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The Strengthening Effect of Geotextiles on Soil—Geotextile—Aggregate Systems

L'effet de renforcement des géotextiles sur des systèmes sol-géotextile-agrégat

A two-dimensional model of a geotextile-reinforced unpaved road was constructed and used to evaluate the strengthening effect of the geotextile on the system. The laboratory test equipment, procedures, and results are described in previous reports. This report outlines the parameters needed for evaluation of the structural reinforcing effects of the geotextile in both laboratory tests and field installations. A technique for calculating the tension in the geotextile at any point within the profile is presented along with empirical factors for estimating the shape of the deformed surface at the geotextile.

Un modèle à deux dimensions d'une route non revêtue et renforcée d'un géotextile a été construit et utilisé pour évaluer l'effet de renforcement du géotextile sur le système. La description des matériaux, les procédures et les résultats de l'essai de laboratoire se trouvent dans des rapports précédents. Cet article présente des paramètres intervenant dans l'évaluation des effets de renforcement du géotextile dans les essais de laboratoire et sur le terrain. Une technique pour calculer la traction du géotextile en tous points dans la section est présentée avec des facteurs empiriques pour estimer la forme de la surface déformée au droit du géotextile.

1. INTRODUCTION

A two-dimensional laboratory model of an unpaved road was constructed and used to evaluate the strengthening effects of a geotextile in a soil-geotextile-aggregate (SGA) system when rutting occurs. The test apparatus consisted of a lucite box 1.5 m long, 0.15 m wide and 0.92 m deep. The bottom 0.59 m of the box was filled with soft clay. A geotextile was placed over the clay and covered with 76 to 229 mm of aggregate ranging in size from 6 to 25 mm. A 0.5 second duration load was applied to a 100 by 150 mm flat plate on the surface of the aggregate. Displacement measurements were made photographically through the side of the lucite box on markers placed throughout the system. A complete description of the test configuration, procedures, and results are given by Kinney (1979), and Kinney and Barenberg (1980).

A procedure was developed for analysis of the test data and projection of that data to field conditions. The general model was quite comprehensive and included the following:

* The normal stress on the subgrade induced by the goetextile.
* The shear stresses induced by the geotextile.
* The strain energy stored in the geotextile.

Using the normal stress and strain energy portions of the model, it was possible to accurately predict the behavior of the laboratory tests (Kinney 1979). When only the normal stress portion of the model was used to predict the performance of field tests, the model underestimated the beneficial effects of the geotextile (Kinney and Barenberg 1979).

This report presents the model and describes in detail some of the parameters needed in the model, including a technique for calculating the tension in the geotextile and methods of estimating the system geometry.

2. GEOTEXTILE TENSION MODEL (GTM) CONCEPT

The GTM is a mechanistic model of the behavior of the geotextile in a soil-geotextile-aggregate (SGA) system. It includes methods to determine the geotextile-induced shear and normal stresses, and the strain energy stored in the geotextile.

The normal stress created by the geotextile being stretched over a curved surface increases the stability of the system by decreasing the normal stress on the subgrade directly under the load, and by applying a downward stress on the heaved upward portions of the subgrade on each side of the rut. The net effect is to spread out the load on the subgrade, which mobilizes the resisting shear stress over a larger volume of the subgrade, Kinney and Barenberg (1980).

The shear stress on the subgrade caused by the geotextile decreases the strain naturally developed in the subgrade under the load and therefore increases the stability of the system. The shear stress on the aggregate caused by the geotextile increases the confining pressure in the aggregate, thus allowing it to distribute the load on the subgrade more effectively. It also decreases lateral spreading and subsequent rutting in the aggregate itself.

The strain energy stored in the geotextile acts in the same fashion as the strain energy stored in the soil upon loading. The elastic portion of this energy is released during unloading to cause rebound. If an SGA system undergoes rutting, then a portion of the strain energy in the soil is elastic and a portion is plastic. The strain energy stored in the geotextile reduces the strain energy in the soil, thereby reducing the plastic strains and rutting (Kinney 1979).

The geotextile-induced shear and normal stresses can be calculated if the tension in the geotextile and the deformed shape of the geotextile are both known. The sum of the shear stresses on the two sides of the geotextile is equal to the rate of change in tension per unit width of the geotextile along its length. The distribution of shear stresses between the top and the bottom of the geotextile is not as easily determined unless the geotextile has slipped with respect to one or both of the materials. If slippage has occurred, the shear stress on that side is equal to the maximum available between the geotextile and the adjoining material.

