GEOSYNTHETICS USED TO SUPPORT EMBANKMENTS OVER VOIDS

A

THESIS

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By

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ABSTRACT

Road embankments in permafrost regions undergo serious differential settlement due to an imbalance in the thermal regime causing thawing. This creates hazardous conditions for traffic and requires expensive maintenance. To arrest this critical problem, Dr. T. C. Kinney developed a cost effective and easily implemented solution using geosynthetics under roadway embankments. This unique application of geosynthetics may be extended to many other situations of a similar nature where bridging of voids below embankments is required.

Present research shows that, with the selection of the proper type of geosynthetics, it is possible to span a void of eight feet or more under roadway embankments. It has been suggested that additional supporting capacity could be achieved by adding more layers of geosynthetics to the systems.

This study includes the performance of several large scale laboratory tests to evaluate the effectiveness of using multiple layers of geosynthetics. The results are interesting and informative and lead to the conclusion that more research is needed.
ACKNOWLEDGEMENTS

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I wish to express my profound sense of gratitude to my advisor, Dr. Thomas C. Kinney, for his invaluable assistance, inspiration, and guidance in many aspects. I have no hesitation in saying that without his unstinted support and assistance this project could not have been completed. I shall always remember his contribution with gratitude.

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Finally, I express my thanks to my graduate committee members.

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CHAPTER 1

INTRODUCTION

1.1 HISTORICAL PERSPECTIVE

The use of geosynthetics in civil engineering applications has increased dramatically over the past decade. Selection of geosynthetics for use on a project is usually based on improvement in performance. Improved performance includes more effective installation, reduced maintenance, or increased life, or cost savings.

For thousands of years, non-soil materials have been used together with soil to improve certain desirable properties or correct some undesirable properties of soil. Human attempts have included adobe bricks, bamboo fascines, and corduroy roads. Bamboo fascines have been used for many centuries under low embankments and levees in southeast Asia.

Rankilor (1981) describes the use of corduroy in the United Kingdom as early as 2500 B.C. Brush mattresses of birch and hazel branches were used to support wooden tracks constructed over marshes.
In the Middle and Far East, larger earth structures, particularly temples and buildings, were reinforced with woven mats of reeds, rushes, or bamboo [8]*.

In Colonial North America, levee and road embankments were constructed directly on the brush and small trees that commonly grew on marshy ground. Heavier loads and larger roadways were supported on logs or timbers in North America and Europe.

The first recorded attempt of using a textile material (woven cotton) in road construction was in South Carolina between 1926 and 1935 [49]. The first use of a synthetic fabric was in the late 1950's when a permeable, woven fabric made of a synthetic fiber was placed beneath concrete block revetments for erosion control in Florida. This work was done by Mr. R.J. (Bob) Barrett who is acknowledged as the Father of Geosynthetics in the United States.

*Numbers in parentheses refer to numbered citations in the Bibliography.
1.2 PROBLEM STATEMENT

In the northern districts of Canada, Alaska, Scandinavia, and Siberia, permafrost causes serious road construction and maintenance problems. Permafrost is soil or rock having a temperature below $0^\circ C$ persisting over at least two consecutive winters and the intervening summer. Moisture in the form of water and ground ice may or may not be present. The thickness of permafrost may vary from several feet to several hundred feet.

In the Arctic, road alignment occasionally passes through areas of permafrost containing ice wedges, ice lenses, and ice masses of limited extent.

If the temperature increases thaw occurs. The thawing process can leave deep depressions or trenches beneath the road bed. The thawing and subsequent settlement may continue for several years. The settlement results in conditions which are dangerous to traffic and expensive to repair. Geogrids can be used to support embankments.
1.2.1 Thaw Weakening

Soil weakening from thawing is evident early in the spring when thawing is occurring at the top of the subgrade and the rate of thawing is rapid compared to the rate of drainage. Melting of ice from the surface downward releases water that cannot drain through the still-frozen soil below, nor redistribute itself readily. As a result, the base course becomes completely saturated, resulting in a reduction in bearing capacity of the base. The effect of high traffic volume and heavy traffic loading during the thawing period, may cause excessive pore pressures and greatly reduce the load-carrying capacity of the pavement. The reduction in soil strength during the thawing periods and the length of time during which the strength of the soil is reduced depends on the type of soil, the temperature conditions during the freezing and thawing periods, amount and type of traffic during the thawing period, the moisture supply during fall, winter, and spring, and the existing drainage conditions. Geogrids may be used to stabilize the thaw weakened materials.
1.2.2 Small Pipe Crossings

For small drainage crossings, culverts are often used. Culverts should be laid on a firm bedding. Poor soil support and shallow cover may cause excessive pressure on culverts. Overstressing may cause settlement and/or damage to the culverts resulting in inconvenience and hazards to traffic. Geogrids may be used to reinforce the soil around culverts.

1.3 PURPOSE AND SCOPE

The purpose of this project is to explore the conditions described above. Many attempts have been made to calculate and/or measure the strain, and deformed shape of geosynthetics in reinforced road sections.

Dr. Kinney (25, 32, and 34) is one of the pioneers in using geosynthetics to bridge voids under roads. He has conducted a wide range of laboratory and field tests.

This study is a continuation of the previous work and was conducted to find the behavior of multiple layers of geogrid under fill material simulating a roadway embankment spanning a void of six feet wide.
Experimental work consisted of a laboratory investigation. The scope of this study was primarily to measure the strain behavior of single and multiple layers of geogrids while spanning a void of six feet under a specific loading condition. The knowledge of strain of the reinforcing material is vital to developing design guidelines.

Geosynthetic bridges have applications in roadways built over ice-rich permafrost, in drainage structures on temporary roadways, in spanning weak spots within strong subgrades, in landslide areas, and other applications requiring spanning of voids.
2.1 HISTORY OF GEOSYNTHETICS

Geosynthetics are made of plastics (synthetics). The term "geosynthetics" was proposed by J.E. Fluet, Jr. in 1983 to encompass all synthetic materials used by civil engineers to improve or modify the behavior of soils [49]. Today the term has been expanded to include any synthetic material used in conjunction with soil in a construction project.

2.1.1 The Forerunners

Forms of soil inclusions have existed for thousands of years. Reinforced soil was used by the Babylonians more than three thousand years ago to build the Ziggurats.

For thousands of years, the Chinese have used wood, bamboo and straw to strengthen soil. The Dutch, in their age old battle with sea, have made extensive use of willow fascines to reinforce dikes as well as protect them against wave action. The Romans used reed and wood for soil
reinforcement. The same materials, as well as animal hides, were used in the Middle Ages.

Between 1926 and 1935, cotton fabrics were tried as means of strengthening road pavements in the United States. These field trials were not followed by synthetic applications.

During World War II, the British Army used armored vehicles specially designed to carry, and lay on the ground, rolls of fascines or canvas.

2.1.2 A Revolution in the Textile Industry

In this century, the textile industry experienced a major revolution - the development of synthetic fibers.

1913: First synthetic fiber, made from polyvinyl chloride (PVC), commercially produced in 1934, with limited applications.

1930: First "modern" synthetic fiber, a polyamide fiber ("nylon"), by W. H. Carothers of DuPont in the United States. This fiber was commercialized in 1940 with great success.

in 1949 in the U.K.

- **1949**: Production of low strength, coarse polythene filaments by ICI (U.K.).

- **1954**: Production of high strength, fine polythene filaments by Ziegler (West Germany), Phillips Petroleum and Standard Oil of Indiana in the United States.

- **1954**: First polypropylene fiber by G. Natta of Montecatini (Italy). Commercial production of polypropylene fibers took place in the late 1950's.

- **1960's**: Another major step was the development of the manufacturing processes for nonwoven fabrics made from continuous synthetic filaments ("spunbounded nonwoven fabrics") by large firms such as Rhone-Poulene (France), ICI (U.K.), and DuPont (U.S.A.).
2.1.3 The First Geosynthetics

With the advent of synthetic materials, civil engineering experienced a rebirth of the techniques used centuries before. Key dates in this rebirth are:

. **1957**: Sand bags made of nylon woven fabrics (Nicolon) were used in the Netherlands at the closing of the Pluimpot. Extensive coastal work had been prompted in the Netherlands by the catastrophic floods that killed 1850 people in 1953.

. **1958**: A synthetic woven fabric produced by Carthage Mills was used between soil and rip-rap for coastal erosion control in Florida (U.S.A.). The fabric was made of polyvinylidene chloride monofilaments, and it was still in an apparently good condition after 27 years. This application is considered as the first use of a geosynthetics in the U.S.A. The man responsible for the application, R. J. Barret, was then involved in many similar applications. However, the market did not develop significantly because of the cost of the geosynthetic, and because the applications were relatively small.

. **1958**: Installation of synthetic sand bags in groins
in West Germany and synthetic sand bags for protection of embankments and slopes in Japan.

. **1959:** Synthetic sheets, sand bags and woven fabrics were used in Japan in the construction of dikes under the direction of Dr. S. K. Kanamori.

. **1960:** Woven nylon mattress filled with sand, for scour protection, were used in the Netherlands.

. **1966:** The first use of a nonwoven fabric for asphalt overlay (U.S.A.) was in 1966. The fabric, composed of staple fibers, was manufactured by Phillips Petroleum. Since then, this application has developed tremendously in the United States, but not in other countries.

. **1967:** Synthetic nets (by Netlon Ltd., U.K.) were used for the first time in a civil engineering project. The field trial, reinforcement of soft ground in Japan, was conducted under the responsibility of professor T. Yamanouchi. This successful trial was followed by many applications, including embankment reinforcement for the Japanese National Railway. Synthetic nets inspired the development of Geogrids.
2.1.4 The Emergence of a Large Market

The geosynthetic market began in the late 1960's when nonwoven geosynthetics became available. The significant sales of geosynthetics began in the early 1970's and the market has grown strongly since then. The seventies and early eighties saw the development of new types of products such as: mats (Enka, Netherlands, 1972); grids (Nelton, U.K., 1981); and composites for drainage (ICI, U.K.; Enka, Netherlands; Ground Engineering, U.K.; Mirafi, U.S.A.).

To illustrate the extent to which geosynthetics are used, it is interesting to note that, by the year 2000, one one-thousandth of Europe is expected to be covered by geosynthetics [49].

2.2 TYPES OF GEOSYNTHETICS

Geosynthetics are generally classified by manufacturing process. Ten types of geosynthetic products are presented:

1. Knitted geotextiles are formed by interlocking a series of loops of one or more yarns to form a planar structure. Monofilament, multifilament, spun and fibrillated yarns are typically used to make knitted geotextiles.
2. Woven geotextiles are composed of two sets (wrap and fill) of parallel yarns systematically interlaced to form a planar structure. Woven geotextiles are constructed of one or a combination of the following yarn types: monofilament, multifilament, spun, slit film, or fibrillated yarn.

3. Nonwoven geotextiles are formed from fibers arranged, in an oriented random pattern, into a planar structure. The fibers are bonded together using one of the following processes: chemical bonding, thermal bonding, and mechanical bonding. The fibers used to produce nonwoven geotextiles are staple fibers or filaments. Nonwoven geotextiles made in a continuous line process, in which filaments are extruded, drawn, formed into a loose web, and bonded, are called spun bonded. Most of the nonwoven geotextiles made from filaments are spun bonded.

4. Geogrids are plastics formed into a very netlike configuration, often stretched in one or two directions for improved physical properties. Any products having a greater than 50% open area with an arranged pattern which is made of a nonbiodegradable material that is placed within soil to improve or strengthen it is considered to be a georid.
5. A geomembrane is defined as a very low permeable synthetic membrane (thin sheets of rubber or plastic material) used to control fluid migration in a man-made project, structure or system. They are frequently referred to as polymeric membranes, flexible membrane liners or pond liners.

6. Geowebs or geocells are rigid geomembranes arranged vertically in a box-like fashion. They are placed horizontally (standing upright) and filled with soil. Thus the web forms a cellular structure which acts with the contained soil to make a strong and stable mattress.

7. Geonets consist of two sets of coarse parallel extruded strands intersecting at a constant angle (generally between $60^0$ and $90^0$). Strands of one set are connected to strands of the other set by partial melting at intersection. Typically, the size of the strands is 1 to 5 mm (3/64 to 3/16 in.) and the size of openings is from a few millimeters to several centimeters.

8. Formed-plastic-sheets include corrugated, waffled, alveolate, etc., structures made by forming a plastic sheet into the desired profile.

9. A geocomposite consists of a combination of materials
such as those discussed above, fastened together.

10. Prefabricated composite structures are combinations of geosynthetics and geosynthetic related products.

2.2.1 Composition of Geosynthetic Products

Geosynthetic is a generic term which includes **geotextiles, geomembranes, geogrids, geonets, geocomposites, and all other similar materials used by civil engineers in conjunction with soil in a construction project.**

Geosynthetics are made of plastics (synthetics) because of their durability and ease of manufacture, and the fact that plastics allow control of physical properties for specific design projects.

A plastic is any synthetic material formed by man by a chemical and/or heat manufacturing process. Geosynthetics are typically made from polymers: propylene, polyester, polyethylene, polyamide, nylon, acrylic, etc.

2.2.2 Elements of a Geotextile or Geogrid

The manufacturing process of a geotextile includes two steps. The first step consists of making linear elements
such as fibers and yarns. The second step consists of combining these linear elements to make a planar structure.

The basic elements of a geotextile are its fibers. There are three types of fibers: the filaments, the staple fibers, and the slit films.

- Filaments are produced by extruding melted polymer through dies or spinnerets.
- Staple fibers are obtained by cutting filaments into short lengths.
- Slit films are flat tape-like fibers produced by slitting an extruded plastic film.

Nonwoven geotextiles are made from filaments and/or staple fibers. Woven geotextiles are made from yarns. A yarn is made of one or several fibers. Several types of yarns are used to construct woven geotextiles:

- A monofilament yarn is made from single filament.
- A multifilament yarn is made from fine filaments aligned together.
- A spun yarn is made from staple fibers interlaced and twisted together.
- A slit film yarn is made from a single slit film fiber.
- A fibrillated yarn is a film which has been nicked and broken up into fibrous strands.
A two-step manufacturing process is also used to produce some geotextile related products such as webs, mats, and nets as described below.

