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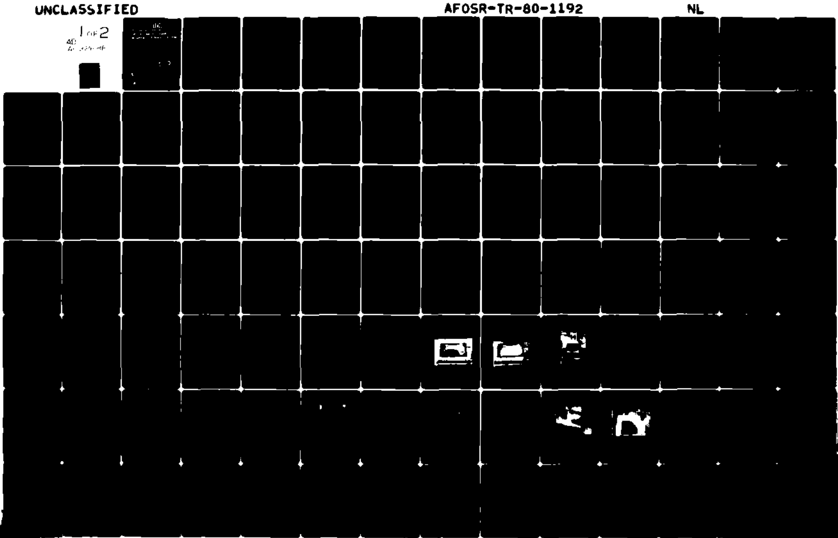

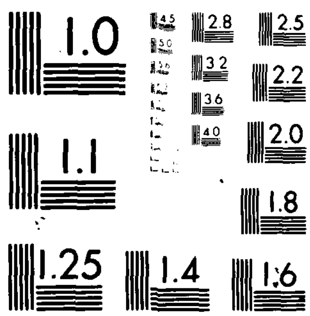

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T. ALLAN HALIBURTON
JACK D. LAWMASTER
JOHN K. KING

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School of Civil Engineering
Oklahoma State University
Stillwater, Oklahoma

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A state-of-the-art literature review and laboratory experimental study of the mechanisms of geotechnical fabric separation and lateral restraint reinforcement were performed. Fabrics of dissimilar physical properties were evaluated for use in lateral restraint reinforcement of a cohesionless soil mass. Though considerable increases in strength and load-deformation modulus were obtained for the fabric-reinforced soil systems, no significant difference in behavior was noted among the four fabrics tested, despite wide variations in their physical properties. Fabric prestressing had little

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effect on behavior. Lateral restraint reinforcement occurred as a result of fabric interference with development of zones of radial shear, underneath and adjacent to the loaded area. The effect is to produce horizontal restraint and confinement, which increases the applied soil stress necessary to develop plastic equilibrium and increases the initial deformation modulus and ultimate load capacity of the system. Lateral confinement induces initial elasto-plastic behavior of the reinforced mass which approximates the classic general shear failure conditions postulated by Terzaghi. An optimum depth of placement for fabric was determined which provides maximum deformation modulus and initial strength and minimizes soil yielding necessary to develop strain hardening effects. The optimum depth is related to the width of the loaded contact area and frictional properties of the reinforced soil.

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POTENTIAL USE OF GEOTECHNICAL FABRIC IN AIRFIELD RUNWAY DESIGN

By

T. Allan Haliburton

Jack D. Lawmaster

John K. King

Conducted Under
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Air Force Systems Command
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Bolling AFB, D.C.

by the

School of Civil Engineering
Oklahoma State University
Stillwater, Oklahoma
October, 1980

PREFACE

Research conducted by the School of Civil Engineering, Oklahoma State University (OSU), and described in this report consists of state-of-the-art interpreting review and basic research into fabric-reinforced soil behavior, with emphasis on establishing qualitative relationships. Funding for the research was obtained as a result of an unsolicited proposal to the U. S. Air Force Office of Scientific Research (AFOSR), Bolling AFB, Washington, D.C. This unsolicited proposal was generated as a direct result of information presented concerning U. S. Air Force (USAF) basic research needs in civil engineering, at a conference on the subject held at the USAF Academy, Colorado Springs, Colorado, in February, 1978. The conference was held under the leadership of Dr. Dan Brown, Intergovernmental Personnel Act (IPA) appointee on loan to the AFOSR, to help reinitiate a USAF basic research program in civil engineering. Proposal evaluation, contract negotiation, and initial contract management activities were conducted by Dr. John Lamb, who succeeded Dr. Brown as IPA appointee in charge of AFOSR basic civil engineering research. Final contract management effort was carried out by LT COL J. J. Allen, who assumed Dr. Lamb's duties.

Dr. T. Allan Haliburton, P.E., Professor of Civil Engineering, acted as principal investigator and was responsible for direction and supervision of the work. Technical assistance was provided by Mr. Jack D. Lawmaster and Mr. John K. King, Graduate Research Assistants. The report was written by Dr. Haliburton. Dr. James V. Parcher, P.E. was Professor and Head of the OSU School of Civil Engineering during conduct of the research,and Professor R. E. Chapel, P.E. was Director, OSU Office of Engineering Research.

ABSTRACT

Research conducted during the study consisted of compilation, interpretive review, and evaluation of available literature concerning applicability of geotechnical fabric for use in airfield runway systems, plus basic research experiments into the mechanisms of geotechnical fabric separation and lateral restraint reinforcement. As a result of the state-of-the-art literature review and experimental research, qualitative evaluations were made concerning potential use of geotechnical fabric in airfield runway design, and recommendations were developed for obtaining future qualitative design relationships.

Four different geotechnical fabrics of widely dissimilar physical properties were evaluated for performance in short-term material separation, to prevent intrusion of wet, soft, cohesive subgrade into cohesionless base material. All four fabrics were found to perform in an acceptable manner, with essentially no difference in behavior among the fabrics, despite their dissimilar physical properties.

Four different geotechnical fabrics were also evaluated for use in lateral restraint reinforcement of a cohesionless soil mass. Though considerable increases in strength and load-deformation modulus were obtained for the fabric-reinforced soil systems, no significant difference in behavior was noted among the four fabrics tested, despite variations of an order of magnitude or more in their physical properties. Fabric prestressing had essentially no effect on lateral restraint reinforcement behavior.

Lateral restraint reinforcement was determined to occur as a result of fabric interference with development of soil mass zones of radial shear, underneath and adjacent to the loaded area. The net effect of fabric interference is to produce horizontal restraint and confinement, increasing the applied soil stress necessary to develop plastic equilibrium in the zones of radial shear, and thus increasing the initial deformation modulus and ultimate load capacity of the fabric-reinforced soil. Lateral confinement also produces initial elasto-plastic behavior of the fabric-reinforced mass more closely approximating the classic general shear failure conditions postulated by Terzaghi.

After initial shear failure and soil yielding, loaded area sinkage

again brings the radial shear zones into contact with the fabric and reinitiates soil strength again. The secondary strength gain phenomenon caused by reinterference of the fabric with radial shear zone development was denoted as soil strain-hardening by the authors. Because interference with radial shear zones is the controlling phenomenon, presence of the fabric in the soil mass is the key to behavior and actual fabric properties are of secondary importance.

An optimum depth of placement for fabric was found to occur, which provides maximum deformation modulus and initial strength and minimizes soil yielding necessary to develop strain-hardening effects. The optimum depth is related to the width of the loaded contact area and frictional properties of the reinforced soil. If fabric is placed at a depth greater than optimum, initial load-deformation behavior is reduced to that of the unreinforced soil system and considerably more soil strain is required to develop the strain-hardening phenomenon.

Considerable potential was found for application of geotechnical fabric to improvement of performance in all types of runway systems, surfaced or unsurfaced and permanent or temporary. Findings will also have application in rapid bomb crater repair and in construction of roads to support airfield activities.

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CHAPTER 1. INTRODUCTION

RELEVANT BACKGROUND INFORMATION

The engineering design and construction of airfield launch and recovery (runway) structures has gone through several evolution periods. Initially, most runways were of an unsurfaced, and often unimproved, nature but would accommodate, under most conditions, a few relatively small and lightly loaded aircraft. In a few instances, permanent wearing surfaces were applied, using technology borrowed from highway engineers. Such surfaced runways were normally found at some military bases and at commercial airfields in large metropolitan areas. With the coming of World War II, military advantages of airpower provided the impetus for rapid development of runway design and construction techniques, both for permanent hard-surfaced runways, to launch and recover large, heavily loaded, multi-engine aircraft, and for expedient runways which could be built rapidly on less than desirable natural soils but still operate under heavy loading and adverse weather conditions.

After World War II, the resulting expansion of commercial aviation and the increase in size and weight of both military and civilian aircraft prompted additional research and development into methods of high-type runway construction, in addition to development of aircraft landing gear that would reduce the magnitude of applied ground pressure but increase the effective depth over which wheel pressures were dissipated. As more and more permanent airfields were constructed, long-term performance and maintenance cost of runways became more important, and these factors were also included in design and construction criteria. In addition to the technology developed during World War II, high-strength Portland cement concrete and multi-layer asphaltic concrete structural systems were developed, and various techniques of lime, Portland cement, and asphalt cement soil stabilization were employed to improve subbase and subgrade characteristics, reducing total cost and improving maintainability of the runway structure.

In recent years, attention has again turned to the concept of improved but unsurfaced or expedient-surfaced runways, capable of use by fairly large and/or heavily loaded aircraft. Reasons for such interest include the extension of commercial aviation to remote areas and military need for potential rapid establishment of airfields in remote and undeveloped parts of the world, as well as in development of alternate runway surfaces. Such alternate runways might allow launch and recovery of aircraft at an airfield whose main hard-surfaced runways were temporarily out of service, as a result of attack damage. Research and development in this area has investigated many concepts, including use of less-than-optimum construction materials, epoxy soil stabilization, fiberglass and resin membrane landing surfaces, and numerous variants of the steel planking used for expedient surfacing of World War II airfields.

STATEMENT OF GENERAL PROBLEM

When considering runway design, engineers have had to resolve, many times with only partial success, two problems and/or limitations:

a. Natural soil materials, even those with the highest density and greatest load capacity, have essentially no tensile strength. Further, Portland and asphaltic cement concrete have only minimal tensile strength, which is normally neglected in design. Thus, use of these admixtures, as well as lime, in soil stabilization does not provide a designable soil tensile strength.

b. Essentially all "layered" theories of airfield pavement design assume that the respective layers will remain "as placed" over existing natural soil subgrade. However, when the subgrade is cohesive and reaches moisture contents at or above its plastic limit, intrusion of low strength cohesive subgrade into stronger overlying granular subbase or base causes a net reduction in the effective thickness of the pavement system, and progressive failure may be initiated.

GEOTECHNICAL FABRIC

Geotechnical fabric is a generic term applied to a wide variety of artificial fiber textile products used in engineered construction of civil works. Other names used for geotechnical fabric include geofabric, filter cloth, geotextile, and civil engineering fabric. Approximately 50 different geotechnical fabrics are commercially available in the United States, in both woven and nonwoven styles and in weights from less than 3 oz/sq yd to over 26 oz/sq yd. Many of these fabrics may be characterized by relatively light weight, moderate to high tensile strength, initial semi-elastic behavior, ability to undergo large amounts of elongation without rupture, permeability equivalent to that of a medium to fine sand, and high resistance to corrosion and bacterial action. Unless treated for resistance, almost all geotechnical fabrics will undergo deterioration after exposure to ultraviolet radiation (sunlight) for a 30- to 60-day period. Geotechnical fabrics are currently produced in 6-ft to 60-ft widths, and in lengths of up to several thousand feet on special order, by commercial weaving and/or bonding processes on standard or modified fabric looms. Approximate fabric costs range from less than $.30/sq yd to over $6.00/sq yd, with heavyweight fabrics normally being more expensive than lightweight fabrics and, for the same fabric weight, woven fabrics being more expensive than nonwoven fabrics.

In 1973, McGowan and Ovelton [1][1], determined that geotechnical fabrics had three basic operational functions: separation, filtration, and reinforcement. In 1974, Leflaive and Puig [2] defined a fourth function applicable to some fabrics, principally nonwoven materials having appreciable thickness, that of drainage in the plane of the fabric. In 1977, Steward et al. [3] defined a fifth function, lateral restraint of cohesionless soils, as a special category of the reinforcement concept applicable to low-volume roadways. Kinney and Barenberg [4], in 1978, further subdivided the reinforcement concept, in evaluation of fabric-reinforced unsurfaced roadways, to include the concept of membrane-type fabric support developed from wheelpath rutting.

POTENTIAL APPLICABILITY OF GEOTECHNICAL FABRIC

In recent years, geotechnical fabric has been used in both expedient and permanent roadway construction, primarily on very soft, wet, cohesive

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[1] References are listed, in order of first citation, at the end of the report.

subgrade, as a separation medium, to prevent contamination of granular base materials by underlying subgrade, and as a reinforcement material, to provide tensile stress-carrying ability to base material, increasing its ultimate strength and load-deformation modulus. Use of geotechnical fabric has, in many instances, allowed road construction and/or prolonged operation in situations where failure would undoubtedly have occurred without fabric.

While reasons for probable fabric behavior are known, no quantitative analysis or design procedures are currently available or widely accepted for selection and use of geotechnical fabric in roadway pavement structures. Most widely used road design procedures are semi-empirical in nature, quite often based on a combination of an arbitrary test of some sort and many years of actual construction experience. As no mathematically correct analytical basis exists for such design criteria, it is not easy to correctly consider effects of geotechnical fabric. Further, use of geotechnical fabric in airfield applications, for both hard-surfaced and unsurfaced runways, has been essentially minimal, thus even detailed observational data concerning success or failure in runway applications is unavailable. However, it would appear that benefits obtained from geotechnical fabric use in roadways would also accrue if such fabric was used in airfield pavement structures. The investigation of this potential applicability is described herein.

SCOPE OF RESEARCH

Use of geotechnical fabric in filtration, subdrainage, and erosion control is rather well known,and satisfactory design criteria and specifications for fabric selection and use to obtain desired performance are available [5, 6]; thus selection and use of geotechnical fabric in filtration, drainage, and erosion control is not within the scope of this study. Also, the use of geotechnical fabric in construction of asphaltic concrete overlays and permanent wearing surfaces is not discussed. Instead, attention will be given to defining the current state-of-the-art and the potential applicability of geotechnical fabric for use below the wearing surface of both permanent and temporary/expedient/alternate airfield runway systems. Basic experimental research into use of geotechnical fabric for material separation and soil reinforcement will also be described and evaluated.

CHAPTER 2. GEOTECHNICAL FABRIC USE IN ROADWAYS

Little definitive data, documented case histories, and design and/or performance criteria have been published concerning use of geotechnical fabric as a separation and/or reinforcement material in airfield pavement structures. However, experimental and analytical research and test section construction and evaluation using geotechnical fabric have been conducted, for use of fabric in construction of both low-volume unsurfaced roads and heavy-duty asphaltic concrete flexible pavements, and results of the work are available in literature. While these projects are not airfield pavement structures, nevertheless the material is relevant because it provides insight concerning the basic mechanisms by which fabric performs separation, confinement, and/or reinforcement, and this knowledge can be interpreted in light of its potential applicability to airfield pavement structure analysis, design, construction, and maintenance, as will be done in Chapter 3.

GENERAL BASIS FOR ROAD DESIGN PROCEDURES

Most rational methods of road design attempt to separate the applied vehicle wheel load from underlying soils not capable of withstanding the load without failure by some thickness of stronger material. As the load actually "felt" or sensed by the material underneath the wheel load decreases with depth below the road surface, as shown conceptually in Figure 2.1, general theories of flexible pavement design have concerned themselves with placing a wearing surface to resist traffic abrasion immediately underneath the wheel load and separating the load from existing natural soil (subgrade) by placement of a stronger material (base) between the wearing surface and the subgrade. In some instances, where an appreciable distance is needed between the subgrade and the wheel load, a material of lower quality than the base but stronger than the subgrade (subbase) is placed between the base and the subgrade. If a road is designed properly according to these concepts, the strength of the soil at any depth below the wheel load will be sufficient to carry the load without bearing failure or excessive deformation.

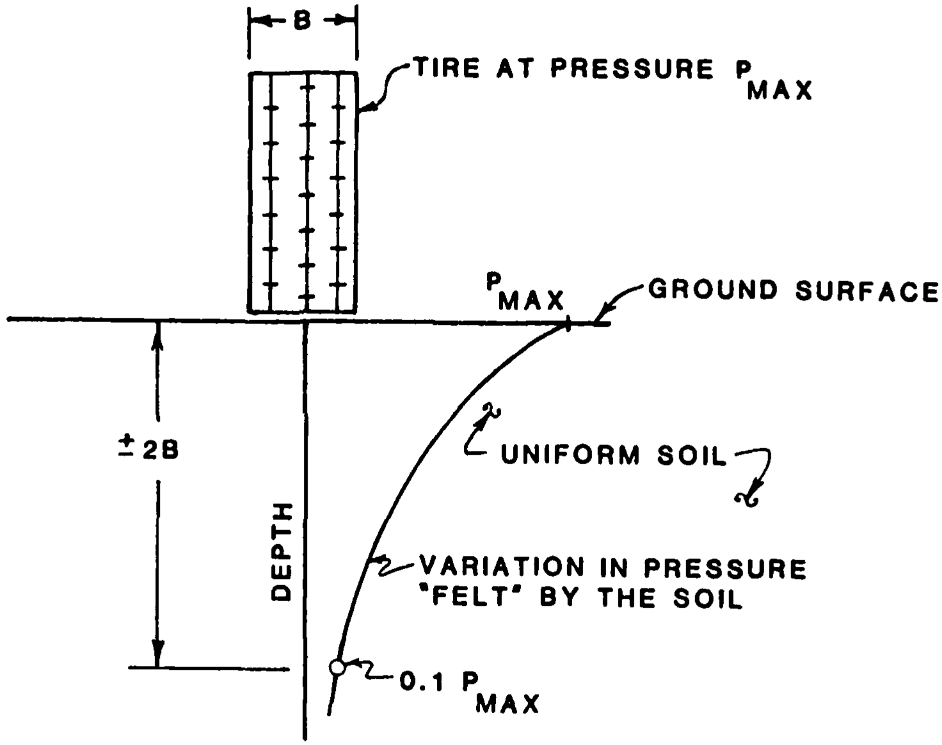


Figure 2.1 Concept of decreasing wheel load with depth in a uniform soil, used as the basis for almost all pavement design theories.

Unfortunately, the dissipation or decrease of wheel load pressure with depth may be predicted theoretically with some accuracy only for uniform soil conditions. In actual road construction, the stronger soil or base layer placed above the weaker soil or subgrade adds a "stiffening" effect to the pavement system, as it has a higher stress-strain modulus, when loaded in compression, than the underlying subgrade. The net effect of this stiffening is to reduce the level of stress "felt" or sensed by the underlying subgrade below that which would occur at a similar depth in a uniform soil. The amount of stress reduction is related to the ratio of the stress-strain modulus of the base material and the stress-strain modulus of the subgrade, often called the "modular ratio." As the modular ratio, or disparity in relative strength, of the two materials increases, the level of stress in the underlying subgrade is reduced, as shown conceptually in Figure 2.2. Despite the excellent work of Burmister [7] and others, it is still difficult to predict, theoretically or analytically, the amount of stress reduction which will actually occur for a given modular ratio. Instead, such data are usually obtained by laboratory or field experiments.

Existing road design methods may or may not consider the effect of modular ratio on stress distribution underneath an applied wheel load. Many methods neglect this effect, essentially assuming a pressure distribution based on completely uniform soil conditions, because the assumption is conservative.

CONCEPTS OF ROAD CONSTRUCTION ON SOFT FOUNDATION OR SUBGRADE

In recent years, geotechnical fabric has enjoyed wide use in construction of roadways, usually expedient haul/access roads, across relatively soft foundation soils (subgrades). Subgrade conditions often consist of relatively soft and wet cohesive soils, with water tables very near or at the ground surface. Geotechnical fabric has been used as an alternative to the corduroy/plank or willow mat support concept, and is placed directly on the soft subgrade, over any grass/weeds present. Large depressions are filled prior to fabric placement and tree stumps, logs, and other materials which would interfere with fairly level fabric placement may be either removed or covered by a working table. The

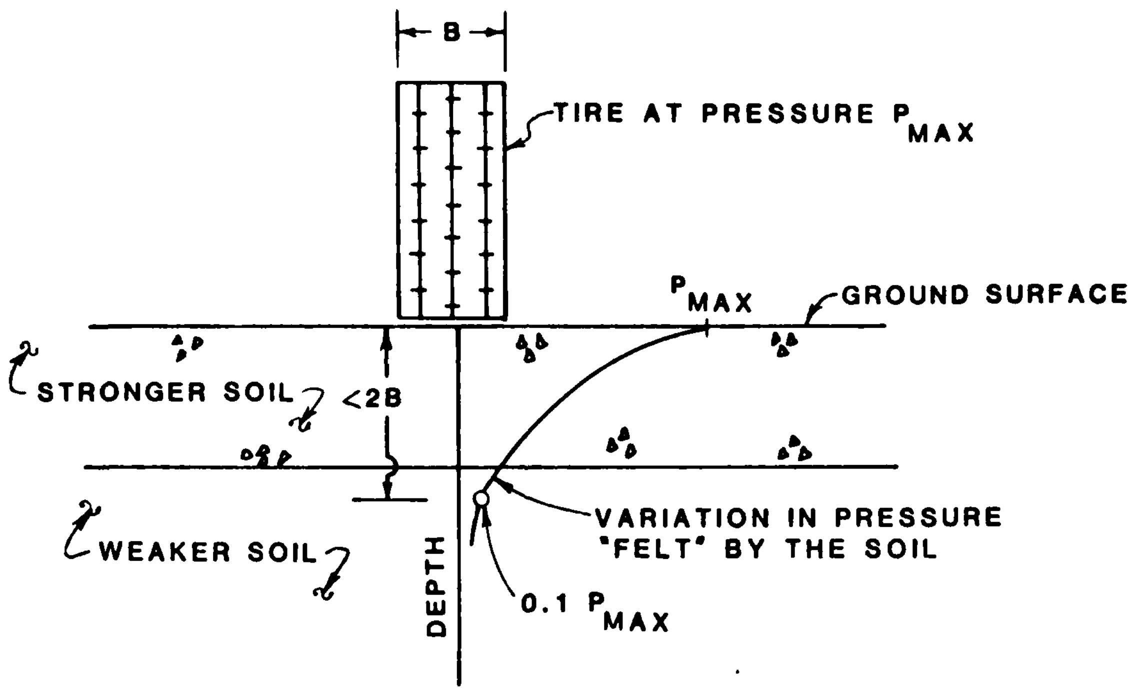


Figure 2.2 Effect of a strong base layer on wheel load distribution, reducing the wheel load pressure in weaker soil underneath a stronger base layer by modular ratio effects.

fabric is then covered with a locally available material having a better traffic support capability than the existing subgrade.

Various types of cover (base) material have been used, including crushed stone, sand, shell, clay-gravel, and other materials of a basically cohesionless nature. In some instances, multi-layer cover might be used to provide increased trafficability; for example: crushed shell over sand over fabric. In most situations only a single type of cover material is used. An asphaltic concrete wearing surface can also be applied to the cover material.

Geotechnical Fabric Separation of Subgrade and Cover Material

One advantage claimed for geotechnical fabric use is to provide physical separation of a soft cohesive subgrade, usually at or above its plastic limit, and essentially cohesionless cover material. The fabric may prevent intrusion of fines into the cohesionless material, which would markedly reduce its frictional strength, or may prevent penetration of the granular cover material into the plastic subgrade, as shown in Figure 2.3. Whichever phenomenon occurs, intrusion of the subgrade into the cover material or intrusion of the cover material into the subgrade, the net result is the same, i.e., reduction of effective cover material thickness and thus overstress of the lower portion of the roadway by wheel loads. Conventional design criteria for roads on soft subgrade will predict the total thickness of cover necessary between the wheel load and the subgrade. However, such criteria do not directly consider the effect of subgrade intrusion into cover material or vice versa. Thus, when road failure occurs, the cause may not have been an incorrect design, but that the original design was not maintained under traffic action.

Accepting this viewpoint, the primary function of geotechnical fabric in a separation mode is to insure that the roadway remains as originally designed during its service life, with the proper thickness of uncontaminated cohesionless cover material between the subgrade and the wheel load. Porous fabrics appear preferable to impermeable membranes for use in separation, as fabric porosity allows dissipation of excess pore pressures created in soft cohesive subgrades by wheel loads. An

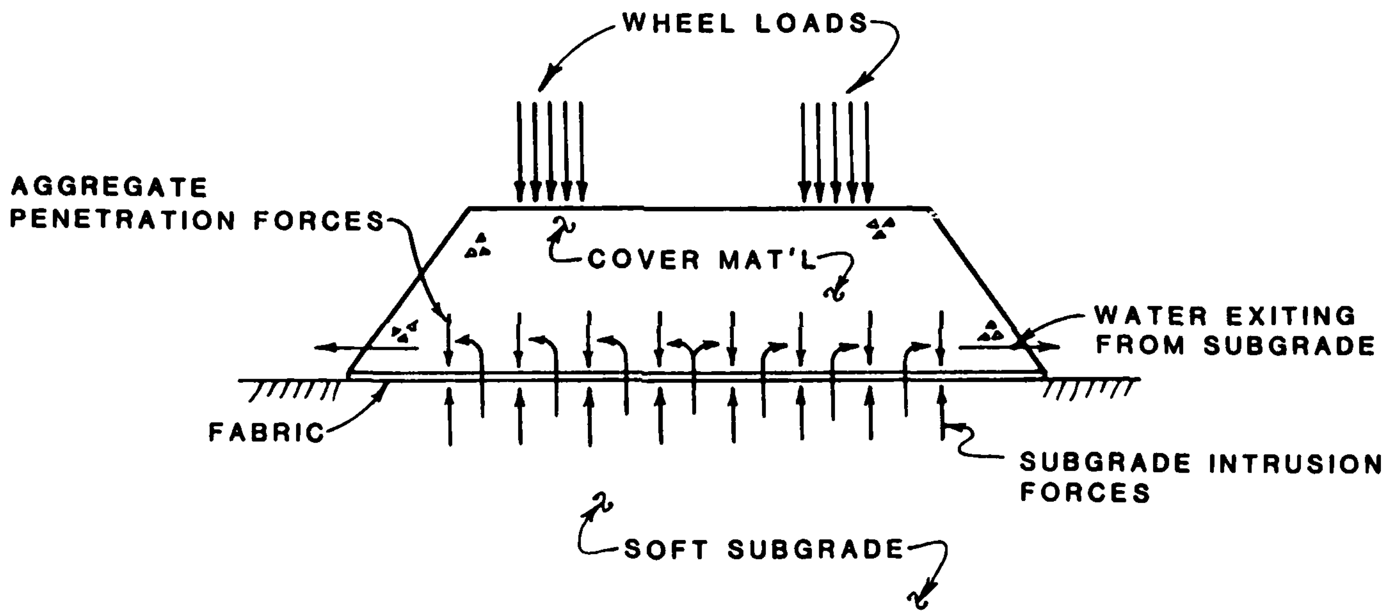


Figure 2.3 Concept of geotechnical fabric as a separation medium, preventing subgrade intrusion and deterioration of planned road design.

appropriate fabric porosity or permeability is one which would allow outflow of excess pore pressure while retaining fine soil particles. Also, the fabric must allow continued drainage during its service life and not become clogged by subgrade fines, else undesirable excess pore pressures may be created and cause a general loss of subgrade support strength. The ability of the fabric to perform adequately in a separation mode will thus depend upon its ability to allow dissipation of subgrade excess pore pressures while retaining subgrade fines, without clogging.

Geotechnical Fabric Restraint of Cohesionless Cover Material

It also has been claimed that placement of geotechnical fabric between a soft, plastic subgrade and cohesionless cover material will increase the total support capacity of the entire soil-fabric-subgrade system. Cohesionless cover materials derive their strength from frictional resistance and are confined under relatively low normal pressures in road situations. Wheel loads applied to the top of the cover material tend to cause tensile strains at the base of the cover layer. As cohesionless materials have essentially zero tensile strength, such strains tend to cause lateral spreading of the cover material. Presence of a geotechnical fabric layer, with tensile strength, at the base of the cover layer where tensile strains would be maximized, provides tensile stress-carrying ability not present in the cover material. Because of the relatively small confining stresses on the cover material, only a small amount of tensile force need be developed in the fabric to markedly reduce the tendency for lateral spreading of the cohesionless cover. Stress development may be similar to that shown in Figure 2.4. As an alternate to the lateral restraint concept, it has been postulated that the fabric interferes with the normal shear failure planes that would be developed in the base (cover) material. This concept will be discussed in subsequent sections.

In any case, the net result of lateral confinement at the base of the cover layer is to increase the deformation modulus of the cover material above the value expected without fabric. Increasing the deformation modulus of the cover material provides a twofold benefit to the system, by:

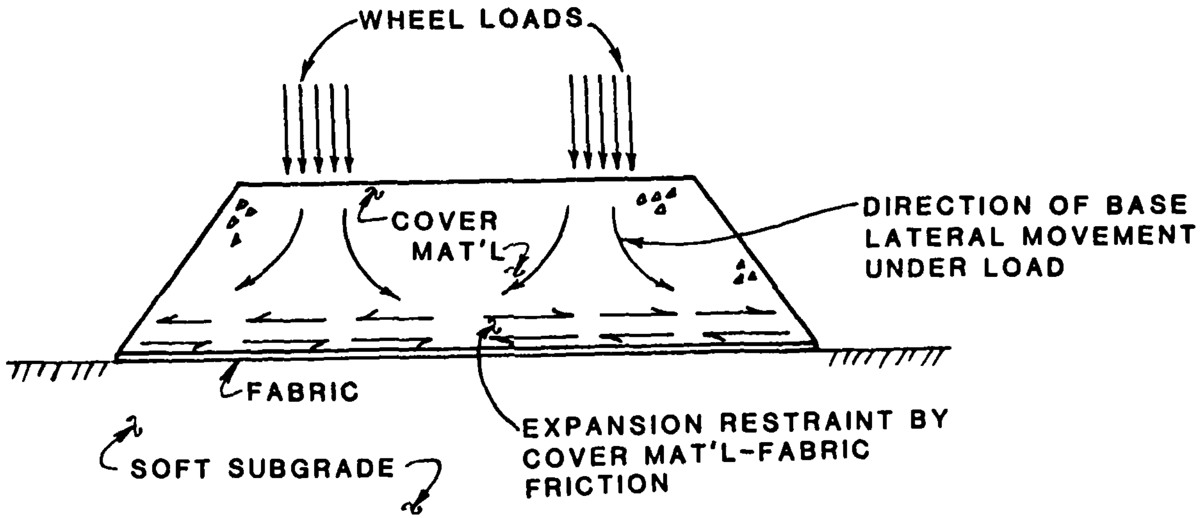


Figure 2.4 Concept of fabric lateral restraint from soil-fabric friction, providing increased deformation modulus to the material above the fabric.

a. Reducing cover material deformation under vehicle loading, thus inhibiting rut development, and

b. Increasing the difference between the modulus of the cover material and the modulus of the soft subgrade (greater modular ratio), which reduces the magnitude of wheel load stresses transmitted to the softer and lower modulus subgrade [7].

