Use of Image Analysis in Determination of Strain Distribution During Geosynthetic Tensile Testing

Ahmet H. Aydilek, M.ASCE1; Murat Guler2; and Tuncer B. Edil, M.ASCE3

Abstract: Determining the deformation response of geosynthetics under load is important in developing an in-depth understanding of the engineering behavior of these materials. Current strain determination methods employed as part of tensile tests mostly assume that the strain is uniform throughout the specimen and, hence, are incapable of determining local strains. Geosynthetics have occasionally been instrumented with strain gauges and extensometers; however, these direct contact methods have limitations in fully defining strain distributions in a test specimen. Recent technological advancements in image analysis offer great potential for a more accurate and noncontact method of determining strains. An image-based particle tracking method was used to define the strain distribution in various geosynthetics during wide-width tensile testing. The method used a block-based matching algorithm functioning under LABVIEW. The measured gross strain values were compared to those determined from strain gauges and extensometers. The strain values determined by these methods were comparable to the image-based ones, and the absolute value of the difference was less than 10% for the geosynthetics tested. Furthermore, the image-based analysis was effective in also determining the local strains.


CE Database subject headings: Image analysis; Strain distribution; Deformation; Geosynthetics.

Introduction

Geosynthetics are plastic polymeric materials and used in a variety of geotechnical applications. In many design applications, information about the tensile strength, failure strain, and deformation modulus of the geosynthetic is required. The stress-strain properties of a geosynthetic are determined from tensile tests (e.g., wide-width tensile test and grab tensile test), and the strength is usually defined at a particular strain or elongation level. Continuous strain measurement during testing of geosynthetics provides a better and more detailed understanding of the material behavior. The accurate determination of the deformation (therefore strain) zones is necessary, and becomes more important in the presence of seams in a geosynthetic specimen. These zones of varying strain, undetected in conventional mechanical strain measurement systems, could identify potential local failure zones in the field and inaccurate determination of strains and may either lead to an unconservative design of the structure or possible catastrophic failures.

The crosshead extension method, which measures the separation distance between two tension grips during testing, is a commonly used method of determining the overall strain; however, the method does not provide information about local strains. Strain gauges and extensometers have occasionally been used to determine local strains; however, concerns have been raised about these direct contact methods for their possible disruption of filaments or yarns in geosynthetics because they often cause additional strains on the test specimen. Generally, these devices cannot define a complete distribution of strains in a test specimen, and particularly strain gauges may break at strains less than that of interest in geosynthetics. In the case of extensometers, on the other hand, the measured deformation is based on the movement of the two contact points of the apparatus, and can only be used to define an average strain value for the area of interest. These sensors are expensive and not all geosynthetic laboratories have the capability of installing them. Furthermore, the relatively small size of most of the strain gauges imposes limitations on the displacement measurements. Due to the shortcomings of the existing strain determination methods, an image-based approach can be utilized to define the strain zones in a geosynthetic during the tensile testing.

Background

The recent progress made in the application of image-based particle tracking techniques in geomechanics and geotechnical engineering has shown that these techniques can be adapted for use in the analysis of the strain distribution in geosynthetics during a tension test. These tracking techniques provide a noncontact approach for determining strain without causing a disturbance in test specimens.

Donohoe and Bacobella (1991) implemented a particle tracking technique for identifying the edges of segmented particles. Statistical correlations were used to match the particles in the entire image sequence. The method was useful when the images were captured at high magnifications; however, it was generally laborious especially with the small-size particles, as they required the use of particle centroids.
Hryciw and Raschke (1996), Hryciw et al. (1996), and Gustaffson and Gustaffson (1996) tracked the movement of colored granular particles in a series of captured digital images. Thresholding and edge detection techniques were employed to separate and count each individual particle. Gustaffson and Marklund (1995) used a similar tracking approach; however, their method counted the number of particle passages in an image rather than particle edges of a granular soil.