- Plastic strips, typically 2 to 10 cm (1 to 4 in.) wide, are used to make coarse woven fabrics known as webs or webbings.
- Coarse and rather rigid filaments are used to make coarse nonwoven fabrics known as mats.
- Coarse strands, typically 1 to 5 mm (3/64 to 3/16 in.) in diameter, obtained by extrusion, are used to make nets.
- Some grids are formed plastic sheets which are cut and stretched.
- Some grids are strips welded together.
2.2.3 Engineering Functions of the Basic Types of Geosynthetics

The basic types of geosynthetics related to their most commonly applied engineering functions are as shown below.

<table>
<thead>
<tr>
<th>Geosynthetic</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotextiles</td>
<td>Reinforcement, Separation, Cushioning, Filtration, Transmission</td>
</tr>
<tr>
<td>Geogrids</td>
<td>Reinforcement</td>
</tr>
<tr>
<td>Geomembranes</td>
<td>Isolation</td>
</tr>
</tbody>
</table>

2.3 PROPERTIES

With the increased usage of geosynthetics in the civil engineering community today, the need for proper referencing of the physical properties is fast becoming a critical issue. A basic understanding of geosynthetic properties as they relate to specific applications will both aid the
producer in meeting the needs of the user, and the user in obtaining products that will meet the project requirements. Standard tests for the engineering properties of geosynthetic provide the means for:

- quality control for products both during production and during installation,
- determination of the suitability of the material for a specific application,
- comparison between products,
- specification of a product for specific applications.

2.3.1 Specific Property Evaluation

The American Society for Testing Materials (ASTM) Committee D-35 on Geotextiles, Geomembranes and Related Products in cooperation with such organizations as the U.S. Corps of Engineers, the Transportation Research Board Task Force No. 25, the Environmental Protection Agency, the Geosynthetic Research Institute, and the National Sanitation Foundation has worked in the development of proposed standard test methods.

A listing of geosynthetic properties and testing methods are included in Tables C.1, and C.2 (Appendix C).
Index tests, in most cases, do not produce an actual engineering design property value, but rather a value (or indicator) from which the property of interest can be qualitatively assessed. Index tests can be used as a means of product comparison, and can be used for specifications and quality control evaluation. They are generally rapid and economical to perform.

Performance tests frequently require testing the geosynthetic with the soil under in-situ environmental conditions to obtain a direct assessment of the property of interest. These tests provide a direct measure of the influence of the soil on the particular geosynthetic property and the influence of the geosynthetic on the particular soil property.

Since performance tests should be performed in conjunction with the site soils under specific conditions, it cannot be expected that the manufacturers of the products have the capability to run these tests, nor should they be required to perform such tests. Performance tests should be performed under the direction of the design engineer in his own or his representative's soil laboratory.

Performance tests are not used in specifications. Geosynthetics are selected for performance testing based on
index values. Performance test results are then correlated to index values for use in specifications.

In any case, specifications should be based on the specific geosynthetic properties required for the design and installation of a specific project. The use of standard geosynthetics chosen based on the type of problem encountered may result in uneconomical or unsafe designs.

### 2.3.2 Practice for Developing Specifications

One of the following three specification types are usually used: generic, performance, and approved list. When properly implemented, each type can be used with success. Any specification must consider the following three aspects of design:

1. functional design requirements for a particular application,
2. the ability of the geosynthetic to withstand the rigors of construction,
3. sufficient durability to perform throughout the life of the project.

Generic Specifications are most widely used and usually use specific properties measured by index tests. Table C.3 (Appendix C) provides a list of important properties
required to evaluate the suitability of geosynthetics for most applications [14]. It should be noted that all of the requirements listed will not be required for all applications, and other properties listed in Table C.1 may also be required for specific applications.

Performance Specifications require a more thorough valuation of the geosynthetic requirements to develop relations between properties and performance test results. A geosynthetic that meet requirements, or performance criteria is specified. Such specifications are generally used on critical projects where the performance of geosynthetic could result in success or failure of a system.

The approved list type of specification is developed based on experience with re-occurring problem conditions and their solutions or on performance testing. Once the list of geosynthetics has been developed specific geosynthetics from this list are specified for the given application without consideration of the specific details of the project.

Other specifications including seam and overlap construction, placement procedures, repair, and requirement for testing and placement observation are required within each of the types of specifications outlined above.
2.3.3 Importance of Geosynthetic Properties

The selection of a geosynthetic for a particular construction application must necessarily depend upon adequate and suitable properties and characteristics. If these properties and characteristics are excessive an uneconomical selection is made. If these properties and characteristics are inadequate a failure may result.

It is always desirable to compare each project with similar field projects. This is called the case history or observational method. Unfortunately, there are very few case histories available in this relatively new field. Some of the more pertinent case histories are summarized in section 2.6.

2.4 GEOSYNTHETIC TEST METHODS

2.4.1 General comments

The study presented herein is limited to structural reinforcement of an embankment. In this context the factor of safety, FS, is defined as:

\[
FS = \frac{\text{Geosynthetic property}}{\text{Required property}}
\]
When a favorable comparison is made to the required factor of safety, an acceptable design is concluded.

There are many tests for the evaluation of geosynthetic properties. Only those tests will be discussed herein which are relevant to this study.

2.4.2 Tensile Strength and Elasticity

Perhaps the single most important geosynthetic property used in this experiment is its tensile strength and the relationship between tension and strain. The concept of the test is to place the geosynthetic in a set of clamps or jaws, place the assembly in a testing machine, and stretch the geosynthetic until failure occurs. It is customary to measure both load and deformation and develop a curve of tension (usually given as load per unit width) versus strain (calculated as deformation divided by original specimen length).

Four values are obtained:

1. maximum tensile strength (referred to as the geosynthetic strength),
2. strain at failure,
3. toughness (work done per unit area before failure, taken as the area under the tension–strain curve),
4. modulus of stiffness (which is the slope of the tension versus strain curve).

Generally, the vertical axis of tension-strain curves have units of force per unit width of fabric (i.e., lb/in.). Stress units are not used because the tension would have to be divided by geosynthetic's thickness. This is not conventionally done since the thickness may vary greatly under load and during the extension process. For most loading conditions, the geosynthetic acts to resist load through tension.

Three types of tests for geosynthetic tension-strain diagram determinations are currently being used: the grab tensile test, the strip tensile test, and the wide width tensile test (Figure 2.1). The grab tensile test is not used for geogrids. The grab tensile test is an index test and the wide width tensile test is the most widely accepted performance test.

Several definitions are available for the modulus:

(a) initial tangent modulus,

(b) offset tangent modulus, and

(c) secant modulus.
Figure 2.1 Methods for Determining Uniaxial Tensile Strength of Geosynthetic
2.4.3 Soil-Geosynthetic Friction Test

In many design problems it is necessary to know the soil-geosynthetic friction behavior. Normal stress is applied as shown in Figure 2.5, and then a shear force is mobilized until sliding occurs between the fabric and the soil with no further increase in required shear force. It can be seen from Figure 2.2 that the geosynthetic sample is anchored along the edge of the box where the tensile (horizontal) force is applied.

2.4.4 Pullout (Anchorage) Test

Geosynthetics are often called on to provide anchorage in many applications. Pullout tests usually have the geosynthetic sandwiched between soil on each side. The two halves of the box are fixed, and one end of the geosynthetic is subjected to a horizontal force as shown in Figure 2.2. The pullout resistance is usually dependent on the applied normal force. When it is pulled out of the soil shear forces exist on both sides of the geosynthetic. If the soil particles are smaller than the geosynthetic openings, efficiencies are higher than when the soil particles are larger than the openings.
Figure 2.2  Schematic Diagrams of Test Setups for Friction and Pullout Test of Geosynthetic
2.5 GEOSYNTHETICS IN ROAD CONSTRUCTION

The most common use of geosynthetics is in the construction of roadways. Applications in temporary road construction are well established. Geosynthetics are gradually being used in embankments of permanent highway construction more often.

Usually the subgrade is the weak point in a road profile, not the surface. It must be realized that the subgrade carries the weight of the vehicles and the function of the base, subbase, and surfacing is merely to distribute the weight over a larger area. The character of the subgrade has a great effect upon the stability of a road surface, no matter what material may be used for the latter.

2.5.1 Functions of Geosynthetics for Roadway Applications

The primary use of geosynthetics in roadway applications is separation. However, the design may be greatly influenced by the secondary functions of reinforcement, and drainage.

Geosynthetics increase stability over weak subgrade soils by separating the aggregate from the subgrade and by providing additional strength through friction or
interlocking developed between the aggregate and fabric. In addition, the geosynthetic provides a secondary function of drainage into the aggregate, allowing excess pore water pressure to dissipate.

2.5.1.1 Separation

Failure of road constructed over soft subgrades most commonly occurs when the base and/or subbase materials become intermixed with the subgrade soil. The geosynthetic performs the function of preventing migration of the subgrade up into the aggregate and penetration of the aggregate down into the subgrade.

2.5.1.2 Reinforcement

several mechanisms of reinforcement may take place in a roadway design. These can be categorized by:

a. lateral spreading restraint,

b. reinforcement along failure planes,

c. membrane-type support of wheel loads, and

d. membrane-type support of the roadway system.
a. Lateral Spreading Restraint

Under load, the stress conditions in the base course are analogous to a loaded beam. Due to bending, the base experiences compressive strain at the top and tensile strain at the bottom. The cohesionless materials that make up the base have no resistance to tensile stress and generally depend on the subgrade to provide lateral restraint. In weak subgrades, very little lateral restraint is available. Thus, the aggregate at the bottom of the base tends to move apart, allowing intrusion of the soft subgrade.

A geosynthetic at the bottom of the base course can provide tensile reinforcement which restrains aggregate and subgrade lateral spreading. If the tensile resistance is significantly high, the geosynthetic may also reduce bending in the system, much like the steel in a reinforced concrete beam.

b. Reinforcement along Failure Planes

Horizontal restraint provided by a geosynthetic may also resist failure in the base course. If the geosynthetic is placed in the road structure at a depth which interferes with the normal bearing failure surface, as shown in Figure 2.3, failure must occur along an alternate surface. Thus, the ultimate bearing capacity is increased and an increase
**Figure 2.3** Conceptual Illustration of Base Material Lateral Restraint Caused by Geosynthetic in Unsurfaced Roadway System [3]

**Figure 2.4** Concept of Partial Wheel Load Support Developed by 'Membrane-Type' Action of Geosynthetic After Being Stretched by Wheelpath [3]

**Figure 2.5** Concept of Roadway System with Geosynthetic Use for 'Membrane-Type' Support of Roadway System [3]
in the elastic modulus of the base is provided. An increase in stiffness of the base also reduces the magnitude of stresses transmitted to the subgrade.

c. Membrane-Type Support of Wheel Loads

If the wheel load stresses transmitted through geosynthetic-reinforced base material are sufficient to cause excessive plastic deformation of a soft subgrade, the base material will subside in the wheel path and ruts will be created. As the geosynthetic is sandwiched between the base and subgrade, it must deform also. If the geosynthetic has a sufficiently high tensile modulus, an appreciable amount of tensile stress resistance may be developed in the geosynthetic. The vertical resultant of this geosynthetic resisting stress may act to help support vehicular loading, as conceptually shown in Figure 2.4.

As stress within the geosynthetic cannot be developed without some elongation, deformation in the wheel path is required to develop membrane-type support. Therefore, this function is generally limited to temporary or unsurfaced permanent roads where the wheel paths are constant throughout the life of the project. For paved roads, surfacing could be postponed until in-service rutting and
rut leveling can be carried out, to minimize wearing surface deformations [3 & §6].

d. Membrane-Type Support of Roadway System

The reinforcing capabilities of a geosynthetic can be used to provide stability to the entire roadway section (Figure 2.5). When soils are extremely soft, the overall bearing capacity of the soil may be such that it will not support the roadway system. Stability can be provided by using geosynthetics [3 & §6]. Geosynthetics provide lateral resistance at the bottom of the fill and additional resistance to failure along a failure plane.

2.5.2 Use of Geosynthetics in Permanent Roads and Highways

Permanent roads include both paved (flexible and rigid pavement) and unpaved sections which are required to remain in service over a number of years, usually 10 years or more and to handle well over 1,000,000 vehicles during the design life of the road. Very little published information is available on the use of geosynthetics in permanent roadway construction. Most of the design information centers on temporary roads, such as haul roads and access roads which are generally unpaved and are required to remain in service
for short periods of time (usually less than one year), and are usually required to handle less than 10,000 vehicles during the life of the system.

At this time, there is no analytical method for quantitatively assessing the benefit of a geosynthetic in the structural support capacity of a paved roadway system. Thus, in permanent roadway design, structural support must be carried by the pavement-aggregate-subgrade system exclusive of fabric. This does not mean that a cost saving or performance increase cannot be realized by using geosynthetics in roadway design. The possible benefits of using geosynthetics include [52 & 56]:

1. reducing the load intensity to the subgrade by distributing the pavement load,
2. preventing the pavement subbase aggregate from penetrating into the subgrade soils,
3. preventing subgrade fines from pumping into the subbase,
4. aiding in drainage,
5. providing for more controlled construction and less disturbance of the subgrade during construction,
6. minimizing rutting of subbase/base course during construction while it is being used as a haul road,
7. aiding and maintaining the integrity and uniformity
of the pavement should settlement of the subgrade occur,

8. reducing maintenance and extending the life of the permanent pavement.

2.6 HISTORY OF PROJECTS

A few studies of geosynthetics in connection with reinforcing embankments are described briefly below:

Study No. 1

Dr. T. C. Kinney [25 & 32] used geosynthetics to fully support roads over voids created by melting out of ice under the embankment materials. The preliminary design scheme was developed in 1981 and a field test was performed in 1984. The design approach was reasonable, but the field test sections failed to carry the design load. The design procedure was then upgraded, and a new field test was performed in the fall of 1985. This test was successful, demonstrating that at least a 6 foot wide void could be spanned with commercially available materials and that the design procedure was indeed reasonable.

In the fall of 1986 more experimental sites were prepared. Final measurements were taken in the summer of
1987. The test results and the theoretical analyses indicate that geosynthetic products commercially available at that time could be used to support roads over voids of 10 feet or more in width.

