Closure to "Stiffness of Soil–Geosynthetic Composite under Small Displacements: I. Model Development" by Jorge G. Zornberg, Gholam H. Roodi, and Ranjiv Gupta

Jorge G. Zornberg, Ph.D., P.E., F.ASCE

Professor, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, Austin, TX 78712 (corresponding author). Email: zornberg@mail.utexas.edu

Gholam H. Roodi, Ph.D., M.ASCE

Postdoctoral Fellow, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, Austin, TX 78712. Email: hroodi@utexas.edu

Ranjiv Gupta, Ph.D., P.E., M.ASCE

Project Engineer, Geosyntec Consultants, 11811 N Tatum Blvd., Phoenix, AZ 85028.

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The writers thank the discusser for his interest in our paper. The geotechnical community has witnessed increasing confusion between the mechanisms and properties relevant for geosynthetics that improve stability (i.e., that decrease the risk of collapse) of geotechnical structures and those relevant for geosynthetics that control deformations in soil–geosynthetic composites (SGCs). Indeed, discussion is ongoing regarding making a clear distinction between the use of geosynthetics for the function of reinforcement or for the function of stiffening (or stabilization according to some researchers) depending on whether the tensile forces developed in the geosynthetic aim at providing stability or controlling deformations (Zornberg 2017a, b). In response to the discusser's relevant comments, this closure addresses the important differences between the discusser's and authors' models, the overall purpose of the authors' paper, some necessary corrections to the discusser's statements, and some final remarks.

The model presented in Shewbridge and Sitar (1990) has fundamental differences with the SGC model presented by the authors. Contrary to the discusser's claim, the framework presented by Shewbridge and Sitar (1990) cannot be simplified or converted into the SGC model. The solution given by Shewbridge and Sitar (1990) was based on the development of a shear zone intersecting the axis of a one-dimensional reinforcement. The width of the shear zone for a shear displacement of magnitude $2B$ intersecting the reinforcement axis was expressed by a deformation decay constant b for a number of one-dimensional reinforcements (including bungy cords, parachute cords, wood rods, wood dowels, steel rods, and aluminum rods). The objective of the analytical solution developed by the discusser was to characterize the increase in the strength of the reinforced soil resulting from the contribution of reinforcement tensile and bending stresses, which is relevant for structures analyzed for limit states using procedures such as limit equilibrium. However, the SGC model was developed for a reinforcement type different than that of the discusser's model (i.e., planar geosynthetics rather than uniaxial reinforcements) and it was based on a shear mechanism also different from that of the discusser's model (i.e., shear plane along the geosynthetic rather than shear plane intersecting the reinforcement). Overall, the focus of the SGC model is on characterizing the stiffness at the onset of relative movement between soil and geosynthetic, which is relevant for geosynthetics used for the function of stiffening, such as base courses in roadways that are designed using deformation or serviceability criteria.

The discusser has apparently misinterpreted the overall purpose of the study presented by the original paper and Roodi and Zornberg (2017). As emphasized in those papers, the purpose of the study was to find a closed-form analytical solution involving a single and repeatable parameter that can capture the stiffness of a soil–geosynthetic composite. Accordingly, the authors' objective was neither to adopt the most accurate assumptions, nor to obtain the most complete and robust solution. Instead, the authors' solution aimed primarily at obtaining a closed-form solution that can capture the stiffness of the soil–geosynthetic composite with a single parameter. While this was the overriding objective, the authors thought to adopt a reasonable shear mechanism along the geosynthetic plane as well as reasonable constitutive relationships for the geosynthetic and soil–geosynthetic interface. The authors comprehensively reviewed (and appropriately cited) previous studies with similar scope and focus (e.g., Alobaidi et al. 1997; Bergado and Chai 1994; Gurung and Iwao 1999; Juran and Chen 1988; Perkins and Cuelho 1999; Sobhi and Wu 1996; Sieira et al. 2009; Weerasekara and Wijewickreme 2010; Wilson-Fahmy and Koerner 1993; Yuan 2011). However, as previously stated, the solution posed by Shewbridge and Sitar (1990) is not relevant to the focus of the study presented by the original paper and Roodi and Zornberg (2017). Indeed, as properly noted by the discusser, the Shewbridge and Sitar (1990) study was appropriately cited by Zornberg (2002, 2007) in previous work involving the use of uniaxial reinforcements (fibers) that intersect the soil shear plane.