The geotextile-induced normal stress is equal to the tension in the geotextile per unit width divided by the radius of curvature.

The strain energy in the geotextile can be calculated if the tension-strain history of the geotextile is known. The general expression for the strain energy is as follows:

$$E_f = \iint_S \left[\int_E T d\varepsilon \right] ds$$

where:

E_f = Strain energy stored in geotextile
T = Tensile force per unit width
E = Strain
S = Surface area of geotextile

Strain energy is stored permanently in the geotextile due to the strain caused by the permanent deformation of the system. Additional energy is stored during the dynamic loading of the system. A complete detailed analysis of an SGA system from its construction through many load pulses would require calculation of both components of the strain energy. In the authors' experience, the permanent strain energy is comparatively small in relation to the total strain energy absorbed by the system; and therefore, only the dynamic strain energy need be considered.

If the assumption is made that the dynamic tension-strain relationship for the geotextile is linear and the problem is considered two dimensionally, the following relationship results:

$$E_f = \frac{W}{2E_s} \int_L (T_p^{\,2} - T_i^{\,2}) dl$$

where:

W = Width of the geotextile being stressed
T_p = Tensile force per unit width under peak load
T_i = Residual tensile force per unit width between loading
E_s = Linear relationship between the unit tensile force in the geotextile and the strain in the geotextile
L = Length of geotextile

The integration can be done graphically by plotting $T_p^{\,2}$ and $T_i^{\,2}$ on the vertical axis and the distance along the geotextile on the horizontal axis. The strain energy is the area between the two curves.

3. TENSION IN GEOTEXTILE

The tension in the geotextile is a function of the strain history throughout the system and the tension-strain response of the geotextile. These aspects are discussed in detail below.

3.1 General Behavior of the Entire System

Analysis of laboratory tests on model SGA systems (Kinney 1979) indicate that when there is no slippage between the geotextile and the materials above and below, the entire system behaves as a continuous unit and displacements throughout the system are proportional. After slippage occurs, the elements act more independently. The permanent displacements in the aggregate under the load and those in the subgrade still appear to be proportional to the displacement of the load, although the proportionality constants are different. The displacements throughout the geotextile and the aggregate to either side of the load, however, are significantly changed in both direction and magnitude.

Analysis of movies from the same laboratory tests indicates that there is very little relative movement between the aggregate directly under the load and the geotextile during loading. Slippage that occurs in this area appears to occur upon unloading. This is reasonable since during loading a high normal stress is built up across the boundary, creating the potential for high shear stress. Upon unloading, the potential for high shear stress is lost, and if there has not been sufficient rebound strain in the system to release the tensile stress, then slippage will occur.

3.2 Tension-Strain Response of Geotextile

If the strain-time history of the geotextile is known, the tension-time history can be determined experimentally by reproducing the strain-time history in the laboratory while measuring the tension. These tests would require very sophisticated equipment and detailed knowledge of the strain-time history of the geotextile in the field. The response can be approximated by comparatively simple tests measuring three properties of the geotextile.

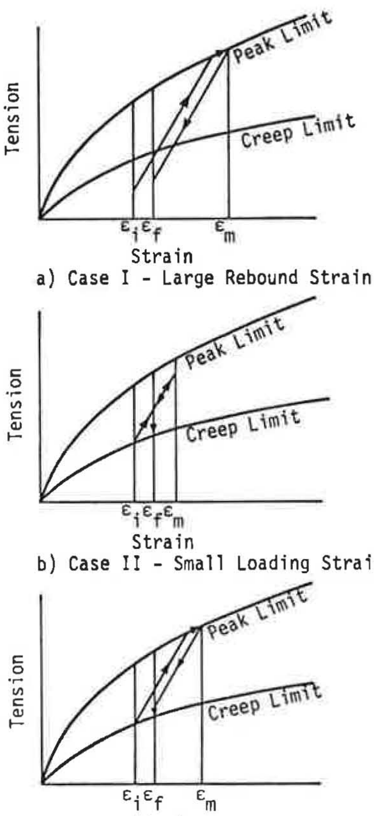
The first property is the creep limit, which is the maximum tension that can be retained in the geotextile at a given strain. A reasonable estimate of this limit may be obtained by holding a constant strain and measuring the decrease in tension with time. It may also be possible to obtain similar results using the traditional approach of holding a constant tension and measuring the increase in strain with time.