Study No. 2

A research study was conducted by Allan Haliburton at Oklahoma State University for the Association of American Railroads in 1980. The study was to evaluate the current state-of-the-art of geotechnical fabric usage in the railroad industry and the potential for geotechnical fabrics to improve the construction and maintenance of railway track systems.

Field site visits were conducted to view geotechnical fabric test installations on the Canadian National Railroad, the Missouri Pacific Railroad Company, the Southern Railway System, and the Southern Pacific Transportation Company. Based on the results of a literature review, field site visits, discussions with railroad engineers and other personnel, and evaluation of all data, Haliburton expressed in the report that geotechnical fabric has potential use in improvement of railway track structure performance, both in new construction and in remedial maintenance applications in a cost effective manner [18].
Study No. 3

A fabric-reinforced embankment test section was designed and constructed by the U.S. Army Corps of Engineers, Waterways Experiment Station and Haliburton Associates across Pinto Pass near Mobile, Alabama (54).

It was concluded that the use of fabric as an embankment reinforcement is a viable construction technique that will enable geotechnical design and construction of embankments on extremely soft foundations. Specific situations dictate exact fabric strength requirements, but the general criteria for fabric selection should include high strength, low elongation, low creep under load, corrosion resistance to various elements found in the environment, and ultra violet resistance prior to installation.

Study No. 4

The results of a research and full scale testing program conducted at the Centre d'Experim entations Routi eres (Laboratoire des Ponts et chaussees - France) on reinforcing base materials by incorporating textile elements (fibers or geotextiles) were published by Khay, M., Morel, G., and Perrier H. (36).
It was concluded that the use of geotextiles in road construction offers an attractive solution when good materials are difficult to find, attain, transport or are extremely expensive. In the case of low-cost roads, when the determining factors are cost of materials and placement, the use of geotextiles permit better use of local resources.

Study No. 5

A finite element model of a culvert-soil-fabric system was used to evaluate the influence of a buried engineering fabric on the culvert behavior in France. This research found that significant moment and axial force reductions can be achieved when a fabric is employed in shallow cover situations [41].

Study No. 6

In a roadway construction project in Southeast Mexico, part of the highway runs through swampy terrain and terrain with high compressibility soils. A non-woven heat-bonded geotextile was used for the construction of the highway. To evaluate the influence of the geotextile on the behavior of the road, instrumentation was installed and monitored in four embankment sections. Two were where high compressibility soils existed and the other two were in the
swampy zone. In each case a non-fabric control embankment was built to compare the results.

It was found that vertical displacements were less in sections where a geotextile was used. A more even surface and a more homogeneous stress distribution was noted in the embankments with geotextiles. From a construction point of view, the use of the geotextiles greatly helped the beginning of construction of the embankment by providing a more stable working pad [42].

Study No. 7

Construction practices by Caltrans in California included the use of reinforcing fabrics to solve embankment stability problems over soft muds at the new Dumbarton Bridge. Woven reinforcing fabric was specified. Construction required embankment placement over open water and bay mud.

The only failure that occurred was in the west approach containment dike during the initial stages of construction. It is believed that major embankment failures would have developed had fabric not been used. Stability analyses indicated that fabric added about 10% to the overall factor of safety. Fabric provided initial support and helped
maintain embankment integrity during periods of high pore water pressures and marginal stability [20].

Study No. 8

The Texas Department of Highways and Public Transportation, as of August 1984, had nine projects in which geosynthetics had been used on an experimental basis. Several of these projects used geomembranes (impermeable geosynthetics) as vertical moisture barriers at the pavement edges to minimize moisture movement into expansive clay subgrades. The moisture barriers reduced pavement roughness and increased the time between overlays.

In another application, a geotextile was placed between the base and the subgrade to act as a separator and possible reinforcing member. Analysis of Falling Weight Deflectometer data indicated that the section containing the geotextile was statically stiffer than the control section [52].
CHAPTER 3

THEORY

3.1 BASIC CONCEPTS

The geosynthetics support the road embankment by a combination of hoop tension and an increase in bridging action caused by an increase in lateral restraint of the aggregate in the embankment. The bridging effect has been discussed by Kinney (1979) and others. Soil bridging does not appear to be the dominant factor for spanning void with geosynthetics. Therefore the soil bridging effect has been neglected resulting in a conservative design. The theory of support by hoop tension was described in detail by Kinney and Abbott (1984), and Kinney (1985). Later a computer program was developed by Kinney (1986).

It is assumed that the full weight of the road fill and traffic is carried one dimensionally across the void by the geosynthetic in hoop tension. The geosynthetic derives its tension from friction with the soil along the embedment length outside the void. The geosynthetic is assumed to stress into a segment of a circular arc and the stress on the geosynthetic is assumed to be normal to the
geosynthetic. The change in length between the width of the void and the circumference of the circular arc comes from stretching of the geosynthetic across the void and throughout the embedded length to the point of zero tension in the geosynthetic, plus any slippage that may occur at the ends of the geosynthetic.

Equations were developed for the strain that creates the extra length in the geosynthetic assuming the maximum tension in the geosynthetic over the void is known. Equations were then developed for the maximum tension in the geosynthetic over the void assuming the extra length equations are satisfied under a unique set of circumstances. No closed form solution has been found. Hence, the solution is iterative in nature.

It has been assumed that the tension in the geosynthetic is constant across the void, that the shear stress on the geosynthetic is constant from the edge of the void to the point where the required tension in the geosynthetic has been developed, and that the modulus of elasticity of the geosynthetic is constant.

These assumptions appear limiting at first glance, however, years of laboratory and field testing have established that they are reasonable (Kinney, 1979; Kinney, 1985; Bolles, 1986). These restrictions are not essential
but the additional complexity introduced by not making them is not warranted with the present state of knowledge about the mechanical properties of the geosynthetics, their response in the system, the properties of the soils and the geometry of the resulting voids.

3.2 MATHEMATICAL MODEL

The mathematical model is a tool for calculating the maximum deflection and strain in the geosynthetic.

3.2.1 Assumptions

The assumptions made in developing the mathematical model are summarized below:

1. The stress on the geosynthetic over the void is normal to the material and the curved surface is a circular arc.
2. The embankment is supported by hoop tension in the deformed geosynthetic.
3. The geosynthetic is linearly elastic.
4. The tension in the geosynthetic is constant across the void.
5. The shear stress on the reinforcing material is
constant from the edge of void to the point of no relative movement between the soil and the geosynthetic or the end of the geosynthetic whichever is less.

3.2.2 Development of Theory

The theory is based on hoop tension as shown in Figure 3.1 and as expressed in Eq. (1)

\[ T = p \cdot r \]  

Eq. (1)

where:

- \( T \) = tension in the geosynthetic per unit width \((\text{lb/ft})\)
- \( p \) = normal pressure on the geosynthetic \((\text{lb/ft}^2)\)
- \( r \) = radius of curvature of the geosynthetic \((\text{ft})\)

According to the assumptions, there is a point of fixity beyond which the reinforcing material does not move relative to the soil unless the ends of the geosynthetic move as shown in Figure 3.2. The full shear stress is developed between the void and the point of fixity or the end of the geosynthetic. The tension in the geosynthetic varies linearly from zero at the point of fixity or end of the geosynthetic to a maximum at the edge of the void.

The tension developed in the geosynthetic over the void is resisted by the shear stress developed on the
Figure 3.1 Freebody Diagram of Geosynthetic Over Void
(Based on Hoop Tension and Circular Arc)

$T =$ Tension in geosynthetic
$r =$ Radius of curvature of geosynthetic
$P =$ Normal pressure on geosynthetic
Figure 3.2 Shear Stress on Geosynthetic Outside Void
geosynthetic outside the void. The shear stress is the shear strength between the geosynthetic and the embankment materials. The Shear strength depends on embankment load on the geosynthetic and on soil characteristics and the physical properties of the geosynthetic.

The maximum possible shear stress on the geosynthetic is the algebraic sum of the shear stresses on the top and bottom of the geosynthetic. There is some question as to whether the shear stress acts on the top and bottom of the geosynthetic or just on the bottom. If the soil on top of the geosynthetic moves with the geosynthetic, there will not be relative motion between the two and no shear stress will develop. This will happen unless there is resistance built up in the void area to inhibit the motion of the fill over the geosynthetic. Resistance will be built up if there is a relatively small deformation into the void relative to the amount of the geosynthetic outside the void. In the laboratory tests, resistance is also developed by the shear stress between the soil over the geosynthetic and the sides of the box. A conservative approach has been taken and shear stress only on the bottom of the geosynthetic has been assumed.

The distance the geosynthetic is pulled out from the edge of the void is defined by the following equation:
\[
d_2 = L \left( \frac{T_{ave}}{E} \right) + d
\]

...Eq. (2)

where:

\( T_{ave} \) = average tension in the geosynthetic over the embedded length (lb/ft)

\( E \) = effective secant modulus (elastic modulus) of the geosynthetic (lb/ft)

\( d \) = distance the end of geosynthetic moves (ft)

As shown in Figure 3.2

\( d_2 \) = distance which the geosynthetic is pulled out from the edge of the void (ft)

\( L \) = length of the geosynthetic from the edge of the void to the point of fixity or the end of the geosynthetic if the end slips (ft)

However, assuming that the ends of the geosynthetic do not slip, the length from the edge of the void to the point of fixity is:

\[
L = \frac{T_{max}}{S}
\]

...Eq. (3)

where:

\( S \) = maximum shear strength between the geosynthetic and the soil (lb/ft\(^2\)) and is considered uniform over the embedded length

\( T_{max} \) = tension in geosynthetic at the edge of void (lb/ft)

\( T_{ave} = \frac{T_{max}}{2} \)

...Eq. (4)
Substituting Eq. (3) and Eq. (4) into Eq. (2)

\[ d_2 = \frac{T_{\text{max}}}{S} \left( \frac{T_{\text{max}}}{2E} \right) = \frac{T_{\text{max}}^2}{2ES} \ldots \text{Eq. (5)} \]

If the ends slip then

\[ L_{\text{max}} = \frac{T_{\text{max}}}{S} \]

\ldots \text{Eq. (6)}

where:

\[ L_{\text{max}} \] = length of geosynthetic from the edge of the void to the end of the geosynthetic, and Eq. (2) becomes

\[ d_2 = \frac{T_{\text{max}}}{S} \left( \frac{T_{\text{max}}}{2E} \right) + d_1 \]

\[ = \frac{T_{\text{max}}^2}{2ES} + d_1 \]

\ldots \text{Eq. (7)}

The length of the arc, \( L_1 \), is the initial width of the void (W) plus the elongation undergone by the geosynthetic as it is stretched across the void (\( d_1 \)) and the extra length created at the edge of the void by stretching within the embankment and slippage of the end of the geosynthetic as described below:

\[ L_1 = W + d_1 + 2d_2 \]

\ldots \text{Eq. (8)}

Note that all of the factors in Eq. 8 are known except the amount of slippage of the ends of the geosynthetic and the maximum tension in the geosynthetic which is assumed to be constant throughout the void. Both the potential for slippage and the maximum tension can be determined if the radius of curvature and the loading over the void on the
geosynthetic are both known. The loading can be calculated from the geometry within the restrictions discussed before.

$L_1$ can also be calculated purely from geometry. Since $L_1$ calculated in this way will be compared to $L_1$ calculated in Eq. 8, it will be called $L_2$ hereafter.

From Figure 3.3 the arc length, $L_2$, is:

$$L_2 = 2*\theta*r$$  \hspace{1cm} \text{...Eq. (9)}

Where:

- $r =$ radius of curvature (ft)
- $\theta =$ 1/2 of the subtended angle (radians)

There are two equations, Eq. 8 & Eq. 9, and three unknowns, $r$, $L$ & $\theta$. Two of the variables are related through geometry as shown in Eq. 10 which makes a unique solution possible but an iterative technique is necessary to find the answer.

$$W = 2*r*\sin\theta$$  \hspace{1cm} \text{...Eq. (10)}

Assuming $r$, $T_{max}$ can be calculated from Eq. 1 and then $L_1$ can be calculated from Eqs. 5, 7 & 8. Using the Same value for $r$, $\theta$ can be calculated from Eq. 10 and then $L_2$ can be calculated from Eq. 9. The values of $L_1$ and $L_2$ will be equal if the correct value of $r$ was chosen hence various values of $r$ are used until the values of $L_1$ and $L_2$ agree. Experience has shown that an $r$ of $(3/4)*W$ is a reasonable starting point.
Figure 3.3 Geometry Used in Theoretical Model

- $r =$ Radius of circular segment
- $2\theta =$ Subtended angle
- $D =$ Maximum deflection of geosynthetic
- $W =$ Width of void
- $L_2 =$ Arc length
Next, the maximum vertical displacement of the geosynthetic into the void can be calculated from the geometrical relationship described by Eq. 11.

\[ D = r - r \cdot \cos \theta \]  

...Eq. (11)

where:

\[ D = \text{maximum vertical displacement of geosynthetic} \] (ft)

The maximum strain, $E$, in the geosynthetic can be calculated using Eq. 12.

\[ E = \frac{d_1}{W} \]

\[ = \frac{(L_1 \text{ or } L_2 - W - 2 \cdot d_2)}{W} \]  

...Eq. (12)

3.2.3 Limitations

The mathematical model is valid if the calculated radius is greater than or equal to $W/2$.

If the embedment length in the field is not sufficient for complete anchorage, the geosynthetic will slip throughout its entire length. Once slippage at the end starts to occur, the tension will remain the same but slippage will increase the arc length, thereby decreasing the radius which increases the load that can be carried by the geosynthetic. The system will continue to become more stable as slippage progresses because the radius continues
to decrease until the radius is reduced to one half of the void width. At that point the system becomes unstable and failure will occur by the geosynthetic pulling out, and the void filling.

If the modulus of the geosynthetic is not high enough, there will be enough stretching to cause the geosynthetic to sag into the void more than a distance of \( \frac{W}{2} \).

To avoid this situation, a higher modulus \( E \) geosynthetic should be used. Preliminary information, Kinney (1979), Koener et. al. (1980), and Gource et. al. (1982) indicate that some geosynthetics have a much higher dynamic modulus than static modulus.