Use of geotechnical fabric to provide confinement and inhibit lateral spreading of cover material would thus result in a design which was somewhat stronger than the same design without fabric, assuming that, without fabric, the design would not be affected by subgrade intrusion. The inherent assumption in obtaining cover material lateral restraint is that tensile strains generated in the cover material by wheel loads will be transmitted to the underlying fabric. As no physical bonding exists between cover and fabric, the fabric can develop tensile stresses only from soil-fabric friction, obtained when the cover material attempts to strain laterally. Thus, slippage between cover material and fabric should be minimized, for it would reduce effectiveness in lateral confinement. Soil-fabric slippage should be minimized if the grain size of the cover material is compatible with the openings or equivalent pore sizes in the fabric, or, in the case of nonwoven fabrics, if the cover material can penetrate the fabric structure. Under optimum conditions, desirable soil-fabric frictional resistance should equal internal frictional resistance of the cover material. The ability of the fabric to provide satisfactory lateral restraint will thus depend upon the effective coefficient of friction between the cover material and the fabric.

Geotechnical Fabric Membrane-Type Support of Wheel Loads

Another mechanism by which geotechnical fabric is claimed to improve road behavior is through mobilization of fabric tensile strength in membrane-type action, to partially support applied wheel loadings. In this mode, shown in Figure 2.5, the applied wheel load causes localized deformation of the cover material and plastic subgrade. The fabric, being sandwiched between the two, must also be deformed. If the fabric is properly anchored against slippage around the boundary of the localized deformation zone, it must undergo tensile strain when being deformed.

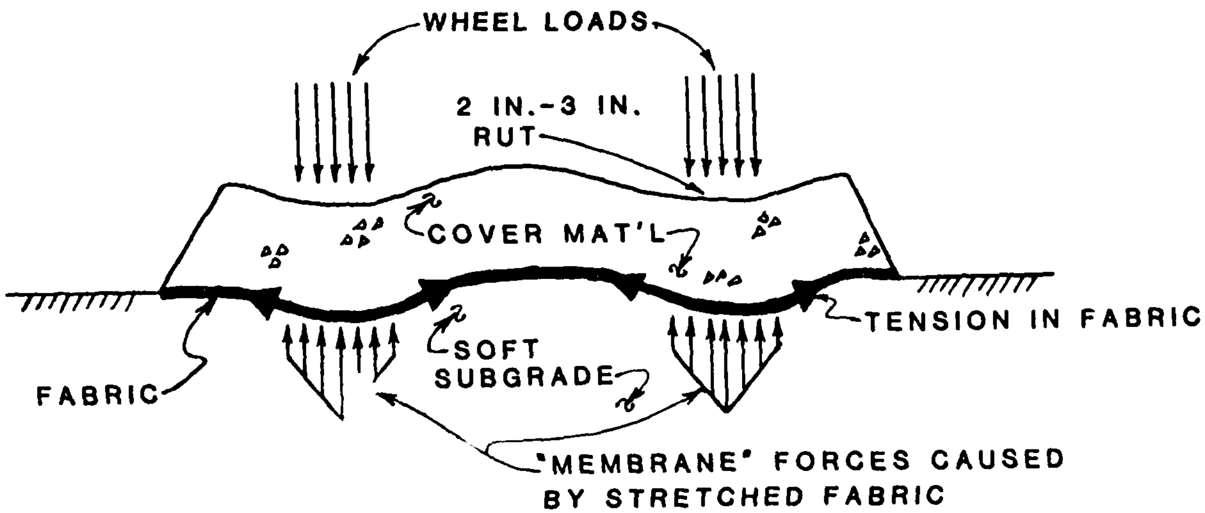


Figure 2.5 Concept of partial wheel load support developed by "membrane-type" action of fabric, after being stretched by wheelpath rutting.

The resulting tensile strain causes tensile stress to be developed in the fabric and, as the vertical component of membrane-type stress opposes the wheel load, the total load-carrying ability of the cover-fabric-subgrade system must be increased.

The amount of load support provided by fabric membrane-type action will depend (assuming that proper fabric anchorage through soil-fabric friction may be obtained around the boundary of the localized area) upon the tensile deformation modulus of the fabric and the amount of deformation produced by the wheel load. It is important to note, however, that this support cannot be developed to any degree without localized relative deformation, i.e., wheelpath rutting. Fabric support from membrane-type action would only be mobilized if the separation and lateral confinement mechanisms were not sufficient to prevent significant rutting. Once rutting occurs, despite fabric separation and lateral confinement, the cover material-fabric-subgrade system has begun to fail under local overstress. Without membrane-type fabric resistance, the failure would be progressive, as continued rutting serves to decrease the thickness of cover material between the wheel load and the cohesive subgrade and subgrade deformation in response to overload stress causes remolding and strength loss.

With developed membrane-type fabric resistance, satisfactory performance may be obtained, if the tensile stress developed in the fabric is sufficient to compensate for both:

a. The excessive wheel loads which caused rutting initiation, and
b. Any reduction in cover material and subgrade load capacity caused by rutting deformation.

Thus, rutting would progress to a certain depth and then stabilize. The depth of stable rutting would be related to the magnitude of applied wheel loads, cover material thickness and strength, and subgrade strength, but, also, almost directly to fabric tensile deformation modulus. This concept is illustrated by Figure 2.6, taken from Reference 4. Heavily loaded military trucks were used to apply dual wheel loadings to a crushed limestone base-fabric-wet plastic clay subgrade system. As noted in the Figure, the control (no fabric) section failed rapidly and a low-strength, low-deformation-modulus fabric (Bidim) failed shortly

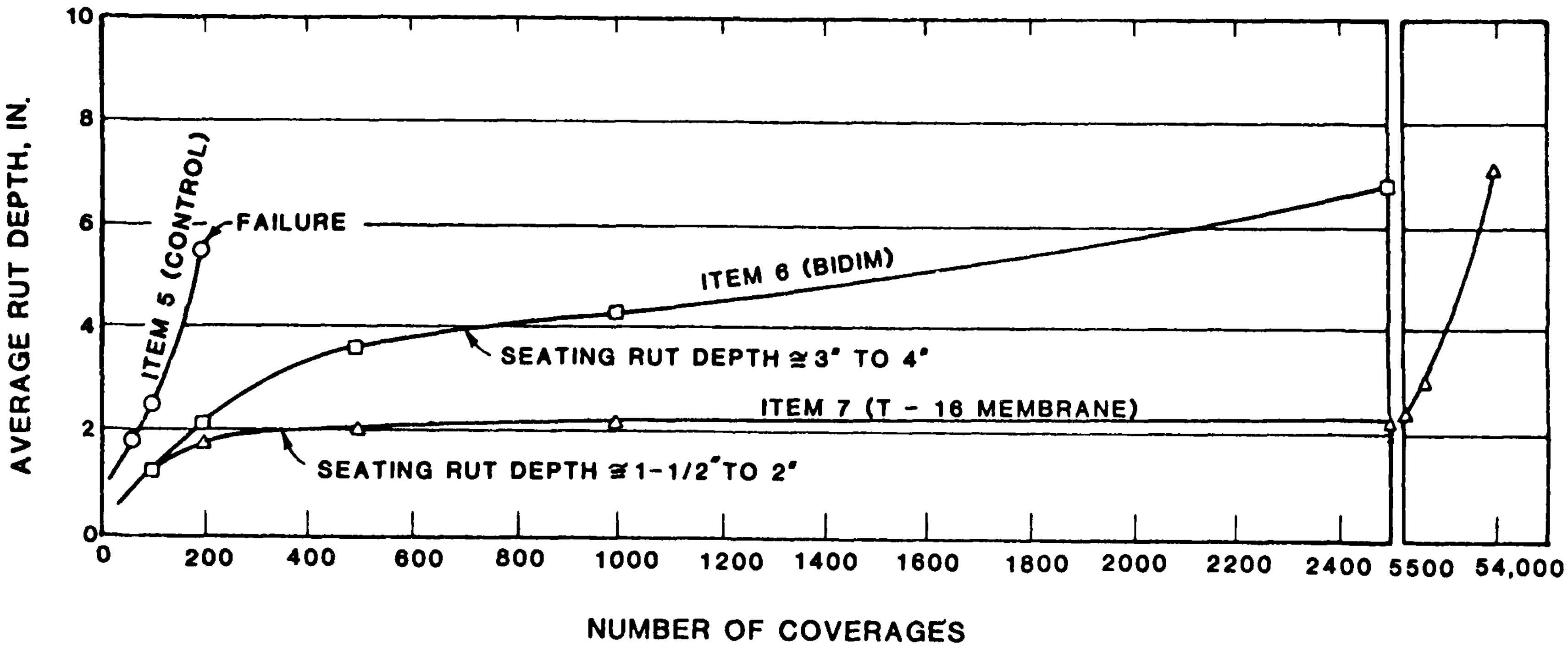


Figure 2.6 Effect of number of coverages on rut development in fabric-reinforced and control (no-fabric) road test sections, truck traffic and plastic clay subgrade (after Reference 4).

thereafter. However, a high-strength, high-deformation-modulus fabric (T-16 membrane) stabilized the rutting, and failed only after a large number of coverages.

Summary

From a conceptual viewpoint, geotechnical fabric may be used to improve performance of roadways on soft subgrade in at least three separate and distinct ways:

a. By separating cohesionless cover materials from soft plastic cohesive subgrades, preventing intrusion which effectively reduces the original design thickness of the cover material.
b. By providing lateral restraint, through soil-fabric friction, at the base of the cover material and thus reducing the tendency for lateral cover material spreading. This confinement increases the deformation modulus of the cover material and reduces the magnitude of wheel load stresses transmitted to the underlying subgrade.
c. By carrying a portion of the applied wheel load in membrane-type action, as a result of localized tensile strain induced in the fabric by cover material and subgrade deformation (rutting). The ability of fabric to provide adequate support, i.e., maintain a stable rut depth sufficient to allow traffic passage, will be directly related to fabric tensile deformation modulus.

DESIGN CONCEPTS AND CRITERIA CURRENTLY AVAILABLE FOR ROAD CONSTRUCTION WITH GEOTECHNICAL FABRIC

No widely accepted design procedures which consider use of geotechnical fabric are currently available. However, numerous attempts have been made to develop design criteria for unsurfaced roadways on soft subgrade, considering the effect of geotechnical fabric placed between the cover material and subgrade, and some criteria are available. Development of such criteria has been inhibited, to some degree, by a lack of understanding concerning the functions fabric might perform in a road system and also by the nature of current roadway design methods. As many of the same concepts are used in both roadway and runway design, the basic road design methods and their modifications to consider fabric should be discussed.

The California Bearing Ratio (CBR) Design Method

One of the most typical and widely used methods of flexible pavement road design (the wearing surface is assumed nonrigid and thus not to carry any appreciable portion of wheel loads through bending) is the California Bearing Ratio (CBR) Method. The CBR test was originally developed by the California Department of Transportation, for comparative evaluation of base materials in highway construction.

A standard well-graded crushed stone base material which had given satisfactory performance was compacted in a 6-in. ID-mold by standard effort and was subjected to punching shear failure by a 2-in.-OD piston moving at 0.05 in./min deformation rate. The punching shear resistance developed for the material was approximately 3000 lb at a deformation of 0.10 in. This value was taken as the CBR Standard Load and assigned a CBR value of 100. Other materials proposed for use as base material could be subjected to the same test and their support capacity related to the "standard" base material by relating the load developed during the test to the CBR Standard Load. Thus, a material with CBR of 80 would develop 80% of the punching shear resistance developed by the standard base material.

Empirical correlations for different CBR values, concerning thickness of base material needed between the wearing surface and the subbase/subgrade for different vehicular loadings, number of coverages, and wearing surface thicknesses, were developed by the California Department of Transportation. During World War II, the CBR Method was adopted by the U.S. Army Corps of Engineers for use in airfield design and the testing broadened include fine-grained cohesive subgrade soils. In-place field testing procedures for CBR determination were also developed. The CBR Method is classified as a "semi-empirical" or empirical plus a strength test method of pavement design, in that the CBR value is a relative number and field correlations rather than soil stress-strain theory are used to determine design requirements. The method thus suffers from having no theoretical basis, but benefits by the availability of an extremely large number of empirical correlations developed over the years. Further, pavement design by the CBR Method is fairly simple once empirical charts have been developed [8].

A typical CBR Method design chart is shown in Figure 2.7. To use the chart, one needs to know the CBR of the given support material, the axle load of the vehicle and, in some instances, the traffic volume anticipated. From these data one can determine the total thickness of cover required between the top of the soil layer for which the CBR is known and the wheel load. In a multi-layer (subgrade, subbase, base, wearing surface) system where the CBR for each component beneath the wearing surface is known, use of the chart for each material will indicate the necessary cover thickness over each layer. By simple arithmetic, the total cover thickness over the subgrade, subbase, and base can be calculated. These numbers are then adjusted to reflect rational lift or layer thicknesses that can be obtained in field construction and the design is complete.

Limitations of the CBR Method

Three CBR Method design assumptions serve to limit direct applicability of the design criteria to unsurfaced roads on soft subgrade:

a. Intrusion and/or mixing of adjacent soil layers with time and/or under traffic is assumed not to occur. Thus, the various soil layers maintain their original thickness and CBR value under extended traffic loading.

b. No direct relationship exists to consider the effect of wheel load stress dissipation by differences in deformation modulus (modular ratio) of strong and weak materials. The total thickness of cover material with a given CBR is that distance necessary to reduce stresses from applied wheel loads to a level the given soil can carry without excessive deformation. For single-cover-material roads without a wearing surface, no standard CBR criteria *per se* exist for the cover materials when necessary cover thickness is determined.

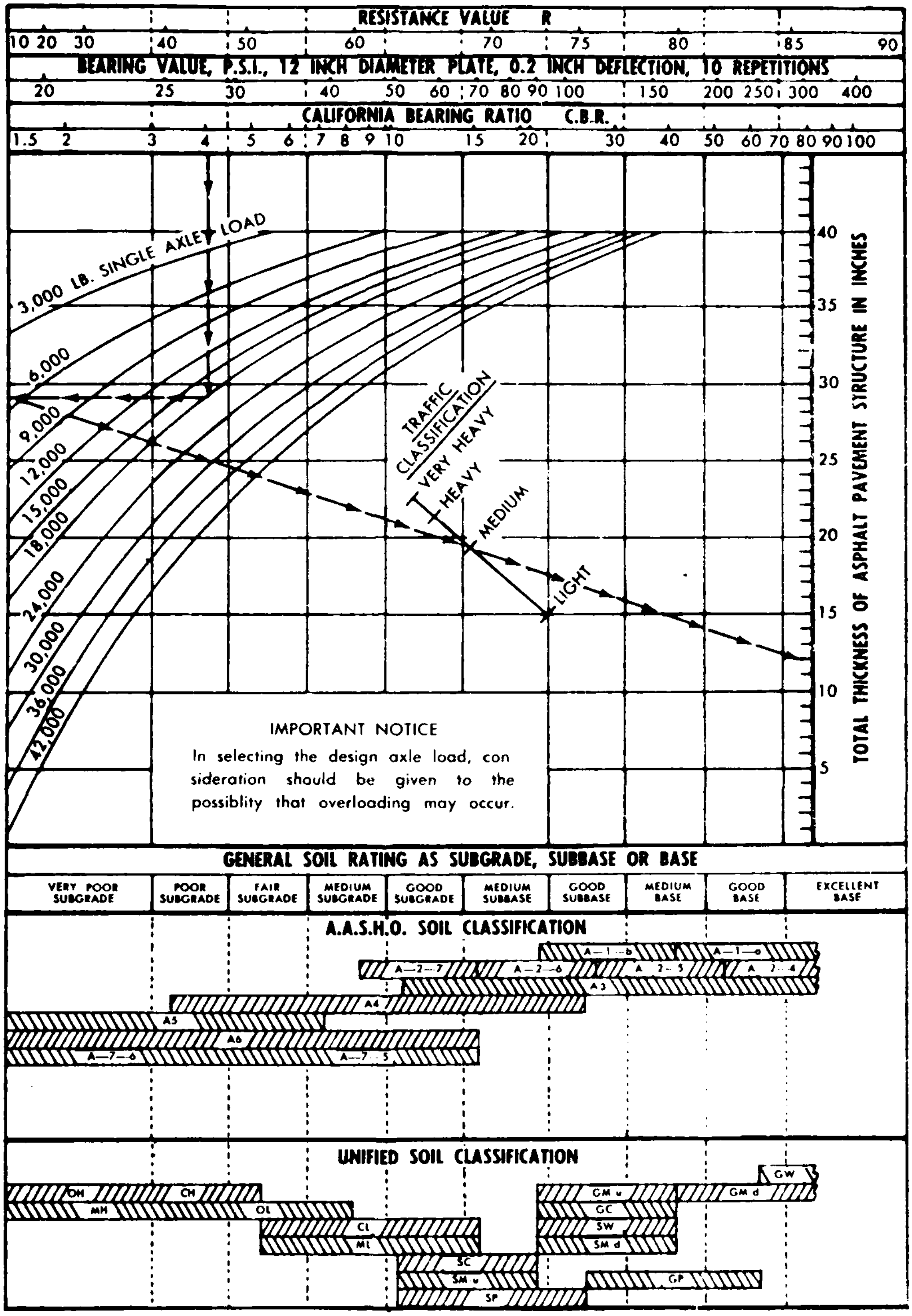


Figure 2.7 Typical California Bearing Ratio (CBR) design chart, from The Asphalt Handbook, The Asphalt Institute, College Park, Maryland.

c. The material used as a wearing surface is assumed to have sufficient abrasion resistance to resist vehicular tire motion and the ability to withstand wheel load application without localized material failure in the zone of wheel contact.

Assmuption a. is often violated in practice after construction on soft subgrades and, for unsurfaced roads where only one type of cover material is used, assumption c. is violated because there is no wearing surface, such as asphaltic cement concrete, applied to the cover material.

Modified CBR Design Method for Unsurfaced Roads

To apply the CBR design concept to unsurfaced roads and roadways on soft subgrade where normal CBR design assumptions [8] are not realized, a typical empirical correlation was developed by Hammitt [9] as:

$$t = 0.176 \log C + 0.120 \left(\frac{P}{8.1 \cdot CBR} - \frac{A}{\pi}\right)^{1/2} \qquad (2.1)$$

where

t = Design thickness, in.,

C = Anticipated number of coverages,

P = Single or equivalent single-wheel load, lb, and

A = Tire contact area, $in.^2$

Hammitt's equation considers the long-term deterioration of an unsurfaced road or airfield with continued use, from rutting caused by both subgrade intrusion/reduction of original design thickness and localized failure of the material immediately under wheel loads. A 3-in. rut depth was used as the failure criterion.

Modification of the CBR Method to Consider Geotechnical Fabric Behavior

Any attempts to incorporate effects of fabric behavior into a semi-empirical design method must, of themselves, be of an equally empirical nature. Also, the design method modifications must consider expected fabric performance. If the primary function of the fabric is to provide separation, then design by standard CBR methods should be conducted. The fabric would make no contribution to the overall system except to insure that original design assumptions were achieved under field conditions. Alternatively, if standard design practice by given agencies in construction of roads on soft subgrade required an additional thickness of cover material to compensate for expected subgrade intrusion, then placement of fabric for separation purposes would eliminate any need for the extra thickness, resulting in a net cost savings. However, such allowances for subgrade intrusion are related to local experience and thus any generalizations, other than on a local/regional basis, cannot be made.

Development of a general thickness road design criteria using the CBR or other currently existing semi-empirical method, and considering the improvement in road support capacity gained from either fabric cover material lateral restraint or membrane-type action, is possible only if an "equivalency ratio" can be assigned to the fabric.

For example, with the CBR Method a total thickness of cover is required over the natural soil subgrade, and thickness does not change with change in the CBR of material placed above the subgrade. Unless an "equivalency ratio" is used for the fabric, a reduction in total section thickness from fabric use is not possible. As an alternative, some fabric manufacturers have attempted to develop a CBR number for their fabric and add it to the CBR of the subgrade, designing as though the subgrade had the combined (higher) CBR. This procedure is technically incorrect for several reasons, one of which being that the material above the fabric is strengthened, not the subgrade. It is thus important that a proper equivalency be assigned and the conditions of testing used to establish any equivalency be consistent with behavior expected under field conditions. Similar problems will occur when attempting to modify existing airfield pavement structure thickness design methods to consider the effect of fabric inclusion on design thickness.

Road Design Criteria Considering Geotechnical Fabric Effects, Based on Subgrade Shear Strength

Barenberg et al. [10] developed road design criteria based on laboratory model studies using aggregate and fabric, for soft subgrades. They postulated that the allowable stress to which subgrade could be subjected without deep (2 in.) rutting was related to its ultimate bearing capacity, using the general Terzaghi relationship for saturated clay soils (ϕ = 0 deg):

$$q = cN_c \tag{2.2}$$

where

q = Contact pressure on the subgrades surface,

c = Undrained shear strength (cohesion) of the subgrade,

and

N_c = Terzaghi bearing capacity factor.

The values proposed by Terzaghi for bearing capacity factors are $N_c = 5.7$ for general shear failure (relatively small soil deformations prior to shear failure) and $N_c = 3.8$ for local shear failure (relatively large soil deformations prior to shear failure). In engineering practice, the value of $N_c = 5.7$ is used for medium to very stiff cohesive soils and the value of $N_c = 3.8$ used for softer cohesive soils.

Barenberg et al. found that N_c values of 3.3 and 6.0 were the subgrade stress levels at which deep (greater than 2 in.) rutting would occur with only a small number of load applications when no fabric and fabric, respectively, were used. Thus, for a given subgrade cohesion c, the subgrade can be stressed, with fabric present, to a value of approximately 6.0c without deep rutting but only to 3.3c without fabric. The marked similarity between the data developed by Barenberg et al. and the classic Terzaghi bearing capacity factors suggests that the fabric inhibits subgrade deformation, so that general shear failure rather than local shear failure is achieved in soft subgrades. Barenberg et al. conducted their tests with Mirafi 140 fabric, which when tested by two of the authors [11], was found to have a relatively low ultimate tensile strength and stress-strain modulus. It is thus probable that the fabric provided enough aggregate lateral restraint to minimize system deformation, and thus produce general rather than local shear failure. It is doubtful that the fabric was stressed significantly by the strains required to produce limiting 2-in.-deep ruts and thus, only a minimal contribution to load support capacity may have occurred from "membrane-type" action.

Design curves developed by Barenberg et al. are available [10] which have the same format as the CBR design curves of Reference 8.

Steward et al. [3] used the work of Barenberg et al. as the basis for development of U. S. Forest Service unsurfaced roadway on soft subgrade design criteria, modifying the recommendations slightly in the light of field experiments. In addition to the stress levels of 3.3c without fabric and 6.0c with fabric which Barenberg et al. postulated would cause considerable rutting under a small number of load applications, Steward et al. determined, based on their own experimental work, that very little (less than 2 in.) rutting would occur under a large number of load applications if stress levels in subgrade did not exceed 2.8c without fabric and 5.0c with fabric. They also postulated that surface roadway depressions at stress levels of 3.3c without fabric and 6.0c with fabric would be equal and that, if relatively poor quality (low CBR) cover material was used, it might be necessary to provide a higher quality surface course to prevent rutting of the poor cover material. Finally, Steward et al. indicated that fabric should not be used for "subgrade restraint" when the soil CBR was equal to or greater than 3. They defined subgrade restraint as ". . . the process or concept of preventing or reducing soil movement and soil strain by use of fabrics for confinement . . ." For soils with a CBR equal to or greater than 3, they postulated that the primary function of the fabric would be to act as a separation medium. The term "subgrade restraint" may be more related to membrane-type action, as the material above the fabric is normally the one restrained.

Analysis of the Steward et al. design criteria and field experiments indicates that they wished to develop a procedure for building roads where deep (greater then 2 in.) rutting could be avoided. Further, their experiments were carried out with a variety of nonwoven fabrics, none of which had appreciable tensile deformation modulus and/or ultimate tensile strength when compared to other commercially available fabrics [11]. Thus, it is unlikely that significant "membrane-type" stresses would have been mobilized in any fabric evaluated by Steward et al. prior to achieving a 2-in. rut depth "failure." Conversely, it is highly probable that all fabrics evaluated by Steward et al. were strong enough to provide cover material lateral restraint or interfere with system deformation. These assumptions are confirmed, in some measure, by the fact that their U. S. Forest Service design criteria does not directly incorporate fabric strength and/or deformation modulus.

Both Barenberg's and Steward's design criteria essentially allow for reduced base thickness compared to the no-fabric case, by allowing a higher design level of wheel load stress in the subgrade. Thus, less cover material is required to separate the wheel load from the subgrade and reduce subgrade stress by distance. The net effect of their procedure is to allow use of subgrade stress levels approximately 1.8 times larger than allowable without fabric. As the shear strength of the subgrade was unchanged, either the actual stress level in the subgrade was reduced by the increased modular ratio between cover and subgrade, or the ultimate strength of the cover material was increased by lateral confinement, or both.

Theoretical Analyses of Cover-Fabric-Subgrade Systems

As an alternative to the development of semi-empirical fabric behavior relationships by laboratory and/or field testing, mathematical analyses using multi-layered elastic system and finite-element modeling have been done, on a relatively limited basis. Limiting assumptions inherent in mathematical modelling of fabric include the necessity for assigning a deformation modulus, shear modulus, and Poisson's Ratio to the material. Sissions [12] attempted to analyze the effect of fabric inclusion in a soil-pavement system, and concluded that the fabric layer made no significant change in the calculated pavement structure stresses or strains. However, he modeled the fabric as direct tensile reinforcement in a system for which minimal rutting would occur under design wheel loads, and did not consider the effect of cover material restraint. Thompson [13] used the finite-element technique to theoretically examine the effect a fabric might have to reduce strains in base layers. Thompson assumed that the fabric would act as reinforcement to prevent tensile stress from developing at the bottom of a granular base layer, and he compared results based on this assumption with those involving a sharp local reduction in base layer deformation modulus. Results of his analysis showed a reduction in strain at the top of the subgrade (below the fabric) of between 24% and 34%, depending upon subgrade strength and thickness assumed for cohesionless cover material. Such a reduction in strain would correspond to an approximate threefold increase in deformation modulus ratio between the cover material and the subgrade.

While these analyses have been of a rather preliminary and hypothetical nature, nevertheless they indicate that modeling the fabric as direct reinforcement, in a manner similar to that used for tension steel in reinforced concrete beams, is not desirable. The computations indicate that, without rutting, the fabric undergoes, on an average basis, only a relatively small amount of strain and thus does not develop large tensile stresses. However, the work of Thompson is promising in that it could lead to a method of analytically predicting the effective increase in cover material modulus resulting from fabric lateral restraint, and thus allow use of multi-layer elastic theory or finite-element methods for predicting wheel load stress distribution with depth.

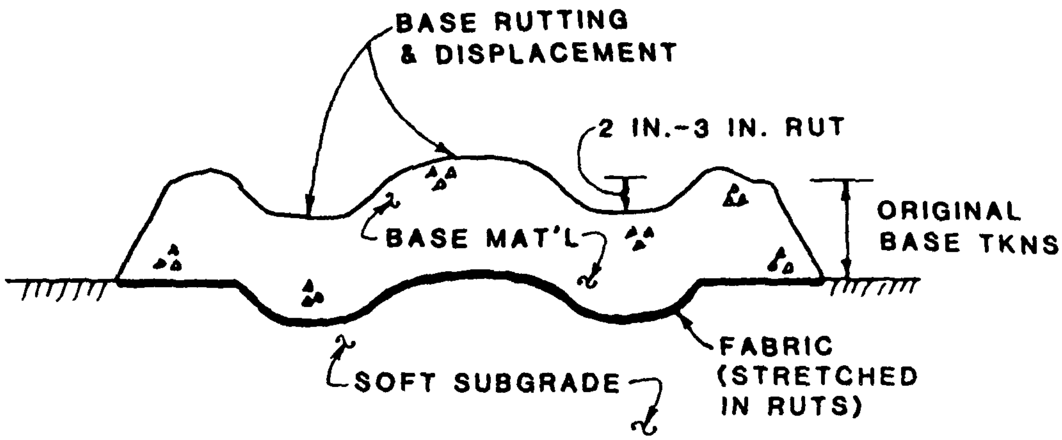
Unsurfaced Geotechnical Fabric Road Construction Procedures Which Allow Rutting to Occur

Alternative methods have been proposed for design of roads on soft subgrade which consider the effect of progressive rutting, and thus eventual mobilization of membrane-type stress in fabric. Webster and Alford [14] conducted experimental tests to determine the total number of coverages which could be applied to a cover material-fabric-soft subgrade system before excessive rutting (3-in., 6-in., and 11-in. rut depths) occurred. The philosophical concept involved appeared to be that a certain degree of rutting was allowable if vehicle mobility was unimpaired and either a thinner (and thus cheaper) section and/or larger number of coverages on the same section could be obtained by allowing deep rutting. Two fabrics were used, Bidim C-38, a nonwoven fabric with relatively low ultimate strength and deformation modulus, and U. S. Army Corps of Engineers specification T-16 membrane, a woven fabric with relatively high deformation modulus and ultimate strength.

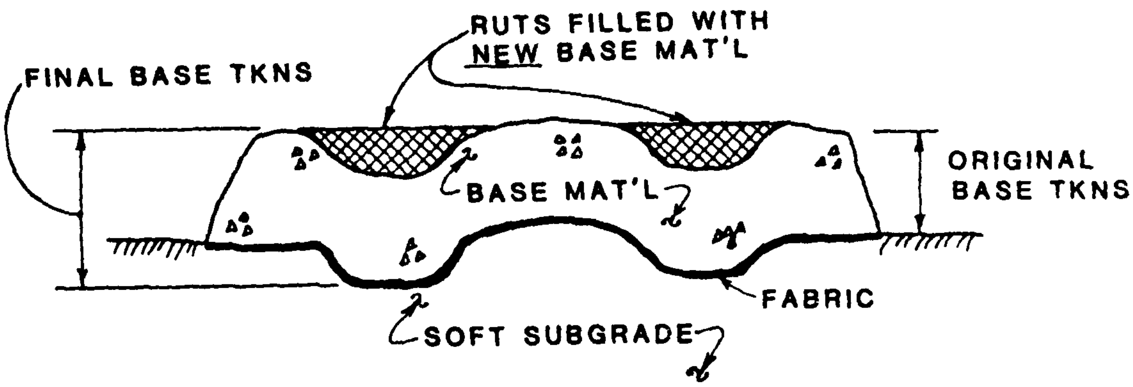
Though no specific design criteria were proposed from their testing, they found, as might be expected, once deep (greater than 2 in.) ruts were developed, rut depth deepening proceeded at a much slower rate with the T-16 woven membrane than with the nonwoven fabric and that a much larger number of load applications were required to cause 6-in.- and 11-in.-deep ruts with the stronger T-16 material, as shown previously in Figure 2.6. It may be tentatively concluded from Webster and Alford's work, that, once deep rutting is allowed, the rate at which rut deepening will occur and the total number of coverages necessary to cause rut deepening are related to the "membrane-type" support of the fabric and thus to its tensile deformation modulus and ultimate strength.

An alternative approach to the problem was used by Haliburton, Fowler, and Langan [15] in construction of fabric-reinforced haul roads in a dredged material disposal area. Subgrade conditions consisted of approximately 12 in. to 18 in. of CBR 1 material over 8 ft of CBR "0" ($<<1$) material. A high-strength, high-deformation-modulus woven fabric was placed over the CBR 1 material and covered with approximately 8 in. of sand and 2 in. of crushed shell, even though this design (according to available criteria) was inadequate to prevent rutting. Under the first day's traffic, rut depths of 2 in.-3 in. were produced. Additional shell was then used to fill the ruts and relevel the road surface. This scheme is shown conceptually in Figure 2.8. Subsequent haul traffic caused minimal rutting during the service life (4,000 + coverages) of the roads.

