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Validation of Discrete Framework for the Design of Fiber-Reinforced Soil

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Abstract

Fiber-reinforcement is a promising solution to applications such as reinforcement of thin soil veneers and localized repair of failed slopes. However, fiber-reinforced structures have been conventionally designed using homogenized approaches. This has possibly compromised a rational basis for design and, consequently, the use of fibers in geotechnical practice. A new discrete approach was recently developed that allows the design of fiber-reinforced soil by independent characterization of soil specimens and of fiber specimens (i.e. similar as in the design of conventional planar-reinforced soil). An experimental testing program involving triaxial testing of unreinforced and fiber-reinforced specimens was undertaken to validate the discrete methodology. The predicted results were found to agree well with the experimental results. Additionally, this paper discusses using peak or residual shear strength of unreinforced soil in the design of fiber-reinforced soil based on the strain compatibility consideration.

Introduction

Fiber reinforcement may provide clear advantage over continuous planar reinforcements in applications such as stabilization of thin soil veneers, localized repair of failed slopes and increasing the seismic performance. Randomly distributed fibers can provide isotropic strength increases to the soil and avoid the existence of the potential planes of weakness that can develop on the soil-reinforcement interface. In localized repair of failed slopes, the irregular shape limits the use of continuous planar reinforcement, making the fiber-reinforcement an appealing alternative. When compared with stabilization approaches involving parallel-to-slope continuous reinforcement, the fiber-reinforcement technique does not require anchoring of the reinforcement into competent underlying soil. Fiber-reinforcement was also found to increase the dynamic shear modulus of soil and decrease the liquefaction potentials (Maher and Woods, 1990; Noorany and Uzdavines, 1989), thus increasing the performance under seismic conditions.

The design of fiber-reinforced soil slopes has typically been performed using composite approaches, where the fiber-reinforced soil is considered as a single homogenized material. Accordingly, fiber-reinforced soil design has required non-conventional laboratory testing of composite fiber-reinforced soil specimens, which has discouraged implementation of fiber-reinforcement in engineering practice. A new discrete approach was recently proposed (Zornberg, 2002), which predicts the 'equivalent' shear strength of the fiber-reinforced soil based on the independent properties of fibers (e.g. fiber content, fiber aspect ratio) and soil (e.g. friction angle and cohesion).

An experimental testing program involving triaxial testing of unreinforced and fiber-reinforced specimens is being undertaken to validate the discrete methodology. Some of these test results are presented in this paper, and compared to the predictions of the discrete framework. Additionally, this paper also discuss the appropriateness of using peak or residual shear strength of unreinforced soil in the prediction of equivalent shear strength based on the strain compatibility considerations.

Overview of the Discrete Framework

Although fibers contribute to increase of the shear strength of soil, they actually work in tension. As in analyses involving planar inclusions, the orientation of the fiber-induced distributed tension should also be identified or assumed. Specifically, the fiber-induced distributed tension can be assumed to act: a) along the failure surface so that the discrete fiber-induced tensile contribution can be directly "added" to the shear strength contribution of the soil in a limit equilibrium analysis; b) horizontally, which would be consistent with design assumptions for reinforced soil structures using planar reinforcements; or c) in a direction somewhere between the initial fiber orientation (which is random) and the orientation of the failure plane.

The equivalent shear strength of fiber-reinforced specimens can be defined as a function of the fiber-induced distributed tension t, and the shear strength of the unreinforced soil, S:

$$S_{eq} = S + \alpha \cdot t = c + \sigma_n \tan\phi + \alpha \cdot t \quad (1)$$

where α is an empirical coefficient that accounts for the orientation of fiber and the efficiency of the mixing of fibers. α is equal to 1 if the fibers are randomly distributed and working with 100% efficiency, otherwise α will be smaller than 1.