### 3.3 COMPUTER PROGRAM

The role of computer oriented techniques in analysis and design of geotechnical structures has been firmly established in recent years.

A computer program developed by Kinney (1986), shown in Appendix E expedites calculations described above.
4.1 CONSTRUCTION METHODS

It is important to describe the construction techniques of few items which played a vital role in the laboratory experimentations.

4.1.1 Box

A wooden box 24 ft. long, 2 ft. wide and 2 ft. deep was fabricated with 3/4 in. plywood reinforced with timber braces. The base of the box was constructed by joining 3/4 in. plywood with 2 in. x 12 in. timbers beneath. The middle 6 ft. length of the bottom of the box was modified to accommodate a trap door. The box was mounted on a frame of steel I-beams and timbers, 3 ft. above the floor level (Figure 4.1).

A provision was made at the middle part of the box to allow sagging of the geogrid during opening of the trap door and loading without spillage of fill material. In the
Figure 4.1 Simplistic Sketch of Box Showing Test Setups
center 6 ft. of the box, the two sides were made 2 ft. 11 in. deep instead of 2 ft. to allow sagging of the geogrid.

4.1.2 Trap Door

The most important aspect of creating an artificial void in the middle of the roadway embankment was the design and construction of a trap door in the middle of the box (Figures 4.1, 4.2, and 4.3). The box was made in such a way that after filling it with sand and after duly compacting it, the whole system was simulating a 2 ft. long section of roadway embankment, 24 ft. wide and 2 ft. deep.

The size of the trap door was 6 ft. long and 2 ft. wide. It was positioned in the middle of the box. The trap door consisted of three parts. Two hinged sections were connected to the bottom of box by hinges on both sides of the void. Each sliding piece was 22 in. square. They were made of 1 1/4 in. thick plywood. A center section which could move vertically was made to close the gap between the two hinged sections when the trap door was to remain closed. A slit was made down the center of the pieces to allow measurement of the grid from below. The above timber structure was supported by a steel frame made of 3 in. square tubing. The three parts of trap door were arranged
Figure 48 Trap Door Details
Figure 4.3 Arrangement of Wires and Dial Gauges
in such a way that when the jacks were lowered the two hinged parts started sliding over removable part until the three parts dropped completely away from the bottom of the box leaving a void.

4.1.3 Loading Frame

A steel frame (Figure 4.1) was made for applying load to the fill surface with the help of a hydraulic jack. The jack was placed between the horizontal member of the frame and the loading plate on the top surface of fill material.

4.1.4 Wooden Tamper

A wooden tamper was made to compact the fill material inside the box. The tamper was made by joining a 1 in. \( \text{dia.} \) steel pipe handle to a 10 pound timber block \( 10\frac{1}{2}\text{in.} \) long, \( 6\frac{1}{2}\text{in.} \) wide and \( 3\frac{1}{2}\text{in} \) high. The fill material was placed inside the box in four inch thick layers. Each layer was well compacted before the next one was placed.
4.2 MATERIALS

4.2.1 Geogrid

Two types of geogrids were used in the laboratory experimentations: (1) Signode TNX-5001 and (2) Tensar BX-1200. The Signode TNX-5001 was placed with its machine direction (roll length) along the length of the box. The Tensar BX-1200 was placed with its cross direction (roll width) along the length of the box.

Since the Tensar BX-1200 was not sufficiently wide to cover the entire length of the box, the geogrid was extended at both ends by adding two short pieces to cover the full length of box. The joint was made by wrapping the cross strands with wire.

The strength and modulus of the geogrids are shown in Table 4.1.

<table>
<thead>
<tr>
<th></th>
<th>Machine Direction</th>
<th>Cross Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signode TNX-5001</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Wide Width</td>
<td>6,000</td>
<td>2,250</td>
</tr>
<tr>
<td>Tensile Strength (lbs/ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Elongation At Break (%)</strong></td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 4.1 (cont'd)

<table>
<thead>
<tr>
<th></th>
<th>Machine Direction</th>
<th>Cross Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sianode TNX-5001</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% Secant Modulus (lbs/ft)</td>
<td>108,000</td>
<td>40,800</td>
</tr>
<tr>
<td>2% Secant Modulus (lbs/ft)</td>
<td>156,000</td>
<td>57,000</td>
</tr>
<tr>
<td><strong>Tensar BX-1200</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexural Rigidity (mg-cm)</td>
<td>75,000 (min)</td>
<td>1,000,000 (min)</td>
</tr>
<tr>
<td>Tensile Modulus (lbs/ft)</td>
<td>18,500 (min)</td>
<td>30,000 (min)</td>
</tr>
<tr>
<td>Junction Strength (lbs/ft)</td>
<td>1,050 (min)</td>
<td>1,890 (min)</td>
</tr>
<tr>
<td>Junction Efficiency (%)</td>
<td><strong>90</strong> (min)</td>
<td><strong>90</strong> (min)</td>
</tr>
</tbody>
</table>

4.2.2 Fill Material

About 4 cubic yards of sand were required to fill the box. The grain size distribution of the sand was determined in accordance with American Society for Testing Materials (ASTM) D-422-84. The particle size distribution is shown in Appendix D. The fill material consisted of 99.4% sand (between 4.75 mm and 0.075 mm) and 0.6% silt and clay sized particles (< 0.075 mm).

The particle size distribution curve can be quantitatively described in terms of the degree of curvature and
the uniformity of the grain size curve. The coefficient of curvature and coefficient of uniformity are defined as follows:

\[ C_u = \frac{D_{60}}{D_{10}} \]  \( \ldots (1) \)
\[ C_c = \frac{D_{30}^2}{(D_{60})(D_{10})} \]  \( \ldots (2) \)

where:

\[ C_u = \text{Coefficient of uniformity} \]
\[ C_c = \text{Coefficient of curvature} \]
\[ D_{10} = \text{Grain size with 10\% particles finer} \]
\[ D_{30} = \text{Grain size with 30\% particles finer} \]
\[ D_{60} = \text{Grain size with 60\% particles finer} \]

The fill material used for laboratory tests had the following values (Figure D.1, Appendix D):

\[ D_{60} = 0.87 \text{ mm} \]
\[ D_{30} = 0.28 \text{ mm} \]
\[ D_{10} = 0.17 \text{ mm} \]

so

\[ C_u = \frac{0.87}{0.17} = 5.12 \]

and

\[ C_c = \frac{0.28^2}{(0.87)(0.17)} = 0.53 \]

According to the Unified Classification (USC) System, this soil is classified as SP, poorly graded sand.
4.3 LOADING EQUIPMENT

A "Port-a-Jack", made by Soil Test Inc., Evanston, Ill., with a stroke length of 3\" and capacity of 60,000 pounds was used. The jack (Figure 4.1) consisted of a hand pump with a high pressure hydraulic line to transport hydraulic fluid from the pump to the ram. Directly tapped in line was a pressure gauge from which the applied pressure directly read in pounds.

4.4 INSTRUMENTATION

The horizontal and vertical location of selected locations on the geogrid were measured throughout testing. The vertical location of the portion of the grid over the void was measured by hanging scales through the slots made in the movable portion of the bottom of the box at eleven different locations. The horizontal location of selected points on the geogrid was measured by attaching piano wire to the geogrid and measuring the movement of the end of the wire where it protruded through the end of the box. The wire was housed in 1/8 inch plastic tubing to eliminate all effects of the soil and geogrid between the point of
anchorage and the end of the box. The wire was placed under tension during measurements.

4.4.1 Dial Gauge Indicator

To measure the movement of piano wires, attached to the lower layer geogrid, dial gauge indicators (Figures 4.3 & 4.4) were used. The gauges were fixed to a light steel frame which was attached to the outside end of box. The range and accuracy of gauges were 2.00 in. and 0.001 in. respectively.

4.4.2 Fish Scale

In multilayer geogrid systems, the movements of various points in the upper layer geogrids were measured by pulling the individual wires each time with a definite amount of force. A fish scale with a 28 lbs. capacity and an 8 oz. accuracy was used in the tests. A loop was made at the end of each piano wire outside the end of box. After each application of load, the hook of the fish scale was attached to the loop of individual piano wire and pulled with a force of ten pounds. With the ten pound force the location of the wire was measured from a fixed point.
Figure 4.4 Longitudinal Section of Box Showing Double Layer Geogrid System
4.4.3 Dial Caliper

To measure the locations of the piano wires on the upper layers of geogrid, a dial caliper was used in conjunction with a fish scale. After pulling the wire, the length of the wire outside the end of the box was measured with the caliper. The "NSK Dial Caliper", with a range of 6 in. and an accuracy of 0.001 in., was used for measurement.

4.4.4 Suspended Scales

To determine the vertical displacement of the geogrid ordinary scales were suspended at different points from the bottom layer of geogrid (Figure 4.4). 6 oz. weights were used to keep those scales vertical. With the help of vertical scales and a reference string, the vertical displacement of the geogrid at different points was measured. The scales had a precision of 1/16th of an inch.
4.5 TEST SETUP

The objective of the tests was to find the possibility of supporting a roadway embankment over a void with the help of geogrid. For this purpose it was essential to measure the strain in the geogrid and the deformation over the void. The other objective was to find the effect of adding several layers of geogrid.

A wooden box of size 24 feet long, 2 feet high, and 2 feet wide was made to represent a roadway section 2 feet long, 2 feet high, and 24 feet wide. Centrally located in the roadway was a six-foot wide artificial void created by constructing a trap door at the middle of the box as shown in Figures 4.1 and 4.2.

Vehicular loading was simulated by loading with a hydraulic jack over the center of the void (Figure 4.1). Test sections with single and multiple layers of geogrid were tested to find the effect of adding layers to the total performance of the system.

Before placing the geogrid, the inner sides of the box were covered with two layers of clear plastic sheeting to minimize the effect of side friction. The geogrid was cut 1.5 inches narrower than the inside of the box and 24 feet long.
The first layer of geogrid was placed inside the box on a 1-inch thick sand layer. After placing the first layer of geogrid, one end of the piano wires, used to measure movement of various locations along the geogrid, were attached to the geogrid. To avoid friction, the piano wires were passed through 1/8 in. dia. plastic tubes. The other end of piano wires were passed through holes in the ends of the box and passed over pulleys and tied to weights as shown in Figures 4.3 and 4.4. As the test progressed the weights would move upward an amount equal to the movement of the grid towards the center of the test section. The movement was measured with dial gauges and the strain in the geogrid was determined by the relative movement of the weights.

Pieces of geotextile, 9 inches wide and 2 feet 4 inches long, were placed lengthwise across the bottom over the geogrid. The geotextile extended 1.5 inches up the side of the box to retain the sand from falling through the grid while opening the trap door. Opening the trap door was controlled by four jacks placed on the floor at the four corners of a steel frame supporting the trap door.

In multilayer systems, the spacing between two successive layers of geogrid was six inches. Filling the box was achieved by pouring the sand into the box in layers and
compacting each layer with a ten pound wooden tamper. The thickness of each layer was four inches before compaction.

In multilayer systems, the piano wires were attached to the upper layers of geogrid at various points by connectors and the wires were passed through a 1/2-inch dia. plastic tube to bring their free ends outside of box. These wires were individually pulled at their free ends with a ten pound force and relative locations were measured by a dial caliper against a reference block.

For measuring the vertical displacement of the top surface of the fill material, a reference string and an ordinary scale were used. For measuring the vertical displacement of the bottom layer of geogrid, scales were tied to the geogrid and hung with weights from various points along the geogrid as shown in Figure 4.4.

After the geogrid(s) and sand were placed inside the box a 3/4-inch thick and 6 inches wide wooden plate was placed over the full 24 inch width of the box at the center. After opening the trap door, loads were applied to the wooden plate by a hydraulic jack and measurements were recorded.
4.6 TEST RESULTS

The data from the four tests are presented in Appendix A and the peak values are summarized in Table 4.1

Table 4.1 Summary of Experimental Results

<table>
<thead>
<tr>
<th>Test Run No.</th>
<th>Geogrid Type</th>
<th>No. of Layers</th>
<th>Applied Vertical Load (lbs)</th>
<th>Maximum Vertical Displacement (in.)</th>
<th>Maximum Strain in Geogrid (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Signode TNX-5001</td>
<td>1</td>
<td>1,500</td>
<td>10.13</td>
<td>1.86</td>
</tr>
<tr>
<td>2</td>
<td>Signode TNX-5001</td>
<td>2</td>
<td>1,500</td>
<td>9.02</td>
<td>1.10 (Bottom)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- (Top)</td>
</tr>
<tr>
<td>3</td>
<td>Tensar BX-1200</td>
<td>2</td>
<td>600</td>
<td>11.00</td>
<td>3.43 (Bottom)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.13 (Top)</td>
</tr>
<tr>
<td>4</td>
<td>Tensar BX-1200</td>
<td>3</td>
<td>1,500</td>
<td>10.50</td>
<td>2.74 (Bottom)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.90 (Middle)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.42 (Top)</td>
</tr>
</tbody>
</table>

4.7 TEST PERFORMANCE

After setting up the test apparatus an initial set of measurements was taken. Following the initial measurements the trap door was opened completely and another set of measurements was taken. After opening the trap door the load was applied in increments by the hydraulic jack and measurements were taken after each load increment.
Loading was stopped in the first test (single layer of Signode TNX-5001) when the geogrid sagged to the bottom of the test apparatus walls, about 11 inches. The second test (double layer of Signode TNX-5001) was stopped at the same maximum load achieved with the single layer system. The third and fourth tests were terminated when the 11 inches of displacement had occurred.

Each measurement set consisted of measuring the locations of the piano wires attached to the geogrids, measuring the vertical locations of the ground surface and the lower geogrid at several locations and recording the load on the hydraulic jack.

The test run data and curves are furnished in Appendix A and B respectively.

4.8 DISCUSSION OF EXPERIMENTAL PROBLEMS ENCOUNTERED

Though the test runs were conducted with the utmost care, due to some of the conditions mentioned below the results obtained may vary to a limited degree from their actual values. The possible areas of problems are listed below:

1. The hydraulic jack used for applying the loads leaked fluid and as a result the pressure was not
constant over a period of time.

2. The four hydraulic jacks used for regulating the movement of the trap door, leaked fluid. Consequently during the filling of the box there was some slight downward movement of the trap door.

