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Modeling the pullout behavior of short fiber in reinforced soil

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ABSTRACT

Fiber reinforcement is an effective method for improving engineering properties of soil. However, the interaction mechanism of the fiber and the surrounding soil is not well understood. Based on mechanical analysis of fiber-soil interface under pullout condition, a tri-linear model is proposed to describe the shear stress-displacement relationship. The progressive pullout process of a short fiber in soil is divided into five consecutive phases: (1) the initial pure elastic phase (Phase I); (2) the elastic-softening phase (Phase II); (3) the pure softening phase (Phase III); (4) the softening-residual phase (Phase IV); and (5) the final pure residual phase (Phase V). For each phase, the analytical solutions of the distributions of tensile force, interfacial shear stress and displacement are derived. Through a comparison between the pullout test results of polypropylene fiber (PP-fiber) and the predicted results, the effectiveness of the proposed model in capturing the progressive load-deformation behavior of a short fiber in soil is verified. Moreover, the effects of water content and dry density of soil on the model parameters are analyzed in detail. It is found that the interfacial peak/residual shear resistance and shear stiffness of fiber reinforced soil significantly depend on soil compaction conditions. In general, two transition phases (Phase II and Phase IV) are not evident during the whole pullout process of PP-fiber.

1. Introduction

The concept of reinforcing soils by introducing tension-resisting elements, such as fibers, is becoming increasingly popular in ground improvement engineering. Previous experimental studies on fiber reinforced soils have shown significant increase of cohesion and friction angle (e.g., Maher and Gray, 1990; Consoli et al., 1998, 2009; Michalowski and Cermark, 2003; Yetimoglu and Salbas, 2003; Yetimoglu et al., 2005; Cai et al., 2006; Tang et al., 2007), reduction of desiccation cracking (Consoli et al., 2003; Miller and Rifai, 2004; Tang et al., 2012), improvement of hydraulic conductivity (Miller and Rifai, 2004), mitigation of liquefaction risk (Ibraim et al., 2010; Liu et al., 2011), and improvement of piping resistance of hydraulic structures (Estabragh et al., 2014). In modeling the performance of fiber reinforced soils, most traditional approaches assume that the fiber reinforced soil is a composite material with improved properties from a macroscopic scale. Michalowski and Zhao (1996) first proposed a close-form failure criterion for fiber-reinforced sand using the energy-based homogenization scheme. Both the fiber and the granular fill are assumed to be perfectly plastic without considering the influence of confining stress on the fiber tensile strength. Zornberg (2002) established a discrete framework to predict the equivalent shear strength parameters based on the independent properties of fiber and soil. A theoretical model was proposed by Rifai and Miller (2009) to quantitatively describe the contribution of randomly distributed fiber to cracking reduction in soil undergoing desiccation. In this model, the Mohr-Coulomb failure criterion is used to model the fiber-soil interface behavior. Taking the fiber orientation and strain rate/stress direction at failure into consideration, Gao and Zhao (2013) presented a three-dimensional anisotropic failure criterion, and verified their findings using laboratory test results.

Generally, the pullout failure of discrete fiber from soil matrix as subjected to external load is recognized as one of the dominant failure mode of fiber reinforced soils. The interaction mechanism between a fiber under pullout condition and the surrounding soil is therefore of great importance. In order to quantify the interfacial shear strength, Tang et al. (2010) conducted a series of single fiber pullout tests using a modified testing apparatus. Soil water content, dry density and cement content were varied in these tests and the results show that both the peak and the residual strengths are

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influenced by these factors. More recently, Li and Zornberg (2013) and Hejazi et al. (2013) performed fiber pullout tests to study the mobilization of reinforcement forces due to the inclusion of straight fiber and loop-formed fiber, respectively. The slippage theory, together with an artificial neural network technique, was utilized by Hejazi et al. (2013) to interpret the experimental data. However, the literature review shows that few attempts have been made to develop a comprehensive theoretical model to describe the fiber-soil interaction.

In this study, the interaction between a fiber and the surrounding soil is systematically investigated and the pullout process of a short fiber in soil is divided into five consecutive phases. A theoretical model based on the tri-linear interfacial shear stress-displacement relationship was derived and the distributions of tensile force, interfacial shear stress and displacement were obtained, as well as the pullout force-displacement relationship. This model was used to interpret the pullout test results of polypropylene fiber (PP-fiber). Some conclusions have been made on the influence of water content and dry density of soil on the model parameters.

2. Mechanical analysis of fiber-soil interface

An illustrative model of the pullout of a fiber in soil is shown in Fig. 1. The fiber is idealized as a cylindrical rod with a diameter D along the fiber length L. During pullout, the fiber is assumed to be an axially loaded tension member while radial deformation is neglected. When a pullout force F_0 is applied, shear stresses are mobilized at the fiber-soil interface to resist the pullout force.

