Li, C., and Zornberg, J.G. (2005). "Interface Shear Strength in Fiber-Reinforced Soil." Proceedings of the *Sixteenth International Conference of Soil Mechanics and Geotechnical Engineering* (ISSMGE), Osaka, Japan, September 12-17, pp. 1373-1376.

Interface shear strength in fiber-reinforced soil

Interfacer de la force de cisailles dans le sol fibre-renforcé

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ABSTRACT
Under confining pressure typical of geotechnical project, the governing failure mode of fiber-reinforced soil is the pullout of fibers from the soil matrix. Accordingly, interface shear strength between fibers and soils is required for the prediction of equivalent shear strength of fiber-soil composite using the recently-proposed discrete framework. A specially-designed pullout test was conducted to study the interface shear strength between individual fibers and soil. The interface friction angle was found to decrease as confining pressure increases due to the dilatancy effect. For confining pressure between 0 to 200 kPa (typical of triaxial test), the pullout resistance of fibers is well presented by a coefficient of interaction of 0.8 and an effective surface area determined from assuming a circular cross-section.

RÉSUMÉ
Sous la pression d'emprisonnement typique de géotechnique projetez, le mode de défaillance régissant de sol fibre-renforcé est le dégagement des fibres du sol matrice. En conséquence, la résistance au cisaillement d'interface entre les fibres et les sols est exigée pour la prédiction de force de cisailles équivalente de composite de fibre-sol utilisant le récemment proposé cadre discret.Un essai spécial-conçu de dégagement a été conduit pour étudier la résistance au cisaillement d'interface. Le frottement d'interface l'angle s'est avéré pour diminuer comme confinant des augmentations de pression dues au effet d'épaississement. Pour la pression d'emprisonnement entre le kPa 0 à 200 (typique d'essai de trois axes), la résistance de dégagement des fibres peut être estimé en utilisant un coefficient de interaction de 0.8 et une superficie efficace déterminée à partir de la circulaire prétention en coupe.

1 INTRODUCTION

Fiber-reinforcement is a promising solution to applications such as reinforcement of soil veneer and repair of failed slope. Soils mixed with randomly distributed fibers can be used as patches in the localized repair of failed slopes as it can accommodate the irregular shape of failed slopes. In the reinforcement of soil veneer such as landfill covers, fiber reinforcement eliminates the need of anchorage that exists with planar reinforcement.

A discrete framework was recently proposed (Zornberg, 2002), which predicts the shear strength of fiber-soil composites based on the independent properties of fiber and soil (e.g. fiber content, fiber aspect ratio and shear strength of unreinforced soil).

For the polymeric fibers commonly used in engineering practice, the critical failure mode under confining pressure typical of geotechnical projects is the pullout of fibers from the soil matrix. Consequently, the interface shear strength is needed as input of the discrete framework. For pullout type of failure, a coefficient of interaction of 0.8 is assumed in the discrete framework. Due to the lack of experimental data, this value is inferred from pullout test results conducted on woven polypropylene geotextiles (Koutsourais et al., 1998), which was considered representative of the interface shear strength on individual fibers

The surface area of single fibers is also needed in order to estimate the pullout resistance. However, the irregular shape of fibers (especially for fibrillated fibers) is difficult to quantify. At the microscopic level, the contact area between the fiber and soil depends on the size and shape of soil particles, and of the shape of fibers. Consequently, the portion of surface area that is in effective contact with soil is also unknown. The discrete framework typically assumed a circular cross-section of fibers, for which the surface area of fiber is estimated using the equivalent diameter calculated from the cross-sectional area of fibers.

A specially designed pullout test program using a single long fiber embedded in soil matrix was conducted to more accurately quantify the interface shear strength between fibers and soil. Interface shear strength parameters were obtained by analyzing the pullout test results using a load transfer model. The circular fiber cross-section assumption is also evaluated in this study.