3. Although the geogrid sections were cut to sizes less than the inside width of box, the possibility of them contacting the sides of the box during movement can not be ruled out.

4. The geotextile pieces that were used over the bottom layer of geogrid to retain the fill material might have caused a limited amount of bridging.

5. The dial gauges which were available for instrumentation, were not protected from the effects of dust particles during use.

6. In test run no. 2, piano wires were passed through one 1/2"-dia. plastic tube for measuring the stretching of the of the top layer geogrid. The readings were inaccurate as the wires got entangled.

These problems became apparent during testing so for subsequent test runs the following precautionary measures were taken:

1. The readings from test runs were completed rapidly to minimize the effect of any pressure drop in the
hydraulic jack with time.

2. The dial gauges were cleaned and were provided with a plastic **cover during loading and unloading of the box** to prevent dust particles within the laboratory from affecting them.

3. By passing four wires through the same tube the entanglement problems were avoided. Therefore, from test run no. 3 onward instead of one plastic tube, two tubes were utilized with four wires **in each**.

**4.9 COMPARISON BETWEEN THEORY AND TESTS**

A computer program developed by Dr. Kinney for **single layer geosynthetic systems** as shown in Appendix E was used to compare the experimental results of the single layer geogrid system (Signode TNX-5001) with theoretical analysis presented in Chapter 3. The steps taken for comparison are shown below:

**Load:**

- Hydraulic Jack = **64 lbs**
- Timber Platform = **13 lbs**
- Timber pieces to adjust height = **2 lbs**
- Suspended Scales = **4 lbs**

**Sub total = 83 lbs**
Weight of fill material over trap door area
\[(2' \times 1.10'' \times 6' \times 117\# / \text{cft}) = 2,574 \text{ lbs}\]
Load applied by Jack = 1,500 lbs

\[
\text{Sub Total} = 4,074 \text{ lbs}
\]

Total = 4,157 lbs

The geogrid width was 22 inches. Assuming the total vertical force acts uniformly over the void, the estimated pressure over the geogrid in the void area is:

\[
4,157 \text{ lbs} / (1'10'' \times 6'0'') = 376.6 \text{ psf.}
\]

No deduction was made for the friction between the sand and the box or for arching within the sand.

The input data used for the computer solution are given below:

1. Width of void = 6 ft.
2. Embedment length = 8.9 ft.
3. Applied pressure = 376.6 psf
4. Shear stress on geosynthetic = 188.8 psf
   (from shear stress calculation, Appendix G)
5. Effective secant modulus of geosynthetic = 156,000 lbs/ft
   (at 2% strain from Table F.1, Appendix F)
6. Ultimate tensile strength of geosynthetic = 6,000 lbs/ft
   (from Table F.1, Appendix F).

The printout generated from the computer solution is as follows:

1. Maximum tension = 1,679 lbs/ft
2. Factor of safety with respect to tension = 3.57
3. Maximum strain = 1.077%
5. Radius of curvature = 4.46 ft.
6. Required embedment = 8.89 ft.
The laboratory experimental results for the single layer geogrid system, Signode TNX-5001, (Test No. 1, Appendix A) are given below:

1. Maximum strain = 1.86%
2. Centerline displacement = 10.13 in.

The experimental results from this test does not match very well with the theory. The possible reason may be that the proposed theory today does not account for an increase in shearing resistance at the edge of the void due to the tension in the geosynthetic and concave downward shape. Neither does the theory account for any bending resistance in the soil geosynthetic system over the void or any increase in stiffness of the soil over the void caused by confining properties of the geogrid.
4.10 DISCUSSION OF TEST RESULTS

In total four tests were conducted in the laboratory with two types of geogrids as listed below:

(a) Test No. 1, single layer system with Signode TNX-5001,
(b) Test No. 2, double layer system with Signode TNX-5001,
(c) Test No. 3, double layer system with Tensar BX-1200,
(d) Test No. 4, triple layer system with Tensar Bx-1200.

The discussion of the test results are made with reference to various curves as shown in Figures 4.5 through 4.20, at the end of this section.

Deformed Shape of Geogrid (Test No. 1)

Figure 4.5 shows the deformed shape of the geogrid for Test No. 1. The vertical displacement, starting from zero at the edge of the void, increases toward the center and the peak displacement occurs at the center of the void. Three curves are shown for comparison: one from the laboratory data, a second represents a circular arc approximation to data, and the third represents the calculated values using the theory presented in Chapter 3. The peak value of vertical displacement from the calculations is higher than the measured peak value in the tests. It is observed that the theory overestimates the maximum displacement by about 20%. The possible reason for this, may be that the theory proposed
today does not account for an increase in shearing resistance at the edge of the void due to the tension in the geosynthetic and concave downward shape. Neither does the theory account for any bending resistance in the soil geosynthetic system over the void or any increase in stiffness of the soil over the void caused by confining properties of the geogrid.

**Maximum Displacement vs. Total Load (Test Nos. 1, 2, 3, & 4)**

The maximum displacement is a function of total load over the void as shown in Figure 4.6 for each test. It is interesting that the relationship between displacement and jack load is almost linear in all tests.

**Strain at 4 in. from Centerline Vs. Total Load (Test Nos. 1, 2, 3, & 4)**

The strain measured at a distance of four inches from the center line is shown as a function of total load in Figure 4.7. It is interesting that the relationship between strain and jack load is linear in almost all tests. The rate of increase in strain is nearly the same for all layers in a single test.

By comparing Test Nos. 1 and 2, it is obvious that the strain increases as a function of load and is greater for the one layer system than for the two layer system. The same trend can be seen in Test Nos. 3 and 4.
The radii of curvature of the lower geogrid of different systems at various locations over the void are shown in Figures 4.8 through 4.11.

The radius of curvature is calculated using two measured points on geogrid and assuming that the section is symmetrical and that the center of the circle is at the center line of the test section. The vertical displacement was measured to a precision of 1/16 of an inch. An error in the readings of 1/8 of an inch will make about a 10% error in the calculation in radius of curvature. Considering the accuracy of calculations a linear relationship provides a good estimate for the radius of curvature in all the tests as shown in Figure 4.8 through 4.11.

The correlation coefficient is 0.9 or over in each of the four tests except Test No. 3 where it is 0.66. The equations and corresponding correlation coefficients are shown on the figures.

The radii of curvature for Test Nos. 1, 2, and 4 are very similar. The radius of curvature for Test No. 3 is significantly higher near the center and lower near the edge of the void.
Strain in Geoarid (Test No. 1)

Figure 4.12 shows the strain in the geogrid for Test No. 1. The strain, starting from zero at a point near the end of the geogrid, increases toward the center of the void. The rate of increase is much higher from the edge of the void toward the center. Strain attains a maximum value at the center of void.

Measured and Calculated Strain in Geoarid (Test No. 1)

In Figure 4.13, a comparison is made between the measured and the calculated strain. In both the measured and the calculated curves the strain, starting from a point near the end of the geogrid, increases toward the edge of the void. The calculated strain is found to be higher than measured value from the end of the geogrid up to the edge of the void. In void area the measured strain is found to be higher than the calculated value. The calculated strain remains constant from the edge over the void area.

Since the strain at the edge of the void is only about 40% of the calculated value it is obvious that the theory greatly overpredicts the tension in the geosynthetic at the edge of the void. This coupled with the observed differences between the measured and the theoretical strains over the void lead to the conclusion that the theory does not accurately predict the stress distribution over the void.
Pressure on Geogrid (Test No. 4)

In Figure 4.14, the pressure is shown over the void in each of the layers of geogrid for the three layer system (Test No. 4). The pressure was calculated from the measured strain and the measured radius of curvature by estimating the relationship between the geosynthetic tension and strain and by using hoop theory. The pressure is maximum on the bottom layer and minimum on the top layer for the whole length of the geogrid except for a short length at the center of the void. The reason for this may be that the application of the jack load at the center of the void over a small area relative to the width of the void. The jack load was applied to a 6-inch wide wooden plate which was placed over the full width of the box at the center of void. So, at the center, the top layer of geogrid received the maximum pressure and the bottom layer the minimum. The amount of pressure in the middle layer is always found to be between the pressures on the top and bottom layers.

Shear Stress on Geoarid (Test Nos. 1 & 2)

In Figure 4.15, the shear stresses on the bottom layer of the geogrid are shown for Test Nos. 1 and 2. The shear stresses are calculated from the measured strain and the estimated relationship between tension and strain in the geosynthetic. The shear stresses on the geogrid in Test No. 1
and the bottom layer of geogrid of Test No. 2 are low and nearly equal outside the area of the void. From near the edge of the void, the shear stress increases at a higher rate and after attaining a peak value it starts decreasing toward the center. At the center of the void, the single layer geogrid has higher shear stress than the lower layer of the two system. It is unlikely that the negative stress indicated near the center in Test No. 2 is real. It appears more likely that there is an error in the data especially considering the other problems associated with running that test.

Shear Stress on Geoarid (Test No. 3)

In Figure 4.16, it is shown that the maximum shear stress in geogrid occurs near the edge of the void. The lower layer has higher peak shear stresses than the upper layer. The shear stress on the lower layer was found to be equal to the total shear stress available from the dead weight of soil.

Comparing the shear stresses between Test Nos. 2 and 3 (Figures 4.15 & 4.16), we find that both of them are two layer systems, and the bottom layer of geogrid of Test No. 2 experienced a higher shear stress than the bottom layer of Test No. 3. Again if we compare the shear stresses between Test Nos. 3 and 4 (Figures 4.16 & 4.17), we see that the total shear stress in the three layer system is higher than that of
the two layer system indicating that the three layer system is stiffer than the two layer system.

**Shear Stress on Geoarid (Test No. 4)**

In Figure 4.17, it is shown that the shear stresses for various layers of geogrids in the three layer system attained their peak values near the edge of the void. The peak values of each of the three layers are found to be nearly same and each one is less than the total shear stress available from the dead weight of the soil. The shear stresses are found to decrease gradually from a peak value at the edge of the void toward the center and the end of the geogrid. The total shear stresses for all the three layers are obtained by adding the shear stresses of the three layers at the corresponding locations.

**Strain in Bottom Layer Geoarid (Test Nos. 1, 2, 3, & 4)**

In Figure 4.18, a comparison is made between the strain observed in the bottom layers of geogrid in all the four tests. Test Nos. 2 and 3, each had two layers of geogrid and it is obvious that the strain is much lower in the geogrid in Test No. 2.

Comparing Test Nos. 1 and 2, it is obvious that peak strain is higher in a single layer system than in a double layer system. It is not obvious that there is any difference
in the strains outside the width of the void when the geogrid is very stiff. The difference shown in strain outside the void was not within the accuracy of our measurements.

Comparing Test Nos. 3 and 4, it is obvious that strains in three layer system are much lower than in two layer system.

**Strain in Geogrid (Test Nos. 3 & 4)**

A comparison is made between the strains in the various layers of multiple layer systems in Figure 4.19. All of the loads are normalized to a 1000 pound jack load.

It is obvious in both Test Nos. 3 and 4 that the lower layers of geogrid undergo higher strain than the upper layers in the same system. It is also obvious that the geogrid in the two layer system, as shown in Test No. 3, has a much higher strain than the three layer system under the same load as shown in Test No. 4.

By comparing Test No. 3 to Test No. 4, it is obvious that less embedment is required with three layers than two layers. This could mean that the three layer system is carrying more of the load in bending and less in pure geosynthetic tension than the two layer system. However, it might also indicate that the shear stress on the geosynthetic in the immediate vicinity in the edge of the void is higher in three layer system than the two layer system, perhaps because of increased bending resistance in the three layer system.
Deformation of Bottom Layer Geoarid (Test Nos. 1, 2, 3, & 4)

The shape of the deflected geogrid in each of the test sections is shown in Figure 4.20. A third order polynomial fits the data from each test extremely accurately (with correlation coefficients greater than 0.996) indicating that the radius of curvature should vary linearly from a minimum at the center of void.

It is obvious from comparing curves of Test Nos. 1 and 2 that there is less displacement in the two layer system than the one layer system. Comparing Test Nos. 3 and 4, it is obvious that there is more displacement in the two layer system than the three layer system. Comparing Test Nos. 2 and 3, both of which are two layer systems, it is obvious that there is less displacement with the stiffer geogrid.
Figure 4.5 Deformed Shape of Geogrid (Test No. 1)
Figure 4.6 Maximum Displacement vs. Total Load (Test Nos. 1, 2, 3, & 4)
Figure 4.7 Strain at 4 in. from Centerline vs. Total Load (Test Nos. 1, 2, 3, & 4)
4.8 Radius of Curvature vs. Distance from Centerline (Test No. 1)
4.9 Radius of Curvature vs. Distance from Centerline (Test No. 2)
4.10 Radius of Curvature vs. Distance from Centerline (Test No, 3)
4.11 Radius of Curvature vs. Distance from Centerline (Test No. 4)
Figure 4.12 Strain in Geogrid (Test No. 1)
Figure 4.13  Measured and Calculated Strain in Geogrid (Test No. 1)
Figure 4.14  Pressure on Geogrid
(TesTest No. 4t No. 4)
Figure 4.15 Shear Stress on Geogrid
(*Test Nos. 1 & 2*)
Figure 4.16  Shear Stress on Geogrid  (Test No. 3)
Figure 4.17  Shear Stress on Geogrid  
(Test No. 4)
Figure 4.18 Strain in Bottom Layer Geogrid (Test Nos. 1, 2, 3, & 4)
Figure 4.19 Strain in Geogrid
(Test Nos. 3 & 4)
Figure 4-20  **Deformation of Bottom Layer Geogrid (Test Nos. 1, 2, 3, & 4)**

**Equations of Best Fit Curves:**

**Test 1:**  
\[ y = 16100 - 2.5857e^{-3x} - 9.599e^{-3x^2} + 6.6415e^{-5x^3} \]  
\[ R^2 = 0.956 \]

**Test 2:**  
\[ y = 9.025 - 19255e^{-2x} - 1.2944e^{-2x^2} + 18965e^{-4x^3} \]  
\[ R^2 = 1.000 \]

**Test 3:**  
\[ y = 1.4648 - 1.0299e^{-2x} - 1.4572e^{-2x^2} + 1.0437e^{-4x^3} \]  
\[ R^2 = 0.999 \]

**Test 4:**  
\[ y = 10.551 - 0.2150e^{-2x} - 1.0901e^{-2x^2} + 0.5250e^{-4x^3} \]  
\[ R^2 = 1.000 \]
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

It was found from the experiments that multiple layers of a given geosynthetic provide additional strength and stiffness to support embankments and reduce load-deformation. To support embankments, and the load over them, the importance of selecting the proper type of geosynthetics cannot be overemphasized.