The design philosophy in this instance was to develop rutting and obtain some "membrane-type" support from the fabric and, once this support had been developed, to stop the tendency for continued rutting by placing additional cover thickness. By the described procedure, the high-deformation-modulus fabric was strained to produce significant "membrane-type" stresses, and long-term satisfactory performance was achieved by placement of high quality cover material only in the wheel paths. The



(a) Development of 2 in.-3 in. deep ruts under initial road traffic.



(b) Filling ruts with new base material provides an increased finial base thickness in wheel paths, and minimizes future rutting.

Figure 2.8 Concept of initial traffic rutting to generate fabric membrane-type support, followed by rut filling to assure long-term minimal rutting performance.

total amount of good cover material necessary over the fabric was thus reduced and more of the less expensive sand could be used as fabric cover. The cost of maintenance to fill the ruts was less than the cost of shell and/or sand necessary to provide a thicker initial cover over the fabric and thus prevent any rutting under wheel loads. In future practice, some of the required cover/base material could be withheld from initial placement and then used to fill the ruts, giving a greater effective cover thickness in the wheel paths at a lower cost.

When it is undesirable to produce rutting by initial trafficking of the roadway, prior "rutting" can be carried out by overcompaction of the cover material, followed by finish grading. The best technical procedure is to place the fabric, apply approximately 1/2-2/3 of the required cover or base material, and subject the cover material to pneumatic rolling, until either approximately twice the normal number of coverages have been made or 2 in.-3 in. deep rutting is produced by the pneumatic roller. The remaining cover material may then be placed and compacted in a normal manner. Use of this procedure will essentially "set the fabric" in place, such that "membrane-type" support should be developed with considerably less deformation of the road surface. This type of procedure should definitely be followed when some sort of permanent (asphaltic concrete) wearing surface will be placed on the fabric-reinforced roadway. If the surfacing is placed immediately, strains necessary to "set the fabric" and obtain lateral restraint and/or "membrane-type" support may allow lateral elongation of the road system, with longitudinal cracking and rutting of the permanent wearing surface.

When attempting to develop ruts and resulting "membrane-type" support, some problems may occur with inward slippage of fabric along the outer edges of the roadway, for if insufficient soil-fabric frictional drag exists at the outer edges of the roadway, the fabric will simply slip inward under rutting wheel load forces rather than elongate and develop "membrane-type" support. One alternative suggested to remedy this behavior is to construct the road some 3-4 ft wider than necessary. However, such a procedure requires additional cover material, and, as a practical matter, vehicles using the roadway may still move over to the actual finished road edge, thus nullifying the effects of widening. A rather simplistic and low-cost solution is to wrap the fabric around and attach it to a series of logs or timbers placed along the outer edges of the roadway, after installation of fabric but prior to placement of cover material. As indicated conceptually in Figure 2.9, wheel loads tend to cause outward lateral displacement of the cover material. This displacement is resisted by the fabric-anchored log or timber, providing additional "stiffening" of the cover material. Also, the tendency for the cover material to expand laterally under wheel loads, thus pushing against the timber or log, provides a stable anchorage for the fabric and prevents fabric slippage toward the center of the roadway, allowing the fabric to stretch and provide more "membrane-type" support. Similar behavior could be obtained by lapping the fabric back in toward the roadway, approximately 3 ft-4 ft, with a layer of cover material sandwiched between the two fabric layers. This alternative procedure might be possible if timbers or logs are not available and may be especially attractive if the cover material is to be placed and compacted in two lifts, such that lapping could occur after first-lift placement. A difficulty likely to be encountered with the lapping procedure is the need for handwork finishing along the edges of the roadway, to allow proper fabric fold-back into the road.

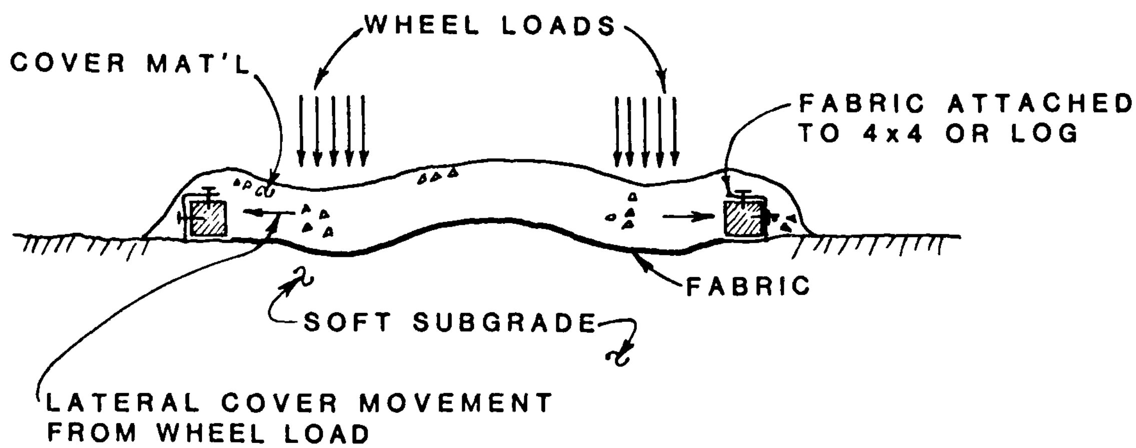


Figure 2.9 Concept of anchoring outside edges of fabric to prevent edge slipping from insufficient soil-fabric friction and/or wheelpath rutting.

CHAPTER 3. APPLICABILITY OF EXISTING INFORMATION TO AIRFIELD RUNWAY DESIGN

In Chapter 2, fabric behavior in road construction was divided into separation, cover material restraint, and membrane-type support. Airfield runways with permanent, expedient, or no hard-surfacing and designed as flexible systems are somewhat analogous to surfaced or unsurfaced roadways with one and sometimes two layers of cohesionless cover material (base and subbase) over soft cohesive subgrade. Thus, apparent benefits from use of fabric between soft subgrade and road structure may be scrutinized for potential applicability in airfield runway systems.

It should be noted however, that several basic differences exist between an airfield runway and the type of roads where geotechnical fabric has received wide use:

a. Most geotechnical fabric-reinforced roads are constructed on very soft, wet, cohesive subgrade. In many instances the runway alignment subgrade will be, at least initially, stronger even though still cohesive.

b. As opposed to new road construction to reach a difficult location, economical construction and long-term maintenance is the primary operational problem for hard-surfaced permanent runways and assurance of constructability and desired performance is the primary operational problem for unsurfaced runways.

c. Aircraft runway loadings are of larger magnitude than encountered in normal road situations, though the number of design load repetitions may be lower, especially for expedient and/or unsurfaced runways.

d. Load repetitions in roads are normally confined to well-defined wheel paths. However, in runway applications the loadings may be applied over any part of the runway structure.

Potential applicability of roadway concepts to runway design must consider these differences. Also, in most widely used roadway fabric applications, the fabric has been placed on soft subgrade to provide separation and any reinforcement benefits gained are secondary. In runway design, particularly for expedient/alternate unsurfaced runways, reinforcement to obtain optimum cover material strength may be the most important consideration, thus alternate fabric locations may be desirable.

MATERIAL SEPARATION TO STOP SUBGRADE INTRUSION

As with both unsurfaced and surfaced roadways, one problem associated with construction of permanent-type runway pavement structures, either hard-surfaced or unsurfaced, is that vertical subgrade intrusion into the base material, and vice versa, reduces the effective distance between wheel load and subgrade. Once subgrade intrusion is initiated, a progressive failure may result from subgrade-contaminated base overstress. The problem becomes evident when the wearing surface subsides locally or ruts and, in some instances, the cohesive subgrade is extruded through the base material to or through the wearing surface.

The conventional solution to such problems has, historically, been placement of a finer but still cohesionless subbase between base and soft subgrade. While satisfactory in many instances, in others the subbase served only to retard the rate of subgrade intrusion. In recent years lime modification of the upper 6 in.-12 in. or more of subgrade has been used prior to new construction, to reduce subgrade plasticity and thus intrusion tendency. However, not all cohesive subgrades, particularly those containing kaolinitic clays, respond satisfactorily to lime treatment.

Placement of geotechnical fabric between base and soft subgrade to provide long-term material separation can be a viable alternative to use of a subbase or upper subgrade lime modification in new runway construction. The fabric should function as a material separator in almost the same manner noted in road construction. A proper fabric would posses the long-term ability to separate base from soft subgrade materials. When placed on subgrades where complete subgrade saturation could occur, the fabric should also allow unhindered water flow from the subgrade (and thus allow dissipation of excess subgrade pore pressures) into the more permeable base, from which it may drain into collector pipes or other runway subdrainage for removal. This behavior is shown conceptually in Figure 3.1.

The fabric should not clog while performing its separation function,

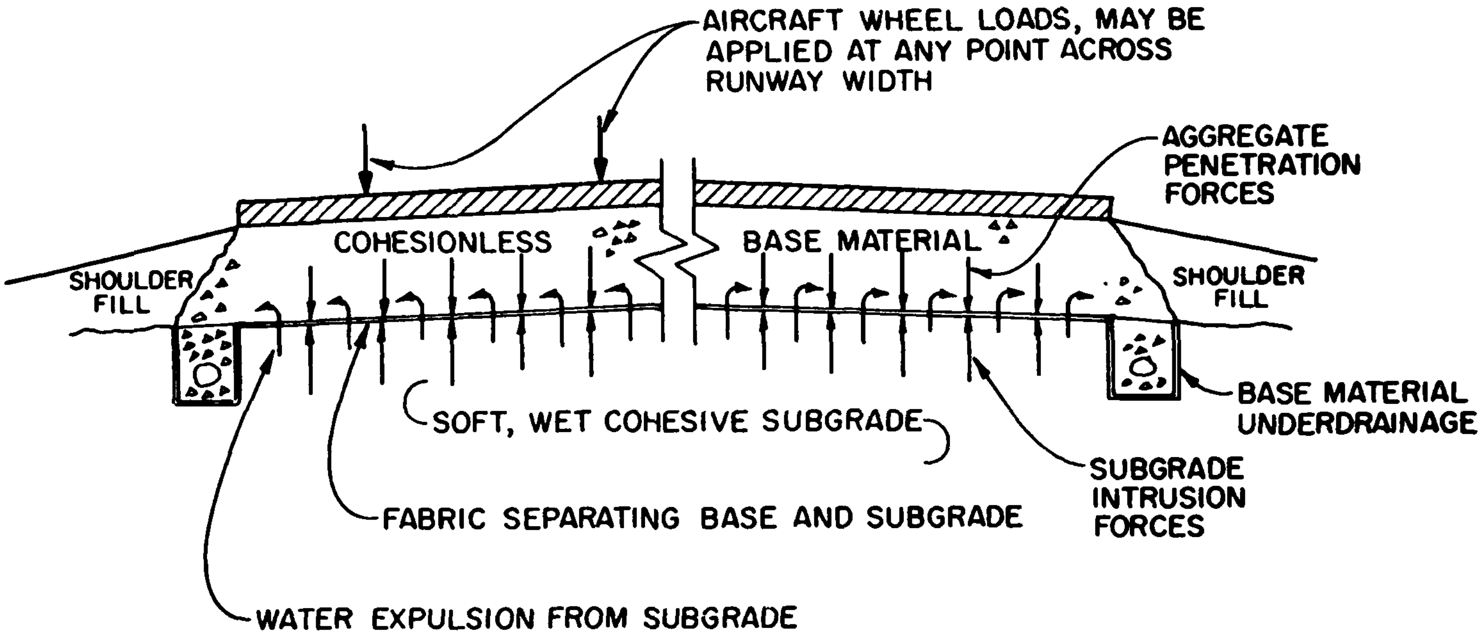


Figure 3.1 Conceptual Use of Geotechnical Fabric as Separation Medium for Airfield Runways

because excess pore pressures generated in the subgrade could not be quickly dissipated by upward flow through the fabric and might cause a severe reduction in subgrade strength. Further, dynamic loads produced by aircraft operation might force soil against and/or into the fabric, accelerating potential clogging behavior. Thus, clogging resistance becomes a very important fabric property, and subgrade retention is less important than clogging resistance, given a choice between the two. However, plastic subgrade is very unlikely to be extruded, in appreciable quantities, through a properly sized fabric. Finally, the fabric must have sufficient puncture and abrasion resistance to avoid localized rupture by sharp aggregate faces, when base material is initially placed and compacted and later, under aircraft load.

For expedient launch surfaces such as metal matting placed directly on clay subgrade, fabric should prevent subgrade remolding and extrusion through matting joints. The fabric must also have sufficient strength, puncture resistance, and abrasion resistance to resist rupture or tearing as a result of contact with the metal matting.

MATERIAL SEPARATION TO STOP SUBGRADE AND/OR SUBBASE PUMPING

In addition to subgrade intrusion, problems can also arise in airfield runway pavements with pumping of saturated low plasticity or nonplastic fines up into the base material and, in some instances, up through cracks and joints in the wearing surface for paved runways and matting of expedient runways. As opposed to plastic fines from subgrade intrusion, these fines are of low plasticity or nonplastic. Under dynamic live load conditions high excess pore pressures will be generated in such saturated fines and these pore pressures will be dissipated by pumping the fines upward as a soil-water slurry. These fines may coat the base material, reducing its frictional strength. Also, as pumping occurs voids are created in the subbase or subgrade, which are filled by settlement of overlying base material, causing subsidence or localized settlement of the wearing surface. When aircraft moving at high speeds pass over such localized depressions, the dynamic wheel loads are further magnified, causing additional pumping and more base and/or wearing surface subsidence. A progressive failure mechanism has now been initiated, with the phenomenon propagating from the initial point to adjacent runway areas.

Placement of geotechnical fabric as a separation medium between base material and a fine, low plasticity subbase or subgrade which would be susceptible to saturation and pumping, should stop progressive failures of this type. The fabric should pass water and allow dissipation of excess pore pressures generated in the saturated material. The ability of the fabric to resist clogging in this application is of critical importance. When excess pore pressures are created in nonplastic or low plasticity fines, dissipation of pore pressure by pumping is essentially nature's safety valve. If pore pressures cannot be dissipated and reach levels equivalent to existing soil effective pressure, a liquifaction-type failure, with abrupt immediate loss of soil strength, could occur. Retention of fines is of secondary importance, as the few nonplastic fines passing a properly sized fabric, necessary to allow formation of a "filter cake" beneath the fabric, should not be in pumpable quantity. As the fines being pumped are essentially nonplastic, pore pressure gradients would push the fine particles against, and perhaps into, any fabric used as a separation layer. Such behavior could place a greater stress on the fabric, in terms of potential clogging behavior, than that expected for plastic subgrade intrusion-type behavior.

BASE MATERIAL RESTRAINT

As discussed in Chapter 2, placement of geotechnical fabric between cohesionless base (cover) material in road construction and subgrade provides lateral displacement restraint (through soil-fabric friction and/or interference with normal base material deformation patterns) of the base material. A direct analogy appears to exist between the cohesionless base material of roadways and the cohesionless base used in airfield runways. If the base material is well-compacted, a relatively small amount of lateral strain should be sufficient to develop full friction at the soil-fabric interface, for soils that have some portion of their grain size approximating the pore size of the fabric. Laboratory test data [11] have shown that soil-fabric friction for cohesionless soils equals or exceeds the soil-soil friction angle for loose relative density conditions and is somewhat less than the soil-soil friction angle for dense relative density conditions. Some nonwoven fabrics do not have definable pore openings but may allow cohesionless soil particles to embed themselves, and thus provide good frictional resistance. The concept of runway lateral base restraint developed at the base-fabric interface is shown conceptually in Figure 3.2.

If good frictional resistance can be developed at the base material-fabric interface, the net effect of such restraint would be to increase the deformation modulus of the base, as well as its ultimate strength, resulting in less runway deformation under transient aircraft loads, and to reduce the magnitude of wheel load stress transmitted to subbase and/or subgrade. Stress reduction should reduce chances of subbase and/or subgrade failure from overstress and reduce pumping or extrusion tendencies in saturated materials. With simplifying assumptions the problem may be analyzed theoretically by the finite-element technique. Preliminary analyses [13] have indicated an increase in deformation modulus ratio between the base and subgrade on the order of three or more is possible. The optimum fabric for use in such situations should have enough strength, durability, puncture, and abrasion resistance that it would not be torn or worn by base aggregate particles, but would not be so hard and/or stiff that appreciable base material slippage would occur at the soil-fabric interface during wheel load application.

If proper base material restraint and resulting increase in strength and deformation modulus can be obtained, the concept should be applicable to both unsurfaced and hard-surfaced runways, including metal mat surfacing placed over crushed stone, sand, or similar cohesionless base material. Increasing base material stiffness and strength may either allow the use of reduced base thicknesses to achieve desired performance, or reduce total runway deformations and extend runway service life.

It should be noted that, in road applications, the fabric is usually placed on existing poor quality subgrade, to achieve separation, and improvement in cover material deformation modulus by lateral restaint is a secondary, though important, benefit. In runway applications, the ability to stiffen the upper portion of the runway structure may be of considerably more importance. Prevention of subgrade intrusion or

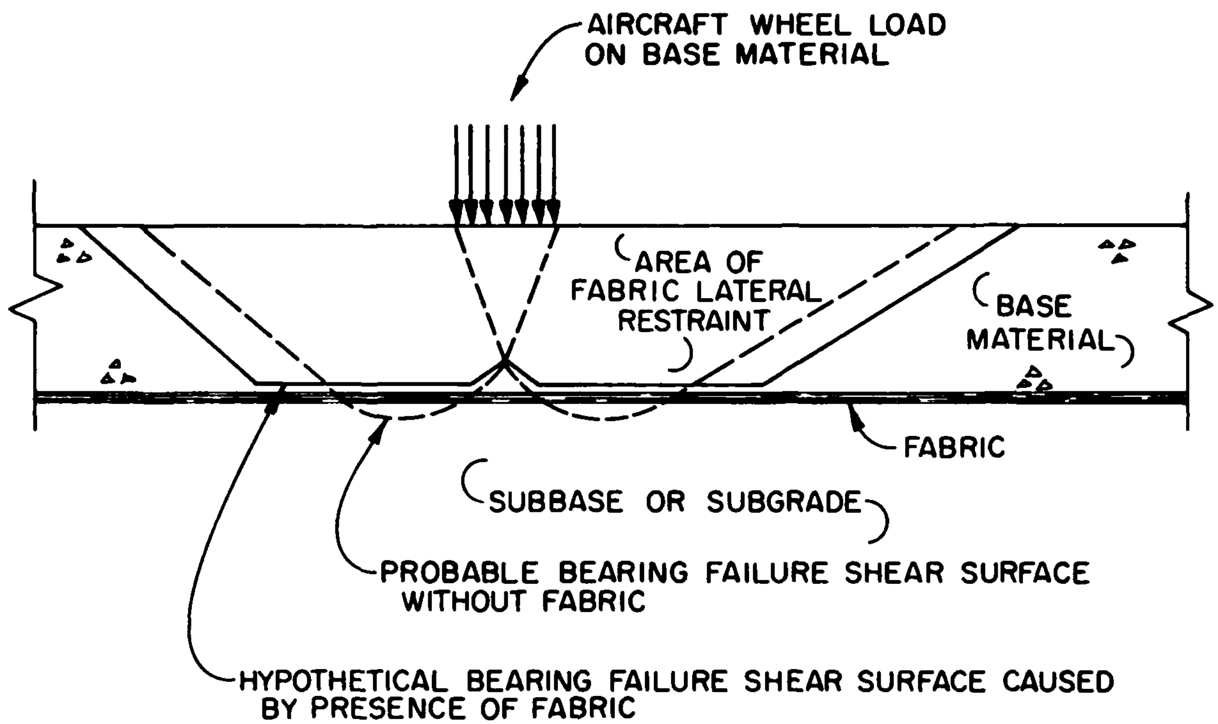


Figure 3.2 Conceptual Illustration of Base Material Lateral Restraint Caused by Geotechnical Fabric in Runway System

cohesionless fines pumping may be secondary or nonapplicable, especially in situations where a nonsaturated subgrade exists, or for alternate launch surfaces in which only a few load repetitions over a short time period are anticipated. Perhaps material separation should be considered a desirable long-term property, while improvement of cover material deformation modulus would be desirable for both long-term and short-term runway use.

Also, it should be noted that little, if any, research has been carried out to determine the optimum fabric location to maximize reinforcement behavior in an essentially cohesionless base/cover material. Obviously, if the fabric is placed too close to the surface, insufficient anchorage from weight of overlying material will cause fabric slippage and prevent full restraint from being developed. Conversely, if the fabric is placed too deep in the runway structure, wheel load overstress and failure, probably by wheel path rutting, will occur above the fabric and thus restraint potential of the fabric will, again, not be realized.

MEMBRANE-TYPE FABRIC SUPPORT

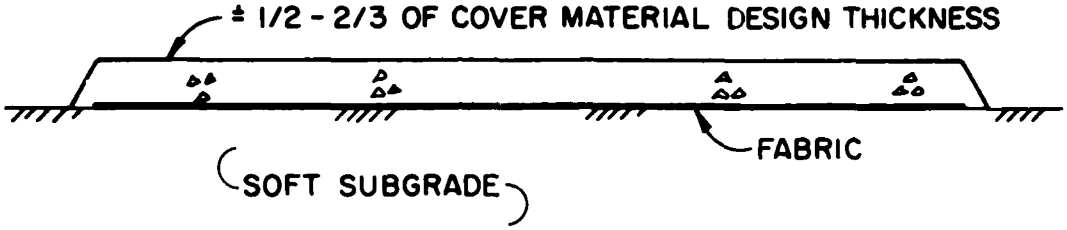
In Chapter 2, it was concluded that development of membrane-type support characteristics by geotechnical fabric in unsurfaced road construction on soft subgrade occurs only after wheelpath rutting is initiated by heavy traffic. Also, while not specifically verified, results of several investigations referenced in Chapter 2 indicate that rutting to at least 2-in.-3-in. depth is necessary before any appreciable localized strains (and thus tensile stresses) are developed in fabric beneath road wheel paths. Once such deep rutting occurs, the rate of rut depth growth and thus the total number of coverages possible for roadway failure appear almost directly related to the tensile deformation modulus and ultimate strength of the fabric. Evaluations by Kenney and Barenberg [4] indicated that once a "critical rut depth" was reached, strong woven fabric with high tensile deformation modulus reduced the rate of further rut deepening, but a relatively low strength, low deformation modulus nonwoven fabric had very little effect on rate of rut depth development.

Concepts of membrane support from rutting developed under operating loads, while applicable to low-volume expedient haul/excess roads, are not directly applicable to airfield runways. The "wheel path" for aircraft can vary from place to place across the entire width of the runway and, because of the relatively high speeds associated with aircraft operation, wheelpath rutting, to the depth of 2 in.-3 in. necessary to develop appreciable membrane support with some fabrics, appears undesirable. However, the "prior rutting" concept discussed in Chapter 2 might have considerable merit in providing increased deformation resistance to a runway system, especially when very heavy loads and/or relatively soft subgrade conditions exist. As shown conceptually in Figure 3.3, after the subgrade has been prepared, fabric is placed and approximately 1/2-2/3 of the cover material is spread on the fabric. This cover material is then overcompacted by pneumatic roller to produce rutting and, in the process, stretch the fabric. The remaining cover or base material is then applied and compacted in normal manner. A permanent wearing surface may or may not be applied. The stretched fabric and resulting fabric tensile stress will provide incipient membrane-type support upon application of wheel loads, and operational rutting of the finished (wearing) surface is unnecessary to produce the support.

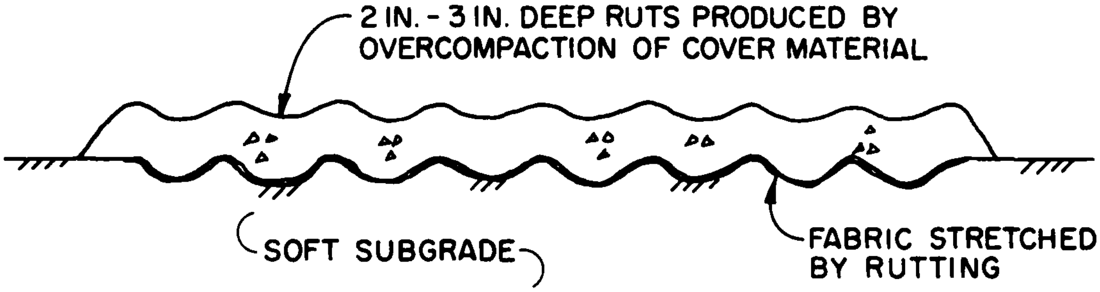
The procedure shown conceptually in Figure 3.3 is essentially a method of prestressing the fabric. Preliminary investigations with fabric prestress [16, 17] have shown that the concept has merit in providing increased deformation resistance at low strains, and the prestressing concept shown in the Figure appears to be more operationally practical than attempting to stretch long sheets of fabric spread horizontally on the subgrade and then provide anchorage by placing base material, prior to release of prestress force.

The concept of "prior rutting" is also applicable when a hard surface, such as asphaltic cement concrete paving or, for expedient runways, metal matting, is to be applied over a compacted base material. In both instances the total support capacity of the runway system would be increased, allowing a reduced thickness of base material and/or surfacing or greater loads and/or coverages without unsatisfactory performance.

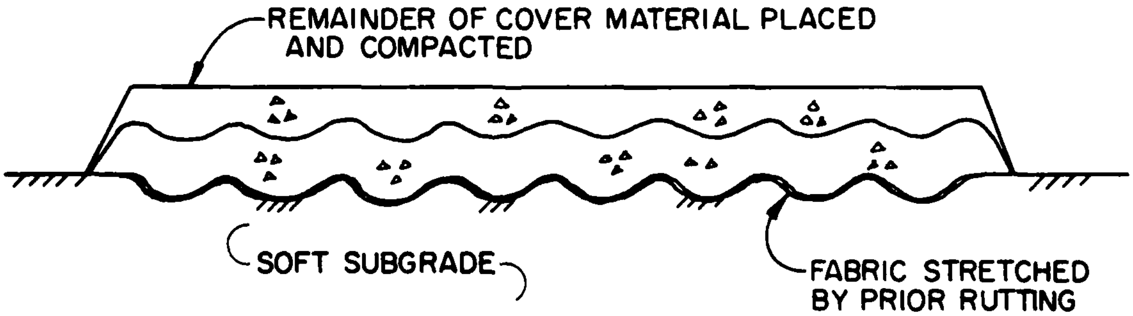
Primary fabric requirements for desirable membrane-type support include high tensile deformation modulus and high ultimate strength, as well



a. INITIALLY, FABRIC IS PLACED ON SOFT SUBGRADE AND COVERED WITH 1/2-2/3 OF DESIGNED COVER.



b. FABRIC IS STRAINED TO DEVELOP MEMBRANE TYPE ACTION BY OVERCOMPACTION.



c. REMAINDER OF COVER MATERIAL IS PLACED AND COMPACTED NORMALLY, TO COMPLETE THE PROJECT.

Figure 3.3 Conceptual Use of Prior Rutting Procedure to Develop Membrane-Type Support in Airfield Runways as fabric puncture and abrasion resistance, so that the fabric will not be damaged by the "overcompaction" necessary to strain the fabric after placement.

From a maximum reinforcement potential viewpoint, it might be desirable to locate the fabric in the runway pavement structure at the optimum depth to provide lateral base restraint and then subject it to prior rutting, to provide incipient membrane support. In this manner the maximum fabric contribution to base material (and thus runway) strength might be obtained.

SUMMARY

Based on the material presented in Chapter 2 concerning fabric behavior in roadways, and the assessments and evaluations presented in this Chapter concerning the differences between roadways and hard-surfaced, expedient surfaced, and unsurfaced airfield runway structures, it may be conceptually supposed that:

a. Geotechnical fabric has considerable potential for use as a separation medium, to prevent intrusion of wet cohesive subgrades into base and/or subbase courses of runway systems, preventing deterioration of the original design with time and number of coverages. Optimum location for fabric placement is directly on top of the cohesive material. This concept is applicable to all types of runways but should be more important for permanent or semi-permanent runways than alternate launch surfaces. Important fabric properties appear to be clogging resistance and soil retention ability, as well as puncture and abrasion resistance.

b. Geotechnical fabric has considerable potential for use as a separation medium to stop pumping of saturated nonplastic or low cohesion fines from the lower portions of a runway structure into the base material and, in some instances, through the surfacing, resulting in better performance and lower long-term maintenance cost. The concept is applicable to all types of runways but would be perhaps less important for alternate launch surfaces, where only a few coverages would be made during operating life of the runway. The optimum fabric location is immediately above the material which might be susceptible to pumping. Important fabric properties appear to be clogging resistance and soil retention ability, as well as puncture and abrasion resistance.

c. Use of geotechnical fabric to provide lateral restraint of cohesionless materials placed between the fabric and the wheel load appears directly applicable to runway pavement structures, either hard-surfaced, expedient surfaced, or unsurfaced. Primary benefits should accrue from increasing the deformation modulus and ultimate strength of the material above the fabric and in reducing the stress levels applied to underlying runway system components. Advantages include ability to sustain more coverages or heavier loads with a given runway design thickness (as opposed to the no-fabric case) and the potential for upgrading lower quality cohesionless construction materials to high-quality performance levels, through use of the additional "stiffening" created by fabric. While lateral restraint concepts appear important in normal hard-surfaced runway design, they may be extremely important in construction of expedient runways when local materials are less-than-optimum, and in economical construction of alternate launch surfaces. The concept may also be applicable in instances such as bomb damage crater repair, where stiffening the backfill material is desirable. Important fabric properties appear to be good soil-fabric friction, high tensile deformation modulus and tensile strength, as well as puncture and abrasion resistance. The primary unknown at this time is the exact location for fabric placement in the runway system to provide optimum reinforcement.

d. Use of geotechnical fabric to provide membrane-type support appears directly applicable to runway pavement systems. As opposed to the roadway practice of developing membrane-type support by rutting the roadway in service, prior stretching of the fabric to provide incipient membrane support, as described previously, will be desirable. The concept should be applicable to all types of runways, but might be most important for expedient runways when marginal quality construction materials are available and for alternate launch surfaces where an economical but satisfactory design is desired. Necessary fabric properties include high tensile deformation modulus and high tensile strength, as well as good soil-fabric friction, puncture resistance, and abrasion resistance. The primary unknown at this time is the magnitude of membrane-type support that can be developed and whether or not this support will constitute a significant portion of the necessary runway system support. While several commercially available fabrics have high enough tensile modulus and strength to provide adequate membrane-type support in road applications, aircraft loads are normally much greater than those of roadways. Also, the optimum location in the runway structure for membrane support has not been established.

e. Greatest improvement in runway system behavior from "reinforcement" would appear to accrue from a combination of lateral restraint obtained by placing the fabric at an "optimum" depth below the wheel load and membrane-type support obtained from prior rutting of fabric placed at this location.

With a view towards establishing the validity or nonvalidity of the above conceptual suppositions, a small-scale experimental research program was undertaken, to investigate the behavior of fabric in separation and reinforcement modes. Results of these experimental investigations will be described in the following two chapters.

CHAPTER 4. EXPERIMENTAL EVALUATION OF FABRIC SEPARATION ABILITY

In previous chapters, geotechnical fabric observed behavior as a separation medium, under relatively undocumented field conditions, was discussed. While such observations allow interference of expected behavior, a lack of quantitative data exists, especially with respect to what degree of improvement results from fabric separation and whether or not any large difference in separation performance occurs between various types of commercially available geotechnical fabrics. In order to develop initial answers to these questions, a relatively simple experiment was designed, based somewhat on procedures used by Snaith and Bell [18].