The fiber-induced distributed tension t, defined as the average of the fiber-induced tensile force over the area of soil, has different expressions depending on whether the mode of failure is fiber pullout or yielding. In the case of polypropylene fibers, which are commonly used in fiber-reinforced projects, the failure mode under confining pressure typical of geotechnical projects is pullout of fiber from the soil matrix because of the relatively high tensile strength of the fibers. In such case, the fiber-induced distributed tension, t_p, can be expressed as:

$$t_p = \chi \cdot \eta \cdot \left(c_{i,c} \cdot c + c_{i,\phi} \cdot \tan\phi \cdot \sigma_{n,ave}\right) \quad (2)$$

where χ is the volumetric fiber content, η is the aspect ratio (length of fiber divided by the equivalent diameter of fiber), c and ϕ are the cohesion and friction angle of unreinforced soil, $\sigma_{n,ave}$ is the average normal stress acting on the random fibers, and $c_{i,c}$ and $c_{i,\phi}$ are the coefficient of interaction defined as:

$$c_{i,c} = \frac{a}{c} \tag{3}$$

$$c_{i,\phi} = \frac{\tan\delta}{\tan\phi} \tag{4}$$

where a is the adhesive component of the interface shear strength between soil and the polymeric fiber, $\tan\delta$ is the frictional component. The equivalent shear strength for the pullout failure mode can be derived as follows:

$$S_{eq,p} = c_{eq,p} + (\tan\phi)_{eq,p} \cdot \sigma_n \tag{5}$$

$$c_{eq,p} = (1 + \alpha \cdot \eta \cdot \chi \cdot c_{i,c}) \cdot c \tag{6}$$

$$(\tan\phi)_{eq,p} = (1 + \alpha \cdot \eta \cdot \chi \cdot c_{i,\phi}) \cdot \tan\phi \tag{7}$$

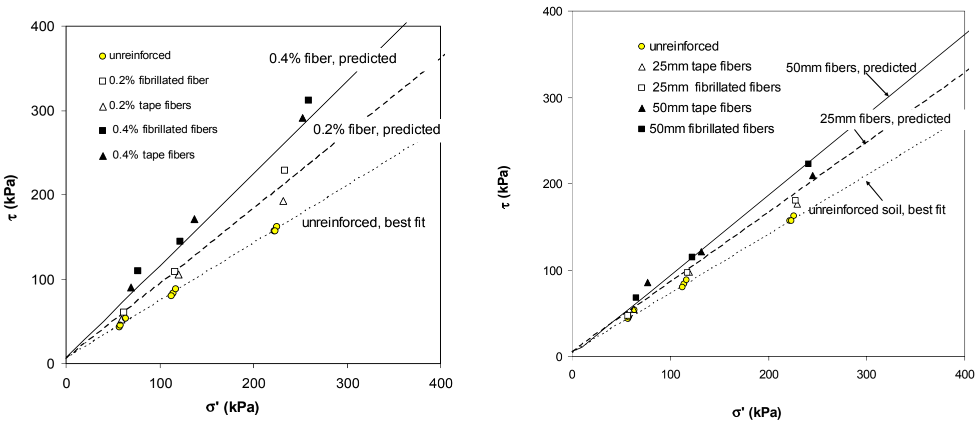
Validation of the Discrete Framework

A triaxial compression testing program on fiber-reinforced soil was implemented to validate the proposed discrete framework. Soil 1 (classified as SP), used in the testing program had a friction angle of 34.3°. The fibers used have linear densities of 360 denier and 1000 denier, and lengths of 25 mm and 51 mm. The fiber contents used are 0.2% and 0.4%. A different combination of fiber type, fiber length and fiber content were used.

Equations (5) through (7) were used to predict the equivalent shear strength for fiber-reinforced specimens. Interaction coefficients ($c_{i,c}$ and $c_{i,\phi}$) of 0.8 are assumed in the analyses conducted in this study based on the interface shear strength obtained from pullout test results conducted on woven geotextiles (Koutsourais et al., 1998). α is assumed to be 1.0 for randomly distributed fibers.

The experimental results and the predicted equivalent shear strength are compared in Figure 1. The effect of fiber content on shear strength is shown in Figure 1(a). For soils reinforced using the 360 denier fibers, the experimental results show a clear increase in equivalent shear strength with increasing fiber content. As predicted by the discrete framework, the distributed fiber-induced tension increases linearly with the volumetric fiber content. The shear strength increase using 0.4% fiber content is approximately two times of the shear strength increase using 0.2 % fiber content. Good agreement is observed between experimental data points and predicted shear strength envelopes.