If the modulus of the geosynthetic (E), is not high enough, there will be sufficient stretching to cause the material to sag into the void. The tensile strain of the material must be kept below the percent elongation at break for the material and a reasonable factor of safety must be provided.

If a single layer of reinforcing material fails to achieve this objective then a multilayer system should be considered.

To support the embankment over the void area, there must be some stretching and deformation of the geosynthetic resulting in a depression on the surface of an embankment which later should be filled to make it level.
The assumed circular arc configuration of the geosynthetic and other assumptions made in the theory lead to a reasonable comparison with the laboratory results.

The tension and strain in geosynthetic varies along the length. The strain is zero at the free end and increases to a maximum at the center of the void.
5.2 RECOMMENDATIONS

5.2.1 Test Setup

In connection with the present experimentations the following recommendations are made:

1. Test methods employed in the laboratory should attempt to simulate as closely as possible the conditions which exist in the field, e.g., load conditions, moisture, temperature, nature of soil, etc.

2. Laboratory studies should be conducted to determine the shear strength between the reinforcing material and the fill material.

3. Theoretical work and testing should be done to determine the friction between the sand and the box.

4. Testing should be carried out to determine the effects of placing the geotextile pieces (to retain the fill material) over the layer of bottom geogrid.

5. For present experimentations, two sides of the box where the trap door was located were 2 ft. 11 in. deep. The remainder of the sides were 2 ft. The extra 11 in. extension below the side was for the retention of fill material during the sagging of
geogrid, but this extension was insufficient. An additional extension should have to be made so that the geogrid material could be tested for higher loads.

6. In measuring the stretches of upper layer geogrids with a fish scale and a dial caliper, inaccurate readings were obtained when eight wires were passed through a 1/2 in. dia. plastic tube. But this problem does not occur if a maximum of four wires are passed through a tube.

5.2.2 Future Research

Gotechnical engineering, being a new development of engineering science, shows tremendous potential for expansion and research.

Following in the footsteps of Kinney, Giroud, Koerner, and others and due to the steady increase of global demand for the use of geosynthetics, many talents will be attracted in this area of new technology in the future. Areas for future research are:

1. The possibility of reinforcing embankments must be considered in terms of two different situations:
   (a) low embankments in which the live loads are rel-
atively large and the dead load is relatively small, and
(b) high embankments in which the dead load is large and the live load is relatively small and has little influence on stability,

2. Testing should be carried out to determine the performance of geosynthetics at different orientations.

3. Testing should be carried out for a single geosynthetic with varying heights of fill.

4. Testing should be done for a single geosynthetic with varying void widths.

5. Standardization of the methodology for inspection, maintenance, and repairing of geosynthetic structures should be developed,

6. The processes of cutting, joining, splicing, lapping etc., of geosynthetics should be studied in detail.

7. For multilayer systems research should be done by varying spacing between the layers and combining different types of geosynthetics,

8. Research should done to explore the possibility of using pretensioned geosynthetics.

9. Tests should be conducted for developing appropriate anchor systems to stop slippage of geosynthetics.
10. Theoretical work and testing should be performed on the stability of void walls.

11. The effect of lateral restraint imposed on the fill material by the reinforcing material should be studied in detail since this factor may be significant for large deflection.

12. Elaborate field and laboratory studies should be conducted to more precisely ascertain the shear stress characteristics between the reinforcing materials and the soils in the road profile.

13. Laboratory tests of reinforcing materials are required before field applications to verify manufacturer's supplied data.

14. Research should be done with dynamic and cyclic loading that are relevant to field conditions. More data regarding creep, fatigue, and dynamic behavior are required.

15. There is need for the development of comprehensive durability testing methods. These should assess the potential change in properties, especially strength caused by the following effects:

   (i) Chemical
   (ii) Biological
   (iii) Ultra violet radiation
(iv) Aging under stress
(v) Construction damage
(vi) Temperature and humidity
BIBLIOGRAPHY


5. "Cellular Confinement System", Product Literature (Geoweb), Presto Products Company, 1 800-558-325, p. 3.

19. "Hydraway Drain", Product Literature, Monsanto Chemical Company, 2381 Centerline Industrial Drive, St. Louis, M 063146.
23. Koerner, R.M., 1986, Bowman Professor of Civil Engin-


35. Khanna, P.N., 1979, "Indian Practical Civil Engineers' Handbook", New 6th Edition, New Delhi, India, pp. 19 (Ch. 18), 48 & 53 (Ch. 19).


39. "Miramat", Product Literature, Mirafi Inc., P.O.Box-240967, Charlotte, North Carolina, U.S.A.

40. "Mirascape", Product Literature, Mirafi Inc., P.O.Box-240967, Charlotte, North Carolina, U.S.A.


44. Product Literature, Ambco Fabrics and Fibers Company, 900 Circle, 75 Parkway, Suite 300, Atlanta, Georgia 30339, U.S.A.

45. Product Literature, Bay Mills Ltd., Midland Division, 277 Lakeshore Road East, Suite 400, Oak Ville, Ontario, Canada L6J6J3.

46. Product Literature, Tenax Corporation, A member of the RDB Group, 8291 Patuxent Range Road, Jessup, MD 20794.

47. Product Literature, Synthetic Industries, P.O.Box-1118,
Calhoun, Georgia 30701.


55. "The Application of Polymeric Reinforcement in Soil Retaining Structures", edited by Peter M. Jarrett and Alan

56. "The Design Specification and Use of High Performance Geotextiles", *Seminar No. 1*, Anchorage and Fairbanks, Alaska, April 10–11, 1985, sponsored by Nicolon Corporation, Suite 300, 3150 Holcomb Bridge Road, Atlanta, Georgia 30071, pp. 1–19 (Ch. 4).

APPENDIX A

TEST RUN DATA

The data from the laboratory tests are shown on the following few pages. In total four tests were conducted with two types of geogrids: (1) Signode TNX-5001 (single and double layer) and (2) Tensar BX-1200 (double and triple layer).

The average strain between measurements in percent is calculated from the relative locations of the geogrid reference points.

In Test No. 2, the relative movements of the reference points on the top layer of geogrid were too small to be measured accurately with the techniques used in this experiment. Therefore, location of the reference points and strain in the upper layer of geogrid are not provided.
Test No. 1

Single Layer Geoarid (Signode TNX-5001)

Table A.1  Vertical Displacement of Fill Surface

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Test No. 1

Table A.2  Vertical Displacement of Geogrid

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Test No. 1

### Table A.3 Locations of Geogrid Reference Points

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<th>Reference Point Distance from Initial Mid-box Points Reading (no.)</th>
<th>Dial Gauge Reading in inches on application of load by Hydraulic Jack (in.)</th>
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Test NO. 1

### Table A.4 Geogrid Strain

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Test No. 2

Double Layer Geogrid (Signode TNX-5001)

Table A.5 Vertical Displacement of Fill Surface

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Table A.6 Vertical Displacement of Bottom Layer Geogrid

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### Test No. 2

**Table A.7 Locations of Bottom Layer Reference Points**

<table>
<thead>
<tr>
<th>Reference Point (no.)</th>
<th>Distance from Mid-box (in.)</th>
<th>Initial Dial Gauge Reading in inches on application of load by Hydraulic Jack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reading 0 300 500 600 1000 1200 1500 lbs lbs lbs lbs lbs lbs lbs lbs</td>
</tr>
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<td>1.800 1.388 1.311 1.286 1.268 1.208 1.183 1.164</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>1.900 1.531 1.463 1.438 1.420 1.362 1.337 1.320</td>
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<tr>
<td>3</td>
<td>8</td>
<td>1.900 1.588 1.532 1.511 1.497 1.444 1.423 1.408</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>2.000 1.720 1.671 1.651 1.638 1.589 1.569 1.555</td>
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<tr>
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<td>28</td>
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### Test No. 2

**Table A.8 Bottom Layer Geogrid Strain**

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<th>Distance from Mid-box toward End (in.)</th>
<th>Average Strain between Measurements in Percent</th>
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<tr>
<td></td>
<td>lbs 300 lbs 500 lbs 600 lbs 1000 lbs 1200 lbs 1500 lbs</td>
</tr>
<tr>
<td>0-8</td>
<td>0.538 0.650 0.650 0.650 0.675 0.675 0.700</td>
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<td>8-16</td>
<td>0.713 0.863 0.913 0.963 1.000 1.080 1.100</td>
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<td>16-24</td>
<td>0.400 0.488 0.500 0.513 0.563 0.575 0.588</td>
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<td>24-60</td>
<td>0.361 0.436 0.458 0.472 0.522 0.536 0.547</td>
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<td>60-88</td>
<td>0.179 0.218 0.221 0.229 0.254 0.264 0.270</td>
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<td>88-116</td>
<td>0.179 0.218 0.218 0.218 0.232 0.239 0.246</td>
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<tr>
<td>116-144</td>
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Test No. 3

Double Layer Geoarid System (Tensar BX-1200)

Table A.9 Vertical Displacement of Fill Surface

<table>
<thead>
<tr>
<th>Reference from Point (no.)</th>
<th>Distance from Mid-box (in.)</th>
<th>Displacement in inches due to application of load by Hydraulic Jack</th>
</tr>
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<tbody>
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<td>lbs</td>
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</tr>
<tr>
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<td>8.25</td>
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<td>7</td>
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<td>8</td>
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Test No. 3

Table A.10 Vertical Displacement of Bottom Layer Geogrid

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<th>Reference from Point (no.)</th>
<th>Distance from Mid-box (in.)</th>
<th>Displacement in inches due to application of load by Hydraulic Jack</th>
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<td>Lbs</td>
<td>200 Lbs</td>
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<td>8.35</td>
<td>9.10</td>
</tr>
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<td>8.95</td>
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Test No. 3

Table A.11 Locations of Bottom Layer Geogrid Reference Points

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<th>Reference Point</th>
<th>Distance from Initial Mid-box Points (in.)</th>
<th>Distance Adjusted from Initial at Points Reading 0 (in.)</th>
<th>Dial Gauge Reading in inches on application of load by Hydraulic Jack</th>
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<td>1.723</td>
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<td>-</td>
</tr>
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<td>1.745</td>
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<td>1.008</td>
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The dial gauge attached to reference point no. 5 failed. Therefore the relative movement between reference points 4 and 6 was used for strain calculation.

Test No. 3

Table A.12 Bottom Layer Geogrid Strain

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<th>Distance from Mid-box toward End (in.)</th>
<th>Average Strain between Measurements in Percent</th>
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<td>16–24</td>
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<td>109–144</td>
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Test No. 3

Table A.13 Locations of Top Layer Geogrid Reference Points

<table>
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<th>Reference Point from Mid-box Points (no.)</th>
<th>Distance Between Initial Reading (in.)</th>
<th>Dial Caliper Reading in inches on application of load by Hydraulic Jack</th>
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<td></td>
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<td>9</td>
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Test No. 3

Table A.14 Top Layer Geogrid Strain

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<th>Average Strain between Measurements in Percent</th>
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<td>0.630 0.681 0.733 0.778 lbs lbs lbs lbs</td>
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<td>0.000 0.000 0.000 0.000 lbs lbs lbs lbs</td>
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</table>
Test No. 4

**Triple Layer Geoarid (Tensar BX-1200)**

### Table A.15 Vertical Displacement of Fill Surface

<table>
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<th>Reference Point (no.)</th>
<th>Distance from Mid-box 0 (in.)</th>
<th>500 lbs</th>
<th>1000 lbs</th>
<th>1500 lbs</th>
</tr>
</thead>
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</tr>
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<td>6.25</td>
<td>7.25</td>
<td>8.25</td>
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<td>9</td>
<td>31</td>
<td>1.75</td>
<td>1.88</td>
<td>2.13</td>
</tr>
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<td>10</td>
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<td>1.50</td>
</tr>
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<td>11</td>
<td>38</td>
<td>0.74</td>
<td>0.80</td>
<td>0.89</td>
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<td>0.60</td>
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<td>13</td>
<td>43</td>
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<td>14</td>
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<td>0.00</td>
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Test No. 4

### Table A.16 Vertical Displacement of Bottom Layer Geogrid

<table>
<thead>
<tr>
<th>Reference Point (no.)</th>
<th>Distance from Mid-box 0 (in.)</th>
<th>500 lbs</th>
<th>1000 lbs</th>
<th>1500 lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>7.15</td>
<td>8.30</td>
<td>9.35</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6.70</td>
<td>7.90</td>
<td>9.10</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>6.40</td>
<td>7.50</td>
<td>8.50</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>6.11</td>
<td>7.03</td>
<td>7.65</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>5.33</td>
<td>6.36</td>
<td>6.70</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>4.70</td>
<td>5.02</td>
<td>5.28</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>3.85</td>
<td>4.02</td>
<td>4.35</td>
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<td>8</td>
<td>27</td>
<td>2.80</td>
<td>3.02</td>
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<td>9</td>
<td>31</td>
<td>1.70</td>
<td>1.80</td>
<td>1.90</td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>0.80</td>
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<td>11</td>
<td>38</td>
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</table>
Test No. 4

Table A.17 Locations of Bottom Layer Geogrid Reference Points

<table>
<thead>
<tr>
<th>Reference Point</th>
<th>Distance from Mid-box points (no.) (in.)</th>
<th>Dial Gauge Reading on application of load by Hydraulic Jack</th>
<th>First time</th>
<th>Second time</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Initial</td>
<td>Adjusted</td>
</tr>
<tr>
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<td>at Reading</td>
<td>at Reading</td>
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<td>0</td>
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<tr>
<td>1</td>
<td>9</td>
<td></td>
<td>1.529</td>
<td>1.638</td>
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<tr>
<td>2</td>
<td>7.5</td>
<td></td>
<td>1.523</td>
<td>1.680</td>
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<td>1.450</td>
<td>1.797</td>
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<tr>
<td>4</td>
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<td>1.600</td>
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<td>1.730</td>
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<td>1.775</td>
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<td>7</td>
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<td>1.400</td>
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<td>8</td>
<td>1.250</td>
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<td>1.172</td>
<td>1.400</td>
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Test No. 4