2 BACKGROUND

A brief overview of the discrete framework (Zornberg, 2002) is presented in this section. Under shearing, fiber reinforcement contributes to the increase of shear resistance by mobilizing tensile stress within fibers. Accordingly, the equivalent shear strength of fiber-reinforced specimens, S_{eq}, can be defined as:

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

where α is an empirical coefficient that accounts for the partial contribution of fibers (assumed α=1 for randomly distributed fibers); t is the fiber-induced tension defined as the tensile force per unit area induced in a soil mass by randomly distributed fibers; S is the shear strength of the unreinforced soil; and c and ϕ are the shear strength parameters of unreinforced soil.

The expression of t can be derived for different failure modes. At low confining stress when failure is governed by the pullout of the fibers, the fiber-induced distributed tension, t_p, can be estimated as:

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

where η is the aspect ratio, defined as the ratio of fiber length over equivalent diameter of individual fibers; χ is the volumetric fiber content defined as the ratio of fiber volume over the volume of fiber-soil composite; and $\sigma_{n,ave}$ is the average normal stress acting on the random fibers. The interaction coefficients, $c_{i,c}$ and $c_{i,\phi}$, commonly used in soil reinforcement literature for continuous planar reinforcement, are adopted herein to relate the interface shear strength to the shear strength of the soil. The interaction coefficients are 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, and $\tan\delta$ is the frictional component.

When failure is governed by the yielding of the fibers, the distributed tension, t_t , is determined from the tensile strength of the fiber:

$$t_t = \chi \cdot \sigma_{f,ult} \tag{5}$$

where $\sigma_{f,ult}$ is the ultimate tensile strength of the individual fibers.

Accordingly, the following expressions can be used to define the equivalent shear strength when failure is governed by fiber pullout:

$$S_{eq,p} = c_{eq,p} + (\tan\phi)_{eq,p} \cdot \sigma_n \tag{6}$$

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

$$(\tan\phi)_{eq,p} = (1 + \alpha \cdot \eta \cdot \chi \cdot c_{i,\phi}) \cdot \tan\phi \tag{8}$$

The following expressions can be obtained to define the equivalent shear strength when failure is governed by tensile breakage of the fibers:

$$S_{eq,t} = c_{eq,t} + (\tan\phi)_{eq,t} \cdot \sigma_n \tag{9}$$

$$c_{eq,t} = c + \alpha \cdot \chi \cdot \sigma_{f,ult} \tag{10}$$

$$(\tan\phi)_{eq,t} = \tan\phi \tag{11}$$

The above expressions yield a bilinear shear strength envelope, which is shown in Figure 1.

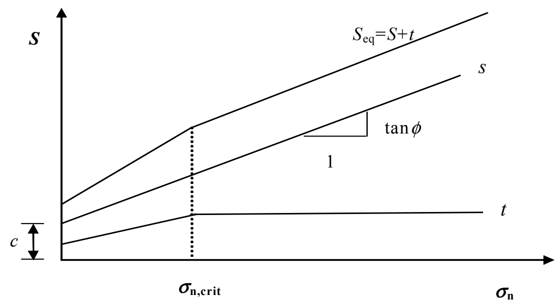

Figure 1. Representation of the equivalent shear strength according to the discrete approach

3 EXPERIMENTAL TESTTING PROGRAM

A large scale direct shear box was modified to perform the individual fiber pullout test. The test setup is shown in Figure 2. The fiber used was a single long polypropylene tape fiber that had not been cut into the specified length in the manufacturing process. The upper box of the direct shear box has in-plane dimension of 508 mm by 508 mm and height of 127 mm. The bottom box has a dimension of 1016 mm by 508 mm by 127mm. A vertical hydraulic actuator was used to generate the normal load. The fiber was passed through the plastic tubes, placed at the bottom of the upper box, and used to control the effective length of fiber subjected to interface friction. The actual effective length of fiber is 152mm (6 inches), which equals the length of upper box minus the length of the two plastic tubes as shown in Figure 2. Use of a small anchored length would have made the pullout force too small to measure, while use of a longer embedded length would have made the pullout force to be larger than the tensile strength of fibers. Accordingly an embedded length of fiber larger than the typical embedded length of fibers within fiber-reinforced soil was selected in the pullout test. The test setup is similar to a 'pull through' test, in which the length of fiber under interface friction remains constant during the test. The The section of fiber subjected to interface friction was located in the center of upper box, which was under a uniform distribution of normal stress.

