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Characterization of Soil-Geosynthetic Interaction under Small Displacements Conditions

Caractérisation de l'Interaction sol-géosynthétique sous des conditions de petits déplacements

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ABSTRACT: While ultimate failure governs the performance of some geosynthetic-reinforced systems (e.g. reinforced walls), the small displacement response governs the behavior of geosynthetic-reinforced pavement systems. Yet, quantification and characterization of the effectiveness of geosynthetic products under small displacement conditions has been limited. The purpose of this study is to develop a soil-geosynthetic interaction model that captures the stiffness of the soil-geosynthetic interaction under small displacement conditions. The proposed model assumes: (1) a linear relationship between the axial strain of the confined reinforcement and its unit tension, and (2) a uniform soil-geosynthetic interface shear over the active length of the geosynthetic. The resulting force equilibrium differential equation is solved using a force boundary condition at the free end of the geosynthetic, and a displacement boundary condition at the end of the active length of the geosynthetic. The solution results in a parameter, the stiffness of soil-geosynthetic interaction, which consolidates the tensile properties of geosynthetic with the interaction properties of the soil-geosynthetic interface. Results of laboratory pullout tests illustrate the validity of the soil-geosynthetic interaction model.

RÉSUMÉ : Alors que la rupture finale régit les performances de certains systèmes renforcés par des géosynthétiques (par exemple les murs renforcés), la réponse en petits déplacements régit le comportement de chaussées renforcées par des géosynthétiques. Pourtant, la quantification et la caractérisation de l'efficacité des produits géosynthétiques sous des conditions de petit déplacement ont été peu étudiées. Le but de cette étude est de développer un modèle d'interaction de sol-géosynthétique qui prenne en compte la rigidité de l'interaction sol-géosynthétique sous les conditions de petit déplacement. Le modèle proposé suppose: (1) une relation linéaire entre la déformation axiale du géosynthétique confiné et la contrainte de traction, et (2) un cisaillement uniforme à l'interface entre le sol et le géosynthétique sur la longueur active du géosynthétique. L'équation différentielle résultant de l'équilibre des forces est résolue à l'aide des conditions aux limites à l'extrémité libre du géosynthétique, ainsi qu'une condition aux limites de déplacement à la fin de la longueur active du géosynthétique. La solution met en évidence un paramètre, le coefficient de rigidité d'interaction sol-géosynthétique, qui combine les propriétés en traction des géosynthétiques avec les propriétés de l'interaction de l'interface sol-géosynthétique. Les résultats des essais d'arrachement en laboratoire illustrent la validité du modèle d'interaction sol-géosynthétique.

KEYWORDS: Geosynthetics, Interface Shear, Soil-Geosynthetic Interaction, Small Displacement Conditions, Reinforced Pavement.

1 INTRODUCTION

Geosynthetic reinforcements are widely used in two groups of geotechnical systems: 1) Retaining walls and slopes, and 2) Pavement systems. In retaining structures and slope stabilization projects, geosynthetic reinforcements are designed to prevent the development of failure surfaces within the soil mass. Accordingly, tensile forces develop within the geosynthetic reinforcements that contribute to the stability of geosynthetic-soil composite (e.g. Zornberg and Christopher 2007). Instead, geosynthetic reinforcements in pavement applications are used to improve the performance of the paved road under in-service conditions induced by traffic and environmental loads (e.g. Zornberg et al. 2012, Roodi and Zornberg 2012). While ultimate tensile failure is the condition of concern in the design of geosynthetic-reinforced retaining structures, the small displacement response governs the performance of geosynthetic-reinforced systems in pavement reinforcement applications.

Most of the methodologies and models developed for the analysis and design of the geosynthetic-reinforced structures have focused on the maximum strength or ultimate capacity of the geosynthetic layers (Gupta 2009). However, capturing the initial stiffness of soil-geosynthetic interface is central to accurately address the small displacement behavior of geosynthetic reinforced pavement systems. In the absence of proper specifications to characterize the behavior of soil-geosynthetic interfaces under small displacements, designers have typically relied on the mechanical properties of geosynthetics in isolation (e.g. ultimate tensile strength or tensile stiffness/modulus) in an attempt to satisfy a certain level of performance (Archer and Wayne 2012). Studies have aimed at establishing correlations between geosynthetic index properties and their field performance. These index properties have included the rib strength, junction strength, aperture size, wide-width tensile strength, tensile modulus, tensile strength at 2% and 5%, and flexural rigidity (e.g. Perkins et al. 2004, Christopher et al. 2008, Cuelho and Perkins 2009, Mahmood et al. 2012, Chen and Abu-Farsakh 2012). However, most of these properties correspond to the behavior of the geosynthetics in-isolation rather than to the soil-geosynthetic interaction.