Table A.18 Bottom Layer Geogrid Strain

<table>
<thead>
<tr>
<th>Distance from Mid-box toward End (in.)</th>
<th>Average Strain between Measurements in Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lbs</td>
</tr>
<tr>
<td>0–9</td>
<td>1.911</td>
</tr>
<tr>
<td>9–16.5</td>
<td>1.747</td>
</tr>
<tr>
<td>16.5–25.5</td>
<td>1.600</td>
</tr>
<tr>
<td>25.5–34.5</td>
<td>1.456</td>
</tr>
<tr>
<td>34.5–64.5</td>
<td>0.650</td>
</tr>
<tr>
<td>64.5–94.5</td>
<td>0.237</td>
</tr>
<tr>
<td>94.5–144</td>
<td>0.000</td>
</tr>
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</table>
## Test No. 4

### Table A.19  Locations of Middle Layer Geogrid Reference Points

<table>
<thead>
<tr>
<th>Reference Point from Mid-box (no.)</th>
<th>Distance between Initial Points (in.)</th>
<th>Dial Caliper Reading in inches on application of load by Hydraulic Jack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lbs</td>
<td>500 lbs</td>
</tr>
<tr>
<td></td>
<td>1000 lbs</td>
<td>1500 lbs</td>
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<tr>
<td>1</td>
<td>3.462</td>
<td>3.009</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2.778</td>
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<td></td>
<td></td>
<td>2.648</td>
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<tr>
<td>2</td>
<td>5.753</td>
<td>5.424</td>
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<td></td>
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</tr>
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<td>4.101</td>
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<td>4.067</td>
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<td>5.079</td>
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<td>5.023</td>
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<td>5.017</td>
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<td></td>
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<td>5.013</td>
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<td>6</td>
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<td></td>
<td>4.540</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>4.540</td>
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<tr>
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<td>4.322</td>
<td>4.322</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
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<td>4.322</td>
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</table>

---

### Table A.20  Middle Layer Geogrid Strain

<table>
<thead>
<tr>
<th>Distance from Mid-box toward End (in.)</th>
<th>Average Strain between Measurements in Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lbs 500 lbs 1000 lbs 1500 lbs</td>
</tr>
<tr>
<td>0-12</td>
<td>1.033 1.317 1.592 1.900</td>
</tr>
<tr>
<td>12-21</td>
<td>0.967 1.244 1.522 1.800</td>
</tr>
<tr>
<td>21-30</td>
<td>0.844 1.133 1.400 1.667</td>
</tr>
<tr>
<td>30-58</td>
<td>0.404 0.500 0.600 0.743</td>
</tr>
<tr>
<td>58-86</td>
<td>0.189 0.200 0.221 0.236</td>
</tr>
<tr>
<td>86-144</td>
<td>0.000 0.000 0.000 0.000</td>
</tr>
</tbody>
</table>
Test No. 4

Table A.21 Locations of Top Layer Geogrid Reference Points

<table>
<thead>
<tr>
<th>Reference Point from Mid-box Points (no.)</th>
<th>Distance between Initial Reading (in.)</th>
<th>Dial Caliper Reading on application of load by Hydraulic Jack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>1 12</td>
<td>3.499</td>
<td>3.244</td>
</tr>
<tr>
<td>2 12</td>
<td>3.800</td>
<td>3.808</td>
</tr>
<tr>
<td>3 12</td>
<td>2.534</td>
<td>2.482</td>
</tr>
<tr>
<td>4 25</td>
<td>2.759</td>
<td>2.737</td>
</tr>
<tr>
<td>5 30</td>
<td>2.553</td>
<td>2.550</td>
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<tr>
<td>6 37</td>
<td>3.120</td>
<td>3.120</td>
</tr>
<tr>
<td>7 37</td>
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<td>3.111</td>
</tr>
</tbody>
</table>

Test No. 4

Table A.22 Top Layer Geogrid Strain

<table>
<thead>
<tr>
<th>Distance from Mid-box toward End (in.)</th>
<th>Average Strain between Measurements in Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lbs</td>
</tr>
<tr>
<td>0-12</td>
<td>0.700</td>
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<tr>
<td>12-24</td>
<td>0.600</td>
</tr>
<tr>
<td>24-36</td>
<td>0.500</td>
</tr>
<tr>
<td>36-61</td>
<td>0.120</td>
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</tr>
<tr>
<td>91-144</td>
<td>0.000</td>
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</table>
APPENDIX B

TEST RUN CURVES

On the following pages test data has been presented in terms of vertical displacement as a function of location (Figures B.1 through B.4) and strain in the geosynthetic as a function of location (Figures B.5 through B.11).
FIGURE B.1 DEFORMATION CURVES FOR A SINGLE LAYER SYSTEM (SIGNODE TNX-5001)

Vert Displacement

1. X & Y axes show distances in inches.
2. A=Fill+0#; B=Fill+500#; C=Fill+1000#; D=Fill+1500#.
FIGURE B.2 DEFORMATION CURVES FOR A DOUBLE LAYER SYSTEM (SIGNODE TNX-5001)

Fill @ 4'       3'  ton Layer Geogrid

Vert. Displacement

1. X & Y axes show distances in inches.
2. A=Fill+0ft; B=Fill+500ft; C=Fill+1000ft; D=Fill+1500ft.
Figure B.3 Deformation curves for a double layer system (Tensar BX-1200)

Fill Surface  Bottom Layer Geogrid

Vert. Displacement

1. X & Y axes show distances in inches
2. A=Fill+0#; B=Fill+200#; C=Fill+400#;
   D=Fill+600#.
FIGURE B.4 DEFORMATION CURVES FOR △
TRIPLE LAYER SYSTEM (TENSAR Bx-1200)

Fill Surface    Bottom Layer Geogrid

Vert. Displacement

1. X & Y axes show distances in inches
2. A=Fll+0#; B=Fll+500#; C=Fll+1000#;
   D=Fll+1500#.
FIGURE B.5 GEOGRID STRAIN IN SINGLE LAYER SYSTEM (SIGNODE TNX-5001)

Strain in Percent

Dist. from Mid-box

1. X axis shows distances in inches.
2. A=Fill+0#; B=Fill+500#; C=Fill+1000#;
   D=Fill+1500#.
1. X-Axis shows distances in inches.
2. A=Fill+0; B=Fill+300; C=Fill+500; D=Fill+600; E=Fill+1000; F=Fill+1200; G=Fill+1500
FIGURE B.7 BOTTOM LAYER GEOGRID STRAIN IN DOUBLE LAYER SYSTEM (TENSAR EX-1200)

Strain in Percent

1. X-Axis shows distances in inches.
2. A=Fill+0 ft; B=Fill+200 ft; C=Fill+400 ft; D=Fill+600 ft.
FIGURE B.8 TOP LAYER GEOGRID STRAIN IN DOUBLE LAYER SYSTEM (TENSAR BX-1200)

1. X-Axis shows distances in inches.
2. A=Fill+0#; B=Fill+200#; C=Fill+400#;
   D=Fill+800#.
Strain in Percent

Dist. from Mid-box

1. X-Axis shows distances in inches.
2. A=Fill+0'; B=Fill+500'; C=Fill+1000'; 
   D=Fill+1500'.
FIGURE B.10 MIDDLE LAYER GEOGRID STRAIN
IN TRIPLE LAYER SYSTEM (BX-1200)

Strain in Percent

1. X-Axis shows distances in inches.
2. A=Fill+0#; B=Fill+500#; C=Fill+1000#;
   D=Fill+1500#.
FIGURE B.11 TOP LAYER GEOGRID STRAIN IN
TRIPLE LAYER SYSTEM (BX-1200)

Strain in Percent

1. X-Axis shows distances in inches.
2. A=Fill+0#; B=Fill+500#; C=Fill+1000#;
   D=Fill+1500#.
APPENDIX C

LISTS OF GEOSYNTHETIC PROPERTIES

AND

TESTING METHODS
<table>
<thead>
<tr>
<th>Property (from manufacturers)</th>
<th>Test Method</th>
<th>Units of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type and Construction Polymer</td>
<td>N/A</td>
<td>lbs</td>
</tr>
<tr>
<td>Weight</td>
<td>N/A</td>
<td>lbs</td>
</tr>
<tr>
<td>Thick (~)</td>
<td>ASTM proposed (FHWA Manual)</td>
<td>in.</td>
</tr>
<tr>
<td>Roll Length</td>
<td>N/A</td>
<td>ft</td>
</tr>
<tr>
<td>Roll Widths</td>
<td>N/A</td>
<td>ft</td>
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<tr>
<td>Specific Gravity &amp; Density Absorption</td>
<td>N/A</td>
<td>Ib/ft²</td>
</tr>
<tr>
<td>Surface Characteristics Geotextile Isotropy</td>
<td>N/A</td>
<td>percent</td>
</tr>
</tbody>
</table>

### II. Index Properties

#### Mechanical Strength

- **Uniaxial Loading**
  - a) Tensile Strength
    - 1) Grab Strength
      - ASTM D-4632
    - 2) Strip Tensile Strength
      - ASTM D-1882, Sections 18 and 20 using CPE of 12-inch/min
    - 3) Wide Width Strength
      - ASTM D-4595 (FHWA Manual)
  - b) Poisson’s Ratio
    - No Test
  - c) Stress-Strain Characteristics
    - ASTM D-4595 (FHWA Manual)
  - d) Dynamic Loading
    - NH
  - e) Creep Resistance
    - Modified Corps of Engineers EM 1110-2-1965 using Ottawa
  - f) Friction/Adhesion
    - No standard
  - g) Seam Strength
    - See II a) Tensile Strength above:
      - use 1, 2, or 3 depending on requirements
    - lb (grab) or lb/in (strip) as required
  - h) Tear Strength
    - ASTM D-4533

#### Mechanical Strength — Rupture Resistance

- a) Burst Strength
  - Mullen Burst—ASTM D-3786
  - Modified ASTM D-4833
- b) Puncture Resistance
  - Modified ASTM D-355
- c) Penetration Resistance (Dimensional Stability)
  - No standard
- d) Fabric Cutting Resistance
  - Modified ASTM D-1388—Option A using 2-in. x 12-in. sample
  - (FHWA Manual)
- e) Flexibility (Stiffness)
  - (Fed. Std. 191A, Method 5206)

#### Endurance Properties

- a) Abrasion Resistance
  - ASTM D-4886
- b) Ultraviolet (UV) Radiation Stability
  - No standard for geotextiles
- c) Chemical and Biological Resistance
  - No standard
- d) Wet and Cry Stability
  - No standard
- e) Temperature Stability
  - No standard

#### Hydraulic

- a) Opening Characteristics
  - 1) Aperture Opening Size (AOS)
    - ASTM D-4751 (FHWA Manual)
  - 2) Porosity (pore size distribution)
    - Use AOS for O₅, O₆, O₇, O₈, and O₉
  - 3) Percent Open Area (POA)
    - (FHWA Manual)
  - 4) Porosity (n)
    - No Standard
  - b) Permeability (k) and Permeability (η)
    - ASTM D-4491 (FHWA Manual)
  - c) Soil Retention Ability
    - Empirical Relations to Opening Characteristics
  - d) Clogging Resistance
    - No standard — See Soil-Fabric Tests
  - e) In-Plane R₂w Capacity (Transitivity)
    - ASTM D-4716

### TABLE C.1 (14)

**Table 2 Geomembrane Properties and testing methods for selection**

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Units of Measurement</th>
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<tbody>
<tr>
<td><strong>I. General Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer</td>
<td>From Manufacturer</td>
<td></td>
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<tr>
<td>Weight</td>
<td>ASTM D751</td>
<td>oz/yd²</td>
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<td>Thickness</td>
<td>ASTM D751</td>
<td>in. @ 20kPa</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>ASTM D792</td>
<td>lb/in</td>
</tr>
<tr>
<td>Surface Characteristics</td>
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<td></td>
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<tr>
<td><strong>II. Index Properties</strong></td>
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<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>1) Quality Control</td>
<td>Narrow Strip, ASTM D882</td>
<td></td>
</tr>
<tr>
<td>2) Design</td>
<td>Grab ASTM D751</td>
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</tr>
<tr>
<td>Tear Resistance</td>
<td>Wide Width Strip, ASTM D412</td>
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</tr>
<tr>
<td>Creep Resistance</td>
<td>Wide Width Strip, ASTM D1004</td>
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<tr>
<td>Puncture Strength</td>
<td>No Standard, ASTM D4833</td>
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</tr>
<tr>
<td>Seam Strength</td>
<td>ASTM D4545, ASTM D4437</td>
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</tr>
<tr>
<td>1) Factory</td>
<td>(standard practice)</td>
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<tr>
<td>2) Field</td>
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<td>% change</td>
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<td>2) Soil Burial</td>
<td>ASTM D3063, ASTM D1204</td>
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<td>Dimensional Stability</td>
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<td>Stress-Strain Characteristics—Wide Width Method</td>
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<tr>
<td>Friction/Adhesion</td>
<td>Direct Shear Method—Modified (see Koerner 1996)</td>
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<td>Large Scale Hydrostatic</td>
<td>ASTM Proposed</td>
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### Table C.3 [14]

**Criteria**

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<th>Property</th>
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<td><strong>Design Requirements</strong></td>
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<td>Mechanical Strength</td>
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<td>Tensile Strength</td>
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<td>Tensile Modulus</td>
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<td>Seam Strength</td>
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<td>Creep</td>
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<td>So-Fabric Friction</td>
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</tr>
<tr>
<td>Hydraulic</td>
<td>Filtration</td>
</tr>
<tr>
<td>Flow Capacity</td>
<td></td>
</tr>
<tr>
<td>Piercing Resistance</td>
<td></td>
</tr>
<tr>
<td>Clogging Resistance</td>
<td></td>
</tr>
</tbody>
</table>