As properly pointed out by the discusser, the constitutive relationships and force equilibrium differential equations adopted by the authors in the SGC model [Eqs. (1)–(7) in the original paper] are well established in the technical literature and are similar to those adopted in the previously cited studies. However, it appears that the discusser has only paid attention to the initial background equations in the authors' paper without focusing on the important aspects of the model, as expressed subsequently in Eqs. (8)–(21). This has led to some incorrect statements by the discusser that require correction. The aspects of the authors' formulation that go beyond considerations previously adopted in the technical literature involve the selection of specific boundary conditions that, along with specific constitutive relationships, result in a closed-form solution between the geosynthetic unit tension (T) and geosynthetic displacement along its plane (u). This analytical solution is not only explicit, but is also characterized by a single stiffness parameter (referred to as the stiffness of the soil–geosynthetic composite, or K_{SGC}). Characterization of the load transfer with a single parameter that captures both the tensile characteristics of the geosynthetic and shear behavior of the soil–geosynthetic interface is particularly relevant for practical applications such as geosynthetic stabilization of unbound base courses. The solution by Shewbridge

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and Sitar (1990) has not provided (and is not able to provide) a closed-form solution between T and u, nor has it resulted in (or is able to result in) a stiffness parameter for the soil–geosynthetic composite. In fact, contrary to the discusser's claim, neither the solution presented, nor the experimental setup reported by Shewbridge and Sitar (1989, 1990), can be simplified or reconfigured to the solution and experimental setup reported by the original paper and Roodi and Zornberg (2017). Specifically, the experimental setup employed by Shewbridge and Sitar (1989) generated reinforcement horizontal movements (i.e., movements along the reinforcement axis) only as a consequence of vertical movements induced by a shear plane intersecting the axis of the uniaxial reinforcement. Shewbridge and Sitar's (1990) solution was actually expressed in terms of the vertical displacement in the soil along the axis parallel to the direction of shear ($X1$) [or perpendicular to the direction of reinforcement ($X2$)], as follows:

$$X1 = B - B \cdot e^{-b \cdot |X2|} \tag{1}$$

Since the formulation proposed by Shewbridge and Sitar (1990) assumed a perfect adherence (i.e., strain compatibility) between soil and geosynthetic along the $X1$ direction, the soil vertical movement (along the $X1$ direction) was apparently assumed to be equal to the reinforcement movement in this direction. Consequently, the discusser's model did not address (and is evidently not able to address) the development of geosynthetic horizontal movements when vertical movements do not occur. As a result, the discusser's claim that his model can be simplified into the SGC model in the case of zero width of the shear zone (i.e., for the case when "shear displacement B is zero and b is small") is clearly not true. Specifically, an evaluation of Shewbridge and Sitar's (1990) Eqs. (6) and (7) for the case of zero shear displacement (i.e., $B = 0$ and small b) yields the following:

$$\frac{\tau}{E \cdot r} l^2 + l = l \tag{2}$$

where τ = shear stress on the skin of the reinforcement; E = elastic modulus of the reinforcement; r = radius of the reinforcement; and l = length of reinforcement in tension, according to the terminology from Shewbridge and Sitar (1990).

Apparently, Eq. (2) results in a length of reinforcement in tension equal to zero ($l = 0$). It is not the writers' intention to discredit the discusser's work or model. Indeed, the writers consider the discusser's model particularly insightful for problems such as fiber reinforcement or geosynthetic reinforcement in general when using approaches such as limit equilibrium. However, the writers' objective in this closure is to point out the significant differences between the geotechnical problems that can be addressed by the discusser's model and those that can be addressed by the authors' model. An unexpected benefit of this debate is that it highlights that the mechanical improvement geosynthetics can provide in geotechnical systems warrants being characterized by more than one function (currently the only mechanical function traditionally identified for geosynthetics is that of reinforcement).

As final remarks in this closure, it may be concluded that the correlation between the interface shear stress and vertical displacement along the shear plane (i.e., the main focus of the discusser's studies) may be useful for a variety of problems, but is not relevant to define the stiffness of the soil–geosynthetic composite (along the direction of the geosynthetic). This stiffness is particularly relevant for problems such as the stabilization of base courses in roadway applications. Although procedures and properties relevant for the design of geotechnical structures at limit states, such as reinforced walls, are comparatively well established, the procedures and properties relevant for the design of geotechnical structures under working stress conditions are not, contrary to the discusser's understanding. In particular, the main mechanism relevant to geosynthetic-stabilized base roadways involves lateral restraint in which the geosynthetic prevents lateral displacements of base aggregates through the development of interface shear. Appropriate characterization of this mechanism and relevant parameters that quantify it (e.g., parameters for use in a mechanistic-empirical design procedure) are not properly established. It is through implementation of the outcomes of the SGC model proposed by the authors into design frameworks (e.g., for geosynthetic-stabilized base courses in roadways) that advances in the design of geotechnical structures for serviceability conditions can be achieved. In the words of George Box, one of the great statisticians of the last century (Box 1979), essentially, "all models are wrong, but some are useful."

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