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Paikowsky and Xi (2000) developed a system capable of investigating the interparticle interaction of two-dimensional photelastic disks representing granular materials. Tracking of the disks was performed through the use of charge-coupled device (CCD) cameras, and semiautomatic image processing coupled with analysis algorithms. The kinematic analyses conducted as part of the study presented the displacement fields and described the incremental translation and rotation of the disks. The system provided detailed tracking of a large number of particles when compared to other available systems.

Alshibli and Sture (2000) defined the deformation patterns in plane strain experiments of sand. Square grid patterns with a line thickness of 0.5 mm were drawn on the membranes that confined the sand specimens. The images of specimen during compression were captured using a video camera and a frame grabber. Digitization of the images was performed manually using a commercially available image processing software. The analyses indicated that deformations localized into narrow shear bands during compression. The shear band inclination angles determined with the aid of image analysis compared well with those predicted using the theoretical solutions.

Computer vision techniques have also been used in fluid mechanics for the last two decades. Browand and Plotcher (1985) and Drake et al. (1988) monitored the trajectory of particles to simulate sediment movement in a riverbed using an imaging tool. The image-based techniques later developed by Pilotti et al. (1997) employed a solid-state linear camera to count the sediment particles moving along a line. In a similar study, Capart et al. (1997) described the kinematics of water-sediment interaction by using digital image analysis. Papunicolaou et al. (1999) used an image analysis system, called KHOROS, to study the bedload movement of particles in a laboratory flume. The images were captured using a video camera, and were digitized using a frame grabber. The imaging workspace accurately identified the displacements of even very small particles which would otherwise be visually undetectable.

Limited studies exist about the application of image-based tracking techniques to the testing of geosynthetics. Skochdopole et al. (2000) used a laser extensometer to determine displacements in wide-width tensile tests conducted on geosynthetics. The laser extensometer, with a separation capacity of 280 mm, measured the displacements by tracking the distance between two reflecting tapes attached to the specimen. Since it did not penetrate the specimen, it did not cause disturbance, a commonly observed phenomenon in the use of strain gauges. In general, the calculated strains were comparable with those obtained using the crosshead extension (i.e., grip separation).

To investigate the strain distribution in multiaxial testing of a geosynthetic specimen, Bray and Merry (1999) divided a latex membrane into segments and measured the displacements using digital calipers. They did not use image analysis due to expected large effects of parallax along a spherical surface. The use of strain gauges were not considered since the stiff nature of these devices relative to the latex membrane may affect the local strains. Test results indicated that the membrane did not creep and the deformed shape of membrane was constant.

Jones (2000) captured the digital images of three different geotextiles during wide-width tensile tests and analyzed them to define the displacements. The technique, named video extensometry, measured strain by tracking two contrasting lines placed on the specimen. Depending on the lens selection, a calibration procedure was needed for a particular optical field of view. The geotextiles were tested in their machine and cross-machine directions, and displacements were measured with a conventional direct contact extensometer and the noncontact image-based video extensometry technique. The results showed that the image-based methodology for measuring displacements had accuracy in the range of 86–100% relative to the extensometer.

The method described in this paper is based on a rapid automated technique to determine strain distributions in a geosynthetic without requiring significant user effort and judgment. The method uses typical hardware and image acquisition tools that are commonly employed in image analysis applications. The digital images of geosynthetics captured during tension tests were analyzed using a technique adapted from the moving expert group (MPEG) by Guler et al. (1999). The results were compared with the strain values registered by the strain gauges and extensometers placed on the geosynthetics.

Test Specimens

A laboratory test program was established to make automated measurements of the strain distribution of geosynthetics. The following four types of geosynthetics were included in the testing program: A woven geotextile, a nonwoven geotextile, a geogrid, and a polyethylene sheet cut from a geocell specimen. The geotextiles and geogrids are commonly used in geotechnical construction. A polyethylene sheet cut from a geocell specimen (referred to herein as a geocell) was also employed in the testing program, since the strain performance of the same material is currently being tested in a field cell using strain gauges. Duplicate tests were performed on each geosynthetic type for quality control. The specimen dimensions were selected for the wide-width tensile test in accordance with ASTM D4595 (ASTM 2001). The physical properties of the geosynthetics used in this study are given in Table 1.