The purpose of this study is to introduce a soil-geosynthetic parameter capable of quantifying the performance of geosynthetic reinforcement under small displacement conditions. This parameter is defined as "Stiffness of Soil-Geosynthetic Interaction" or K_{SGI}, which is expected to be constant for a given soil-geosynthetic system under specific confinement stress. This paper describes the assumptions and formulations used to derive the K_{SGI}. The paper also reports on the results obtained suing a conventional pullout test setup conducted for validation of the model.

2 ASSUMPTIONS OF THE SOIL-GEOSYNTHETIC INTERACTION MODEL

The proposed model is based on two major assumptions. The first assumption concerns the Unit Tension - Strain relationship of geosynthetic products. Researchers have assumed different relationship between the unit tension in geosynthetics (T) and strain (ε). While Wilson-Fahmy et al. 1994 assumed a linear relationship between T and ε, Perkins and Cuelho, 1999 used a nonlinear relationship, and Ochiai et al. 1996 and Sieira et al. 2009 assumed it to be equal to unconfined stiffness of the geosynthetic obtained from the in-isolation wide-width tensile test. For the purpose of this study, it is assumed that the T-ε relationship of geosynthetic materials remains linear under soil confinement. However, the slope of this line would be not necessarily the same as (probably higher than) in the unconfined condition. As shown in Figure 1, the slope of T-ε line (J_c or Confined Stiffness of Geosynthetic) is assumed constant for small displacement:

$$T = J_c\, \varepsilon \tag{1}$$

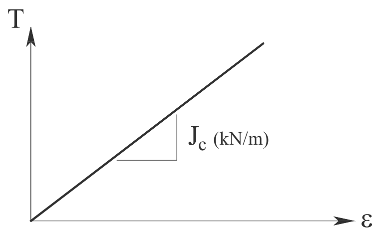

Figure 1. Tensile load-strain relationship for geosynthetic reinforcement under confinement

The second assumption addresses the relationship between soil-geosynthetics interface shear and the displacement of the geosynthetic, which is also known as interaction law. Various assumptions for the distribution of interface shear have been adopted in previous studies. For example, Sobhi and Wu, 1996 assumed a constant interface shear, while Abdelouhab et al., 2008 considered linear distribution of interface shear. In addition, a bi-linear distribution was used by Juran and Chen 1988 and Madhav et al. 1998, other non-linear distribution were used by Perkins and Cuelho, 1999, and an hyperbolic interface shear relationship was assumed by Gurung and Iwao, 1998. Sugimoto and Alagiyawanna (2003) showed that the direct evaluation of the interface properties from the ultimate state may not be appropriate to simulate the actual geosynthetic behavior in reinforced soil masses before failure in a pullout test. Sobhi and Wu (1996) defined the limit shear stress for pullout test, which was lower than the maximum shear stress and a function of overburden pressure applied to the soil-geosynthetic interface. They showed results from finite element analyses indicating the development of uniform shear stress independent of the frontal pullout force magnitude and length of the geosynthetic. In the study presented in this paper, a uniform distribution of interface shear is assumed over the active length of the reinforcement, as shown in Figure 2. The constant interface shear stress is defined as the yield shear stress (τ_y), which is independent of the interface displacement at any point along the confined active length of geosynthetic.

3 FORMULATION

The model assumptions are considered in order to solve the governing differential equation of a confined geosynthetic. The solution can be used to obtain the displacement, strain and force at any point x along the length of the geosynthetic.

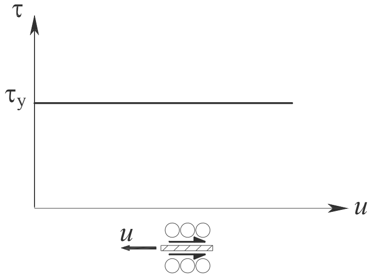

Figure 2. Interface shear-displacement relationship

As shown in Figure 3, the force equilibrium of a differential segment of the confined geosynthetic can be written as:

$$(T) - (T + dT) - (2\,\tau\, dx) = 0 \tag{3}$$

Where:

dx: *A differential segment of the geosynthetic*

T : *Unit tension in the geosynthetic*

τ: *Interface shear between soil and the geosynthetic*

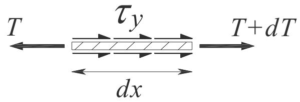

Figure 3. Force equilibrium for a differential segment of geosynthetic

Rearranging this equation returns the force equilibrium differential equation governing soil-geosynthetic interaction:

$$\frac{dT}{dx} = -2\,\tau \tag{4}$$

According to the second assumption described in the previous section, the soil-geosynthetic interface shear is constant along the active length of the geosynthetic (i.e. $\tau = \tau_y$). Also, using confined stiffness of geosynthetic system (J_c), the unit tension (T) can be replaced using Equation (1). Substituting accordingly into Equation (4) returns the following equation:

$$\frac{d(J_c \varepsilon)}{dx} = -2\,\tau_y \tag{5}$$

The axial strain in the geosynthetic can be replaced by the derivative of displacement. In addition, J_c is considered constant for a given normal pressure and under small displacements. Therefore, Equation (5) can be rewritten as follows:

$$-J_c \frac{d^2 u}{d\,x^2} = -2\,\tau_y \tag{6}$$

where u is the interface displacement. Equivalently:

$$u'' = \frac{2\,\tau_y}{J_c} \tag{7}$$

Integrating twice the differential Equation (7), returns equations for u' and u , respectively:

$$\frac{du}{dx} = \frac{2\tau_y}{J_c} x + c_1 \tag{8}$$

$$u = \frac{\tau_y}{J_c} x^2 + c_1 x + c_2 \tag{9}$$

Taking into account that $\varepsilon = -\frac{du}{dx}$, the unit tension in the geosynthetic, T, can be obtained by replacing Equation (8) into Equation (1):

$$T = -2\tau_y x - c_1 J_c \tag{10}$$

The constants c_1 and c_2 can be found using by two boundary conditions. Assuming geosynthetic reinforcement confined with aggregates, unit tension will be decreasing from one end to another (Figure 4). Conventional solutions have used two force boundary conditions at the two ends of the geosynthetic to solve the governing differential equation. However, under small displacement movements, these boundary conditions are not realistic because the entire geosynthetic length is not mobilized. In this study, and as presented in Figure 4, the geosynthetic length includes two portions: an “active portion” which moves under small displacement (i.e. portion AC in Figure 4), and a “non-moving part” (i.e. portion BC in Figure 4).

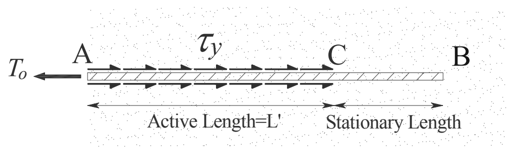

Figure 4. Boundary conditions differential segment of geosynthetic

In this study, two realistic boundary conditions are assumed to solve the differential equation under small displacement. A force boundary condition is assumed at Point A ($T_A = T_0$), and a displacement boundary condition is assumed at Point C ($u_c = 0$). Using these boundary conditions leads to unit tension and displacement functions in the active length of geosynthetic reinforcement. According to this solution unit tension in the active length is related to the displacement of geosynthetic as follows:

$$T(x)^2 = (4J_c\tau_y)u(x) \tag{11}$$

Since the confined stiffness of geosynthetic (J_c) and the yield shear stress (τ_y) are assumed constant for specific soil-geosynthetic system for a given stress conditions, the multiplier ($4J_c\tau_y$) represents a key parameter in soil-geosynthetic interaction under small displacements. This parameter is defined as the “Stiffness of Soil-Geosynthetic Interaction” or K_{SGI}.

$$K_{SGI} = 4J_c\tau_y \tag{12}$$

Equations 11 and 12 establish a linear relationship between the interface displacement ($u(x)$) and the square of the unit tension ($T(x)^2$) at any location within the active length ($0 < x < L'$). The slope of this line is K_{SGI}. These equations also suggest a parabolic relationship between T and u under small displacement regime.

4 EXPERIMENTAL EVALUATION

As an illustration of the extensive program conducted to validate the proposed model, the authors conducted a conventional geosynthetic pullout test in a large pullout box with internal dimensions of 1.5 m (60 inches) length, 0.6 m (24 inches) width and 0.3 m (12 inches) height. The test involved a biaxial geosynthetic with dimensions of 300 x 600 mm. The fill material used was clean poorly graded sand, which classifies as SP in the unified system. The sand is composed of medium to fine, and sub-angular to sub-rounded particles. The mean particle size (d_{50}) is 0.44 and the coefficient of uniformity, C_u, and the coefficient of curvature, C_c, are determined as 1.6 and 1.0, respectively. Figure 5 shows the gradation curve of this soil.

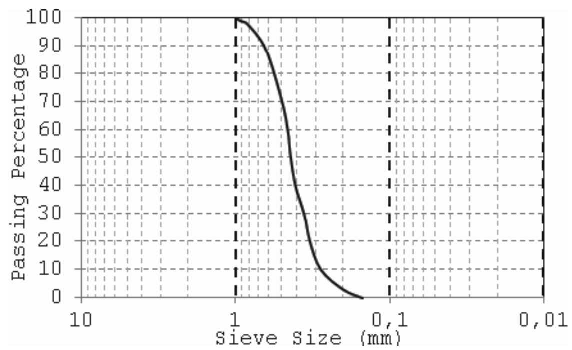

Figure 5. Gradation of the fill material used in the pullout test

Telltale wire cables were used to connect 5 linear variable differential transformers (LVDTs) to evenly spaced points along the geosynthetic length in order to accurately measure displacements of the geosynthetic during testing (Figure 6).