**Construcatability Requirements**

<table>
<thead>
<tr>
<th>Property</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>Filtration</td>
</tr>
<tr>
<td>Seam Strength</td>
<td></td>
</tr>
<tr>
<td>Bursting Resistance</td>
<td></td>
</tr>
<tr>
<td>Puncture Resistance</td>
<td></td>
</tr>
<tr>
<td>Tear Resistance</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Longevity (Durability)</strong></th>
<th>Filtration</th>
<th>Drainage</th>
<th>Separation</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasion Resistance*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV Stability**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sc Compatability***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

* Compression Creep
** Erosion control applications where armor stone may move
*** Laced fabrics only
**** Where required

---

**Notes**

- Wide Width Strength
- Wide Width Modulus
- Wide Width
- Creep
- Friction Angle
- Permeability
- Transmissivity
- Apparent Opening Size (AOS)
- Porometry
- Gradient Ratio
- Grab Strength
- Grab Strength
- Mullen Burst
- Rod Puncture
- Trapezoidal Tear
- Reciprocating Block Abrasion
- Resistant Block Abrasion
- Chemical Resistance
- Biological Resistance
- Wet-Dry Resistance
- Freeze-Thaw

---
APPENDIX D

SIEVE ANALYSIS DATA AND GRAIN SIZE DISTRIBUTION CURVE OF FILL MATERIAL
TABLE D.1

PARTICLE-SIZE ANALYSIS OF SOIL

Total weight of sample = 287.75g

<table>
<thead>
<tr>
<th>Sieve No.</th>
<th>Opening (mm)</th>
<th>Weight (g)</th>
<th>Retained Weight (g)</th>
<th>Retained Soil (g)</th>
<th>Soil Percent Finer Retained (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.36</td>
<td>478.80</td>
<td>478.80</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>2.00</td>
<td>964.60</td>
<td>1029.40</td>
<td>64.80</td>
<td>22.50</td>
</tr>
<tr>
<td>16</td>
<td>1.18</td>
<td>653.10</td>
<td>685.60</td>
<td>32.50</td>
<td>11.30</td>
</tr>
<tr>
<td>30</td>
<td>0.60</td>
<td>606.70</td>
<td>636.50</td>
<td>29.80</td>
<td>10.40</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
<td>558.50</td>
<td>621.20</td>
<td>62.70</td>
<td>21.80</td>
</tr>
<tr>
<td>100</td>
<td>0.15</td>
<td>343.30</td>
<td>429.50</td>
<td>84.20</td>
<td>29.20</td>
</tr>
<tr>
<td>200</td>
<td>0.075</td>
<td>512.60</td>
<td>524.60</td>
<td>12.00</td>
<td>4.20</td>
</tr>
<tr>
<td>Pan</td>
<td></td>
<td>465.40</td>
<td>467.00</td>
<td>1.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Total = 287.60

Loss during sieve analysis = \( \frac{(287.75 - 287.60)/287.75 \times 100}{\%} \)

= 0.05\% (O.K. if less than 2%)
Figure D.1  Particle size distribution of experimental sand.
APPENDIX E

COMPUTER PROGRAM
FIGURE E.1 FLOW CHART

(After Kinney [34])
TABLE E.1  COMPUTER PROGRAM

1 REM COMPUTER PROGRAM TO SOLVE DESIGN EQUATIONS
10 INPUT "WIDTH OF VOID (FT.)"; W
20 INPUT "EMBEDMENT LENGTH (FT.)"; EL
30 INPUT "APPLIED PRESSURE (PSF)"; P
40 INPUT "SHEAR STRESS ON GEOTEXTILE (PSF)"; S
50 INPUT "EFFECTIVE SECANT MODULUS OF GEOTEXTILE (LBS/FT)"; E
60 INPUT "ULTIMATE TENSILE STRENGTH OF GEOTEXTILE (LBS/FT)"; TMAX
70 PRINT
80 REM START WITH R = W/2
90 R = W/2
100 T = P*R
110 IF T < TMAX THEN GOTO 140
120 PRINT "MAXIMUM TENSION EXCEEDED WITH R = W/2  T ="; T; "LB/FT"
130 GOTO 510
140 L = T/S
150 IF L < EL THEN GOTO 180
160 PRINT "INSUFFICIENT EMBEDMENT WITH R = W/2 - REQUIRED L ="; L; "FT"
170 GOTO 510
180 A = T*W/E + T*L/E
190 IF A < 3.1416*R - W THEN GOTO 240
200 PRINT "VERTICAL DISPLACEMENT > W/2 AND ENDS DO NOT SLIP"
210 D = A/2 + 0.2146*W
220 DX = 0
230 GOTO 420
240 REM EQUILIBRIUM R > W/2
250 R = R+0.01
260 T = P*R
270 IF T < TMAX GOTO 300
280 PRINT "MAXIMUM TENSION EXCEEDED WITH R > W/2"
290 GOTO 510
300 L = T/S
310 A = T*W/E + T*L/E
320 TH = 2*ATN(SQR(1/((2*R/W)^2 - 1)))
330 IF L >= EL THEN GOTO 370
340 IF A < TH*R - W THEN GOTO 250
350 DX = 0
360 GOTO 400
370 PRINT "R > W/2 AND ENDS SLIP"
371 L = EL
372 T = L*S
373 R = T/P
374 TH = 2*ATN(SQR(1/((2*R/W)^2 - 1)))
375 A = T*W/E + T*L/E
DX = (R*TH - W - A)/2
GOTO 410

400 PRINT "R > W/2 AND ENDS DO NOT SLIP"
410 D = R - R*COS(TH/2)
REM PRINT OUTPUT
430 PRINT "MAXIMUM TENSION (LBS/FT) ="; T
440 PRINT "FACTOR OF SAFETY WITH RESPECT TO TENSION ="; TMAX/T
450 PRINT "MAXIMUM STRAIN (%) ="; 100*T/E
460 PRINT "CENTERLINE DISPLACEMENT (IN.) ="; D*12
470 PRINT "RADIUS (FT.) ="; R
480 PRINT "FACTOR OF SAFETY WITH RESPECT TO SLIPPAGE ="; EL/(T/S)
490 PRINT "END SLIPPAGE (IN) ="; DX*12
500 PRINT "REQUIRED EMBEDMENT (FT) ="; L
510 END
APPENDIX F

MANUFACTURER'S TECHNICAL DATA
**PRODUCT**
TNX-5001 Geogrid

**POLYMER**
Polyester (Polyethylene Terephthalate)

**COLOR**
Black

**MECHANICAL PROPERTIES**

<table>
<thead>
<tr>
<th>Property</th>
<th>Machine Direction</th>
<th>Cross Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Width</td>
<td>6000 lbs/ft</td>
<td>2250 lbs/ft</td>
</tr>
<tr>
<td>Tensile Strength:</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>% Elongation At Break:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% Secant Modulus:</td>
<td>108,000 lbs/ft</td>
<td>40,800 lbs/ft</td>
</tr>
<tr>
<td>2% Secant Modulus:</td>
<td>156,000 lbs/ft</td>
<td>57,000 lbs/ft</td>
</tr>
</tbody>
</table>

Creep: Polyester inherently exhibits superior resistance to creep than many other polymers.

Soil Pullout: Preliminary results indicate pullout resistance exceeds the shear strength of the soil.

**ENVIRONMENTAL PROPERTIES**
Chemically stable - Unaffected by naturally occurring soil conditions
Stabilized against U.V. degradation
Remains elastic with no brittleness to -50 F
Biologically Inert

**AVAILABLE ROLL SIZE**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width:</td>
<td>5.9 ft</td>
</tr>
<tr>
<td>Length:</td>
<td>152 ft</td>
</tr>
<tr>
<td>Weight:</td>
<td>100 lbs</td>
</tr>
<tr>
<td>Area:</td>
<td>100 yds</td>
</tr>
</tbody>
</table>
FIGURE F.1

TYPICAL STRESS–STRAIN CURVE
SIGNODE TNX–5001 GEOGRID

MACHINE DIRECTION

CROSS DIRECTION

TENSILE STRENGTH (LBS/FT)

% ELONGATION

0 1 2 3 4 5 6 7 8 9 10

0 1000 2000 3000 4000 5000 6000 7000
The geogrid shall be a regular grid structure formed by biaxially drawing a continuous sheet of selected polypropylene material and shall have aperture geometry and rib and junction cross-section sufficient to permit significant mechanical interlock with the material being reinforced. The geogrid shall have high flexural rigidity and high tensile modulus in relation to the material being reinforced and shall also have high continuity of tensile strength through all ribs and junctions of the grid structure. The geogrid shall maintain its reinforcement and interlock capabilities under repeated cyclic loads while in service and shall also be resistant to ultraviolet degradation. To damage under normal construction practices and to all forms of biological or chemical degradation normally encountered in the material being reinforced.

The geogrid shall also conform in all respects to the property requirements listed below.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>TEST METHOD</th>
<th>UNITS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interlock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• aperture size:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• MD</td>
<td>I.D. Calipered²</td>
<td>in</td>
<td>1.0 (nom)</td>
</tr>
<tr>
<td>• CHD</td>
<td></td>
<td>in</td>
<td>1.3 (nom)</td>
</tr>
<tr>
<td>• open area</td>
<td>COE Method³</td>
<td></td>
<td>70 (min)</td>
</tr>
<tr>
<td>• thickness</td>
<td>ASTN D 1777-64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• ribs</td>
<td></td>
<td>in</td>
<td>0.05 (nom)</td>
</tr>
<tr>
<td>• junctions</td>
<td></td>
<td>in</td>
<td>0.16 (nom)</td>
</tr>
<tr>
<td>Reinforcement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• flexural rigidity</td>
<td>ASTN D1388-64⁴</td>
<td>mg-cm</td>
<td>750,000 (min)</td>
</tr>
<tr>
<td>• MD</td>
<td></td>
<td>mg-cm</td>
<td>1,000,000 (min)</td>
</tr>
<tr>
<td>• CHD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• tensile modulus</td>
<td>GRI GG1-87⁵</td>
<td>lb/ft</td>
<td>18,500 (min)</td>
</tr>
<tr>
<td>• MD</td>
<td></td>
<td>lb/ft</td>
<td>30,000 (min)</td>
</tr>
<tr>
<td>• CHD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• junction strength</td>
<td>GRI GG2-87⁶</td>
<td>lb/ft</td>
<td>1,050 (min)</td>
</tr>
<tr>
<td>• MD</td>
<td></td>
<td>lb/ft</td>
<td>1,890 (min)</td>
</tr>
<tr>
<td>• CHD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• junction efficiency</td>
<td>GRI GG2-87⁶</td>
<td></td>
<td>90 (min)</td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• polypropylene</td>
<td>ASTN D 4101</td>
<td></td>
<td>98 (min)</td>
</tr>
<tr>
<td>Group 1/Class 1/Grade 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• carbon black</td>
<td>ASTN 4218</td>
<td></td>
<td>0.5 (min)</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• roll length</td>
<td></td>
<td>ft</td>
<td>164</td>
</tr>
<tr>
<td>• roll width</td>
<td></td>
<td>ft</td>
<td>9.3 &amp; 13.1</td>
</tr>
<tr>
<td>• roll weight</td>
<td></td>
<td>lb</td>
<td>102 &amp; 135</td>
</tr>
</tbody>
</table>

Notes:
1. MD dimension is along roll length. CHD dimension is across roll width.
2. Maximum inside dimension in each principal direction measured by calipers.
4. ASTM D 1388-64 modified to account for wide specimen testing as described in Tensar Test method TMT-5.0 "Stiffness of Geosynthetics".
5. Secant modulus at 2% elongation measured by Geosynthetic Research Institute test method GG1-87 "Geogrid Tensile Strength". No offset allowances are made in calculating Secant modulus.
6. Geogrid junction strength and junction efficiency measured by Geosynthetic Research Institute test method GG2-87 "Geogrid Junction Strength".

Geosynthetic Research Institute

The Tensar Corporation
1219 Citizens Parkway
Morrow, GA 30260

Tensar Corporation
Shear Stress on single Layer System
(Signode TNX-5001)

\[ T = \gamma HT \tan \delta \]

Average passive value = 589 lbs/ft²

\[ \gamma \times 8.9' \times \frac{1/2(17)(22/12)^2}{3'} = 589 \text{ lbs/ft}^2 \]

\[ \gamma \text{ (shear stress) on bottom} = \gamma H \left( \frac{\tan \delta A_s + \tan \delta A_p}{A_T} \right) \]

Where

\[ \gamma \text{ (unit weight of sand)} = 117 \text{ pcf} \]

\[ H \text{ (depth of sand)} = 22 \text{ in.} \]

\[ \theta_s \text{ (angle of internal friction of sand)} = 30 \text{ (deg)} \]

\[ \delta_p \text{ (frictional angle of plastic)} = 1/2 \theta_s = 15 \text{ (deg)} \]

\[ A_T \text{ (total area)} = 6.00 \text{ ft}^2 \]

\[ A_s \text{ (area of sand)} = 3.50 \text{ ft}^2 \]

\[ A_p \text{ (area of plastic)} = 2.50 \text{ ft}^2 \]

\[ T \text{ (shear stress on bottom)} = (117)(22/12) \left( \frac{\tan(30)3.50 + \tan(15)2.50}{6.00} \right) = 96.2 \text{ psf} \]

\[ T \text{ on top} = \left( \frac{1/2 \gamma H^2 K \tan \delta_p}{2 \text{ feet wide} \times 2 \text{ sides}} \right) \]

\[ K_p = 1 - \sin \delta_p = 1 - \sin 30° = 0.5 \]

\[ K_p = 1/k = 1/0.33 = 3.0 \]

\[ K_\alpha = \frac{1 - \sin \delta_p}{1 + \sin \delta_p} = 1 - \sin 15° = 0.5 \]

\[ \delta_p = \text{frictional angle of polyethylene sheet (clear plastic sheet)} \]

\[ K_\alpha = \frac{1 - \sin \delta_p}{1 + \sin \delta_p} = 1 - \sin 15° = 0.5 \]

\[ \delta_p = \text{frictional angle of polyethylene sheet (clear plastic sheet)} \]

\[ = 26.3 \text{ lbs/ft}^2 \]

Total shear stress \( \leq 96.2 + 26.3 + 66.3 = 188.8 \text{ lbs/ft}^2 \)