The second property is the peak repeated load tension-strain relationship. When a geotextile is strained repeatedly, there is some maximum tension that can be obtained before it will yield permanently. The results of tests performed by the authors show that a definite peak repeated load tension-strain limit is established in a relatively few number of load cycles.

There is some logic to the assumption that the peak repeated load tension-strain limit should approach the creep limit, but the experimental evidence suggests something much higher.

The third property is the relationship between the tension and the strain during the dynamic loading. Results of tests performed by the authors indicate that a fairly linear relationship is reached after a few load cycles, and that the relationship is independent of stress level.

Given these three properties, the tension in the geotextile for any strain-time history can be reasonably estimated. Figure 1 shows three possible tension-strain relationships that may exist under conditions of repetitive loading of constant magnitude. In Case I the rebound strain is sufficient to lower the tension below the creep limit. The residual tension between loadings will be below the creep limit and could be zero. The tension under peak load will be on the peak limit.



a) Case I - Large Rebound Strain

b) Case II - Small Loading Strain

c) Case III - Large Loading Strain and Small Rebound Strain

Fig. 1: Typical Geotextile Tension-Strain Relationships

In Case II the loading strain is insufficient to increase the tension from the creep limit to the peak limit. Upon unloading, the instantaneous residual tension is greater than the creep limit, hence the geotextile relaxes with time to the creep limit ready for the next load. In this case the length of time between loadings is significant. If the loadings are separated by long intervals, the residual tension between loadings will always be at the creep limit and the peak tension will be below the peak limit. Short intervals between loadings, however, will cause the peak tension to increase to the peak limit, and the residual tension between loadings to be above the creep limit.

In Case III the peak strain is more than sufficient to increase the tension from the creep limit to the peak limit; however, the rebound strain is insufficient to reduce the tension below the creep limit. The response in this case is not significantly affected by the time between loadings since the peak stress is independent of the residual starting point.

The geotextile response to any repetitive loading situation of constant magnitude will reduce to one of these three cases after a few load repetitions. If small loads are applied following a large load, the response would be controlled to a large extent by the response under the large load. If the large load caused a response as in Case I, the response under the small loads would be elastic, following the response curve from unloading the large load. When the residual tension between the small loads exceeds the creep limit, either Case II or III will control.

3.3 Calculation of Geotextile Tension

Calculation of the geotextile tension is done in two stages with two parts to each stage. First, the tension in the geotextile between loadings is determined, followed by the dynamic increase in tension during loading. In each stage the assumption is first made that there is no slippage between the geotextile and the base or subgrade. Under the condition of no slippage, the strain in the base and subgrade at the interface is estimated, giving the geotextile strain. The geotextile tension is calculated from the tension-strain relationship for the geotextile, and the tension in the geotextile is differentiated along the length of the geotextile to give the total shear stress on the geotextile. If this shear stress is greater than the maximum available, then slippage must occur. An iterative graphical procedure is described herein to demonstrate the method of determining the extent of slippage and the subsequent tension in the geotextile.

In somewhat more detail the analysis proceeds as follows:

3.3.1 Tension Between Loadings, Assuming No Slippage

The assumption of no slippage would be correct if the shear stress between the soil and the geotextile was sufficiently great. If the geotextile is soft or the deformation small, the actual shear stress developed may be high enough to validate the assumption. The geotextile tension is calculated using the following steps:

1. Determine the general tension-strain response of the geotextile.
2. Estimate the strain in the aggregate and subgrade at the interface.
3. Calculate the geotextile tension. Assume that geotextile response Case II or III is applicable and that the tension in the geotextile between loadings falls on the creep limit. Refinements for large recoverable strains, mixed loading, and rapid loading intervals can be made later if it is considered warranted.

3.3.2 Tension Between Loadings with Slippage

The analysis is then continued to determine if slippage has occurred using the following steps:

4. Determine the total shear stress on the geotextile necessary for the no-slippage condition to hold; differentiate the geotextile tension with respect to length along the geotextile.