GEOTECHNICAL FABRICS SELECTED FOR EVALUATION

Four commercially available geotechnical fabrics were selected for evaluation as material separators, from the more than 50 such fabrics now commercially available. The four fabrics were:

a. Bidim C-34 - a nonwoven, needle-punched polyester fabric manufactured by The Monsanto Company.

b. Typar 3401 - a nonwoven, heat-bonded polypropylene fabric produced by E. I. DuPont De Nemours & Company.

c. Mirafi 500X - a woven, split tape polypropylene fabric produced by Celanese Corporation.

d. Geolon 66475 - a woven, fibrillated polypropylene fabric produced by Nicolon Corporation.

Bidim C-34, Typar 3401, and Mirafi 500X are all advertised as separation materials by their respective manufacturers. Geolon 66475 is advertised primarily as a fabric to be used in reinforced embankments and placed under heavy riprap in erosion control applications, but was chosen because it was the strongest fabric identified, of those currently available in the U. S. Each of the four fabrics was tested to determine the physical properties of ultimate tensile strength, elongation at failure, stress/strain modulus, using the secant through the 10% strain point, soil-fabric frictional resistance using standard Ottawa 20-30 testing sand (ASTM C-190), and creep potential. Test procedures and methods used were those developed by two of the authors in previous geotechnical fabric research for the U. S. Army Corps of Engineers [11]. Results of physical property testing on the four fabrics are given in Table 4.1.

As may be seen from the Table, a relatively large variation exists in tensile modulus and ultimate tensile strength among the four fabrics, ranging from relatively low values for Typar 3401 to high values for Geolon 66475. However, soil-fabric frictional resistance was approximately the same for all four fabrics. The four fabrics selected for testing are also fairly representative of the various different kinds of geotechnical fabric available, i.e., needle-punched nonwoven, bonded nonwoven, split tape woven, and multi-filament woven. A monofilament woven fabric was not included in the test program, based on previous research [11] which indicated that such fabrics behave very similar to multi-filament woven materials.

DESIGN OF SEPARATION EXPERIMENT

The separation experiment was designed to simulate a subgrade-fabric-aggregate system, subjected to a "rocking type" load which might approximate the effects of wheel load passage. A schematic of the test setup is shown in Figure 4.1. The subgrade-fabric-aggregate portion of the experimental apparatus was simulated by constructing several test boxes of 13 in. x 6.5 in. dimension, 13 in. high. A white Georgia kaolinite clay was used as a subgrade. This clay had an Atterberg liquid limit of 70 and an Atterberg plastic limit of 33, with resulting plasticity index of 37. The material is classified CH by the Unified Soil Classification System.

The kaolinite was mixed at a water content of 45 percent (dry weight basis) and compacted to 9.0 in. depth inside each test box in three 3.0-in.-thick lifts by static compaction, using a hydraulic compression testing machine, to a dry unit weight 76± pcf. At this water content and density the kaolinite had a cohesion of 0.10± tsf or 200± psf, approximating material with California Bearing Ratio (CBR) of approximately 1-2.

After the kaolinite was compacted to form the "test subgrade", fabric, cut into an 8.0 in. x 15.0 in. strip, with the 15.0 in. dimension

TABLE 4.1

WARP DIRECTION PHYSICAL PROPERTIES OF GEOTECHNICAL FABRICS USED IN SEPARATION TESTING PROGRAM

Fabric Name	Ultimate Tensile Strength (lb/in.)	Elongation at Failure (%)	Secant Tensile Modulus @ 10% Strain (lb/in.)	Ottawa Sand-Fabric Friction Angle (deg)	Creep Potential
Bidim C-34	88	50[1]	100	31	nil
Typar 3401	30	34	525[2]	32	high
Mirafi 500X	104	35	480	29	moderate
Geolon 66475	903	21	3620	40	nil

[1] Test Terminated

[2] Initial Tangent Modulus - Secant modulus at 10% strain 225 lb/in. Only this fabric had a higher initial tangent modulus than 10% strain secant modulus.

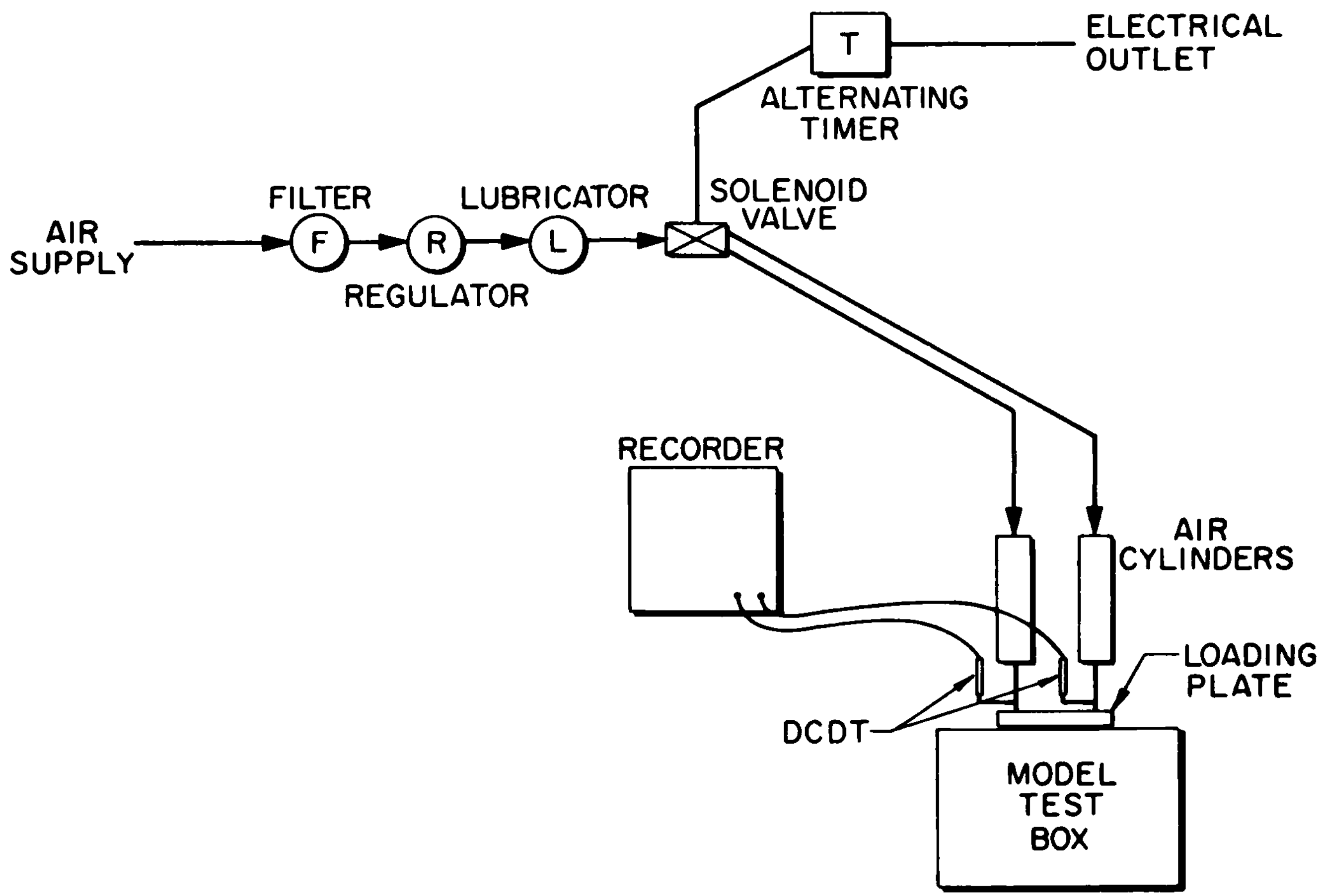


Figure 4.1 Skematic Drawing of Test Apparatus Used for Fabric Separation Experiment

parallel with the fabric warp direction or finished edge, was placed on the "subgrade." The edges of the fabric were fastened, by bolt clamping, to the perimeter of the test box, providing fabric anchorage and restricting fabric slippage under the "rocking load" during the test. Aggregate cover on the fabric was simulated by using 0.5-in.-diameter steel ball bearings, placed over the fabric to a depth of 2.0 in. The steel ball bearings were used to provide aggregate repeatability during the test, such that:

a. Changes in effective particle size would not occur from aggregate edge crushing and/or abrasion,

b. The ball bearings had a uniformity coefficient C_u of 1, thus "aggregate" density would not change during the loading process, and

c. Use of the 0.5-in.-diameter ball bearings tended to minimize soil-fabric friction at the "aggregate"-fabric interface, and thus eliminate the effect of aggregate lateral restraint.

After the ball bearings had been placed, a plate of 0.75-in.-thick plywood, with a rectangular cutout for the loading plate, was placed on the ball bearings and clamped to the box. The plate was used to keep the bearings from being displaced upward during the test, thus simulating a "wearing surface."

Once the model subgrade-fabric-aggregate-cover plate system had been prepared, as shown in Figure 4.2, it was placed in the loading frame. Load was supplied to the surface of the ball bearing aggregate by a 6-in.-long x 3-in.-wide steel plate which was connected to the loading rams of two side-by-side mounted 2.5-in.-dia double-acting hydraulic cylinders. The loading plate was placed through the cutout hole in the plywood plate used to restrain the ball bearing "aggregate." A seating load with the same pressure (20 psi) in both cylinders was applied to the surface of the aggregate, and then 40 psi hydraulic pressure was cycled back and forth between the cylinders on 5.0-sec intervals, using a mechanical clock timer and solenoid valves, to produce a "rocking" motion. Compressed air was used as the hydraulic fluid, with the air supply controlled by standard commercial pressure regulators.

For the "rocking type" load, vertical displacement of the loading plate, measured at the point of load application from each cylinder, was

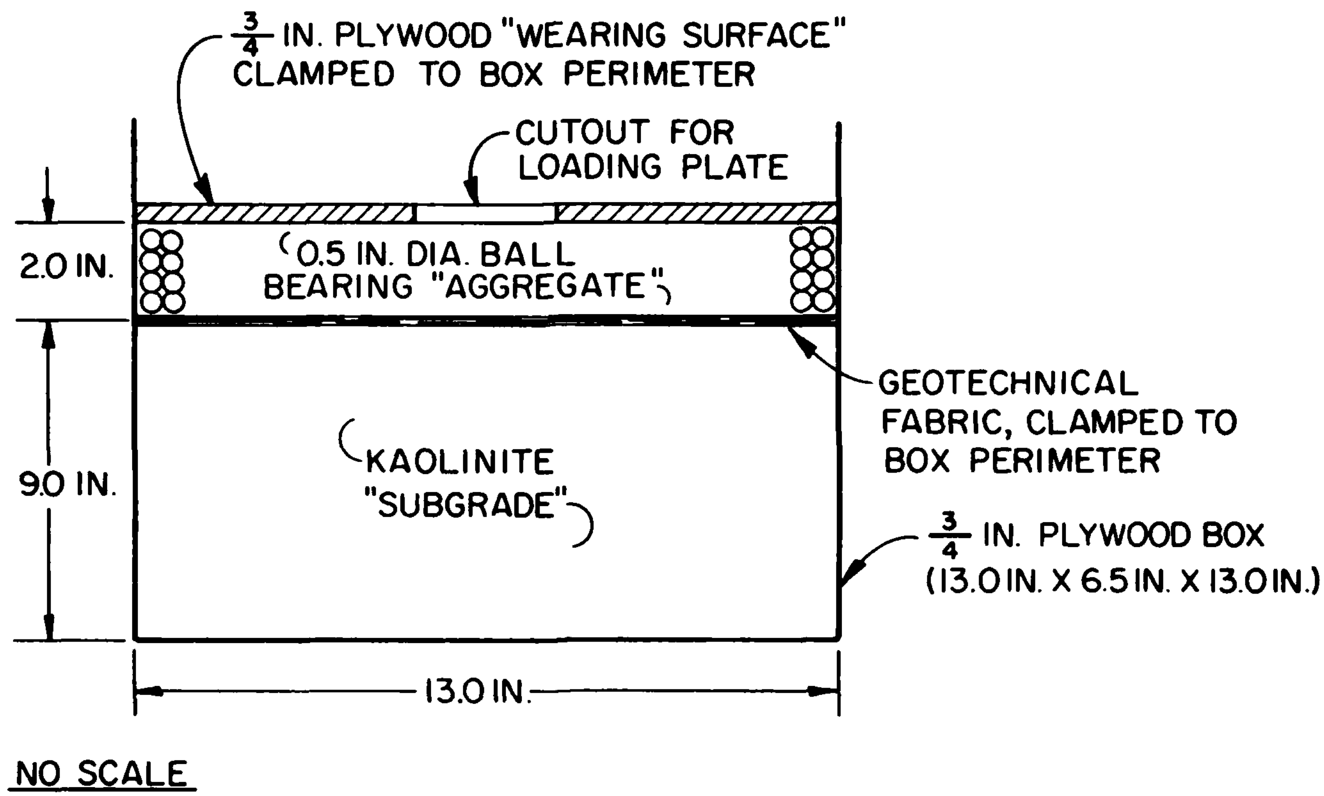


Figure 4.2 Detail Drawing of Model Test Box Used in Fabric Separation Experiment

obtained by two Hewlett-Packard direct current displacement transducers (DCDT). The dual DCDT output was monitored graphically with a Sergeant-Welch Model DSRG dual pen strip chart recorder. Figure 4.3 shows the test box with fabric placed on the "subgrade," while Figure 4.4 shows the "aggregate" cover. A photograph of the complete apparatus, ready for testing, is shown in Figure 4.5.

CONDUCT OF EXPERIMENT

After the model subgrade-fabric-aggregate-cover plate system had been prepared, placed in the loading frame, and seating load applied, the apparatus was activated and displacement-time data recorded for the system. An arbitrary performance criterion of either 0.5-in. total loading head displacement or 500 rocking cycles was established. However, after initial observations that all systems containing fabric essentially stabilized after 100 cycles, the cycling limit criterion was reduced to 200 rocking cycles. The 0.5-in. depth was arbitrary but based on the concept that after the diameter of the steel spheres had been exceeded, aggregate rearrangement under the cover plate could occur and subsequent displacement data might not reflect true fabric-subgrade deformation.

Each of the four fabrics was tested four (4) times, and four control (subgrade-aggregate-cover plate without fabric) tests were also conducted. Good consistency was obtained between individual tests with the same type of fabric and average displacement versus number of rocking cycles curves for the four fabrics and control (no-fabric) case are shown in Figure 4.6. As may be noted from the Figure, the control (no-fabric) test displaced at an essentially linear rate, reaching the 0.5-in. arbitrary depth at approximately 110 rocking cycles. The net result of control test behavior at the limiting 0.5-in. depth was to embed one layer of ball bearings in the soft kaolinite subgrade, with some extrusion of displaced kaolinite into bearings immediately above the embedded layer.

Behavior for all four fabrics was markedly similar. After initial displacements required to "set the fabric" under the loading plate, a linear rate of increase in displacement with number of rocking cycles was achieved for all fabrics at approximately 100 cycles. Conduct of

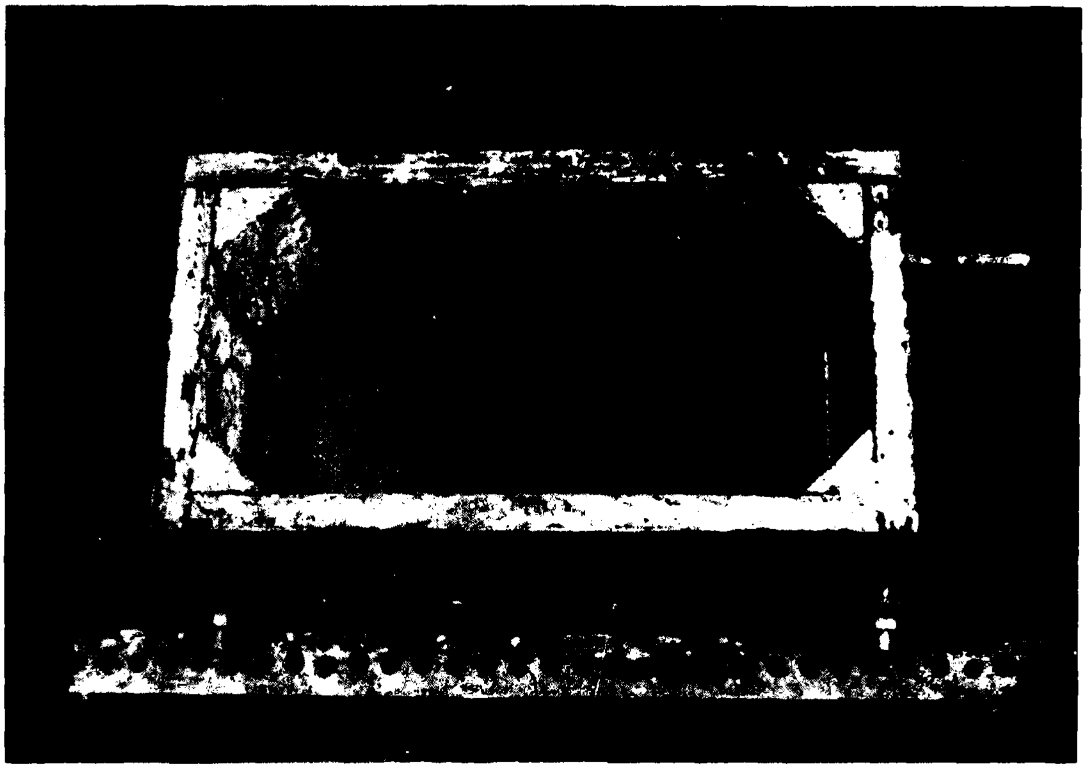


Figure 4.3 Separation Experiment Test Box Containing Kaolinite Subgrade, with Geotechnical Fabric Anchored in Place

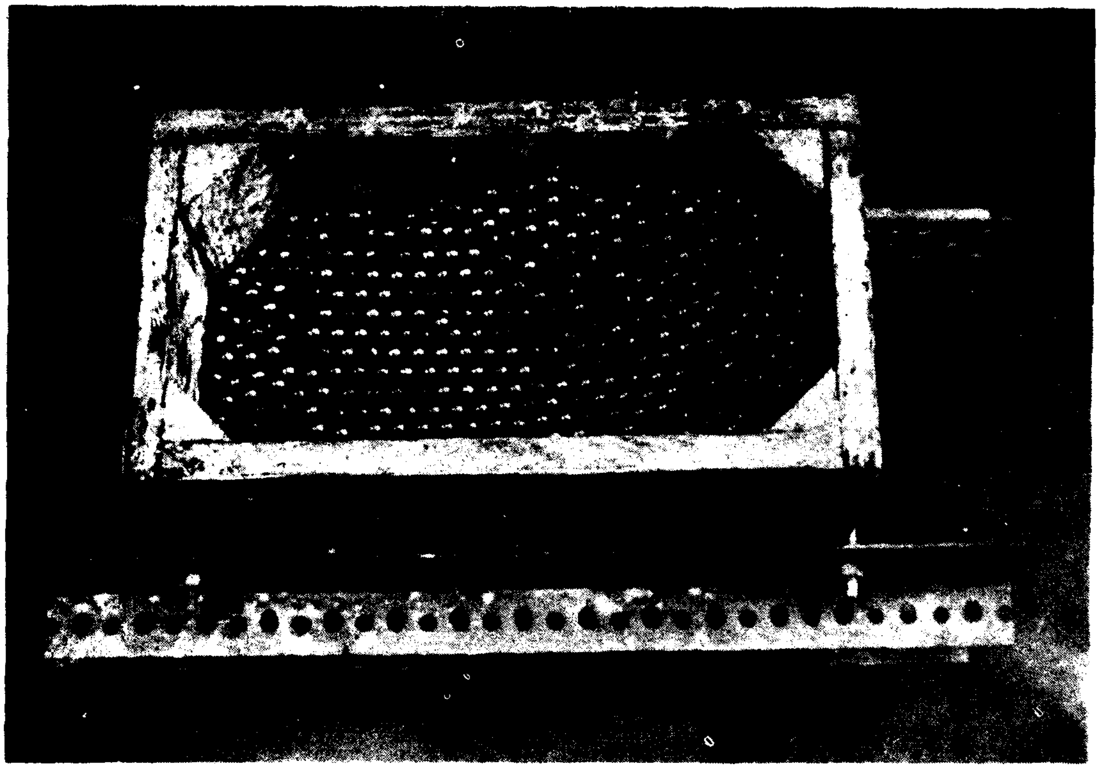


Figure 4.4 Separation Experiment Test Box with 0.5-in.-dia Ball Bearing Aggregate Placed Over Geotechnical Fabric

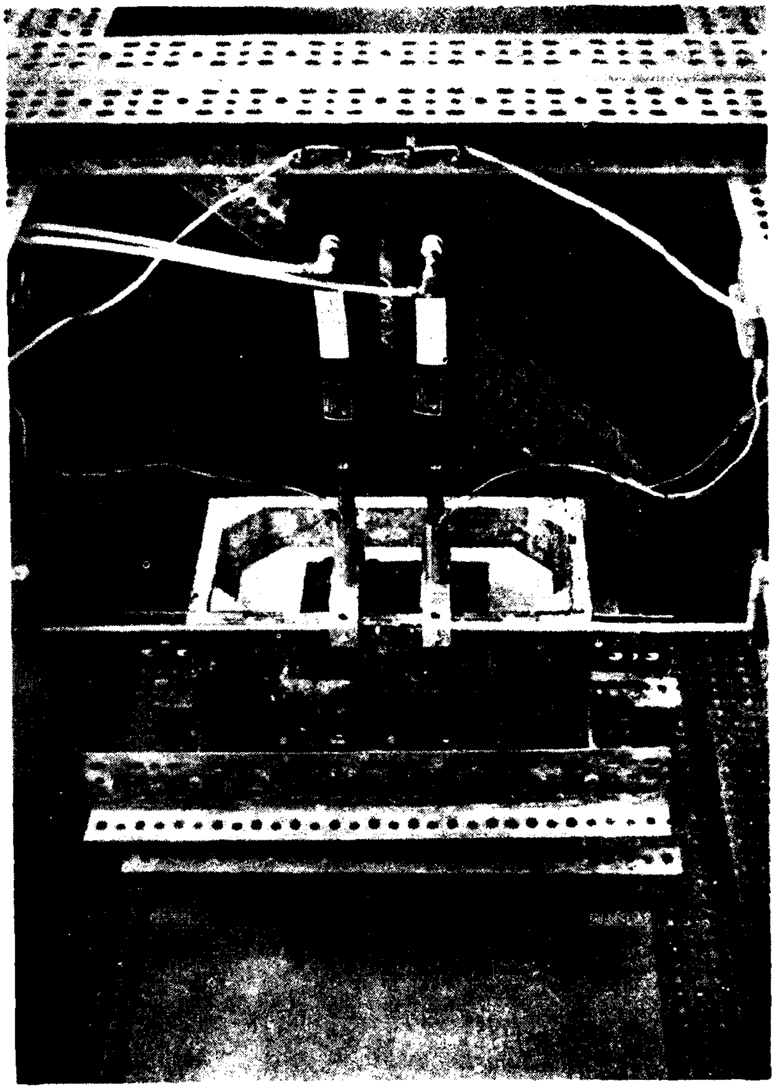


Figure 4.5 Separation Experiment Test Setup, Ready for Conduct of Testing

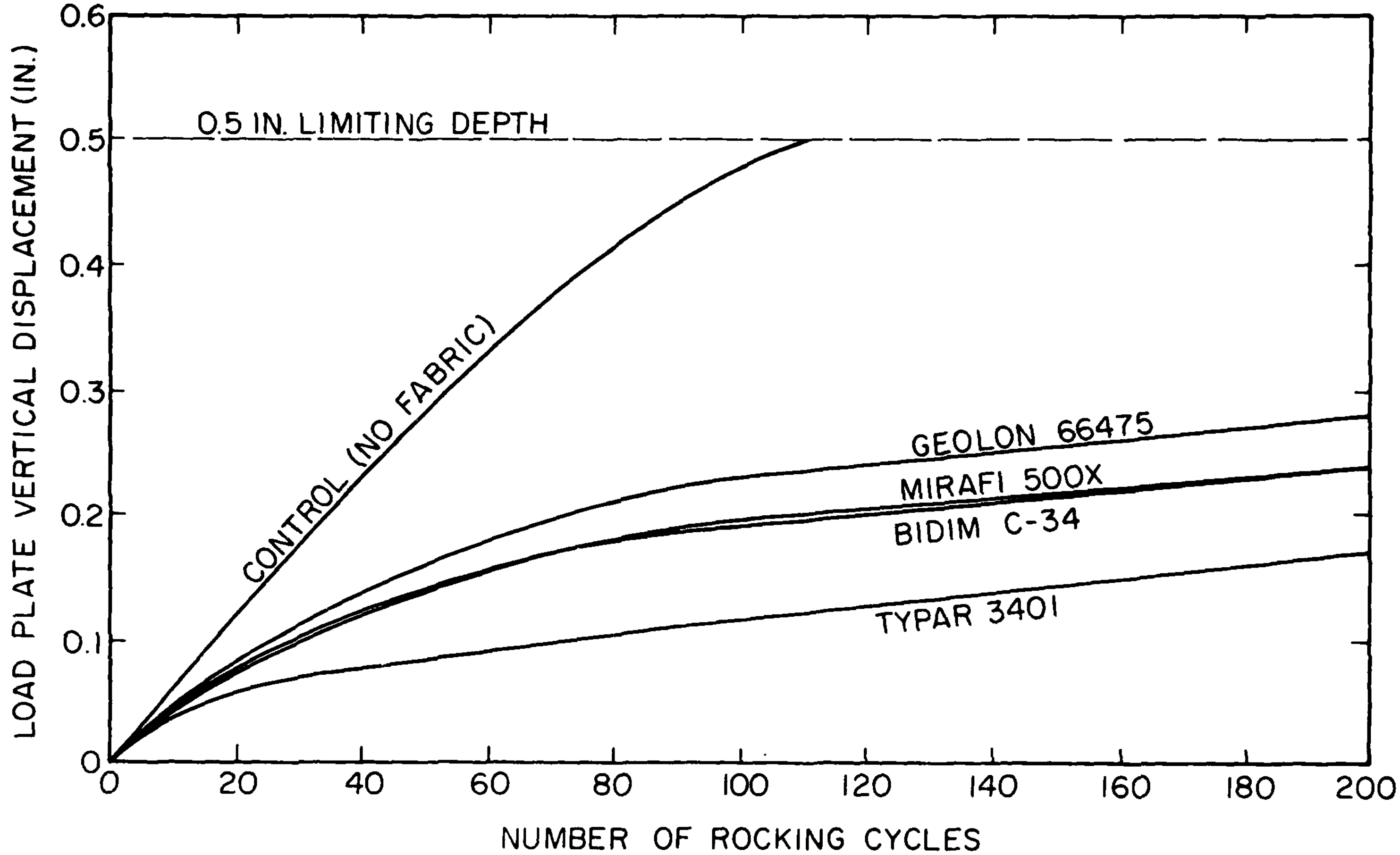


Figure 4.6 Displacement vs. Number of Loading Cycles Relationships for the Four Test Fabrics Used in Separation Experiment

testing past the 200-cycle limit shown in Figure 4.6 indicated a continuation of the linear relationship.

Examination of all fabric test kaolinite "subgrades" after test completion and disassembly indicated that some lateral displacement had occurred in the plastic clay, with the displacement approximating the total deformation measured during the test. It thus may be reasonably assumed that the linear vertical displacement-number of rocking cycles relationship achieved by all fabrics after about 100 cycles was related to plastic displacement of underlying "subgrade." No significant elongation or tension was noted in any fabric after removal of aggregate during test box disassembly, which further substantiates the essentially similar displacement-number of cycles relationships obtained for all fabrics, despite their dissimilar physical properties.

In all instances, water was extruded or pumped from the subgrade and was found on the surface of all fabrics except the thicker Bidim C-34, where it was found in the fabric itself. Kaolinite was extruded into the Bidim C-34, to approximately one-half the thickness of the fabric, and was extruded to and slightly through the Mirafi 500X and Geolon 66475 fabrics. The underside of the Geolon 66475 fabric after testing is shown in Figure 4.7. A definite coating of kaolinite was seen on the underside of the Typar 3401 fabric but no noticeable extrusion through fabric pores was observed.

Thus, during 200 rocking cycles no significant extrusion of kaolinite through any fabric occurred. All fabrics were obviously clogged to some extent by the kaolinite subgrade filling some of the fabric openings, but the exact magnitude of clogging and/or permeability reduction was not determined. No fabric showed significant deterioration of the surface exposed to the "aggregate" during the short-term test. The Typar 3401 fabric had noticeable aggregate indentations in its surface, and the upper surface of the Bidim C-34 had some of the surface and near-surface fibers pulled apart, apparently unlocking the needle-punch mechanical interlock. However, as noted from Figure 4.6, these slight abrasions and indentations did not affect performance. For longer-term cycling and if angular aggregate was employed, different results might be obtained. The Mirafi 500X and Geolon 66475 fabrics showed no obvious effects of aggregate indentation or abrasion.

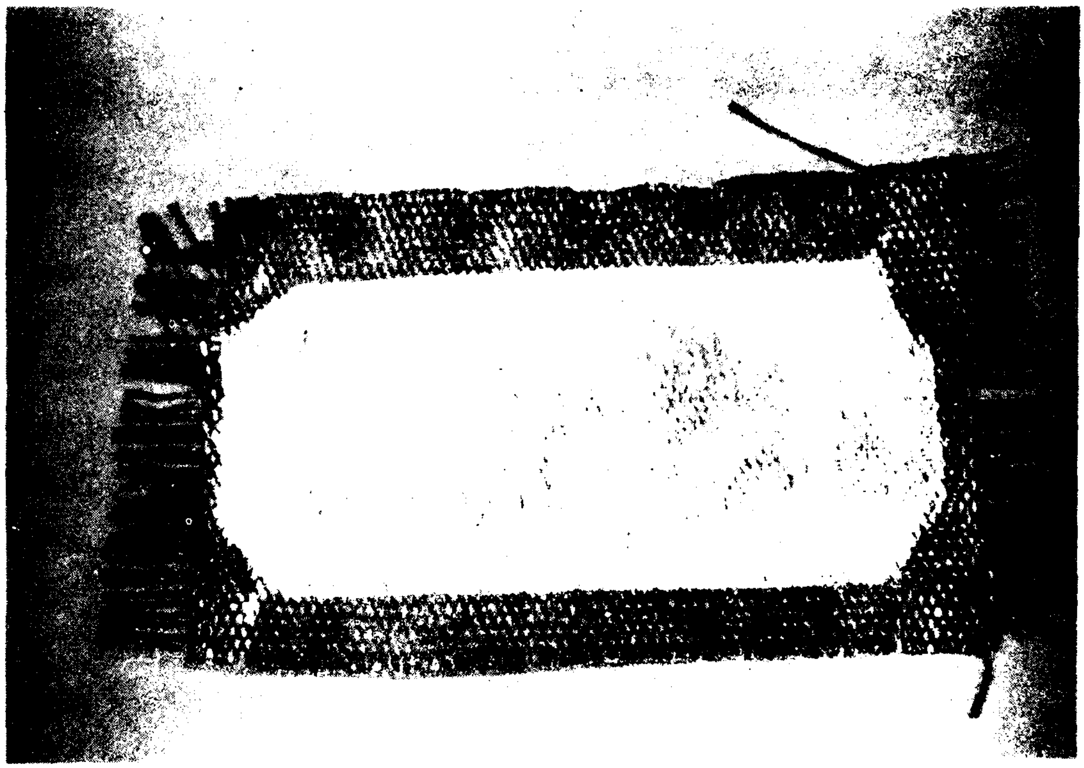


Figure 4.7 Underside of Geolon 66475 Fabric After Separation Testing, Showing Kaolinite Subgrade Smeared on the Fabric

As may be noted in Figure 4.6, while all fabrics achieved essentially a linear displacement-time relationship after approximately 100 rocking cycles (apparently related to displacement of underlying "subgrade") different amounts of load plate, and thus fabric, deformation were required to achieve linearity. Further, the displacements required to obtain linearity are not related to the ultimate tensile strength or 10% strain secant tensile modulus of the fabrics, as given in Table 4.1. However, a review of each fabric's construction and their actual tensile stress-strain curves [11] gives some insight into observed behavior. Typar 3401 is a heat-bonded nonwoven fabric and the heat bonding produces a fairly high initial modulus, as the nonwoven fibers need not be pulled into the direction of load application to provide deformation resistance. The needle-punched nonwoven Bidim C-34 fabric develops mechanical interlock of nonwoven fibers over extremely short lengths (between needle punches). Thus, only a very short length of fiber is initially strained, despite the absence of physical bond between individual fibers. The Mirafi 500X fabric is a woven, essentially flat, split tape fabric and, though the material has more ultimate strength than either Bidim C-34 or Typar 3401, initially the woven fibers must be pulled flat before they can develop any resistance. Similar behavior would occur for Geolon 66475, which was the strongest fabric, both in ultimate strength and tensile deformation modulus. However, this fabric is woven of fairly large diameter strands and each strand must be pulled flat before any fabric resistance can be mobilized.