The effect of fiber aspect ratio on shear strength is shown in Figure 1(b). For soils placed using gravimetric fiber content at a gravimetric fiber content (χ_w) of 0.2%, the shear strength increase using 50 mm 1000 denier long fibers is approximately two times of the shear strength increase using 25 mm long fibers. As predicted by the discrete framework, increasing the fiber length increases the pullout resistance of individual fibers, and results in a higher fiber-induced distributed tension. Consequently, for the same fiber content, specimens reinforced using longer fibers will have higher equivalent shear strength. This trend agrees well with the experimental data.



(a) 0.2% and 0.4% 50 mm long, 360 deniers fibers

(b) 0.2% 25 mm long and 51 mm long, 1000 deniers fibers

Figure 1. Comparison of the predicted shear strength and experimental results.

Additional insight into the validity of the proposed discrete approach can be obtained by comparing the results obtained for specimens with a constant value of ($\chi_w \cdot \eta$). The specimens are reinforced with 50 mm-long fibers placed at a fiber content of 0.2% with those obtained for specimens reinforced with 25 mm-long fibers placed at a fiber content of 0.4%. That is specimens with a constant value of ($\chi_w \cdot \eta$). As inferred from inspection of Equation 2 the fiber-induced distributed tension is directly proportional to both the fiber content and the fiber aspect ratio. Consequently, the predicted equivalent shear strength parameters for the above combinations of fiber length and fiber content are the same. Figure 2 combines these experimental results.

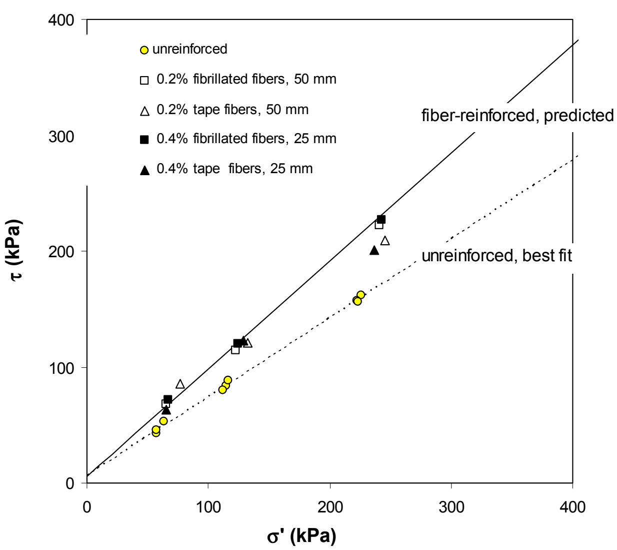


Figure 2. Consolidated shear strength results for specimen reinforced with 50 mm-long fibers (1000 denier) placed at χ_w =0.2% and 25 mm fibers placed at χ_w =0.4%.

Use Peak or Residual Shear Strength of Unreinforced Soil in the Discrete Framework

The discrete framework treats the fiber-reinforced soil as a two-component material. As shown in Equation 1, the equivalent shear strength of the reinforced soil is a function of the shear strength of soil matrix, S, and fiber-induced tension, t. Using peak or residual values of S in the discrete framework should account for strain compatibility if S and t are not mobilized at the same strain level.

An additional series of triaxial tests was conducted on fiber-reinforced soils compacted to two different densities. The purpose of this test series is to determine if the equivalent shear strength of soil-fiber composites depends on peak or residual shear strength of soil matrix. The soils used in this test series are Monterey No. 30 sand, which also classifies as SP soil according to the USCS classification system. The gravimetric fiber content varies from 0 to 0.4% in increments of 0.1%. For each fiber content, specimens with different relative densities (48% and 65%) were tested.

