList<ParticleInformation>();
k = 0;
for(i=0;i<vis.length;i++) for(j=0;j<vis[i].length;j++) {
    int cs[] = new int[2];
    int area = visitNow(k, j, i, vis, img, cs);
    //System.out.printf("for id=%d, bi.q.size()=%d\n", k, bi.q.size());
    ParticleInformation pi = new ParticleInformation(k, cs[0], cs[1], area);
    particleInformations.add(pi);
    k++;
}

int n = particleInformations.size();
for(i=0;i<n;i++) {
    ParticleInformation pi = particleInformations.get(i);
    pi.initializeDps(n-1);
}

void findClosestPointsBoundaries() {
    int i, j, k;
    int n = particleInformations.size();
    for(i=0;i<n;i++) {
        ParticleInformation pii = particleInformations.get(i);
        for(j=i+1;j<n;j++) {
            ParticleInformation pij = particleInformations.get(j);
            pii.findDistance(pij);
        }
        Arrays.sort(pii.dps);
    }
}

void writeClosestPointsBoundaries() {
    try {
        PrintWriter pw = new PrintWriter(new FileWriter(distancesFileName));
        for(int i=0;i<particleInformations.size();i++) {
            ParticleInformation pi = (ParticleInformation) particleInformations.get(i);
            DistanceCenterToCenter dbtb[] = pi.dps;
            pw.printf("%d\t%d\t%d\t%d\n", pi.id+1, pi.cx, pi.cy, pi.area);
            int min = Math.min(totalClosestParticles, dbtb.length);
            for(int j=0;j<min;j++) {
                pw.printf("%d\t", dbtb[j].id2+1);
                pw.printf("%d", (int)Math.round(Math.sqrt(dbtb[j].d)));
            }
        }
        pw.println();
        pw.flush();
        pw.close();
    } catch(Exception e) {
        e.printStackTrace();
    }
}
```
void doIt() {

    //open the image
    System.out.println("opening image");
    openTheImage();
    System.out.println("done opening image");

    //find boundaries
    System.out.println("finding particle boundaries");
    generateParticleBoundaries();
    System.out.println("done finding particle boundaries");

    //find closest points (boundaries)
    System.out.println("finding closest points using boundaries");
    findClosestPointsBoundaries();
    System.out.println("done finding closest points using boundaries");

    //write closest points (boundaries)
    System.out.println("writing closest points using boundaries");
    writeClosestPointsBoundaries();
    System.out.println("done writing closest points using boundaries");

    displayGUI();
}

public void paint(Graphics g) {
    g.drawImage(image, 0, offsetY, null);

    if(displayOneDistanceOnly) {
        if(displayDistance<=totalClosestParticles) {
            g.setColor(Color.GREEN);
            for(int i=0;i<particleInformations.size();i++) {
                ParticleInformation pi = particleInformations.get(i);
                DistanceCenterToCenter dbtb[] = pi.dps;
                int j = displayDistance-1;
                int x1 = dbtb[j].sx;
                int y1 = dbtb[j].sy;
                int x2 = dbtb[j].ex;
                int y2 = dbtb[j].ey;

                g.drawLine(x1, y1+offsetY, x2, y2+offsetY);
            }
        }
    }

    for(int i=0;i<particleInformations.size();i++) {
        ParticleInformation pi = particleInformations.get(i);
        DistanceCenterToCenter dbtb[] = pi.dps;
        int j = displayDistance-1;
        g.setColor(colors[j%colors.length]);
        int x1 = dbtb[j].sx;
        int y1 = dbtb[j].sy;
    }
}
g.fillOval(x1-radiusOval, y1+offsetY-radiusOval,
radiusOval*2, radiusOval*2);
}
else {
    System.out.println("Warning! Input
displayDistance<=totalClosestParticles\n");
}
else {
g.setColor(Color.blue);
for(int i=0;i<particleInformations.size();i++) {
    ParticleInformation pi = particleInformations.get(i);
    DistanceCenterToCenter dbtb[] = pi.dps;

    for(int j=0;j<totalClosestParticles && j<dbtb.length;j++) {
        int x1 = dbtb[j].sx;
        int y1 = dbtb[j].sy;
        int x2 = dbtb[j].ex;
        int y2 = dbtb[j].ey;
        g.drawLine(x1, y1+offsetY, x2, y2+offsetY);
    }
}
for(int i=0;i<particleInformations.size();i++) {
    ParticleInformation pi = particleInformations.get(i);
    DistanceCenterToCenter dbtb[] = pi.dps;

    int min = Math.min(totalClosestParticles, dbtb.length);
    for(int j=min-1;j>=0;j--) {
        g.setColor(colors[j%colors.length]);
        int x1 = dbtb[j].sx;
        int y1 = dbtb[j].sy;

        int dx = dbtb[j].ex - dbtb[j].sx;
        int dy = dbtb[j].ey - dbtb[j].sy;

        x1 += dx/4;
        y1 += dy/4;
        g.fillOval(x1-radiusOval, y1+offsetY-radiusOval, radiusOval*2,
radiusOval*2);
    }
}
}
g.setColor(Color.RED);
for(int i=0;i<particleInformations.size();i++) {
    int x1 = particleInformations.get(i).cx;
    int y1 = particleInformations.get(i).cy;
    g.drawString("\n"+(i+1), x1-5, y1+offsetY+5);
}

public static void main(String args[]) {
    DoItNowCenterToCenter din = new DoItNowCenterToCenter();
    din.doIt();
}
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VITA

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