SUMMARY

Results of the experiment indicated a marked increase in deformation resistance of the model subgrade-fabric-aggregate-wearing surface system, as compared to the no-fabric case. Behavior of the system was essentially changed from that of aggregate embedment and subgrade intrusion without fabric to a linear, but fairly small, rate of plastic subgrade displacement, for all fabrics used in the test program. Results of the test program showed that all four fabrics performed essentially alike, and, despite some initial differences in the amount of displacement required to "set the fabric," all fabrics should give similar short-term separation performance.

During all tests, water was pumped from the kaolinite subgrade through or into the test fabrics and clay was pushed into fabric pores and smeared along the bottom surface of the fabrics. The effect of this behavior on long-term fabric clogging was not evaluated, but could be significant. Though it did not affect their performance in the short-term tests, aggregate indentation marks were noticed on the surface of the Typar 3401 fabric, and the upper surface of the Bidim C-34 fabric was slightly abraded by ball bearing aggregate action. Such behavior, if continued for extended periods or accelerated by angular aggregate, might cause a degradation in performance.

Because of the relatively small displacements involved, it may be reasonably assumed that membrane-type support was not developed by any fabric. Also, use of the ball bearing aggregate, with extremely low coefficient of aggregate-fabric friction, appears to have eliminated effects of lateral restraint from the system.

For short-term separation potential, it may be concluded, based on results of the simplistic experiments conducted, that essentially all types of available geotechnical fabric will provide adequate separation of cohesive subgrade and cohesionless aggregate. As long as the fabric is not punctured, torn, or abraded by the aggregate or clogged by the subgrade, no noticeable difference in separation performance will occur.

CHAPTER 5. EXPERIMENTAL EVALUATION OF GEOTECHNICAL FABRIC REINFORCEMENT ABILITY

In Chapter 2, it was noted that placement of fabric in a road structure had been observed to increase the deformation modulus and ultimate strength of cohesionless material placed above the fabric, which was postulated to result from lateral restraint by interference with normal deformation patterns for the cover (base) material. When discussing potential applicability of this concept to runway design in Chapter 3, it was noted that, in the majority of instances, fabric placement in road construction was made directly on cohesive subgrade, to obtain material separation. Any reinforcement benefits, accruing either from lateral restraint or membrane-type support, were helpful, but secondary. However, for expedient runways when less than optimum construction materials are available, for economical alternate launch surface construction, and for localized bomb damage crater repair activities, improvement of cover material strength and deformation modulus may be the most important consideration. Such conditions could occur if the subgrade had relatively low strength but no plastic intrusion or pumping tendencies, or if the number of load repetitions would not be sufficient to cause system deterioration from intrusion or pumping. Total strength of the runway system could be enhanced by placement of fabric only for base material reinforcement.

Also, in Chapter 3 it was hypothesized that maximum strengthening of the runway system could be achieved by locating the fabric at an optimum depth for lateral restraint and then subjecting the fabric to prior tensioning, perhaps by overcompaction, to develop incipient membrane-type support. Based on experimental data [14] which indicated that rutting on the order of 2 in.-3 in. was required to develop appreciable membrane-type support in roadways, it was concluded that this magnitude of deformation would be difficult to develop in a laboratory model soil system, without a relatively large test setup. Thus, it was decided to design a laboratory study to investigate only the effect of cover material reinforcement at deformations below those needed for membrane-type support, with a view toward determining, if possible, the optimum depth for fabric placement as a function of loaded contact area size.

GEOTECHNICAL FABRIC USED IN TEST PROGRAM

Three of the four geotechnical fabrics used in the separation experiment, Bidim C-34, Typar 3401, and Geolon 66475, were also selected for use in the soil reinforcement experiment. Physical and mechanical properties of these fabrics were described in Chapter 4 and in Table 4.1. Mirafi 600X, a woven split tape fabric similar to but slightly stronger than Mirafi 500X, was used as the fourth reinforcement fabric. Laboratory test values for Mirafi 600X included an ultimate tensile strength of 181 lb/in., a strain of 35% at failure, a secant tensile modulus of 630 lb/in. at 10% strain, and a sand-fabric friction angle of 29 deg. Use of these four dissimilar fabrics in the test program would evaluate the effects of variation in fabric type, tensile modulus, and ultimate tensile strength on reinforcement behavior.

DESIGN OF EXPERIMENT

In order to obtain information concerning the optimum depth of fabric placement, a uniform cohesionless soil mass was selected for testing, rather than a layered system such as might be encountered in roadway and runway pavement systems. However, use of the uniform soil mass would eliminate influences on reinforcement behavior resulting from presence of a weaker underlying soil layer; thus any variations in deformation modulus and strength of the uniform soil mass must result from the fabric and/or its location. Standard Ottawa 20-30 testing sand (ASTM C-190) was selected for use as the cohesionless soil to be reinforced, primarily because of the ease in compacting this white, rounded, poorly graded quartz sand and the fact that Ottawa sand has become a widely used laboratory test medium in geotechnical engineering. In order to facilitate compaction, all placement and testing would be conducted with the sand in a flooded condition.

Figure 5.1 shows a simplified drawing of the reinforcement experiment load testing apparatus, and Figure 5.2 is a schematic of the control panel used for controlling load magnitude, frequency, and duration. A photograph of the test setup is shown in Figure 5.3.

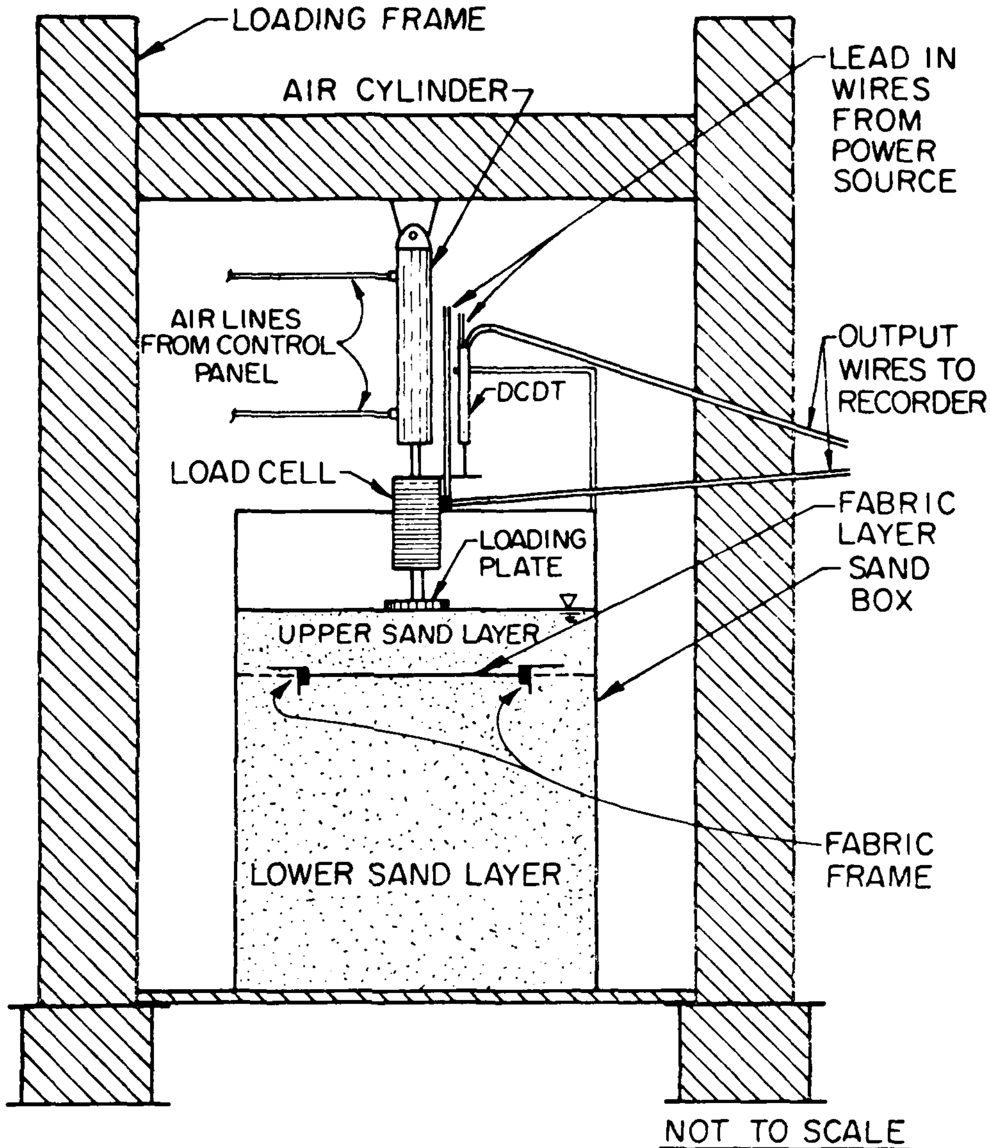


Figure 5.1 Drawing of Loading Frame and Test Box Arrangement for Soil Reinforcement Experiment

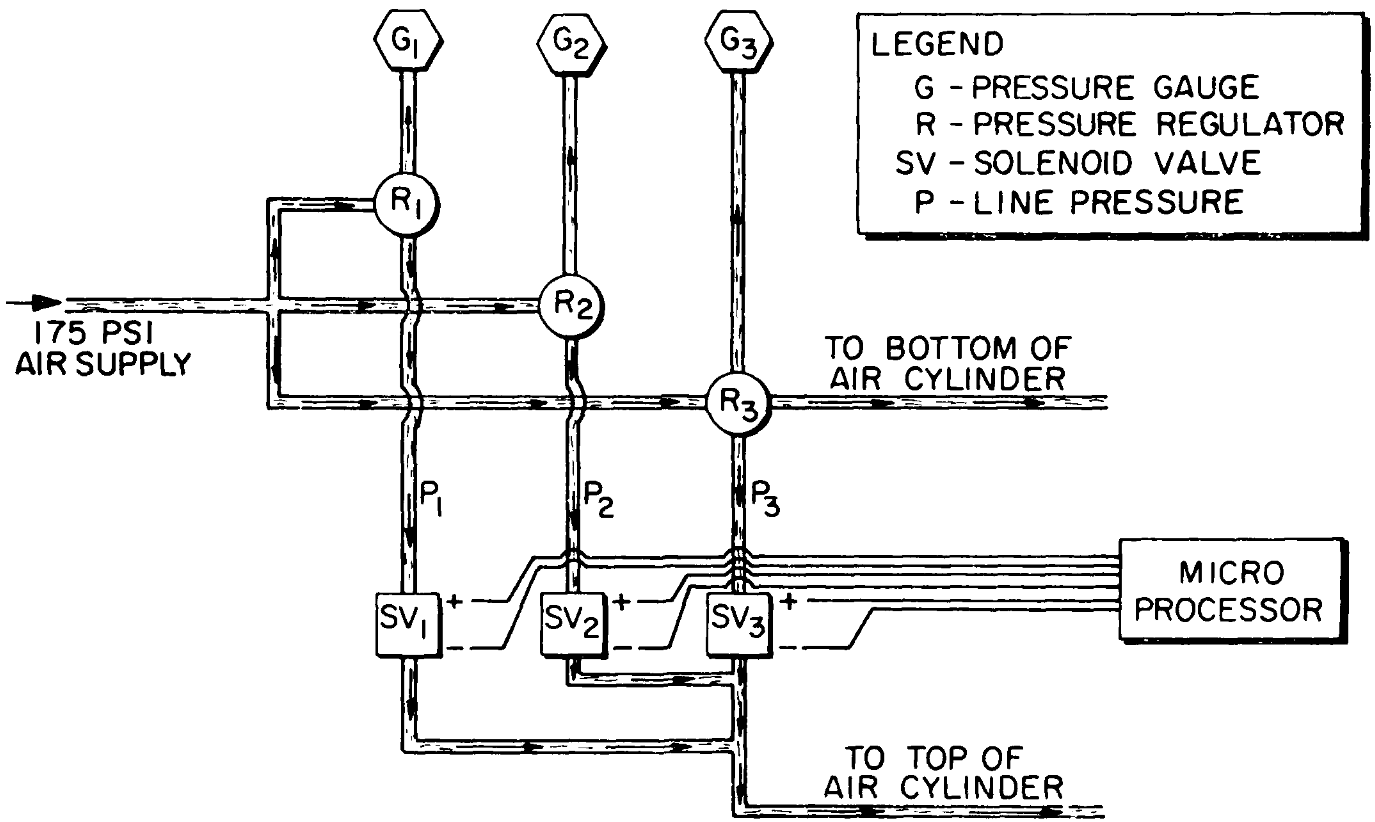


Figure 5.2 Detail of Load Control Arrangement for Soil Reinforcement Experiment

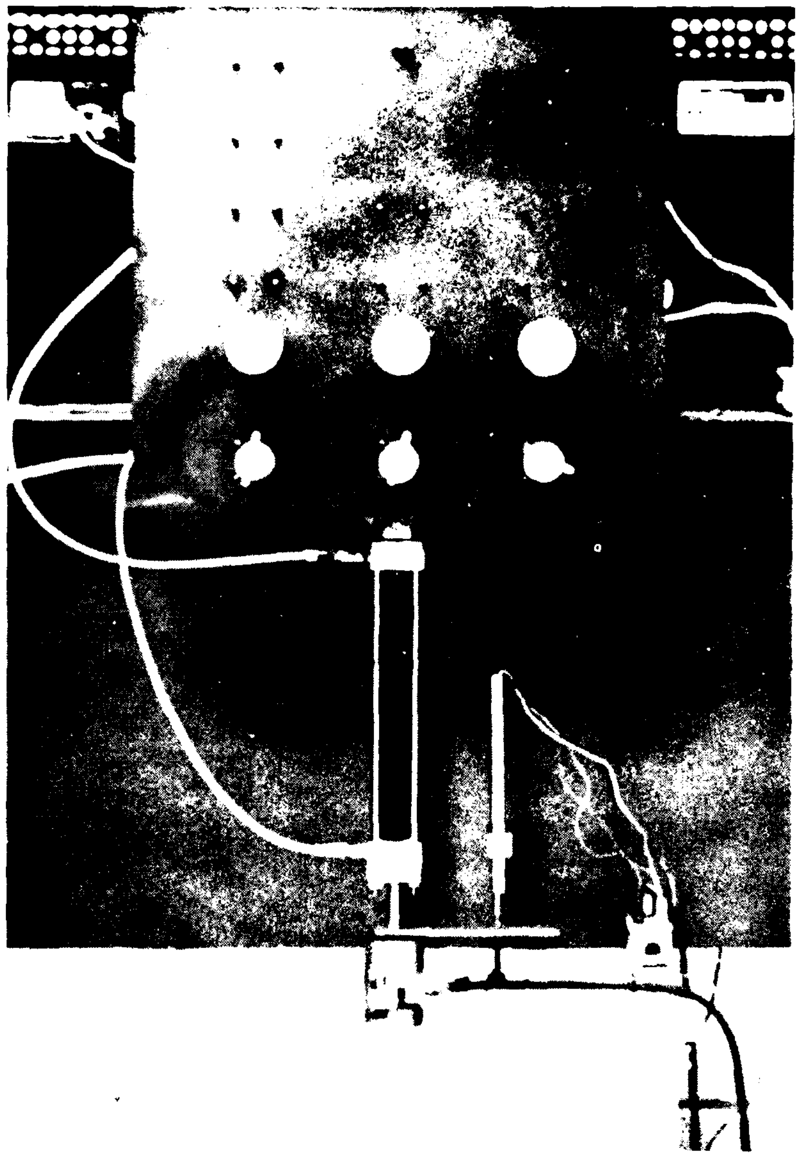


Figure 5.3 Photograph of Reinforcement Experiment Equipment Set-up, Ready for Testing

Load was applied to the loading plate with a Schrader air cylinder with 2.0-in.-dia piston and 12 in.-stroke. The applied load was monitored with a Baldwin-Lima-Hamilton Model U1 strain gage load cell of 2000 lb capacity. Two steel loading plates, of 4.0-in.-dia and 6.00-in.-dia, were used. Vertical displacement of the loading plate was monitored by a Hewlett-Packard Model 3000 Direct Current Displacement Transducer (DCDT). Loads and corresponding displacements were continuously recorded on a Sargent-Welch Model DSRG-2 dual pen strip chart recorder.

As previously stated, the magnitude and duration of loading were controlled as shown in Figure 5.2. Air pressure was used for hydraulic loading and was controlled by Wilkerson air regulators and gauges. Three AAA Model-S03 solenoid valves were used for directing air flow through the various lines. The key part of the control panel was a MicroMaster Model UP-6001 MicroProcessor Controller (MPC) manufactured by Western Pacific. The programmable capabilities of the MPC allowed actuation of the solenoid valves at regular, precise intervals, to ensure multiple test accuracy.

Testing was conducted with no fabric reinforcement, with fabric reinforcement initially in a "no slack--no tension" state, and with pretensioned fabric. The anchorage frame used in the fabric test is shown in Figure 5.4, with fabric installed. This frame has the capability of holding fabric sizes from 12.0 in. x 12.0 in. to 13.2 in. x 13.2 in. between grips, allowing up to 10% biaxial strain for pretensioned tests. However, a biaxial strain of only 2% was used for all pretensioned tests, because of the difficulty of applying pretensioning load without localized fabric tearing at grip points.

Prior to placement of the fabric and frame, the lower sand layer was vibrated with a WYCO Model 990-M concrete vibrator to a depth of 14.5 in. Figure 5.5 shows the pattern and sequence of vibration. Location 5 was directly beneath the loading plate center, and vibration lasted for 15 seconds at each location. Following vibration, the sand was rodded with a 3/8-in.-dia steel bar for a period of two minutes, and then was struck level using the device shown in Figure 5.6. The fabric and frame were then installed as shown in Figure 5.7 and the upper sand layer was placed to desired thickness. Rodding of the upper sand layer was performed for a period of two minutes and the sand was again struck level.

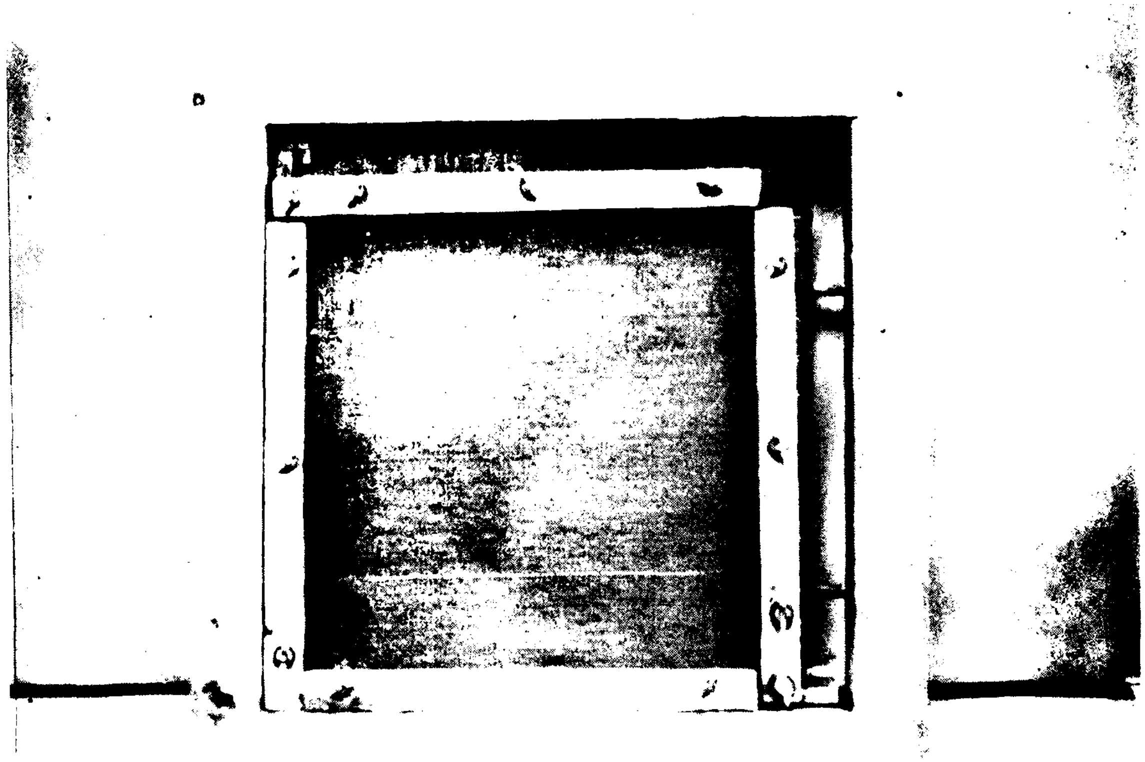


Figure 5.4 Photograph of Fabric Anchorage Frame, with Fabric Installed, Used in Soil Reinforcement Experiment

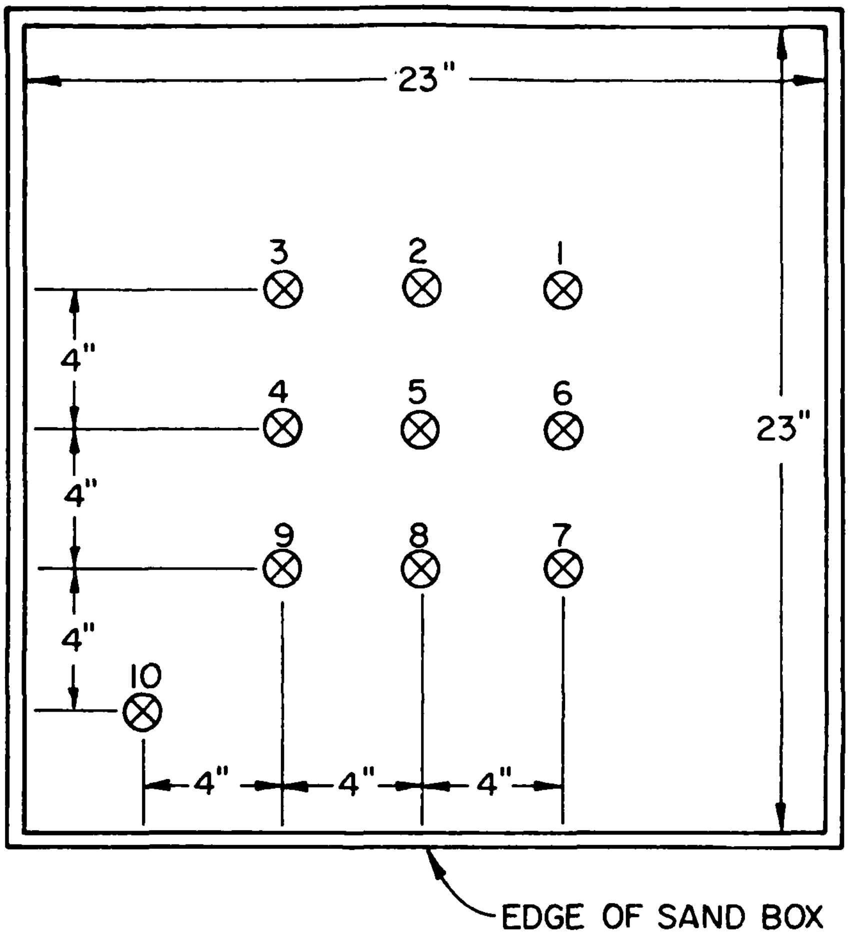


Figure 5.5 Sequence Used for Vibratory Compaction of Lower Sand Layer in Soil Reinforcement Experiment

Figure 5.6 Photograph of Device Used to Level Surface of Sand After Vibratory Compaction

Figure 5.7 Photograph of Fabric and Anchorage Frame Placed on Surface of Compacted and Levelled Lower Sand Layer

The water level was maintained at the surface of the sand at all times during preparation.

Following preparation of the sand box, the loading plate was lowered to the surface and a seating pressure of 1.0 psi was applied, to eliminate any slack in the system. The load was then returned to zero and the test was conducted, with load being applied by incrementing cylinder air pressure 1.5 psi each 10.0 sec. The test was terminated when the peak air supply pressure of 175± psi was reached.

Load bearing tests were performed on sand without fabric reinforcement, so that "before and after" comparisons could be made. For all cases, tests without fabric used the same sand compaction procedure as the fabric tests, except that the fabric and fabric frame were not put into place following initial vibration and rodding of the lower sand layer.

TEST RESULTS AND DISCUSSION

The test program was composed of initial and secondary testing phases. A total of 63 tests were run during initial testing, and, after data were initially analyzed, 18 tests were run during secondary testing. All tests were conducted in the manner described previously.

Initial Testing

In the initial testing portion, a series of tests were run for each plate size-embedment depth combination. A test series consisted of three tests each for the following three conditions:

a. Each fabric with no pretensioning,

b. Typar 3401 and Mirafi 600X in 2% strain pretensioned state, and

c. The no-fabric system.

Each series thus consisted of 21 load bearing tests, with three different plate size-embedment depth combinations: 6 in. plate-3.0 in. embedment depth, 4 in. plate-2.0 in. embedment-depth, and 4 in. depth-4.0 in. embedment depth. Results for each plate size-embedment depth combination are separated into tests without fabric pretensioning and tests with 2% pretensioning and are shown in Figure 5.8 through Figure 5.13.

Figure 5.8 shows stress-displacement relationships for the fabric-reinforced system without fabric pretensioning and with a 6-in.-dia loading plate. Results shown are average values for three tests: only a small variation among individual test values was obtained, for all fabrics tested. Stress values are those at the top of the soil layer and were determined by dividing total load by plate area. The plate was initially placed a distance of 3.0 in. or 0.5B (B equals plate dia) above the fabric. During load testing the sand around the loading plate was noted to displace outward and upward with increasing deformation but the position of the fabric layer in the box did not change significantly. Thus, in addition to absolute displacement values, relative displacement in terms of the distance between plate and fabric is plotted at the top of the Figure.

As noted from the test data, all fabrics produced a significant increase in initial deformation modulus, as compared to the no-fabric case, such that 1.5-2 times initial no-fabric load capacity was developed before initial "elasto-plastic" yielding and displacement of soil located above the fabric. This yielding, at 0.2+ in. displacement, was followed by a large increase in strain without change in stress, allowing the load plate to move closer to the fabric. Also, the no-fabric system, which "yielded" at a less-abrupt rate, begin to match the fabric-reinforced systems. However, as the load plate approached a distance of 0.33B above the fabric, all fabric-reinforced systems again began to develop deformation resistance, at approximately the same rate (same stress-deformation modulus) they exhibited during initial deformation. This "second-level" resistance increased linearly, until loading capacity of the test apparatus was reached.

It should be noted that the stress-displacement relationships for both first-level (before "yield") and second-level states are markedly similar for all fabrics, despite the wide disparity in ultimate tensile strength, tensile deformation modulus, and soil-fabric friction among the various fabrics. Bidim C-34 had slightly better deformation resistance than the other fabrics, but the difference does not appear significant.