Methodology

Strain-displacement analyses using the digital imaging technique included the following three steps: sample preparation, test setup for image acquisition, and analysis phase.

Specimen Preparation and Image Acquisition

The key step in the specimen preparation phase was to achieve a sufficient contrast within the image frames to facilitate the block-matching algorithm for the accurate analysis of displacements. The contrast between pixels was maximized by constructing gridlines on specimen surface using paint markers that exhibited largely negative colors relative to the specimen colors. The gridline spacing was selected as 10 mm to increase the contrast and visual clarity that were required for analysis.

A region of interest from the center of each test specimen was selected for image capturing and analysis similar to the work of

Table 1.

<table>
<thead>
<tr>
<th>Geosynthetic Type</th>
<th>Geometric Properties</th>
<th>Physical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven Geotextile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonwoven Geotextile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geogrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geocell</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Skochdopole et al. (2000). The image acquisition rate was determined based on the displacement in terms of pixel counts between successive frames. Generally, the frames were taken at 10 s intervals to achieve sufficient displacement for measurement. The higher acquisition rates may not yield appreciable displacements between the successive frames, and may cause data storage problems during testing. The strain rate of the testing machine was 1 mm/min in all tests. The image frames were saved onto a hard disk and analyzed for the in-plane displacements from which the strain distributions were obtained.

Images were captured using an analog CCD camera with a close focus zoom lens that had a working distance range of 145–330 mm, and a magnification range of $0.06 \times -0.33 \times$. The camera was connected to an IMAQ PCI 1408 image acquisition board installed on a personal computer (PC). The board was controlled with a LABVIEW generated application. The setup for the image analysis included a 330 mm x 460 mm workstation platform, a 460 mm vertical post, a 460 mm horizontal arm, a 90° angle mount, and a 50 mm diameter through-hole focus mechanism (Fig. 1). The geosynthetic specimens were illuminated by fiber optic light guides. The image acquisition board produced eight-bit grayscale images (256 gray colors) at a resolution of 640 x 480 pixels. The selected region of interest covered an area of approximately 64 mm x 48 mm centered between the jaw grips of the tension machine. A typical image of a geocell specimen is shown in Fig. 2.

It is expected that the measurement of localized strains is a function of the scale in which these strains are measured in the image-analysis method. This becomes particularly important when localized slip occurs in the specimen, in which case, small variations in the measurement scale can greatly change the measured strain values. Since the scale of the image-based strain measurement can be varied and made rather small compared to the mechanical methods, there can be a greater difference between the image-based strains and those measured by mechanical methods.

In this study, the images were captured at a field of view being somewhat larger than the gauge lengths of the extensometer and strain gauges. The main purpose was to obtain an image-based average strain and compare this value to those registered by these two sensors. The results were comparable; however, it is understood that the size of field of view may have an effect on the results. A larger field of view will result in lower image resolution (i.e., quality). The choice of field of view for image capturing is

<table>
<thead>
<tr>
<th>Geosynthetic name</th>
<th>Structure, polymer type$^a$</th>
<th>Mass/unit area$^b$ (g/m$^2$)</th>
<th>Thickness$^b$ (mm)</th>
<th>At 5% strain</th>
<th>At 10% strain</th>
<th>At failure (ultimate)</th>
<th>Strain at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>NW-GT, S1, PP</td>
<td>110</td>
<td>1.0</td>
<td>0.5</td>
<td>NR</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>W</td>
<td>W-GT, MF, PP</td>
<td>284</td>
<td>NR</td>
<td>19.8</td>
<td>35</td>
<td>47.3</td>
<td>14</td>
</tr>
<tr>
<td>GG</td>
<td>BA-GG, EXT, PP</td>
<td>253</td>
<td>NR</td>
<td>5.54</td>
<td>10.1</td>
<td>17.2</td>
<td>10</td>
</tr>
<tr>
<td>GC$^c$</td>
<td>Geocell, PE</td>
<td>NA$^c$</td>
<td>1.27</td>
<td>NA$^c$</td>
<td>NA$^c$</td>
<td>NA$^c$</td>
<td>NA$^c$</td>
</tr>
</tbody>
</table>