5. Determine the maximum shear stress available between the geotextile and the materials above and below it.

If the shear stress required for no slippage exceeds the maximum available shear stress at any point in the profile, then slippage must occur and be considered. If slippage does not occur, steps 6 through 12 are omitted, and the calculations for the dynamic strain increment are started with step 13.

If slippage occurs, the following three basic rules of statics and compatibility must be satisfied in an SGA system.

* If there is no slippage, the strain in the geotextile equals the strain in the base and subgrade.
* If there is slippage, the shear stress on the geotextile will equal the maximum available.
* The total elongation within the zones of slippage must be the same for the geotextile and the materials above and below the geotextile unless the ends of the geotextile also slip.

By combining these rules in a trial and error procedure, it is possible to determine the amount of slippage at various points in the section, and to determine the tension in the geotextile.

The elongation of the geotextile can be calculated by integrating the strain in the geotextile. The strain in the geotextile is related to the tension in the geotextile, and the tension is the integral of all the shear stresses on the geotextile starting at the end. If all these relationships are lined up as shown in Figure 2, the solution becomes apparent in light of the three statics and compatibility concepts outlined above. Unfortunately there does not appear to be a closed-form solution for determining the location and width of the area of slippage. Hence, it becomes necessary to use an iterative scheme with the following steps:

6. Draw Figures 2a through 2e using the assumption that there is no slippage.
7. Estimate the location of one end of the zone of slippage.
8. Find the maximum available shear stress on the geotextile in the zone of slippage, Figure 2b.
9. Calculate the tension by integrating the shear stress from the assumed start of slippage, using the calcualted tension at that location. The end of the zone of slippage is determined when the calculated tension at that end within the zone of slippage is equal to the calculated tension just past that point where slippage has not occurred, Figure 2c.
10. Determine the strain throughout the geotextile from the tension, and the tension-strain relationship, Figure 1.
11. Integrate the strain to get the elongation and compare the elongation to the base and subgrade elongation, Figure 2e.
12. If the geotextile elongation does not coincide with the soil elongation in the areas of no slippage, then repeat steps 7 through 11 with a new location for the start of slippage.

Three special conditions may arise, but are all easily handled in turn. First, the end of the geotextile may slip. The end of the geotextile is a fixed boundary condition of zero tension and therefore controls the rest of the analysis. Second, the geotextile may slip through the entire central portion of the profile between the two wheel paths. If this happens, the geotextile can carry tension and have strain, even though the soil appears unstrained and is not slipping against the geotextile at one central point in the section. The third condition arises when the geotextile slips throughout the entire area under the wheel path. If this occurs, the controlling boundary condition is such that there can be no tension discontinuity in the geotextile.

Once the geotextile tension has been determined for the conditions between loadings, the analysis proceeds to the conditions that exist under peak load.

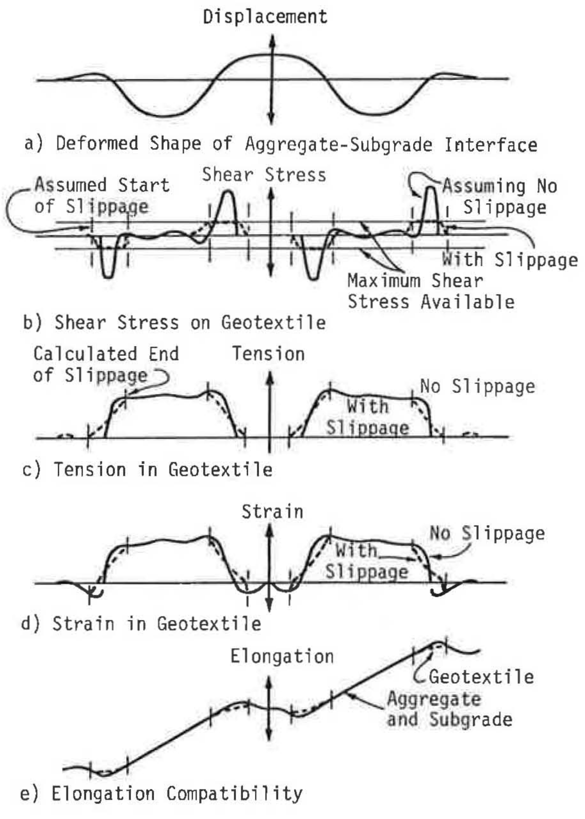


Fig. 2: Flow Diagram for Geotextile Tension Calculations Under Conditions of Local Slippage

3.3.3 Tension in Geotextile Under Peak Load

The tension in the geotextile under peak load is obtained by adding the increment of tension caused by the dynamic load to the tension remaining between loadings. The following steps are used to calculate the increment of tension caused by the dynamic load.