A tri-linear model is adopted to quantify the shear stress-displacement relationship of the fiber-soil interface, as depicted in Fig. 2. In this model, the fiber-soil interface first behaves elastically, which is characterized by an ascending branch up to the peak shear resistance. Afterward, stress softening emerges at the fiber-soil interface. Once the interfacial shear stress decreases to the residual shear resistance, the interface is entirely debonded and the shear stress remains constant. The relationship between shear stress $\tau(x)$ and shear displacement $u(x)$ can be expressed by

$$\tau(x)=\begin{cases} Gu(x) \quad (0\le u<u_1) & (1a)\\ 2\tau_{\max}-Gu(x) \quad (u_1\le u<u_2) & (1b)\\ \tau_{res} \quad (u\ge u_2) & (1c)\end{cases} \tag{1}$$

where $G =$ shear stiffness at the fiber-soil interface that should be determined experimentally (Unit: Pa/m); u_1 and $u_2 =$ shear displacements corresponding to the peak shear resistance $\tau_{\max}$ and the residual shear resistance τ_{res}, respectively. Considering that $u_1=\tau_{\max}/G$ and $u_2=(2\tau_{\max}-\tau_{\text{res}})/G$, there are totally three independent model parameters, namely, G, $\tau_{\max}$ and τ_{res}. It should be noted that these parameters are influenced not only by the physical and mechanical properties of soil, but also by the fiber properties, such as surface roughness.

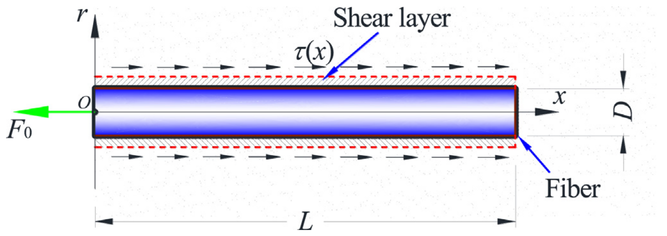

Fig. 1. Schematic illustration of pullout mechanism of a fiber in soil. The fiber is assumed to be a cylindrical rod. During pullout, the fiber is assumed to be an axially loaded tension member while radial deformation is neglected.

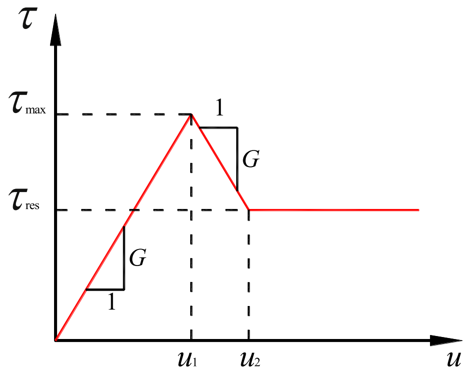

Fig. 2. Proposed model defining the relationship between shear stress and shear displacement at the fiber-soil interface.

Based on the above assumptions, the progressive pullout behavior of a short fiber in soil can be divided into five consecutive phases, as shown in Fig. 3. These five phases are described as following.

(1) Initial pure elastic phase (Phase I): When a relatively small pullout force is applied on the fiber head, the mobilized interfacial shear stress follows a linear relationship with respect to the shear displacement. Neither stress softening nor debonding occurs in this phase.
(2) Elastic-softening phase (Phase II): The fiber-soil interface remains elastic until the shear stress reaches the peak shear resistance at the fiber head, from which stress softening initiates and propagates to the fiber tail. As a result, a transition point P_1 ($x=L_s$), as shown in Fig. 3(b), is introduced here to divide the elastic and softening zones (Misra et al., 2004). Note that the interfacial shear stress at this point is equivalent to the peak shear resistance.
(3) Pure softening phase (Phase III): As the softening zone extends towards the fiber tail, the interfacial shear stress successively reaches the peak shear resistance, and gradually decreases thereafter. Once the shear stress at the fiber tail increases to the peak shear resistance, the softening zone occupies the entire fiber, as shown in Fig. 3(c). Both the pullout force and the interfacial shear stress decrease in this stage, while the shear displacement continues to increase.
(4) Softening-residual phase (Phase IV): Similar to Phase II, once the interfacial shear stress at the fiber head decreases to the residual shear resistance, the fiber turns into the softening-residual transition state. Again, a transition point P_2 ($x=L_r$) is introduced here to divide the softening and residual zones, as shown in Fig. 3(d). In this phase, both the pullout force and the interfacial shear stress decrease slightly.
(5) Final pure residual phase (Phase V): The final stage starts when the interfacial shear stress at the fiber tail decreases to the residual shear resistance. As shown in Fig. 3(e), the residual zone now occupies the entire fiber. In this stage, the pullout force remains constant, whereas the pullout displacement increases continuously.

3. Formulation of the fiber pullout model

The following derivation uses the coordinate system shown in Fig. 1. As the fiber is assumed to be elastic throughout the pullout process, we have

$$F(x)=\frac{\pi}{4}D^2E\varepsilon(x) \tag{2}$$