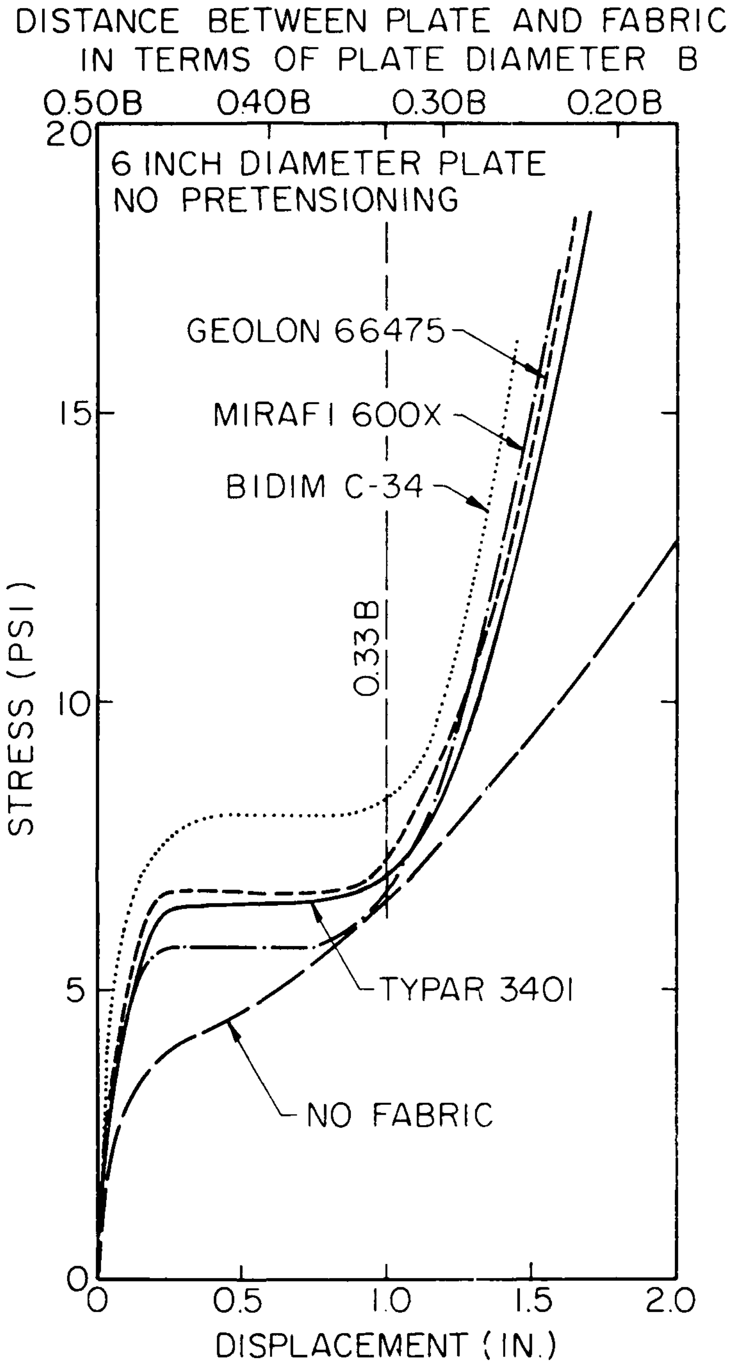


Figure 5.8 Stress-Deformation Behavior for Fabric-Reinforced and No-Fabric Systems With 6.0-in.-dia Plate Initially Located 0.5B Above Fabric Layer

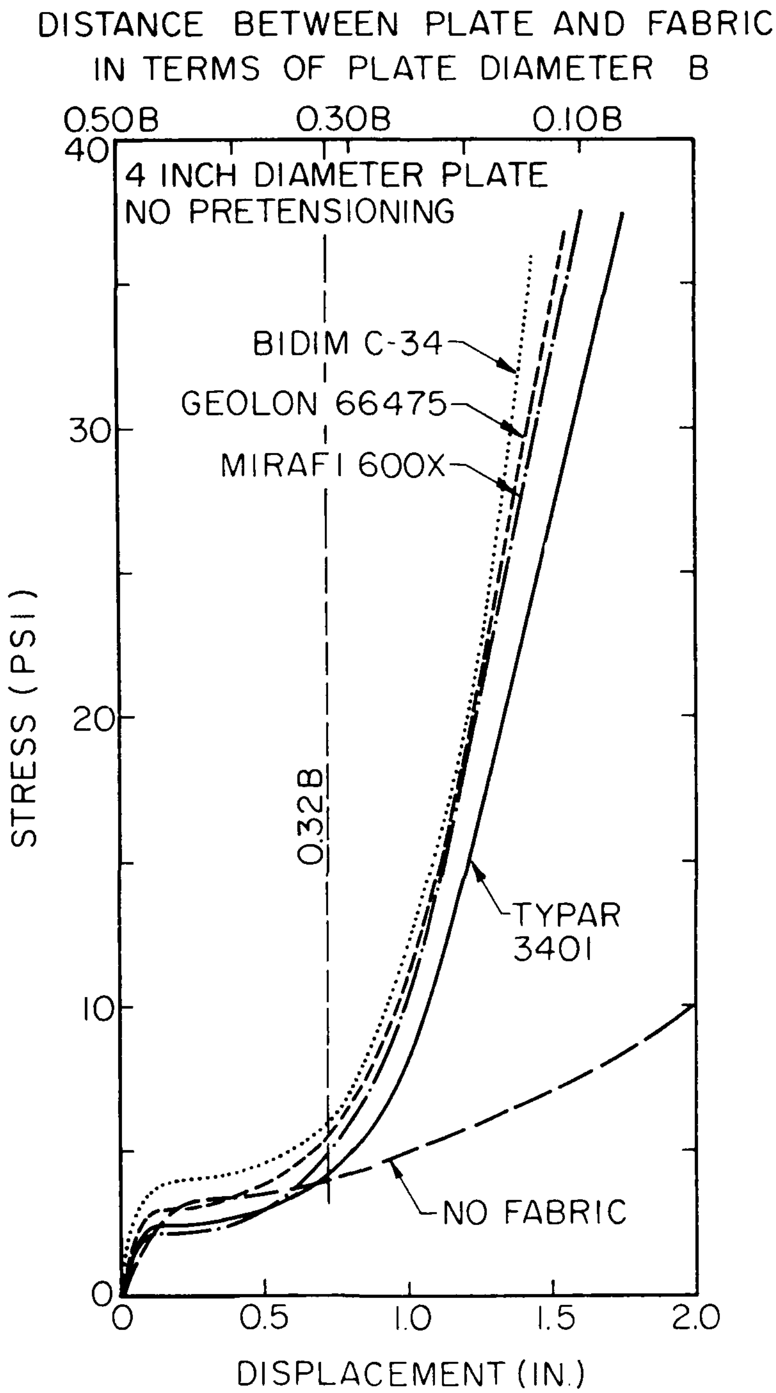


Figure 5.9 Stress-Displacement Behavior for Fabric-Reinforced and No-Fabric System With 4.0-in.-dia Plate Initially Located 0.5B Above Fabric Layer

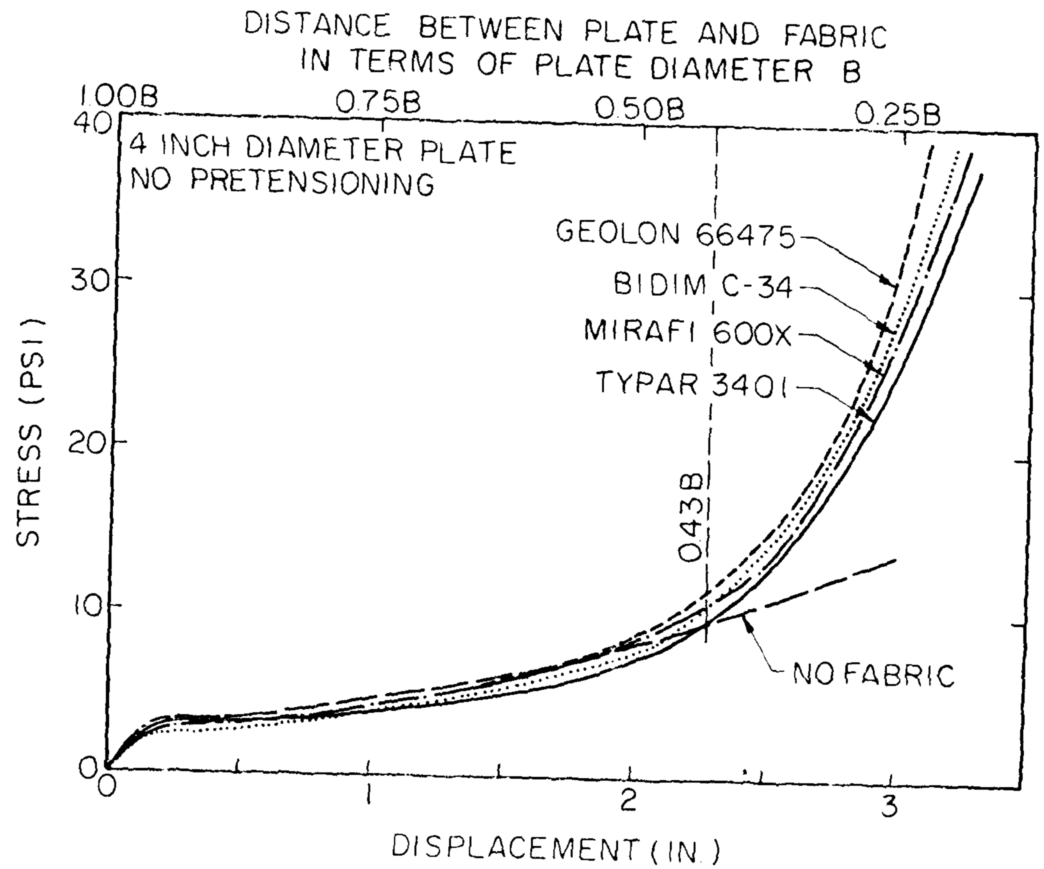


Figure 5.10 Stress-Displacement Behavior for Fabric-Reinforced and No-Fabric System With 4.0-in.-dia Plate Initially Located 1.0B Above Fabric Layer

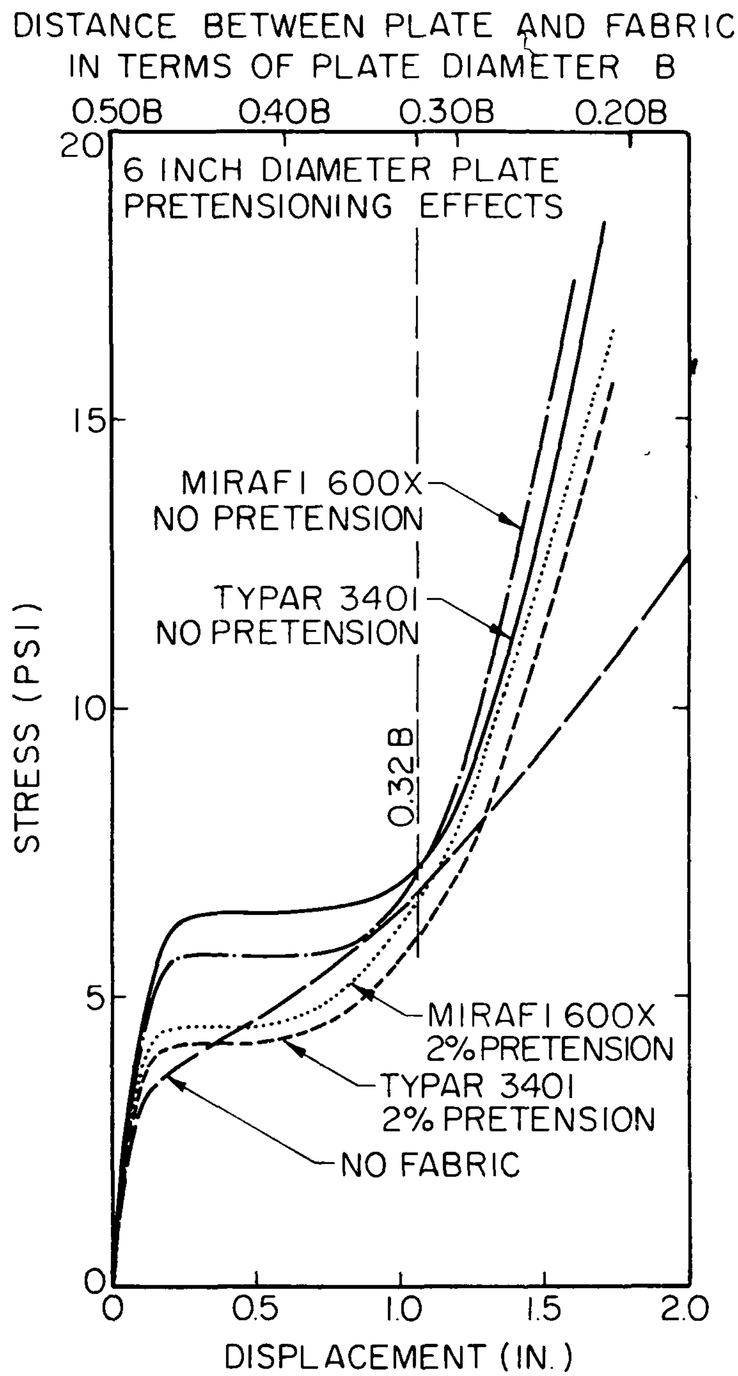


Figure 5.11 Effects of Pretensioning on Fabric-Reinforced Soil Mass Stress-Deformation Behavior, 6-in.-dia Plate Initially 0.5B Above Fabric

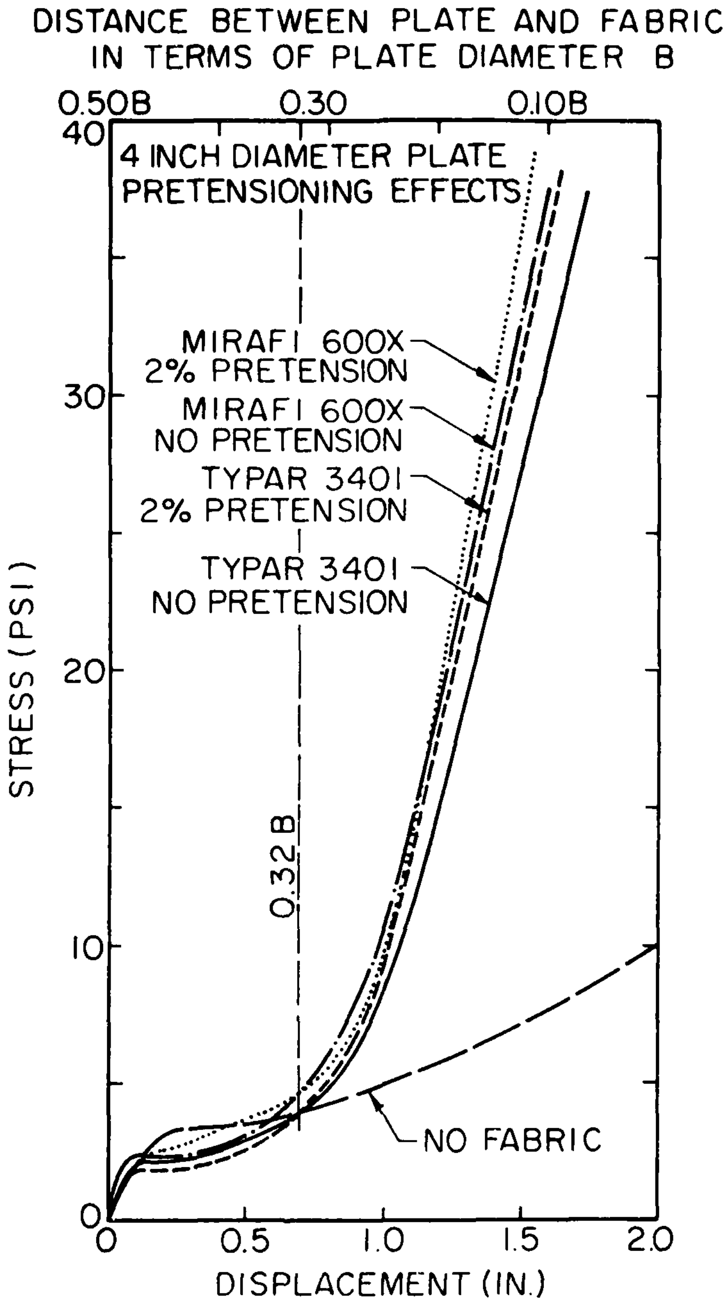


Figure 5.12 Effects of Pretensioning on Fabric-Reinforced Soil Mass Stress-Deformation Behavior, 4-in.-dia Plate Initially 0.5B Above Fabric

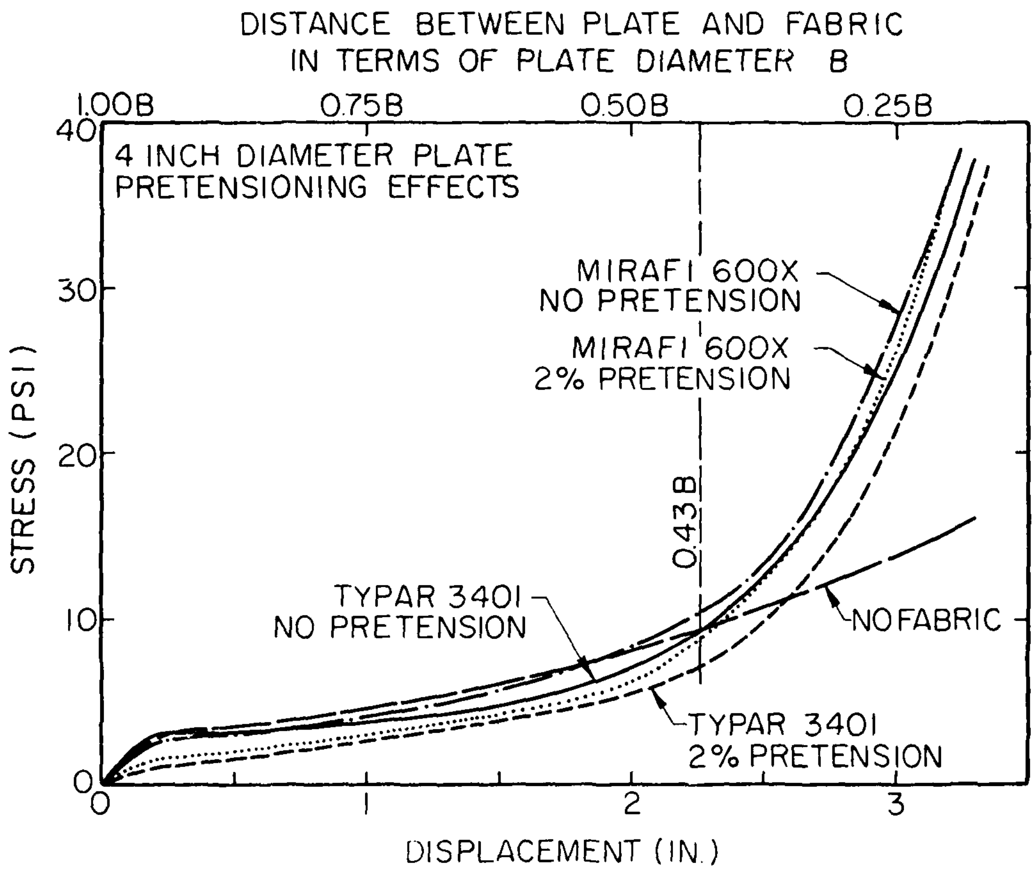


Figure 5.13 Effects of Pretensioning on Fabric-Reinforced Soil Mass Behavior, 4-in.-dia Plate Initially 1.0B Above Fabric

Figure 5.9 presents similar test behavior obtained for a 4-in.-dia plate, initially embedded 2.0 in. or 0.5B above the fabric. While no great improvement in initial deformation modulus (compared to the no-fabric case) is noticed, the same general yielding and second-level resistance behavior is noted to occur, at 0.32B distance between plate and fabric for the fabric-reinforced systems, comparing favorably to the 0.33B value obtained for the 6-in.-dia plate. Above this displacement, marked differences were noted between the fabric-reinforced and no-fabric systems, but no marked difference in stress-displacement behavior was noted among the four fabrics. For all fabrics, soil resistance developed at, essentially, a linear rate, once second-level resistance had been developed, until the loading capacity of the test apparatus was reached.

After evaluation of these data, an additional set of testing was conducted, using the 4-in.-dia plate to develop maximum stress at the soil surface with available load capacity. Fabric pretensioning was not carried out and the test series was conducted with the 4-in.-dia load plate initially a distance of 4.0 in. or 1.0B above the fabric. Similar initial behavior, resulting in surface displacement of sand around the load plate but no movement of the underlying fabric, was noted to occur. Test series results are shown in Figure 5.10. No noticeable difference was noted in initial deformation modulus between the fabric-reinforced and the unreinforced (no-fabric) systems. Also, an extremely large amount of soil displacement occurred prior to development of second-phase resistance, for all fabric-reinforced systems. This second-phase resistance was noted to begin at a distance of 0.43B between plate and fabric. The relatively large deformations undergone by the four systems prior to development of second-level resistance cause some doubt as to the absolute reliability of the indicated transition point, though it is approximately the 0.32B-0.33B value determined from previous testing. Again, consistent results were obtained among the three individual tests conducted for each fabric,and the average values plotted in Figure 5.10 show no marked difference in performance among the four dissimilar fabrics.

After evaluation of these data, it was decided to reduce the number of fabrics evaluated in each test series, to allow conduct of more experiment variations. Based on observed behavior that type of fabric had little effect on load-deformation behavior of the fabric-reinforced mass, it was believed that this modification would not affect overall conclusions. Typar 3401 and Mirafi 600X were selected for future experimental use, primarily because these fabrics were easier to place in the fabric anchorage frame.

A set of tests was then carried out using the 6-in.-dia load plate, placed initially a distance of 3.0 in. or 0.5B above the fabric, with both Mirafi 600X and Typar 3401 pretensioned to 2% strain or elongation prior to placement in the sand mass. Results of these tests are shown in Figure 5.11, as are values obtained from previous no-pretension tests on the same fabrics and the no-fabric data. As may be noted from the Figure, 2% pretensioning had essentially no effect on initial modulus of the fabric-reinforced systems. However, both pretensioned fabric systems "yielded" at a lower stress than the anchored but not pretensioned fabric systems. Perhaps this difference, i.e., yielding at lower stress, can be related to lower soil-fabric friction development along the pretensioned, taut, soil-fabric interface. Finally, both pretensioned fabric systems begin to develop second-phase resistance at slightly smaller system displacements. The pretensioned fabrics begin to develop second-phase resistance at about 0.38B - 0.40B, rather than the 0.32B distance between plate and fabric for the non-pretensioned fabrics. In any case, pretensioning the fabrics did not add to the load-deformation resistance of the system.

This experiment was repeated with the 4-in.-dia plate placed initially 2.0 in. or 0.5B above the pretensioned fabrics. Results of this test series, shown in Figure 5.12, indicated that the early yielding behavior shown previously in Figure 5.11 did not occur and essentially no difference occurred between pretensioned and untensioned fabric over the entire range of behavior.

A final set of pretensioning tests were conducted, with the 4-in.-dia plate initially placed a distance of 4.0 in. or 1.0B above the two fabrics. Test results are shown in Figure 5.13. Again, the behavior of pretensioned and nonpretensioned fabric systems was markedly similar, except that a noticeably lower "yield stress" was observed for the two pretensioned fabrics, compared to the unpretensioned cases. Modulus and resistance developed at smaller displacements, before onset of second-phase behavior for the two pretensioned fabrics, was lower than obtained for the no-fabric case.

As a result of the various observations shown and discussed previously it was tentatively concluded that:

a. Fabric reinforcement increased the total ultimate strength of the system, especially after second-phase fabric reinforcement effects were achieved.

b. Type of fabric made little difference on observed load-deformation behavior.

c. Fabric pretensioning had either no significant effect or a slightly detrimental effect on the systems.

d. Second-phase effects begin to occur, for all fabrics tested, when the effective distance between plate and fabric approximated 0.3B-0.4B, thus indicating the possibility that, if the plate was initially positioned at this location, the "yielding" behavior necessary to mobilize second-phase resistance might be either eliminated or markedly reduced. In order to evaluate this potential behavior, a second testing series was conducted.

Secondary Testing

A total of 18 loading tests were conducted during the secondary testing effort. Only Typar 3401 and Mirafi 600X were tested, for reasons described previously. For all tests, loading was increased until the capacity of the test apparatus was reached.

Figure 5.14 shows results of testing with a 6-in.-dia loading plate, no fabric pretensioning, and an initial distance of 2.0 in. or 0.33B between the plate and fabric. No-fabric test data are also plotted in the Figure. When these data are compared with those of Figure 5.8 for an initial distance of 3.0 in. or 0.5B between the plate and fabric, it is noted that a much larger first-phase stress-displacement modulus and slightly greater first-phase stress (8 psi versus approximately 6.5 psi) is obtained for the 0.33B case. More importantly, a plate displacement of only 0.07B was necessary to develop second-phase

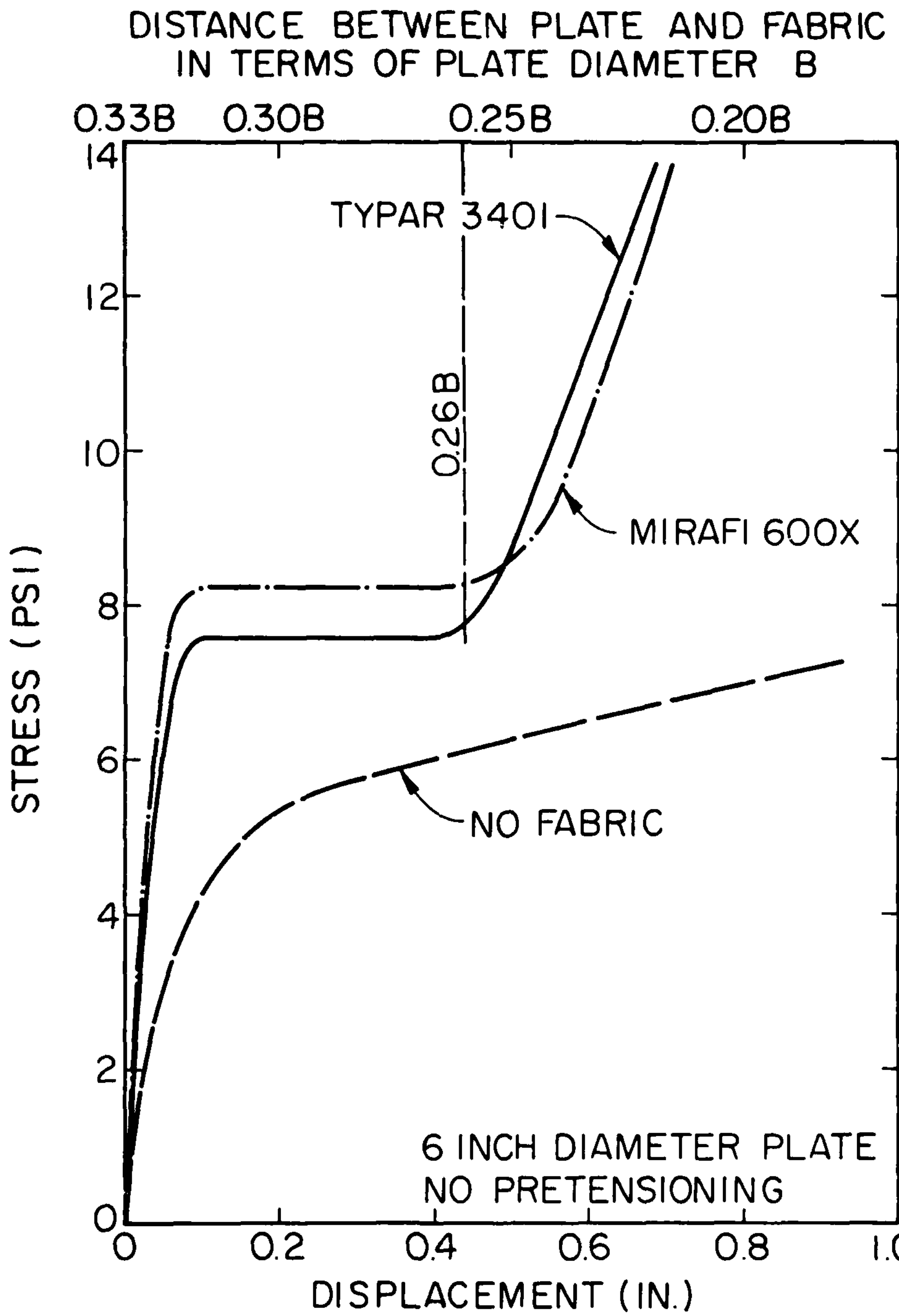


Figure 5.14 Stress-Deformation Behavior for Fabric-Reinforced Soil Mass with 6-in.-dia Plate Initially 0.33B Above Fabric

resistance of the 0.33B fabric-reinforced systems, as compared to approximately 0.17B when the distance between plate and fabric was initially 0.5B. Further, a marked improvement in deformation resistance is noted, compared to the no-fabric case, with initial behavior of the fabric-reinforced systems approximating "elasto-plastic" action. Thus, a secant modulus to the stress-displacement curve at any displacement would indicate considerably more deformation resistance from the fabric-reinforced systems.

The experiment was repeated for the 4-in.-dia plate located at a distance of 1.3 in. or 0.33B above the fabric. Results of this test series are shown in Figure 5.15, as are the no-fabric data. When the curves of Figure 5.15 are compared to those of Figure 5.9 for a 4-in.-dia plate initially 0.5B above the fabric, a large increase in initial deformation modulus and in first-phase stress (from approximately 3 psi to 6 psi) are noted for the 0.33B case. Further, a displacement of only 0.03B is required to develop second-phase resistance for both fabric-reinforced systems, as compared to a 0.18B displacement required for the 0.5B case shown in Figure 5.9. Also, for both fabrics, the fabric-reinforced system secant stress-deformation modulus is greater than the no-fabric case for all displacements, a condition not achieved for an initial distance of 0.5B between plate and fabric.

Again, essentially the same stress-displacement relationships were noted for both fabrics, despite their different physical properties. Also, it is interesting to note that the displacement required to develop second-phase resistance for the 6-in.-dia plate (0.07B) was approximately twice the displacement required to develop second-phase resistance with the 4-in.-dia plate (0.03B). While no exact correlation can be obtained from these limited data, the data do substantiate the well-known concept of decrease in soil modulus with increase in effective size of contact area.