$^b$Mass/unit area, thickness, and wide-width tensile test results are manufacturer’s reported values.

$^c$NA: Not applicable. Mass/unit area and wide-width tensile strength determination methods are not applicable to geocells.
the outcome of a tradeoff between obtaining a representative average strain during the test (how valid an average strain over a larger area is) and assessing distribution of local strains. Therefore, the field of view adopted herein was chosen after considering this tradeoff. It requires further research and interpretation to analyze the images captured at different resolutions, which may further help to identify the sensitivity of the methodology and its ability to identify significant variations in local strains and their distribution, which is not typically available in the mechanical methods.

Analysis of the Captured Images

The captured images were analyzed using a block-based matching algorithm that was originally written in C++ programming language. The algorithm was then compiled under the graphical programming language LABVIEW and embedded into a user friendly application called BMAD (Guler et al. 1999). Using a 1 GHz Pentium-based PC compatible system, strain distribution of each geosynthetic was determined in approximately 2 min by this method. Due to their moderate hardware requirements and ease of implementation, block-based matching algorithms are widely used in pattern recognition problems. The method offers an effective motion estimation and video compression capability accepted by MPEG, the international standard for digital video compression applications. The main assumption of the method is that image frames are composed of moving small patterns rather than particular objects within the frames. The patterns are tracked sequentially from one image to the next and the amount of movement is directly related to the movement of selected patterns. Fundamentally, the block-matching method searches for a constant size of block between successively captured image frames based on a matching criterion. Implementation of the method described in this work is only for a translatory motion estimation, even though more complex algorithms exist for rotational motion estimation applications. Since the search range of blocks is determined by a distance criterion (search window), block-based matching is often called a “spatial domain search approach”. The following three factors control the performance of the BMAD algorithm: macroblock size, the matching criterion, and the search strategy (Tekalp 1995).

The macroblock is a block of pixels used to match a pattern between successive frames. BMAD has the capability to change the aspect ratio of macroblocks depending on the dimensions of individual image frames. However, the macroblock dimensions should be selected in a way that an even number of macroblocks is obtained along the vertical and horizontal dimensions of the image frames. Additionally, the selected macroblock size should be large enough to cover a square zone bounded by the gridlines drawn on a geosynthetic specimen (see Fig. 2), since the matching criterion is based on the contrast between pixel gray colors rather than spatial characteristics of image frames. Because the displacement vectors are calculated for each macroblock, the se-

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**Fig. 2.** Example image frame for geocell specimen (the holes on the image are the locations of the extensometer)

**Fig. 3.** A schematic showing the image analysis process

**Fig. 4.** Flowchart for the block matching method algorithm
lected dimensions also affect the number of displacement vectors that are calculated. In the analyses of the test specimens, several aspect ratios were used to evaluate the performance of the algorithm in comparing the image-based measurements with those determined by the extensometer and the strain gauge.

The search window is essentially a region of pixels which defines the locus of the macroblock in the current frame during the search operation. The macroblock taken from the reference frame is positioned with respect to its central pixel within the search window. The dimensions of the search window are a function of four parameters: the actual magnification of image frames, the image resolution in the direction of motion, the displacement rate employed in the test, and the image acquisition rate. The search window in BMAD is assumed to be a square region, the size of which is calculated using the following relationship:

$$S_D = \frac{S}{t} MR$$

where \(S_D\) = side length of search window; \(M\) = actual magnification (mm/image), in which mm designates image size; \(R\) = image resolution in the direction of motion (pixel/image); \(s\) = displacement rate of test (mm/s); and \(t\) = image acquisition rate (number of images/s).