The effect of fiber content on the stress-strain behavior is shown in Figure 3. For specimens with different fiber content, the initial portion of the stress-strain curve is approximately similar, which shows that the soil matrix handles most of the load at small strain levels, the reinforcement effect of fibers takes place at relatively high fiber content. The strain corresponding to the maximum strength of fiber-reinforced soil, $\varepsilon_{m,r}$, is higher than that of unreinforced soil, and it increases as fiber content increases. This implies that the fiber-induced tension is mobilized at a relatively high fiber content. Accordingly, the use of peak or residual shear strength of unreinforced soil in the discrete framework should be determined based on the difference between strain levels $\varepsilon_{m,r}$ and ε_m.

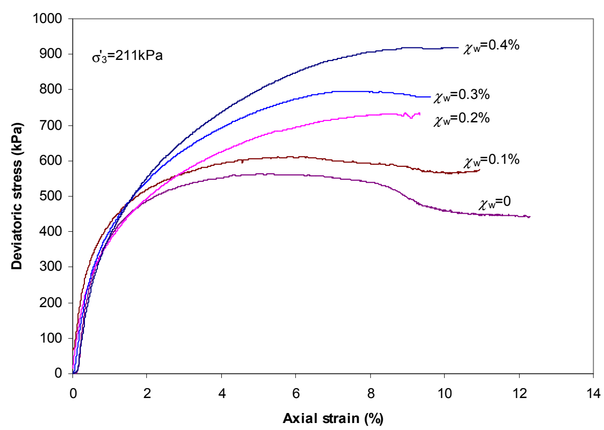


Figure 3. Stress-strain relationships of soil specimens prepared using varying fiber content.

The shear strength results are shown in Table 1. For soils placed using high fiber content (e.g. 0.4%), $\varepsilon_{m,r}$ is found to be significantly larger than ε_m. Accordingly, the soil matrix is approximately at critical state for strain level $\varepsilon_{m,r}$. The residual shear strength of unreinforced soil should then be used to predict the equivalent shear strength. The shear strength test results, as shown in Table 1, suggest the initial density of soil does not significantly influence the shear strength of the reinforced soil. The specimens placed at χ_w=0.4% using two different densities were found to have approximately the same shear strength, which confirms that the shear strength of the fiber-reinforced soil depends on the residual strength of the soil matrix. For dense soils prepared using a relatively low fiber content (e.g. 0.1%), $\varepsilon_{m,r}$ is found to be close to ε_m. Specimens placed at χ_w=0.1% using two different densities show different shear strength, which suggests that the equivalent shear strength in this case depends on the peak shear strength of the soil matrix. Accordingly, peak shear strength of unreinforced soil is recommended in this case for use of the discrete framework. However, at strain level $\varepsilon_{m,r}$, the fiber-induced tension t is not fully mobilized. Consequently, the use of an empirical coefficient α smaller than 1.0 could be considered to account for the partial mobilization of fiber-induced tension.

Table 1 Comparison of the Residual and Peak Friction Angle of Specimens Compacted to Two Different Densities

Gravimetric fiber content	Peak friction angle		Residual friction angle	
(%)	Dr = 48%	Dr = 65%	Dr = 48%	Dr = 65%
0	31.6	35.2	30.9	30.9
0.1	32.8	36.3	32.5	34.4
0.2	38.1	39.1	38.0	38.6
0.3	41.2	42.1	40.7	41.6
0.4	43.2	43.5	43.2	43.1

Summary

The recently proposed discrete framework was validated by a triaxial compression testing program. Specifically, the effects of fiber content and aspect ratio on the shear strength of fiber-reinforced soil are examined. Additionally, this paper discusses using peak or residual shear strength of unreinforced soil in the design of fiber-reinforced soil based on strain compatibility consideration. For soils placed using high fiber content, the initial density of soil does not have significant influence on the shear strength of the reinforced soil. Residual shear strength of the unreinforced soil is recommended to predict the equivalent shear strength using the discrete framework. For soils placed using a relatively low fiber content when the stress-strain curve shows a peak, the peak shear strength of the unreinforced soil is recommended to predict the equivalent shear strength using the discrete framework.

Upcoming research includes calibration of parameters used in the discrete framework, such as the coefficient of interaction for the fiber-soil interface. In addition, the behavior of fiber-reinforced soil when failure is governed the tensile breakage of the fibers will be investigated.

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