EVALUATION OF RESULTS

As a result of the experimental testing program described in the previous section, several observational conclusions may be drawn, some of which were not noted in the state-of-the-art review and literature

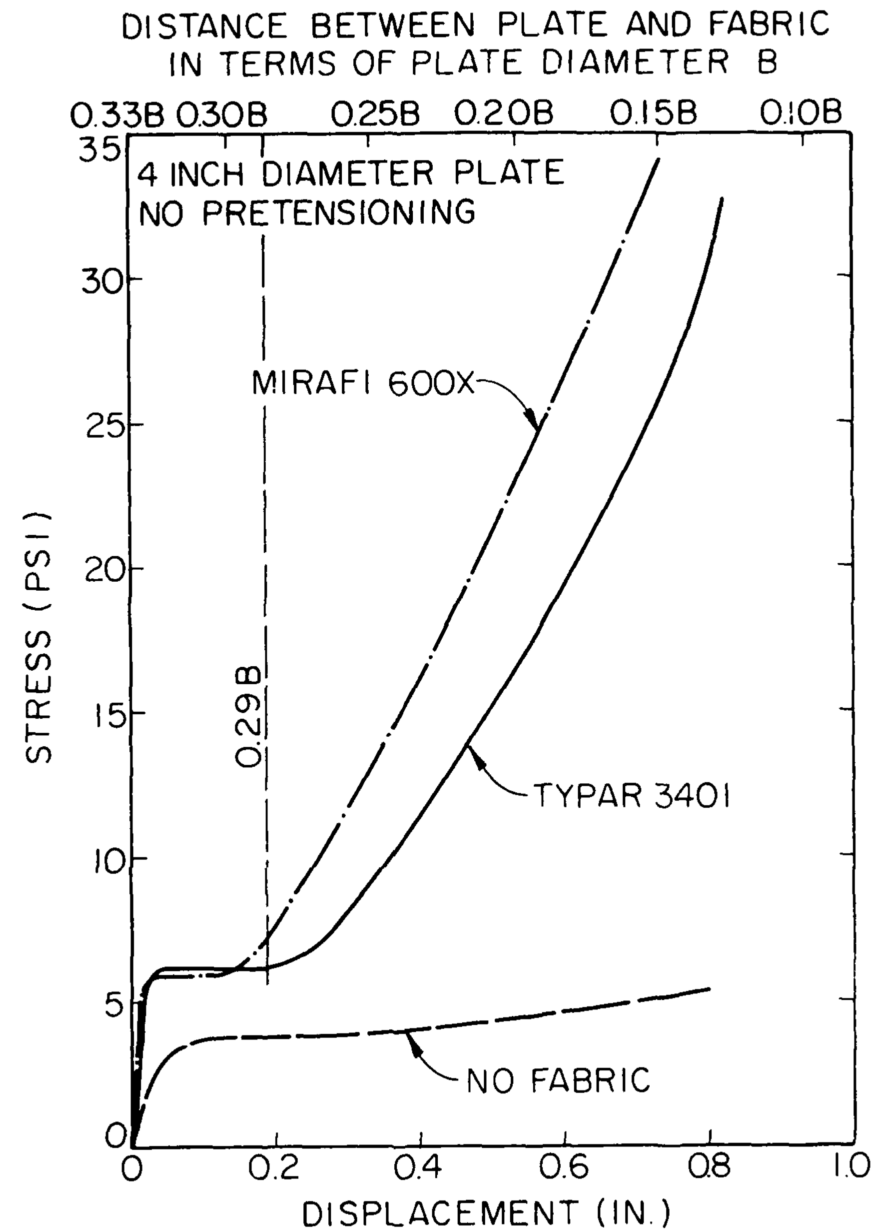


Figure 5.15 Stress-Deformation Behavior for Fabric-Reinforced Soil Mass, 4-in.-dia Plate Initially 0.33B Above Fabric

survey of Chapter 2. However, some of the behavior observed experimentally was discussed conceptually in Chapter 3. Essentially, it was noted that:

a. Stress-deformation behavior for fabric-reinforced soil mass systems is composed of three distinct phases:

1. An initial condition in which applied stress produces relatively small deformations, and with the fabric-reinforced system deformation modulus either essentially the same or greater than the unreinforced soil mass, depending upon initial distance between plate and fabric.
2. A yielding phase, which occurs at a stress either essentially the same or greater than the unreinforced soil mass, depending upon initial distance between plate and fabric. In the yielding phase, loading plate displacement (sinkage) occurred very rapidly and heaving of the soil surface around the boundary of the loading plate was observed.
3. A secondary strength gain phase, in which the fabric-reinforced soil systems continue to develop load at a fairly rapid rate, with deformation modulus approximately equal to the initial modulus of the system. Second-phase resistance was noted to occur, at essentially a linear rate, until the load capacity of the test apparatus was reached.

b. For initial fabric embedment depths of 0.33B, resulting stress-displacement curves for the initial and yielding phases resemble that of an elasto-plastic material, rather than exhibiting the nonlinearity expected for sand and observed for the no-fabric system.

c. Observation of fabric after testing indicated no disturbance, abrasion, or other noticeable effects from the loading, except for the last test sequence conducted with a 4-in.-dia plate located 1.3 in. (0.33B) above the fabric. In this instance the Typar 3401 fabric was bulged under the load plate and some small dimpling occurred from embedment of sand grains, as shown in Figure 5.16. The significance of this behavior will be discussed subsequently.

d. Despite a wide variation in physical properties among the four fabrics, no noticeable difference in observed stress-displacement

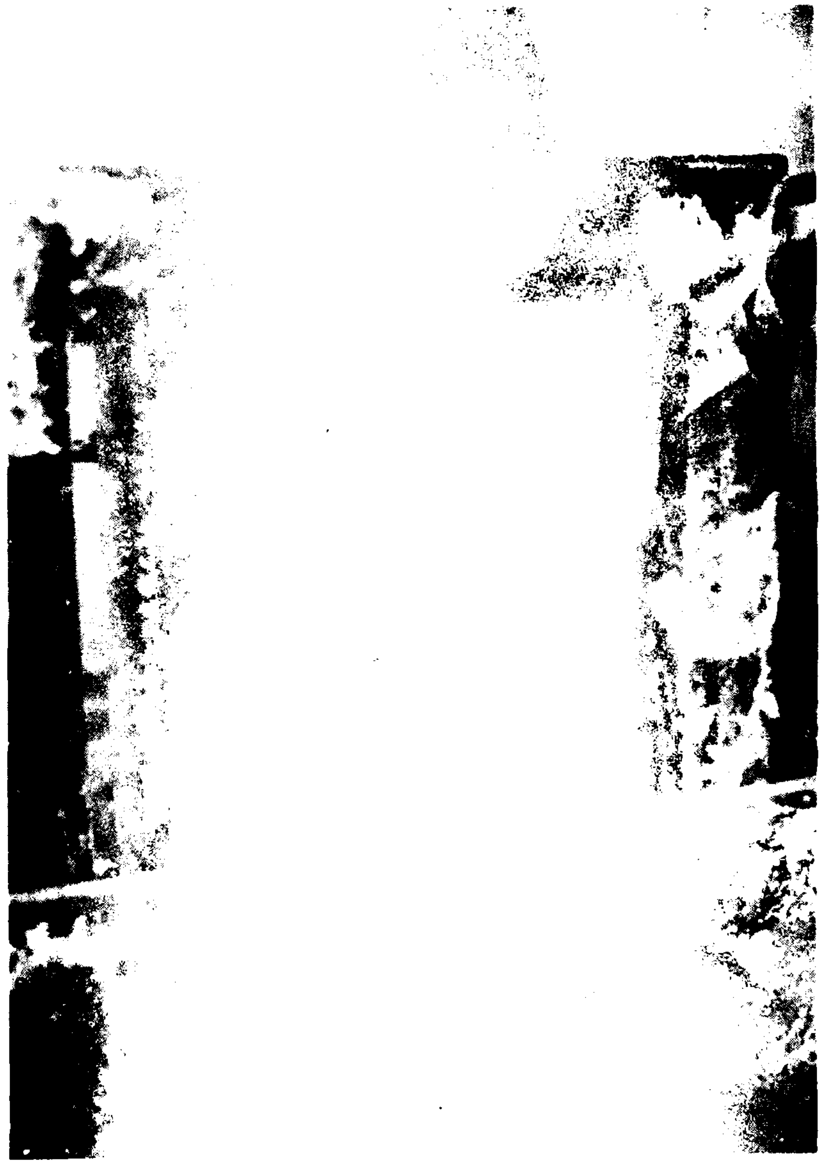


Figure 5.16 Permanent Deformation (Buldging) Noted in Typar 3401 Fabric After Test with 4-in.-dia Plate Initially 0.33B Above Fabric

behavior for fabric-reinforced systems resulted from the type of fabric employed.

e. For the two fabrics tested, the effect of small (2% elongation) pretensioning or fabric prestress was found to be, if anything, slightly detrimental to fabric-reinforced soil mass system behavior.

f. For an initial distance between loading plate and fabric of approximately 1.0B, no significant improvement in fabric-reinforced soil mass behavior was noted until second-phase resistance was developed, at a distance of 0.4B' between the loading plate and fabric. When the initial distance between plate and fabric was reduced to 0.5B, minimal to moderate improvement of initial stress-displacement behavior was noted for the fabric-reinforced systems, but significant differences (compared to the no-fabric case) did not occur until second-phase resistance began, at a distance of 0.3B' between plate and fabric. However, when the initial distance between plate and fabric was decreased to 0.33B, a significant increase in initial stress-displacement modulus and initial strength prior to yielding was achieved, compared to the no-fabric case. Also, second-phase resistance was developed at plate displacements of less than 0.1B, for both plate diameters tested. It would thus appear that the concept of optimum embedment depth as postulated in Chapter 3 is valid and that the optimum embedment depth for obtaining maximum soil reinforcement (not considering membrane-type support) is approximately one-third the width of the loaded contact area.

It should be noted that the tests conducted were of short duration. Had the applied load been held for longer periods or had dynamic loading been applied, different behavior relationships might have been noted. Also, the frame used to secure the fabric provided positive anchorage and did not allow lateral fabric slip during any test. Obviously, as fabric embedment depth decreases, the weight of overlying cover material, which provides fabric anchorage through soil-fabric friction, will also decrease. At some point fabric slippage might occur, such that the behavior described previously might not occur. As fabric slippage from inadequate anchorage occurs, behavior of a fabric-reinforced system would perhaps approximate and approach that of the no-fabric case. Finally, it should be reiterated that the experiments were designed to isolate [illegible] al restraint effects, by eliminating membrane-type action. [illegible]

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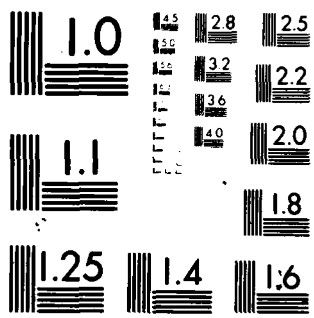

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fabric had been placed on a very weak soil rather than dense sand, failure of the soil under the fabric might have occurred with increasing stress application. In such instance, full second-phase strength gain might not have been developed.

Even though the fabric-reinforced soil mass experiments were of a somewhat simplistic nature, the results are believed to have considerable technical significance. The concept of an optimum placement depth, while previously hypothesized, has not been experimentally verified, to the authors' knowledge. Also, the marked similarity of behavior for all fabric-reinforced systems, without respect to type of fabric, is certainly an important finding. Finally, modification of soil mass stress-deformation behavior from nonlinear to initial elasto-plastic action followed by extremely large second-phase strength gain, if previously discovered, has not been widely publicized.

PROBABLE THEORY FOR SOIL REINFORCEMENT EFFECTS

In seeking to explain observed behavior, when dissimilar fabric type had no significant effect on obtained results but observed overall behavior of the fabric-reinforced systems was significantly different than the unreinforced case, it may be tentatively concluded that increased soil resistance must result from a change in the soil deformation and failure pattern above the fabric. Previous work of Barenberg et al. [10], discussed in Chapter 2, alluded to somewhat similar behavior, as they found that fabric placed on soft cohesive subgrade increased the Terzaghi bearing capacity factor for the subgrade from a value approximating that for local shear failure to a value approximating that for general shear failure.

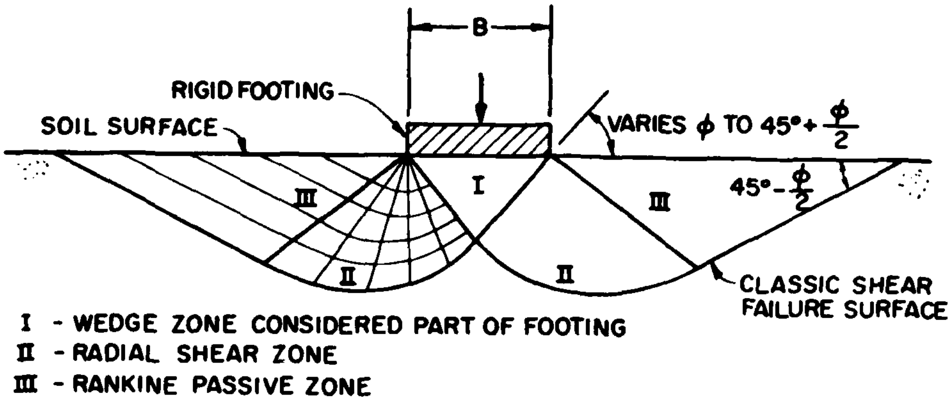
Classical Soil Bearing Capacity Concepts

In any case, to evaluate the effects of fabric interference with normal shear deformation patterns in a cohesionless soil mass, it is appropriate to examine the failure conditions postulated for such material by Terzaghi [19] in 1943. While Terzaghi's derivations were conducted for the two-dimensional case of general shear failure by an infinite strip footing on cohesionless soil, nevertheless a relevant interpretation may be obtained.

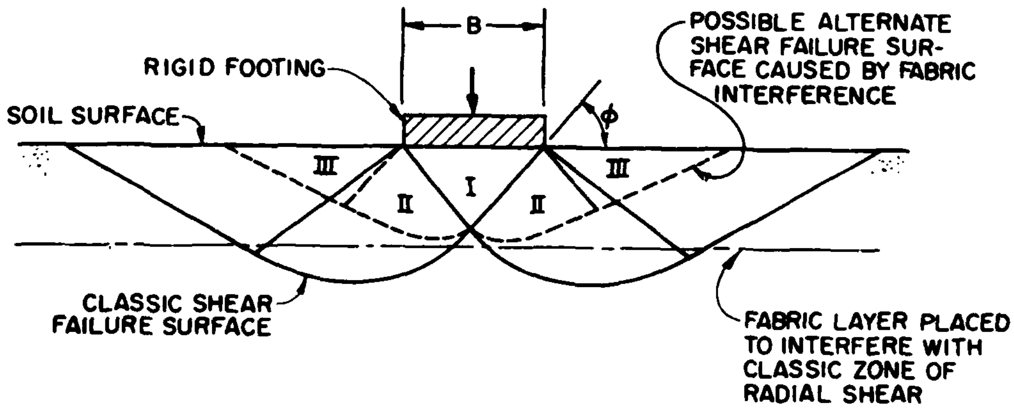
The generalized infinite strip bearing capacity shear deformation pattern is shown in Figure 5.17a. According to Terzaghi, general shear failure of the soil underneath the footing will occur, with resulting rapid sinkage of the footing into the soil, when the footing load exceeds soil resistance to plastic deformation, as expressed by the Mohr-Coulomb hypothesis. The zones of plastic equilibrium under the footing (see Figure 3.17a) can be subdivided into (I) a wedge-shaped zone beneath the loaded area, in which major principal stresses are vertical, (II) two zones of radial shear emanating from the outer edges of the loaded strip, and (III) two passive Rankine zones. Shear failure is initiated by the upward movement of the III zones and the outward rotation of the II zones, while the footing and the I zone sink into the soil. If frictional resistance exists between the soil and the base of the footing, the I zone may be, for all practical purposes, considered part of the footing.

As a result of failure, bulging or heaving of the soil occurs immediately adjacent to the edge of the footing. According to Terzaghi [19, p. 122] " . . . the sharp rise of the soil on both sides of the base of the footing has given rise to various speculations and it has been referred to as edge action. It is nothing else but the visible manifestation of the existence of two zones of radial shear. . . " This edge action behavior was observed during all experimental tests, and produced the deformations associated with the yielding behavior noted previously for the fabric-reinforced system. Second-phase soil resistance development will be discussed subsequently.

From Rankine theory, it can be postulated that the failure surface of sliding for each Rankine zone III must intercept the ground surface away from the footing at an angle $(45^{\circ} - \frac{\phi}{2})$. Also, the central wedge I under the footing will tend to move downward with the footing as bearing failure occurs. The angle of inclination for the sand wedge can vary from $(45^{\circ} + \frac{\phi}{2})$ with horizontal for an ideally smooth footing base to a value ϕ with horizontal for an ideally rough footing base. These angles are shown in Figure 5.17a.



a. CLASSIC CONDITIONS FOR GENERAL SHEAR FAILURE OF INFINITE STRIP FOOTING.



b. POSTULATED INTERFERENCE WITH NORMAL SHEAR FAILURE SURFACE BY PRESENCE OF FABRIC LAYER.

Figure 5.17 Classic Shear Failure Surface for Shallow Footing and Postulated Effect of Fabric Interference With Classic Shear Failure

The failure surface under the footing is approximated by a logarithmic spiral over the zone of radial shear II, with tangent extended to the surface under the Rankine passive zone III. In actual practice the entire failure zone probably takes on a log spiral shape. One point on the spiral is known, the tip of the wedge underneath the footing. Also, the angle of inclination with the horizontal for the Rankine zone III ($45^o - \frac{\phi}{2}$) is known. An infinity of log spirals can be constructed which satisfy this criteria; thus, an infinity of potential failure surfaces exist for the soil under the footing. The problem is similar to that of determining the critical slip circle for a slope or the critical sliding surface behind a non-vertical retaining wall, and may be solved graphically, by repeated trial and error, to develop the controlling minimax function. Failure will actually occur along the trial surface having the smallest value of soil resistance, i.e., the path of least resistance for development of plastic shear failure in zones II and III. If the trial shear surface is either above or below the critical shear surface, additional soil resistance is generated. The problem of predicting the critical shear surface is discussed in detail by Terzaghi in his development of bearing capacity formulae [19].

With this background concerning historical development and the accepted theory of plastic equilibrium bearing capacity for a shallow footing on sand, it is now possible to consider the effect of placing a fabric strip in or near the classic failure zones.

Effects of Fabric Reinforcement on Classic Soil Mass Shear Behavior

Figure 5.17b shows the classic critical failure surface underneath an infinite strip footing and, also, a strip of geotechnical fabric placed horizontally at a depth below the footing through which the critical failure surface, primarily that portion incorporating the zone of radial shear, will pass. As load applied to the footing begins to approach the normal bearing capacity of the soil, incipient failure, i.e., transition of the soil from an "elastic" to a "plastic" equilibrium state, begins to occur. Ordinarily, such behavior would occur along the classic critical failure surface. However, the fabric prevents full development of the critical shear surface, by its mere presence in the soil mass. Thus, in order for shear failure to occur, a different failure surface, acting above the fabric, must form. This condition is shown conceptually in Figure 5.17b. As the new failure surface caused by presence of the fabric is not the classic critical failure surface determined from minimax relationships, the ultimate bearing capacity of the soil mass must be increased.

Accepting this concept of fabric interference, if the fabric is placed at the base of the zone of radial shear or deeper, no increase in initial bearing capacity of the soil mass will occur from fabric placement, as the classic critical failure surface will be formed above the fabric. Also, if the fabric is placed much closer to the soil surface than the downward point of the soil wedge underneath the footing, a conventional log spiral shear failure surface cannot be formed geometrically, and some other failure mechanism or failure surface must control behavior.

In addition to producing an increase in soil mass bearing capacity, placement of a fabric strip in the region above the base of the radial shear surface but at or below the point of the wedge underneath the footing would tend to confine and restrain the soil on either side of the footing, where radial shear zones must develop. This confinement would essentially "stiffen" the soil mass and increase its deformation resistance. In such instance, real soil mass behavior might more closely approximate the theoretical general shear failure case postulated by Terzaghi, in which strains preceeding failure of the soil mass by plastic flow are very small. According to Terzaghi [19, p. 119]:

> . . . in practice the conditions for the general shear failure . . . are never completely satisfied, because horizital compression of the soil located immediately below the level of the base of the footing, on both sides of the base, is not great enough to produce the state of plastic equilibrium within the entire upper part of the [Rankine (sic)] zone . . . . On account of inadequate lateral compression the shear failure occurs while the uppermost part of the zones of potential plastic equilibrium is still in a state of elastic equilibrium . . .

Thus, the net effect of fabric placement in the region described previously would be to enforce horizontal compression of the soil on either side of the footing, by inhibiting formation of the critical failure surface in the zone of radial shear. The net effect of this restraint would be to increase the deformation modulus of the soil mass. Taking the point of the wedge beneath the footing as a point near the "optimum" fabric embedment depth, this value would range from a distance 0.5B tan ϕ for an ideally rough footing to a value of 0.5B tan $(45^{\circ} + \frac{\phi}{2})$ for an ideally smooth footing. Thus, the fabric should be near this depth. Comparison of obtained experimental data with such values, considering the dissimilarity between a continuous strip footing and a finite-diameter circular footing, will be made subsequently.

As discussed previously, if the fabric is placed below the zone of radial shear failure surface, no initial increase in soil bearing capacity should result. However, in such instance, the soil, upon reaching a shear failure condition, will displace laterally and allow rapid footing sinkage. If, according to Terzaghi, the sand wedge under the footing may be considered a part of the footing, then it must subside with the footing. As subsidence occurs, the point of the wedge must sink deeper into the soil and, if plastic shear failure continues, the classic shear failure surface emanating from the point of this wedge and curving below the zone of radial shear and under the passive Rankine zone must also sink deeper into the soil, keeping pace with the advancing tip of the sand wedge underneath the footing. A slight increase in footing load, above the original failure value, would be required to perpetuate the shear failure, because of overburden surcharge effects.

In normal geotechnical practice, conditions of soil mass behavior after initial failure are considered irrelevant. However, if fabric was placed horizontally in a soil mass below the critical shear surface, once failure occurred, downward movement of the footing and sand wedge below the footing would occur and, as the point of the wedge approached the fabric, such that the zones of radial shear (if formed) would have to pass through the fabric, fabric presence would inhibit formation of the classic critical failure surface and, instead, produce horizontal confinement and restraint in the zones of radial shear. This confinement would return the radial shear zones to a state of "elastic" equilibrium and force a different failure surface to be developed for redevelopment of plastic equilibrium conditions.

Thus, placement of the fabric at a "deeper than optimum" depth will not prevent development of soil mass reinforcement effects, but considerably more soil deformation and footing sinkage will be required to mobilize the reinforcement effects. Behavior expected for such a system would consist of initial nonlinear load-deformation behavior similar to that expected for a no-fabric soil mass, followed by large deformations with minimal increase in stress, once initial shear failure occurs, followed by an increase in soil mass resistance as the point of the sand wedge approaches the fabric placement level. In a sense, this secondary soil mass resistance could be called "strain-hardening."

It should be noted that the postulated "strain-hardening" behavior would occur for a fabric-reinforced soil mass even if the fabric was placed initially at the "optimum" depth. Fabric placement at the optimum depth would, as discussed previously, cause a different-than-classical shear surface to be developed, resulting in a higher soil mass initial bearing capacity. However, once a plastic equilibrium state was achieved and shear failure resulted, the footing and underlying wedge must still sink into the soil. As this sinkage occurs, the base of the zone of radial shear for the actual shear surface which developed above the fabric will be brought into closer proximity with the fabric layer. When sinkage has occurred to the point where the shear surface below the actual zones of radial shear would now pass through the fabric layer but cannot because of fabric presence, plastic behavior in the radial shear zones must cease and the soil must return to a state of elastic equilibrium. As a result of this transition back to an elastic state, footing sinkage would cease abruptly. If footing load was further increased, a load-deformation relationship similar to that obtained prior to initial shear failure should result.

As when placed initially at optimum depth, presence of the fabric layer confines and restrains the zones of radial shear and forces any future shear failure to occur along a new shear surface, again located above the fabric. When failure along the new (second) shear surface occurs, it is highly probable that the events of the initial failure would be repeated, i.e., mobilization of plastic behavior in the new (second) zones of radial shear above the new (second) failure surface, followed by rapid footing sinkage until the new (second) zones of radial shear impinged on the fabric, returning these radial shear zones to an elastic state, and reinitiating the process.

How long such a sequence could be repeated, either theoretically or practically, is unknown. Also, even though stress levels in the soil mass under the fabric will be reduced by modular ratio effects when the material above the fabric is stiffened, at some point the sub-fabric soil may undergo its own shear failure. The shear strength of the sub-fabric soil may thus control the ultimate strength of the fabric-reinforced soil mass, no matter how much stronger the material above the fabric becomes. Probable behavior is shown in Figure 5.18. A simple analogy would be that of a rigid slab on very low strength foundation. What can be deduced, however, from consideration of the above-described behavior, is that fabric presence alone would provide the confinement necessary to produce lateral soil restraint, and that restraint is produced by inhibiting development of plastic soil behavior in the zones of radial shear immediately beneath and on either side of the footing.

Summary

The authors believe that the above hypotheses represent rational explanations of the potential effects fabric placement in a uniform soil mass would have on soil mass strength and deformation behavior. The concepts of elastic and plastic soil equilibrium, while idealizations, form the basis of classical soil mechanics. Further, the Terzaghi concept of general shear failure for shallow footings is an accepted theory, which has been verified repeatedly since its publication in 1943. It should be noted that an infinite strip (two-dimensional) footing, from which theoretical Terzaghi bearing capacity concepts were developed and which was used as the authors' model in attempting to infer behavior changes resulting from fabric placement, is certainly different from the finite-diameter (three-dimensional) circular plate or footing used in the authors' experimental tests. However, numerous experiments have shown that the general load-deformation and ultimate bearing capacity behavior of circular finite-diameter footings is markedly similar to that of infinite (long) strip footings. In

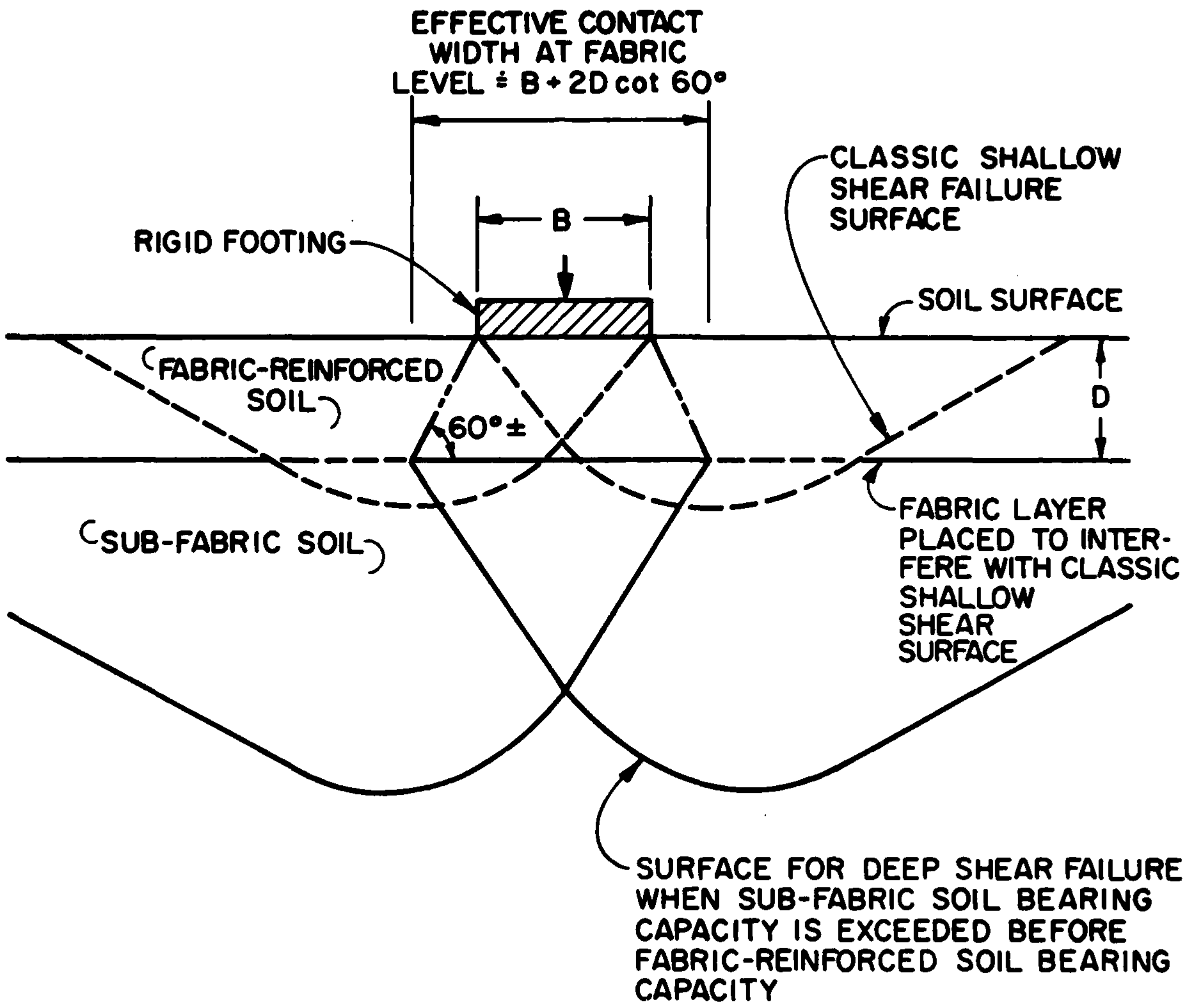


Figure 5.18 Concept of Sub-Fabric Soil Shear Failure Which may Prevent Development of Full Fabric-Reinforced Soil Strength

geotechnical practice, an adjustment is made by multiplying some of the infinite strip bearing capacity terms by empirically determined constants. Also, zones of radial shear must be developed for soil failure in both cases. Thus, the model used for behavioral inference by the authors is believed to represent, at least conceptually, a system similar to that for which experimental behavior was determined.

CORRELATION OF EXPERIMENTAL DATA WITH INFERRED THEORETICAL BEHAVIOR

Behavior postulated by theoretical inference in the previous sections may be either verified or disproved by comparison with experimentally obtained data. Assuming a "rough" footing, at least at higher contact pressures approaching ultimate soil resistance, the "optimum" depth for fabric placement under an infinite strip footing would be near 0.5B tan ϕ. Assuming this depth would not change markedly for the circular footing case and that a reasonable ϕ value for the Ottawa 20-30 sand placed above the fabric and densified by rodding into a moderately dense state would be on the order of 38 deg - 40 deg, the optimum depth for fabric placement should be near 0.39B - 0.42B. Based on actual testing, the "optimum" depth was found to be between 0.33B - 0.43B.

Thus, behavior inferred from theory for a fabric-reinforced soil system with fabric near the optimum depth appears to be realized in fact. Review of Figure 5.14 and Figure 5.15 shows that when the fabric is placed near the optimum depth, a marked increase in a initial deformation modulus and initial bearing capacity occur. Further, initial load-deformation behavior of the sand mass is transformed from the nonlinear form expected without fabric to an elasto-plastic type of behavior, more nearly approximating the classic Terzaghi general shear failure concept. Such elasto-plastic initial behavior was theorized to occur if the fabric inhibited development of plastic equilibrium conditions in the zones of radial shear under the loading plate. Further, after a relatively small amount of plastic deformation, indicated by the horizontal portions of the stress-displacement curves for the fabric-reinforced systems in Figures 5.14 and 5.15, second-phase strength gain occurs in the manner expected from fabric interference with the zone of radial shear.

For a fabric-reinforced soil mass with the fabric near optimum depth, the postulated behavioral scenario of:

a. initial increase in soil mass deformation resistance and inhibition of plastic behavior in the zones of radial shear, followed by

b. rapid footing sinkage once plastic behavior in the radial shear zones is finally developed, followed by

c. return of radial shear zones to the elastic state when footing sinkage results in fabric interference with the radial shear zone of the actual failure surface, and

d. development of additional "elastic" soil mass deformation resistance,

appears to correlate closely with experimental results shown in Figures 5.14 and 5.15. Development of second-yield conditions, which would return the radial shear zones to plastic behavior, did not occur during experimental testing, apparently because the capacity of the loading apparatus was exceeded before enough soil stress could be applied to cause return of the radial shear zones to plastic equilibrium.

Also, according to hypotheses previously described, placement of fabric an initial depth of 0.33B± below the loading plate should have allowed the sand wedge under the plate to impinge on the fabric. If the Terzaghi contention that the wedge actually moves downward as a part of the loading plate (footing) is correct, then fabric underneath the plate should have been deformed. While such behavior was not observed for the Mirafi 600X fabric after overlying sand removal, the Typar 3401 fabric, being stiffer and thus more likely to retain memory of such encounter, was noted, in Figure 5.16, to be bulged downward in the area immediately underneath the loading plate. Numerous indentations from sand grains were also observed in the fabric.

Theoretical conclusions concerning soil mass behavior if the fabric was placed too low in the soil mass are also verified by observed experimental data. As can be noted in Figure 5.10, for fabric placement initially a distance 1.0B below the loading plate, no difference in initial deformation resistance or yielding behavior is noted for the various fabric reinforced and no-fabric systems, until loading plate sinkage brings the loading plate within 0.43B of the fabric. This value corresponds reasonably well with the 0.39B - 0.42B computation for the approximate tip of the sand wedge underneath the plate. Similar behavior was shown in Figure 5.9, with the fabric-reinforced systems showing improvement only after sinkage had moved the loading plate to a distance of 0.32B from the fabric. The postulated hypothesis of initial bearing failure followed by rapid loading plate sinkage until underlying fabric interferes with plastic soil behavior in the zones of radial shear underneath and around the loading plate appears to be reasonably well verified by experimental evidence.

SUMMARY AND SIGNIFICANCE OF FINDINGS

It should be noted that only a limited program of experimental investigation was carried out and, during all experiments, positive fabric anchorage was provided so that fabric slippage was eliminated. Further, the theory used to postulate expected effects of soil mass reinforcement, while using generally accepted principles of classic soil mechanics, is for a geometrical configuration somewhat different than actually used in experimental testing. Nevertheless, the close agreement, on at least a conceptual basis, of experimental results and theoretical suppositions allows several conclusions of significance:

a. Increased initial deformation modulus and peak strength in fabric-reinforced soil systems results primarily from lateral restraint through confinement in the zones of incipient radial shear existing beneath and around the loaded area. Confinement results from fabric interference with development of normal shear surfaces. The net effect of restraint is to increase the magnitude of soil stress necessary to create plastic behavior in the radial shear zones, above that required without fabric interference. Lateral restraint through fabric presence also results in more nearly elasto-plastic behavior for the soil mass, approaching the classic general shear failure concept of Terzaghi.

b. When, despite fabric interference with classical shear behavior, soil stress of sufficient magnitude to cause plastic conditions in the radial shear zones is applied, resulting bearing failure of the soil mass (along a new failure plane above the fabric) and sinkage of the loading element as a result of plastic flow will cause the fabric to reinterfere with the zones of radial shear, returning these zones to elastic equilibrium and rapidly terminating loading element sinkage. This phenomenon is defined as "strain-hardening" of the fabric-reinforced system. The net effect of strain-hardening is to radically increase the ultimate load capacity of the soil above the fabric.

c. Assuming adequate anchorage, the optimum depth for fabric placement to maximize initial soil mass deformation resistance and ultimate strength and minimize the amount of yielding necessary to mobilize strain-hardening is approximately 0.5B tan ϕ beneath a loaded area of width B.

d. The net effect of fabric placement below the optimum depth is to obtain initial soil mass deformation behavior and bearing capacity comparable to that of an unreinforced soil mass, followed by rapid loaded area sinkage, until the base of the soil wedge beneath the loaded area impinges on the fabric, at which time strain-hardening will begin to occur. Thus, too-low fabric placement will require additional soil strain before strain-hardening can occur. In a roadway or runway situation, such an initial bearing failure might be characterized as wheelpath rutting.

e. Interference with the zones of radial shear underneath the loaded area is caused by presence of the fabric in the soil mass. As presence is the key factor in obtaining desired reinforcement, actual fabric physical properties are of only minor significance. This rationale illustrates why similar behavior was obtained for all fabrics used in the test program, despite an extremely wide variation in physical properties among the four materials, and also illustrates why fabric prestressing had no effect on behavior.