Eq. (1) can be used to determine the minimum search window dimension in the analysis of displacement vectors. In general, search side lengths 2 or 3 pixels larger than those calculated are recommended to cover the potential locations of the best matching macroblocks.

BMAD uses the minimum absolute difference criterion (MAD), which is considered to be the most effective search criterion in particle tracking (Guler et al. 1999) and is defined as

$$MAD(d_1,d_2) = \sum |p(x_k,y_k) - p(x_{k+1} + d_1,y_{k+1} + d_2)|$$

(2a)

$$(\tilde{d}_1,\tilde{d}_2) = \arg \min \ M A D(d_1,d_2)$$

(2b)

where \(\tilde{d}_1,\tilde{d}_2\) = displacements in the horizontal and vertical directions, respectively, corresponding to the minimum of the sum of the absolute differences; \(p(x_k,y_k)\) = gray scale pixel values at \(x_k, y_k\); location within the current macroblock in frame \(k\); and \(p(x_{k+1} + d_1,y_{k+1} + d_2)\) = gray scale pixel values at \(x_{k+1} + d_1, y_{k+1} + d_2\) in frame \(k+1\).

Fig. 5. Vector plots (640×480 pixels) of the deformations developed during the wide-width tensile testing of a geocell specimen (x and y axes indicate the coordinates in terms of pixel values) (1 pixel=0.125 mm)
To find the best matching macroblock in the closest proximity from its original position, a spiral-searching path was executed in the algorithm. The search started from the center of the search window, seeking the best matching macroblock in the current frame by scanning through all the pixels within the search window. As the macroblock traveled within this search window, the absolute difference for each pixel was computed. Motion vector corresponding to the minimum absolute difference criterion was calculated between the center of search window and the location where the minimum absolute difference was detected. These operations were repeated for every macroblock within the current frame without exceeding frame boundaries. At the end of this process, final motion vectors were drawn starting from its original position in the reference frame \( k \) to the current position in the current frame \( k+1 \) to obtain a displacement map of the entire frame. The procedure and flowchart for image analysis are briefly summarized in Figs. 3 and 4. The number of searches for each pair of image frames was equal to the total number of macroblocks, which was computed by dividing the area of the image frame by the area of the defined macroblock.

One limitation in the BMAD algorithm is that the displacement vectors calculated at the boundaries of a frame may not reflect the actual displacements due to the constrained motion of macroblocks within the search window. One proposed solution is to stretch the image frame at the boundaries by adding strips equal to the macroblock dimension. The stretched frame is transformed to its original size after the search operation is completed. However, preliminary investigations showed that the displacement vectors at the boundaries are less important in terms of defining the strain distributions for the tested geosynthetic specimens as compared to the interior vectors. Therefore, along with the suggestions of Guler et al. (1999), the displacement fields at the edges were evaluated using the neighborhood displacement vectors.

Verification of the Image-Based Strains

Image-based strains were checked independently by extensometers mounted on the test specimens. Additional checks were performed on the geocell specimens through the strain gauges installed in their center sections. Strain gauges were installed using the methodology outlined by Lau et al. (2001).

Results

Distribution of Strains in Image Frames

Based on the information captured by the digital images, vector plots were generated to demonstrate the motion across the entire specimen. The significance of generating these vector plots was
not only to verify the total displacement of the specimen, but also to visualize the distribution of displacements across the entire sample. The vector plots also verified whether or not any significant strain concentration was present. Fig. 5 presents a set of vector plots generated for Geocell 2 (GC 2). In a wide-width tensile test, one grip is fixed while the other one moves to elongate the specimen at a constant displacement rate. Overall, the vector plots of Fig. 5 show a very uniform uniaxial deformation of the sample toward the right-hand side, which was the direction of the moving grip. No signs of a jaw break or slippage are evident on the plots, and all of the specimens of GC 2 failed at tensile stresses within 20% of the average failure stress. At all times, a major strain concentration was not visible at the extensometer location (located in the center) or any other place on the specimen. Fig. 5(c) (ε~3%) suggests that failure condition begins to develop at the top of the plot where the sample starts to shear and elongate.