13. Estimate the dynamic strain increment in the aggregate.
14. Determine the tension in the geotextile, assuming no slippage between the aggregate and the geotextile during loading.

The analysis should continue to determine if slippage occurs during loading. Steps 4 and 5 are applicable; however, the maximum available shear stress is calculated using the normal stress under the peak load. If the calculated shear stress on the geotextile exceeds the maximum available at any point in the profile, then slippage has occurred. Steps 6 through 12 could be repeated to determine the extent of slippage and, hence, the geotextile tension. If the effect of slippage under peak load appears to be localized and primarily on the steep portion of the deformed interface, then revision of the geotextile tension for slippage during loading is probably not warranted.

4. DETAILS REQUIRED FOR GTM ANALYSIS

Many of the steps in the general GTM procedure require knowledge of various properties of the system that are not usually available. This section is devoted to providing the means to estimate the necessary properties to make a reasonable analysis using the GTM. The methods presented for determining the various aspects of the system geometry are based on laboratory tests, field tests, and geometrical analysis. They appear to adequately represent the system geometry.

4.1 Three-Dimensional Effect

Before application of the wheel load, the rutted profile is two dimensional and the geotextile is not under tension in the direction parallel to the rut. The response of the base and subgrade to the wheel load is three dimensional.

Based on the laboratory tests, Kinney (1979), it seems reasonable to assume that the section is two dimensional with an effective width equal to 3/4 of the width of the depressed portion of the subgrade surface.

4.2 Maximum Shear Stress Available

The maximum available shear stress on the geotextile is the sum of the maximum available shear stresses on the top and bottom of the geotextile. Each may be reasonably represented by a friction angle and an adhesion. The normal stress on the geotextile must be calculated considering the tension in the geotextile and the loading conditions at that time and location.

4.3 Recoverable Displacement of Load

The traditional solution developed by Burmister is based on a uniform circular load on a two-layer elastic system. Figueroa (1979) developed the following regression equation based on an extensive set of finite element analyses which may be more applicable:

$$\log \frac{d}{25.4} = -0.92-0.00067\ t-3.6\ E_r$$

where:

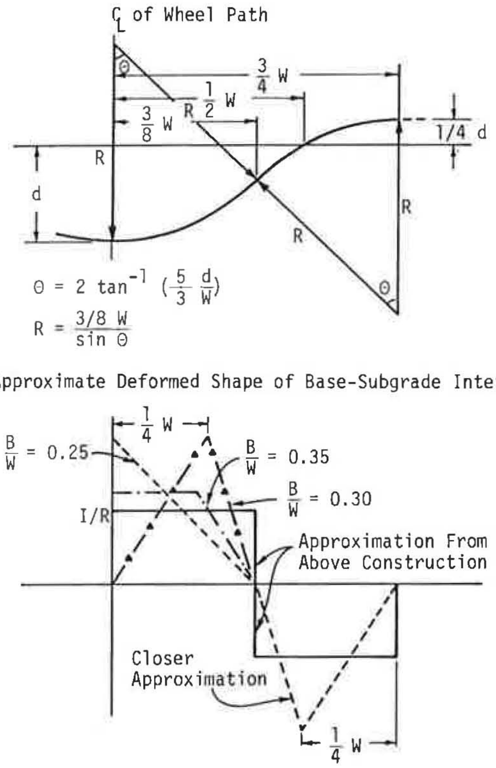
- d = Resilient displacement of load - mm
- t = Thickness of the base - mm
- E_r = Resilient modulus at a deviator stress of 41 kPa - KPa

4.4 Deformed Shape of Interface

A fairly simple graphical construction produces a surprisingly accurate estimate of the deformed shape of the geotextile in laboratory tests, Kinney (1979). The deformed shape in the field should be similar to that measured in he laboratory.

Width of Rut in Subgrade - The width of the depressed portion of the rutted subgrade is a function of the surface rut width, the aggregate thickness, and the geotextile stiffness. The relationship for estimating the width is given in detail in Kinney (1979) and Kinney and Barenburg (1980).