While the above conclusions have considerable technical significance, it should be noted that, as stated originally, the purpose of the experimental work was to separate the effect of reinforcement by restraint or interference with normal shear deformation patterns from the effects of material separation and fabric membrane-type support. The concept of strain-hardening discussed above will probably provide enough soil mass strength such that membrane-type support would never be mobilized (or needed) in a soil mass having appreciable sub-fabric strength. However, for situations in which an extremely soft soil exists beneath the fabric, system failure may occur from sub-fabric soil overstress. It should be obvious, from previous discussions, that the amount of soil support obtainable from reinforcement will be limited by sub-fabric soil strength, and also that placement of fabric cover material to a thickness greater than the optimum depth will actually decrease the initial support obtainable by restraint reinforcement. Under such conditions, if the load requirement exceeds the restraint reinforcement or sub-fabric soil support ability (whichever controls), the only mechanism remaining to provide additional system load capacity is fabric membrane-type action. Additional research to isolate and define fabric membrane-type support will complete the conceptual knowledge of fabric-reinforced soil system behavior, and such knowledge is especially important for cases where soft soils exist under the fabric.

CHAPTER 6. IMPLICATIONS OF CURRENT FABRIC KNOWLEDGE AND RESEARCH FINDINGS TO RUNWAY DESIGN WITH GEOTECHNICAL FABRIC

Considering the benefits observed for geotechnical fabric in roadways and the current state-of-the-art in design of such systems, as described in Chapter 2, the potential implications of such information to the design of airfield runways, as discussed in Chapter 3, and experimental results developed in this study, as discussed in Chapters 4 and 5, qualitative implications concerning runway structure design with geotechnical fabric can be obtained. These implications are discussed herein.

In order to predict, even qualitatively, a set of design concepts for using geotechnical fabric, it is necessary to consider, in turn, effects which might result from the three fabric improvement properties, separation, lateral restraint reinforcement, and membrane-type support, in a runway system. It is fairly obvious that the separation function will be required only where soft, wet, cohesive subgrades exist or saturated cohesionless fines pumping may occur.

While data and conclusions presented in Chapter 5 were based on static loading conditions rather than the dynamic loadings applied to runways, the authors believe that, at least conceptually, the basic conclusions of research are valid for runway design, as whether loadings be static or dynamic, soil mass shear failure can occur only if plastic equilibrium is developed in radial shear zones under the loaded area. Therefore, unless a weak soil layer is present beneath the fabric, strain-hardening of material above the fabric, from lateral restraint reinforcement, will likely provide all the strength necessary to carry aircraft loadings. Thus, the most simplistic design concepts would be for those cases where lateral restraint reinforcement is necessary, separation is not required, and membrane-type support is not expected. These situations should occur primarily for expedient airfields to be constructed of less-than-optimum cohesionless materials but without weak subgrades, alternate launch surfaces, where ability to resist only a few load repetitions without excessive launch surface deformation is required, and bomb damage crater repair, where good material may be available for crater backfill but stiffening the upper portion of the material to approximate adjacent sections of the runway, is required.

Membrane-type support will be required, in addition to lateral restraint reinforcement, for situations where weaker soil under the fabric will prevent development of full strain-hardening effects. These conditions are applicable to all runway types, based on site-specific soil conditions.

DESIGN CONCEPTS USING ONLY LATERAL RESTRAINT REINFORCEMENT

Based on the simplistic experiments carried out in Chapter 5, as correlated with classic soil mechanics theory, maximum lateral restraint reinforcement may be obtained by using cohesionless base material and placing the fabric a distance of approximately $0.5B \tan \phi$ below the surface of this material, where B is the effective width of the loaded contact area and ϕ is the expected in-situ angle of internal friction for the material.

If fabric is located at the optimum depth and significantly weaker underlying materials are not present, the reinforced soil should exhibit elasto-plastic action followed by strain-hardening, even if dynamic or impact loading is applied. The net qualitative effect of this behavior would be to mobilize continued deformation resistance of the fabric-reinforced soil mass at essentially the initial tangent modulus of the unreinforced soil system and markedly increase the initial (pre-yield) load capacity of the soil.

From a design viewpoint, improvement in initial load-deformation modulus should provide a significant increase in the CBR value of the material above the fabric, as the CBR is directly related to soil load-deformation modulus. However, it should be noted that conventional laboratory and field methods for CBR determination may not measure the improvement expected, unless proper consideration is given to the differences between diameter of the CBR loading piston and optimum embedment depth of the fabric. In order to obtain reliable laboratory measurements, the fabric should be anchored properly and placed at an optimum depth related to the width of the CBR piston. Under field conditions a larger-scale CBR-type test, using a loaded contact area similar to that expected for aircraft wheel loads (actually a plate-bearing test), should be employed. Otherwise, CBR data will be measured only for the soil, not for the fabric-reinforced soil system. Similar considerations will apply if "wrong size" bearing test plates, cone penetrometers, or other devices are used to measure strength of fabric-reinforced soil systems. The primary mechanism of improvement from reinforcement results from locations of the fabric with respect to radial shear zones which would be created under an actual wheel load of given contact width; thus, tests to measure such improvement must properly consider pressure bulb and soil modulus effects.

However, even with correct CBR measurement, the resulting higher CBR values will not allow a reduction in total runway section thickness, according to standard design methods, as discussed in Chapter 2. Instead, development of design criteria which used "equivalency ratios," perhaps based on reduction of wheel load stresses below the fabric from modular ratio effects, may be a more satisfactory long-term goal.

If lateral restraint reinforcement cannot provide enough initial resistance to aircraft loading and sub-fabric soil shear failure does not occur, yielding and load sinkage must occur to mobilize soil strain-hardening. Such behavior would be noted as surface rutting, under field conditions. Once soil mass initial ultimate resistance is exceeded, however, only a relatively small amount of sinkage, on the order of 0.1B or less, was found necessary to develop significant strain-hardening of the reinforced soil, when the fabric was located near the optimum depth. From a design viewpoint this indicates that surface rutting on the order of 0.1B depth may occur in order to mobilize strain-hardening soil resistance. However, once this rutting develops, resulting strength gain from soil strain-hardening should effectively prevent further rutting.

It should be noted that the above concepts, while rational and supported by both experimental evidence and observational findings, are merely qualitative. Quantitative methodology for predicting improvement in a given soil type to be placed above the fabric has not been developed and related to aircraft loading and number of load repetitions. The minimum strength of sub-fabric soil necessary to obtain strain-hardening lateral restraint reinforcement behavior above is also unknown, as is the amount of cover required for proper fabric anchorage. These unknowns are, however, amenable to theoretical analysis and experimental verification. Also, differences between fabric-reinforced soil behavior under dynamic loading, as compared to essentially static behavior, must be examined. Resolution of these items should produce a simplistic quantitative methodology of runway structure design and also indicate the maximum performance improvement expected from fabric, allowing fairly rapid technical and cost-effectiveness evaluation of fabric reinforcement as a design alternative. The simplistic design concept is illustrated in Figure 6.1.

DESIGN CONCEPTS FOR RUNWAY SYSTEMS WITH LOW-STRENGTH SUBGRADE

If the reinforced material above the fabric is considerably stronger than the material existing beneath the fabric, it is possible that total load capacity obtainable from strain-hardening in the upper soil will not be realized and a failure of material beneath the fabric will occur. As shown in Figure 5.18, sub-fabric soil bearing capacity will be exceeded before the strain-hardening resistance of the upper soil is exceeded. Stresses which must be carried by the weaker soil should be reduced below levels expected without fabric, because of the increased modular ratio between materials above and below the fabric. An improvement on the order of 1.8 in sub-fabric soil load capacity can be inferred from the work of Barenberg et al. [10] and Steward et al. [3] in construction of fabric-reinforced roads on soft subgrade, as discussed in Chapter 2.

Once sub-fabric soil bearing capacity is exceeded, lateral shear displacement of material underneath the fabric will occur, with resulting sinkage of the fabric, overlying cover material, and wheel load. This behavior may be characterized as classic wheelpath rutting. Once such rutting is initiated, previous research discussed in Chapter 2 indicates that ruts on the order of 2 in.-3 in. depth are necessary to develop appreciable membrane support in high-tensile-modulus fabrics. It should be noted, however, that many of these experiments were conducted with fabric above the optimum depth for lateral restraint reinforcement, and some of the wheel load sinkage associated with numerical values given for rut development may have been that necessary to move the wheel load closer to the optimum depth.

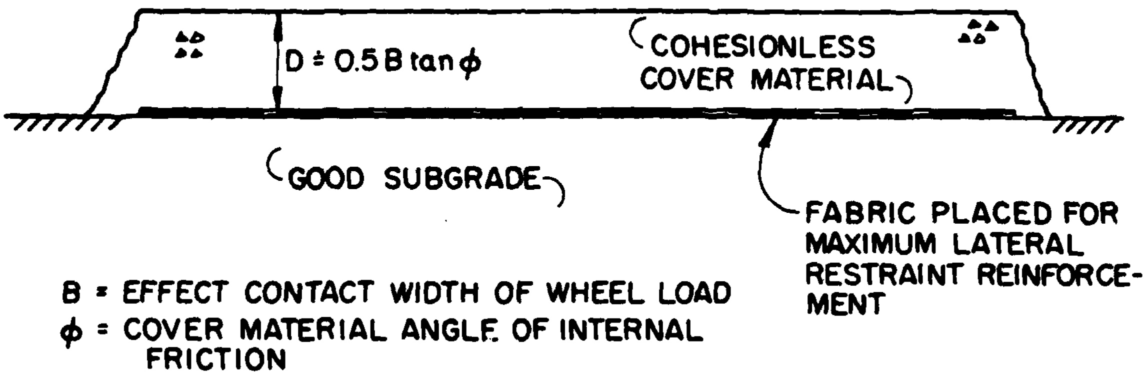


Figure 6.1 Qualitative Design for Fabric-Reinforced Runway on Good Subgrade

In any case, if the cover material strengthening available from lateral restraint reinforcement is not sufficient to carry imposed wheel loads without sub-fabric soil bearing failure, the only mechanism left to carry excess wheel load stress and obtain desired runway support is membrane-type action of the geotechnical fabric. If fabric with a high tensile deformation modulus is used, then only a small amount of wheel-path rutting may be required to develop enough membrane-type support to restore equilibrium to the runway system. Such behavior probably could be developed without in-service wheelpath rutting if the prior rutting concept of Figure 3.3 was used and the average final thickness of fabric cover material equaled the approximate optimum depth for lateral restraint reinforcement. This design is shown conceptually in Figure 6.2. The resulting runway system would have maximum reinforcement from lateral restraint and, should this restraint be insufficient to carry imposed wheel loadings, incipient subgrade failure would mobilize the previously developed membrane-type support.

It should be noted that this behavioral scenario is only conceptual, as the membrane-type support phenomenon was not isolated and evaluated during conduct of this research. Thus, the magnitude of reinforcement obtainable by membrane-type support cannot be inferred, even qualitatively. However, observed behavior in roadways indicates that appreciable values of membrane-type support can be developed in some fabrics, and it is certainly possible that total runway support capacity available from lateral restraint reinforcement and membrane-type action could resist most imposed wheel loadings. Final resolution of this question will require research, initially qualitative and then, if results are promising, quantitative, to isolate and define membrane-type support effects.

Combination reinforcement effects may be of considerable importance when runways must be constructed on soft soils. Only a limited number of engineering alternatives are available for construction on such materials, and none of the existing alternatives are particularly cost-effective. For construction on low-strength cohesive subgrades, function of geotechnical fabric in a separation mode will be important to maintain the fabric-reinforced design from long-term deterioration by subgrade intrusion.

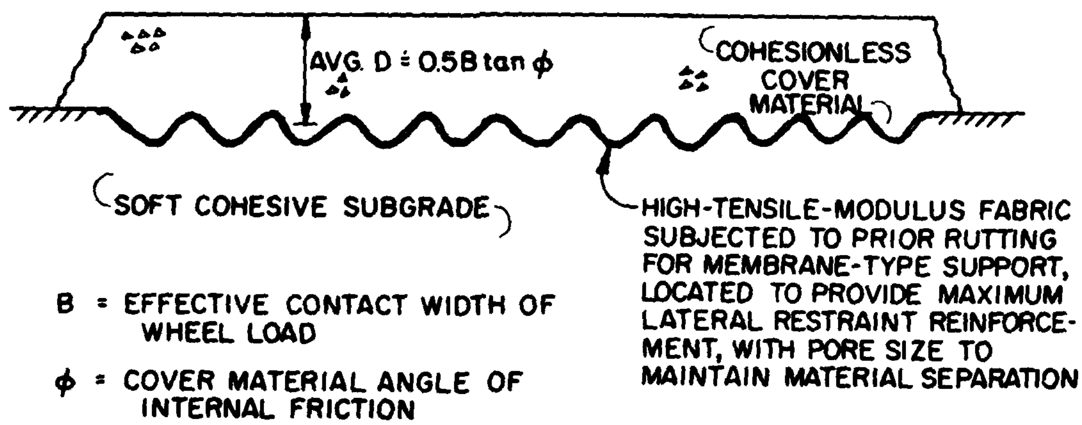
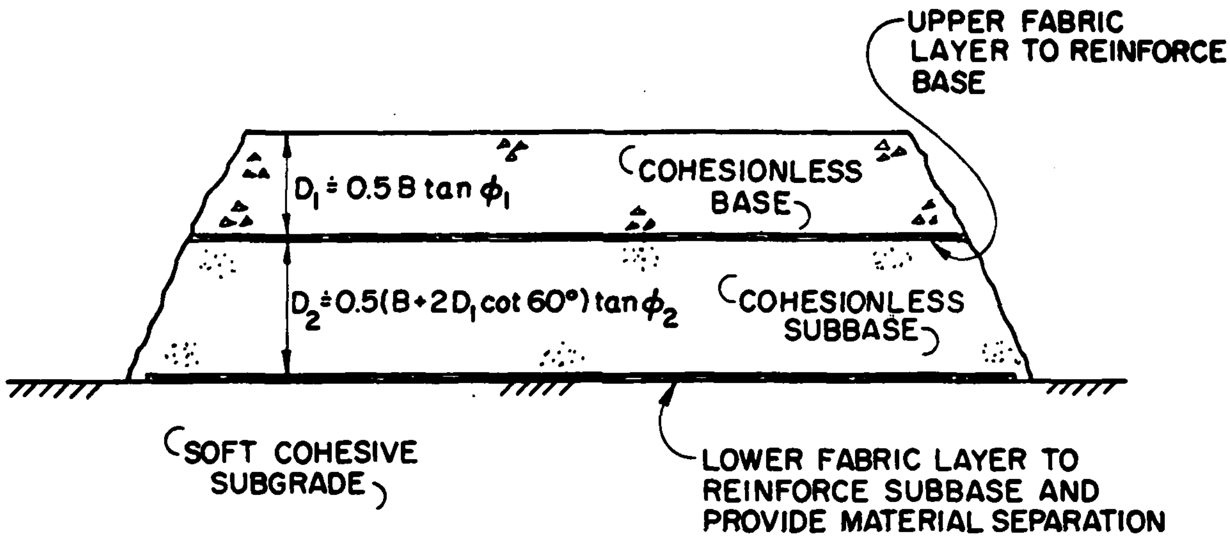


Figure 6.2 Qualitative Design for Single-Level Fabric-Reinforced Runway on Soft Subgrade

If research into membrane-type support does not prove promising, a design to prevent subgrade failure by dual-level fabric reinforcement, with the second reinforcement layer also used to provide subgrade separation, as shown in Figure 6.3, may be a viable alternative.

APPLICABILITY OF CONCEPTS TO ROAD DESIGN

Concepts presented previously have been discussed in light of their applicability to airfield runway structure design. However, it should be noted that most, if not all, of the design concepts are also applicable to road design. Thus, the use of fabric reinforcement to improve and separation to maintain roads needed for support of airfield operations should also be considered. Such applications may be of importance if soft soils are present, or if low-cost unsurfaced roads must carry heavy and/or numerous load repetitions without continuous maintenance. Latter item situations could occur in conjunction with expedient runway operation or in operation of the proposed MX missile system truck haulage network.



B = EFFECTIVE CONTACT WIDTH OF WHEEL LOAD

ϕ_1 = BASE ANGLE OF INTERNAL FRICTION

ϕ_2 = SUBBASE ANGLE OF INTERNAL FRICTION

Figure 6.3 Qualitative Design for Dual-Level Fabric-Reinforced Runway on Soft Subgrade

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

SPECIFIC CONCLUSIONS OF RESEARCH

Based on research conducted and discussed herein, it may be concluded that:

a. Four different types of geotechnical fabric were evaluated for separation potential, to prevent intrusion of soft, wet cohesive subgrade into cohesionless aggregate. Though all fabrics performed significantly better than the no-fabric case, no noticeable difference in performance among the four fabrics was found. Behavior of the model subgrade-aggregate system under cyclic load was changed from one of aggregate penetration into soft subgrade/subgrade intrusion into aggregate to one where small amounts of plastic subgrade were displaced from underneath the loaded area, at an essentially linear rate.

b. For all fabrics tested, water was pumped from the subgrade through or into the fabric and cohesive subgrade was extruded through or into the fabric and smeared along the lower surface of the fabric. Effects of subgrade strength improvement from consolidation by water expulsion or fabric clogging from subgrade intrusion were not investigated.

c. Experimental testing with uniform Ottawa 20-30 Sand (ASTM C-190) compacted to a dense state and reinforced with four different types of geotechnical fabric indicated no difference among the fabrics in development of soil reinforcement potential. Fabric prestress had essentially no effect on reinforcement behavior.

d. Lateral restraint reinforcement of cohesionless materials is caused by fabric interference with development of plastic equilibrium in soil mass zones of radial shear underneath and adjacent to the loaded area.

e. Observed experimental results may be explained by the Terzaghi theory of bearing failure for shallow footings on uniform cohesionless soil, modified to consider fabric effects.

f. Because interference with normal shear patterns is the phenomenon that produces lateral restraint reinforcement, the presence of geotechnical fabric is the important factor, and fabric physical properties are of secondary importance. Thus, essentially equal performance was obtained during the research from all fabrics, despite their widely dissimilar physical properties.

g. Because fabric presence is the controlling factor, an optimum fabric location to obtain lateral restraint reinforcement in cohesionless soils was found to exist. The optimum location for fabric placement, as suggested by theory and confirmed by experimental research, is approximately 0.5B tan ϕ below the soil surface, where B is the effective width of the loaded contact area and ϕ is the angle of internal friction for the material placed above the fabric.

h. Placement of fabric at the optimum depth to obtain lateral restraint reinforcement produces three main types of behavior:

1. Initial elastic deformation of the soil mass, at considerably greater modulus values than will exist for an unreinforced soil, and with a significantly greater ultimate soil resistance to initial shear failure.
2. After initial ultimate shear strength of the reinforced soil is exceeded, rapid yielding occurs, with associated sinkage of the loaded area. The yielding occurs as a result of plastic equilibrium development in modified radial shear zones around the loaded area and soil mass shear failure, along some failure surface above the fabric.
3. As sinkage of the loaded area occurs, the fabric begins to reinterfere with plastic flow in the modified radial shear zones, which produced the yielding of Item h.2. above, and returns these zones to elastic equilibrium, stopping the sinkage. Reinterference with radial shear surfaces generates a second-phase strength gain of extremely large magnitude, which has been denoted by the authors as strain-hardening.

Thus, soil behavior for cohesionless fabric-reinforced systems can be characterized as initial elasto-plastic action followed by strain hardening. When fabric is located at the optimum depth, maximum initial deformation modulus and ultimate strength are developed, and the amount of plastic yielding necessary to mobilize the strain-hardening phenomenon is minimized.

i. If fabric is placed below the optimum depth, minimal improvement will be noted on initial load-deformation modulus and bearing strength of the reinforced soil mass, compared to unreinforced conditions. However, once initial soil shear failure and rapid sinkage of the loaded area occurs, such that the loaded area begins to approach the optimum depth above the fabric, strain-hardening of the soil mass will occur. Thus, the net effect of incorrect (too deep) fabric placement will be to cause extra soil mass strain to obtain soil strain-hardening.

j. Experiments conducted during the research were designed to separate and isolate the effects of material separation and of lateral restraint reinforcement, and appear to have done so. The third mechanism through which geotechnical fabric provides improvement to soil systems, that of membrane-type support, was not experimentally investigated.

GENERAL CONCLUSIONS RELATED TO POTENTIAL RUNWAY DESIGN AND PERFORMANCE

Based on the state-of-the-art material presented and discussed herein and specific research conclusions previously given, it may be concluded that:

a. Geotechnical fabric has considerable potential for improving airfield runway performance, for all types of runways. The current state-of-the-art is such that site-specific design criteria are not yet available, for either estimating performance improvement or quantitatively specifying desired fabric properties. Until such criteria are available, exact prediction of performance and comparison of cost-effectiveness between fabric and any other available engineering design alternative will be seriously hindered.

b. Use of geotechnical fabric to provide material separation, eliminating subgrade intrusion and thus effective reduction in design thickness of runway base material, is a valid concept and should markedly reduce the rate of runway deterioration where soft, wet, cohesive subgrades are encountered, probably at lower cost than lime modification, placement of cohesionless subbase, or other conventional engineering alternatives. Experimental results discussed in Chapter 4 indicate that, for short-term separation, all types of tested geotechnical fabric performed in similar manner. Thus, type of fabric chosen may not be of great importance for short-term expedient runways. However, the ability of geotechnical fabric to remain unclogged for extended periods, when subjected to severe dynamic loads which may force soil particles against and into fabric pores, is an extremely important consideration in obtaining long-term acceptable performance. Such long-term performance is desirable for geotechnical fabrics placed in permanent runway structures, either hard-surfaced or unsurfaced. Long-term laboratory testing and/or field evaluation will be needed to quantitatively define the effect of fabric type and/or porosity on long-term clogging resistance, as well as the quantitative penetration, abrasion, and fatigue resistance properties desirable to withstand long-term repeated dynamic loadings without failure.

c. Based on observed behavior in roadway and railway track structures, geotechnical fabric properties which prevent intrusion of cohesive subgrade materials will also prevent pumping of low-cohesion or cohesionless fines under dynamic loading. Thus, conclusions of Item b. concerning geotechnical fabric material separation to prevent subgrade intrusion are also applicable to use of geotechnical fabric to stop fines pumping. It should be noted, however, that the tendency for fabric clogging may be higher when cohesionless fines are to be retained and the consequences of fabric clogging (excess pore pressure buildup in cohesionless or low-cohesion materials) could be more severe.

d. Use of geotechnical fabric to provide lateral restraint reinforcement of cohesionless materials placed above the fabric has considerable potential for increasing the strength and deformation modulus of such materials. Benefits should accrue from an increase in cover material ultimate strength and deformation modulus. If relatively good subgrade conditions exist, initial reinforced strength plus reserve strain-hardening strength should provide ample support capacity for most runway applications. While use of fabric as lateral restraint reinforcement should have applicability to all types of runways, it may be of most importance in expedient runway construction at remote locations, alternate launch surface construction, and localized runway bomb crater repair, by increasing the strength and deformation resistance of marginal construction materials, reducing the total thickness of the runway section, and/or increasing the magnitude of load and number of coverages that can be carried without deterioration. Lateral restraint reinforcement should also be beneficial in construction of roads, especially unsurfaced roads, needed for support of airfield activities.

e. Qualitative experimental data described and assessed in Chapter 5 indicate that the increase in strength and deformation modulus obtainable for cohesionless cover material is related primarily to the location of fabric in the runway structure, and specific fabric properties are of secondary importance. While available data allow preliminary qualitative estimation of optimum fabric placement depth as a function of wheel size and cover material strength, quantitative soil-fabric system test methods and runway design criteria do not exist to predict expected behavior for a given static or dynamic loading, number of load repetitions, available cover material, and subgrade strength. Rapid development of such criteria will be helped by the apparent simplistic nature of reinforcement mechanisms involved, but will be hindered by the semi-empirical nature of almost all widely accepted airfield runway structure design criteria. Modification of existing design criteria to consider fabric reinforcement will probably have to be done using the "equivalency ratio" concept, as developed previously for lime, soil-cement and soil-asphalt stabilization.

f. Use of geotechnical fabric to provide membrane-type support, in addition to support obtained from lateral restraint reinforcement of base material, is a potentially viable concept for use in all types of runways, at locations where soft, wet, cohesive subgrades exist. Fabric deformation by wheelpath rutting to a 2 in.-3 in. depth has been found necessary to develop appreciable membrane support on such subgrades, for high-tensile-modulus commercially available geotechnical fabrics. Concepts of prior rutting to stretch the fabric followed by final base compaction, finish grading, and, if desired, placement of wearing surface will be necessary to minimize wheelpath rutting during runway operation. At the present time, no data, quantitative or qualitative, are available concerning the magnitude of membrane support which might be developed by such "prior rutting," and whether such support would constitute an appreciable amount of the total runway support necessary for satisfactory performance. Further research effort, initially quantitative with laboratory models, and then, if promising, quantitative under laboratory and field conditions, will be required to determine the exact amount of membrane-type support that can be generated for given fabric properties and soil conditions, as well as the fabric placement procedures required to maximize such support. Direct inclusion of membrane-type support effects into existing airfield runway design criteria will also be hindered by the semi-empirical nature of the existing criteria, and "equivalency ratios" for fabric under these conditions, combined with the effects of lateral restraint reinforcement, may have to be determined.

g. If, after investigation, the membrane-type support concept does not appear viable, dual-level lateral restraint reinforcement concepts, reinforcing the base layer to carry imposed wheel loads and reinforcing a subbase layer to prevent subgrade failure (and maintain separation), should be a viable method for runway construction on soft subgrades.

RECOMMENDATIONS FOR FUTURE RESEARCH

Because of the potential for improvement in both short-term and long-term performance of all types of runways, surfaced or unsurfaced, from use of geotechnical fabric as a separation and/or reinforcement medium, additional research should be undertaken to more quantitatively define expected behavior and develop rational criteria for design of runway systems using geotechnical fabrics. Specific recommendations are as follows:

a. Investigations should be carried out, initially in the laboratory and later under controlled field conditions, to determine the long-term separation ability of geotechnical fabrics considering both separation to resist cohesive subgrade intrusion and cohesionless fines pumping. Laboratory investigations should simulate the extended repeated loading expected under field conditions. Both laboratory and field investigations should attempt to measure the long-term clogging resistance and subgrade retention of various types of geotechnical fabric, as well as the quantitative fabric properties desirable for long-term performance.

b. Initial laboratory investigations, followed by controlled field evaluations, should be carried out to quantify the qualitative lateral restraint reinforcement concepts developed in this research, also considering effects of dynamic loading and of weaker material beneath the fabric, as well as the minimum cover necessary for fabric anchorage. Of particular importance is determining the amount of stress reduction caused in a weak sub-fabric soil from increasing fabric cover material stiffness (and modular ratio) and at which level(s) of sub-fabric soil strength reinforcement of fabric cover material will cause sub-fabric soil failure rather than strain-hardening of the material above the fabric.

c. Large-scale laboratory model testing, first qualitative, then quantitative (if warranted), should be conducted to isolate and determine the magnitude of membrane-type support available from geotechnical fabric placed on low-strength subgrades, as same was not conducted during this research. If membrane-type support is proved a viable concept, controlled field evaluations should be carried out to determine optimum construction procedures for obtaining membrane-type support and the percentage of total runway system support capacity that could be expected to occur from membrane-type action under optimum conditions, separately and in conjunction with lateral restraint reinforcement.

d. Once the three fabric effects of separation, lateral restraint reinforcement, and membrane-type support are quantitatively understood, criteria may be developed for their use, separately and in combination, in both general design situations and site-specific projects, as discussed in Chapter 6. This effort should be carried out in conjunction with a comprehensive state-of-the-art review of available runway design methods and criteria, including their historical development, and of methods used previously to develop "equivalency ratios" for stabilized soils. The end product of this effort should be a rational design method or methods and/or criteria for predicting the improvement in behavior which could result from use of geotechnical fabric to provide separation, lateral restraint reinforcement, and membrane-type reinforcement, either by modification of existing runway design methods or with new design methods.

e. Construction procedures which have been successfully used in fabric-reinforced roadway construction should be scrutinized and modified, as necessary, to consider the differences between roadway and runway construction methods and the specific type of runway under consideration, and verified by controlled field demonstration, in conjunction with quantitative fabric evaluation efforts described previously.

INTERIM RECOMMENDATIONS

In the interim, until quantitative fabric selection methods and runway design procedures and criteria are available, several interim recommendations can be made for use of geotechnical fabric in airfield runway systems. Such recommendations should allow qualitative improvement of runway performance in instances where previous or current performance was/is unsatisfactory or anticipated problems from subgrade intrusion, cohesionless fines pumping, or inadequate strength runway sections might exist, considering available materials:

a. No large capital expenditure for geotechnical fabric to be used in airfield runway structures, especially where long-term performance is desired and permanent wearing surfaces are contemplated, is recommended without a satisfactory field performance test of the fabric under expected design loading conditions and a reasonable number of load applications. In evaluating fabric performance, considerable attention should be given to the potential for fabric clogging and to the observed puncture and abrasion resistance of the fabric in the test section. For short-term and/or expedient use of fabric in separation or lateral restraint reinforcement modes, any type of permeable geotechnical fabric may be acceptable, if it is not punctured and/or abraded by the cover material.

b. The optimum fabric placement location to prevent cohesive subgrade intrusion is directly on top of the cohesive subgrade.

c. The optimum fabric placement location to prevent cohesionless fines pumping is immediately above the soil layer susceptible to pumping.

d. To obtain optimum performance of geotechnical fabric in lateral restraint reinforcement, the fabric should be located at a depth below the surface of approximately $0.5B \tan \phi$, where B is the effective width of the anticipated wheel load and ϕ is the angle of internal friction for the cover material. A minimum cover material thickness of 4 in.-6 in. is suggested, to provide fabric anchorage. While quantitative design criteria are not available to predict the effect of lateral restraint reinforcement, no benefit will accrue from placement of an extra thickness of cover material on the fabric. If the fabric is located at too great a depth below the runway surface, considerable surface rutting may occur before fabric reinforcement effects will be noted.

e. If an extremely weak subgrade is present, lateral restraint reinforcement of cover material may not provide enough runway support capacity, and fabric membrane-type support or dual-level restraint reinforcement may be required. In order to develop membrane-type support, fabric should be subjected to overcompaction rolling, the ruts filled, and the surface recompacted and finish-graded. The optimum location for fabric placement would appear to be that described previously for obtaining maximum lateral restraint reinforcement. While the amount of membrane-type support which would be generated from such activity cannot be predicted at this time, only fabric with high tension modulus, high ultimate strength, and good soil-fabric frictional characteristics is likely to provide acceptable performance.

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