Based on the vector information given, contour plots are developed for motion in the horizontal $x$ direction in Fig. 6. In Fig. 6, the horizontal $x$ direction refers to the direction of tensioning, and deformation on the right-hand side follows the set strain rate of 1 mm/min. Fig. 6 shows the distribution of local displacements, which were represented by different colors. The image-based method defined the variations of displacement in each individual local strain zone successfully (note the small pockets of displacement variations in each local zone). Therefore, using movement at the grip to predict elongation of the specimen (i.e., crosshead extension) would not provide sufficient information about the local strains. The contour plots also confirmed the initial thought that weatherization and epoxy applied to the small 6 mm strain gauge had a negligible effect on the distribution of strain in the specimen, i.e., minimal specimen disturbance.

### Determination of Average Strains

In order to determine the average strain for each geosynthetic specimen, measured displacements were plotted against the length of the image. The slope of the best-fitted line to the data provides the average strain. Fig. 7 shows the measured displacement values and calculated average strains at failure for GC2 and nonwoven (NW) 1. The geocell resulted in a higher strain (20.23% versus 12.55%). A preliminary analysis indicated that the effect of macroblock size (i.e., horizontal resolution×vertical resolution of the selected portion of the image) on the measured strain was insignificant for all geosynthetics. Fig. 8 shows this effect for GC2 and W1. Therefore, a macroblock size of 16×12 pixels was chosen and used throughout the analysis.

The strains defined by the extensometers were compared with the image-based average strains. Depending on the mounting location of the extensometer, strain can vary significantly. In this...
study, the extensometer was mounted in the middle of the specimen in both the horizontal and vertical directions to obtain the average strain. Exten- someter and image-based displacements are plotted on the same graph in Fig. 9, and the average slopes (i.e., the strains from each method in the region of measurement for the extensometer) are determined. These strains are compared in Fig. 10 for all tests. As shown in Fig. 10, the image-based measurements provide comparable strains to those based on extensometer measurements. The difference between the two methods of measurement is defined as

\[
\text{% Difference} = \left( \frac{S_I - S_E}{S_E} \right) \times 100
\]

where \(S_I\) and \(S_E\) = strains determined using the image analysis, and the extensometer, respectively. The percent difference in measurement between the two methods was calculated for different macroblock sizes, and a mean difference is reported for each geosynthetic specimen by averaging these values. Table 2 indicates that the percentage difference is small in most cases. The absolute value of the mean difference between the two methods is in the range from 0.7 to 8.3%, with values less than 11% for all geosynthetic types. A difference as high as 18.3% was observed for one of the geogrid specimens. It should be noted that the extensometers used in this study were not specifically developed for testing of geosynthetics. In the case of geogrids, a relatively high percent difference may be attributed to the incapacity of the extensometer to determine the relatively large displacements occurring on the individual ribs of a geogrid specimen. Overall, the measured strains are highly comparable to manufacturer’s reported values, which further confirms the validity of the image-based approach.

Image-based strains are compared to those determined using strain gauges in Fig. 11. The strains measured by both methods are comparable. The strain gauges had an initial take-up period, which was characterized by a smaller slope in a stress–strain curve at low extensometer strains. After about 3.5% strain, the image analysis and strain gauges recorded comparable strains.

These comparisons of the image-analysis method of determining average strains support the viability of the image-analysis method. The image-based strain analysis, additionally, provides information about how uniformly the strains are distributed throughout the test specimen. The deformations were reasonably uniform over the areas where the extensometer and strain gauge measurements were made.