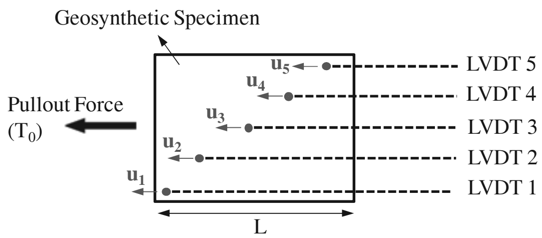

Figure 6. Schematic of geosynthetic specimen and attached LVDTs

Results of the test are presented in Figures 7 and 8 up for the initial portion of the test, up to a displacement of 1 mm. In Figure 7, square unit tension of geogrid (T) is displayed versus displacement (u) for telltale locations of LVDTs 2, 3, and 4. This figure illustrates good consistency of the results obtained using at different locations (LVDTs 2, 3, and 4). K_{SGI} values are obtained as 5.3, 7.9, and 8.6 $(kN/m)^2/mm$. Figure 8 illustrates the parabolic relationship between T and u.

5 SUMMARY AND CONCLUSIONS

Most of the parameters used in the design of geosynthetic reinforced systems consider characterization of the ultimate failure, and typically using unconfined conditions. However, the actual performance of pavement reinforced systems governs by the interaction between surrounding soil and the geogrid in small displacement conditions. In this study, a new parameter, defined as “Stiffness of Soil-Geosynthetic Interaction” or K_{SGI}, was introduced to address soil-geosynthetic interaction behavior under small displacements. K_{SGI} combines the interface shear properties of the reinforced system with the load-strain properties of geosynthetic under confined conditions.

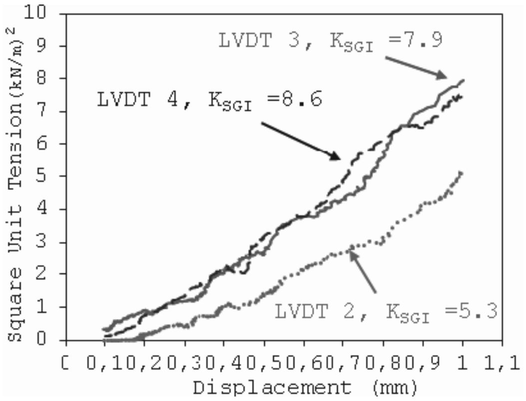

Figure 7. Results of the pullout test for LVDTs 2, 3, and 4 in $(T^2 - u)$ space

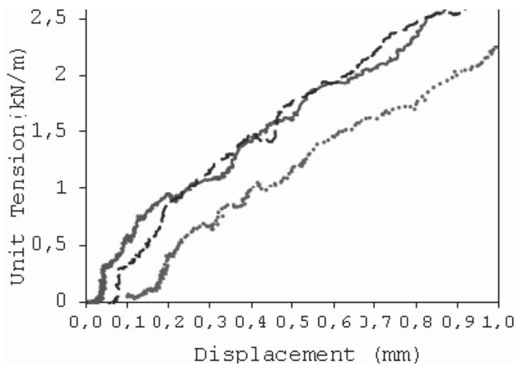

Figure 8. Results of the pullout test for LVDTs 2, 3, and 4 in $(T - u)$ space

The K_{SGI} index was built on the basis of two major assumptions. The first assumption was linear relationship between unit tension and strain in geosynthetic reinforcement under small displacement. The slope of this line is defined as J_c, Confined Stiffness of geosynthetic. In the second assumption a uniform distribution of interface shear, defined as yield shear stress (τ_y), is assumed over the active length of the reinforcement. Both parameters will be constant for a certain soil-geosynthetic system under specific confinement stress. Therefore, K_{SGI}, which corresponds to $4J_c\tau_y$, is constant for a defined geosynthetic reinforcement conditions. This characteristic can then be used as a basis to compare similar geosynthetic products to be placed under same working conditions in the field.

As an illustration, the results of a test conducted as a part of this study are presented to examine the assumptions and the outcome of the model. A biaxial geogrid was used in a conventional pullout box filled with a poorly graded sand. Five LVDTs were attached to evenly spaced nodes along the length of the geosynthetics to read the small displacements during the test. Readings from the three middle LVDTs were used to calculate the K_{SGI} values for the system. The relationships are found to be linear, with the three values reasonably close to each other, providing evidence of validity of the model assumptions.

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