Shape of Rut in Subgrade - The shape of the rut can be approximated fairly accurately by using three circular arc segments of equal radius as shown in Figure 3a.



a) Approximate Deformed Shape of Base-Subgrade Interface

b) Radius of Curvature of Base-Subgrade Interface

Fig. 3: Approximate Deformed Shape of Granular Base-Subgrade Interface

Radius of Curvature of Rut in Subgrade - Although the deformed shape is quite closely approximated by circular arcs, the true radius of curvature can vary significantly from this. The variability appears to be primarily dependent upon the ratio of the width of the surface rut to the width of the depressed portion of the geotextile. Possible modifications to the basic model are shown in Figure 3b.

Elongation of Base and Subgrade at Interface - Throughout the laboratory tests, Kinney (1979) and Kinney and Barenberg (1980), the shape of the elongation curves for the aggregate and the subgrade were similar, particularly near the center. Both materials appeared to undergo nearly constant strain throughout the center portion under the load and very little strain outside this area. The total amount of elongation is the difference between the length of the curved surface of the rut in the subgrade and the original horizontal length of this same surface. The average strain is therefore the total elongation divided by the length over which most of the elongation takes place. The relationships for elongation and strain are given in Figure 4.

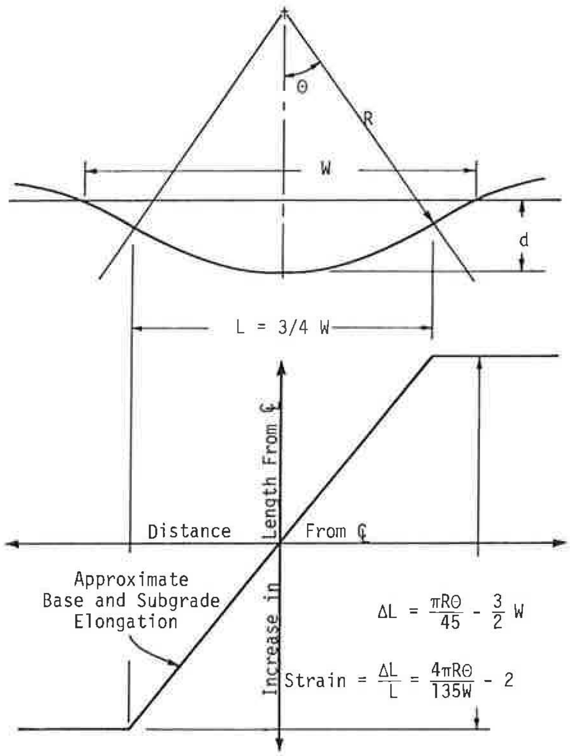


Fig. 4: Approximate Elongation and Strain in the Base and Subgrade Along the Interface

Depth of Rut in Subgrade - The amount of vertical displacement in the base subgrade interface is controlled by the depth of rutting at the surface, plus the volume change and lateral spreading of the granular materials under the load. If the surface is regraded, or aggregate sloughs off the sides of the rut into the bottom, the displacements in the subgrade will no longer resemble the displacements at the surface.

The amount of volume change of the granular material under the load is dependent upon the aggregate properties, the placement conditions, the system geometry, and the conditions of loading. It appears reasonable to assume a 5 to 10 percent total reduction in volume in the absence of any actual data. The decrease in thickness due to lateral spreading of the granular layer under the load can be calculated from the geometry of the system, based on the change in the dimensions of a rectangular block immediately below the load.

5. CONCLUSIONS

The concepts and data correlations presented herein provide valuable insight into the behavior of a geotextile in a rutted unpaved road. A technique is presented which can be used to calculate the tension in the geotextile at any point under the influence of the wheel load and empirical correlations are presented to estimate the shape of the surface of the geotextile in the area of the rut. These are combined into an outline of a design procedure which includes:

* Normal stress on the geotextile.
* Shear stress developed by the geotextile on the aggregate and the subgrade.
* Strain energy stored in the geotextile.

The performance of model tests have been accurately predicted using only the upward-directed normal stress caused by the geotextile and the strain energy stored in the geotextile. Using only the upward-directed normal stress caused by the geotextile underestimates the beneficial effects of the geotextile in field applications. More work is necessary in developing the ideas presented herein and applying them to road design. In particular, the effects of the shear stress caused by the geotextile need refinement.

6. ACKNOWLEDGEMENTS

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