### Table 2. Percent Difference Values for the Image-Based Strain Measurements

<table>
<thead>
<tr>
<th>Grid size</th>
<th>GC1</th>
<th>GC2</th>
<th>NW1</th>
<th>NW2</th>
<th>W1</th>
<th>W2</th>
<th>GG1</th>
<th>GG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>16×12</td>
<td>4.2</td>
<td>-8.4</td>
<td>-0.3</td>
<td>-0.4</td>
<td>9.1</td>
<td>6.5</td>
<td>2.49</td>
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</tr>
<tr>
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<td>-8.7</td>
<td>-0.3</td>
<td>-0.3</td>
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<td>6.5</td>
<td>13.7</td>
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</tr>
<tr>
<td>16×6</td>
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<td>-1.7</td>
<td>-3.9</td>
</tr>
<tr>
<td>32×12</td>
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<tr>
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<td>-9.1</td>
<td>-1.8</td>
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<td>5.9</td>
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</tr>
<tr>
<td>8×12</td>
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<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>5.9</td>
<td>-9.3</td>
</tr>
</tbody>
</table>

Average difference: 3.9% 8.3% 0.7% 0.16% 8.1% 6.2% 4.6% -4.9%

Note: Percent difference = \left( \frac{S_I - S_E}{S_E} \right) \times 100, where \(S_I\) = strain determined from the image analysis, and \(S_E\) = strain determined using an extensometer. GC: Geocell, NW: Nonwoven geotextile, W: Woven geotextile, GG: Geogrid, and NA: Not applicable.
The size of a macroblock used in the image analysis approach does not have a significant impact on the calculated strain values. This was observed for all the geosynthetic types tested.

4. The image-based strain distributions confirmed the initial thought that weatherization and epoxy applied to the small 6 mm strain gauge had a negligible effect on the distribution of the strain of the specimen, i.e., no specimen disturbance due to strain gauge installation. The strains defined by strain gauges are also comparable to the image-based ones after about 3.5% strain. This also provides an independent measurement confirming the effectiveness of image analysis in evaluating strain in geosynthetics during tension tests.

5. The image analysis method is rapid providing strain distribution in approximately 2 min. Even though this is satisfactory for the current application, the speed is planned to be increased in the future after building the plotting program into the LABVIEW/BMAD code, which may allow the use of the technique by the geosynthetic manufacturers for process control.

Acknowledgments

The writers would like to express their appreciation to Mr. John W. Dreger, Jr., manager of the Structures and Materials Testing Laboratory of the Department of Civil and Environmental Engineering at the University of Wisconsin-Madison, for his assistance and guidance during the testing and instrumentation. Mr. W. L. Lau prepared the strain gauges and assisted in their installation on geosynthetic specimens. An initial draft of this paper was reviewed by Professor Richard H. McCuen. All of these efforts are greatly appreciated.

Notation

The following symbols are used in this paper:

\[ d_{x}, d_{y} = \text{displacements in horizontal and vertical directions, respectively, corresponding to minimum of sum of absolute differences; } p(x_{k}, y_{k}) = \text{gray scale pixel values at } x_{k} , y_{k} \text{ location within current macro block in frame } k; \]

\[ M = \text{actual magnification (mm}_{i}/\text{mm}_{o}), \text{ in which } \text{mm}_{i} \text{ designates image size, and } \text{mm}_{o} \text{ is actual size of object;} \]

\[ R = \text{image resolution in direction of motion (pixel/mm}_{i}); \]

\[ S_{E} = \text{strain determined using extensometer (\%);} \]

\[ S_{I} = \text{strain determined using image analysis (\%);} \]

\[ SD = \text{side length of search window;} \]

\[ s = \text{displacement rate of test (mm}_{o}/s); \text{ and } \]

\[ t = \text{image acquisition rate (number of images/s).} \]

References