The pullout force was applied through the horizontal hydraulic actuators. A load cell with capacity up to 50 lbs was installed to measure the normal load. Two LVDTs were used to measure the displacement in the pullout front and end. The front end of fiber was attached to a metal wire, which can be considered as inextensible. Therefore, the measurement of LVDT 1 can be assumed to be the displacement of pullout front. The displacement of the pullout end is measured by LVDT 2.

The soil used was Monterey No. 30 sand, which is a clean uniformly graded sand and classifies as SP according to the unified soil classification system. The soils was compacted to the target density using the pluviation techniques, which involve raining the sand from a fixed height through a specially designed funnel. The target soil densities, D_r, were 48% and 65%.

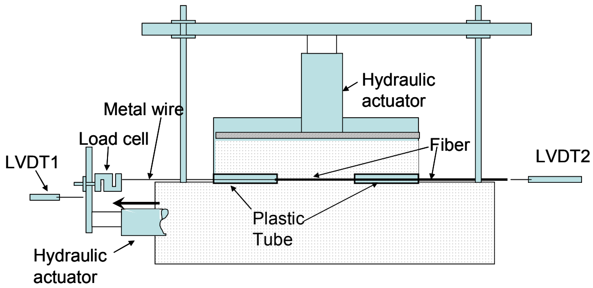

Figure 2. Setup of the fiber pullout test

4 ANALYSIS OF RESULTS

The pullout force vs. displacement curves are shown in Figure 3. Comparatively small displacements are required to mobilize the interface shear strength. Triaxial test results have shown that large strain levels are required to mobilize the fiber reinforcing effect (Li and Zornberg, 2003). The difference in strain levels required to mobilize strength in pullout and triaxial is due to different test conditions. Fibers are pulled out from static soil in the pullout tests, while fibers and soils deform together in the triaxial tests.

The interface shear strength can be obtained by analyzing the pullout force vs. displacement relationship using a load transfer model (Juran and Chen, 1988), in which the interface shear stress τ_s can be expressed as a function of relative displacement between the fiber and soil u_s:

$$\tau_s(x) = u_s(x)\sigma_n C_3 \frac{u_s(x) - C_1}{[u_s(x) + C_2]^2} \tag{12}$$

The constants C_1, C_2, and C_3 are defined as:

$$C_1 = -4\frac{\sigma_n}{G_i}\frac{\tan^2\delta J^2}{\tan\delta_r} \tag{13}$$

$$C_2 = 2\frac{\sigma_n}{G_i}\tan\delta J \tag{14}$$

$$C_3 = \tan\delta_r \tag{15}$$

where: σ_n=normal stress; δ=peak interface friction angle; δ_r=residual friction angle; and G_i=initial interface shear stiffness. The empirical coefficient J can be estimated by:

$$J = 1 + \left(1 - \frac{\tan\delta}{\tan\delta_r}\right)^2 \tag{16}$$

The tensile stress and strain relationship of the reinforcement can be assumed as:

$$F = \frac{\varepsilon}{a + b\varepsilon} \tag{17}$$

where ε is the tensile strain of the reinforcement, and constants a and b can be determined from the initial elastic module E and ultimate tensile strength $\sigma_{f,ult}$ using the relations, as follows:

$$a = \frac{1}{E \cdot A} \tag{18}$$

$$b = \frac{1}{\sigma_{f,ult} \cdot A} \tag{19}$$

where A is the cross-sectional area of the reinforcement. For 360 denier polypropylene fibers, a and b, estimated from a tensile testing results (Zornberg, 2002) are 5.35 N^{-1} and 53.5 N^{-1}, respectively.

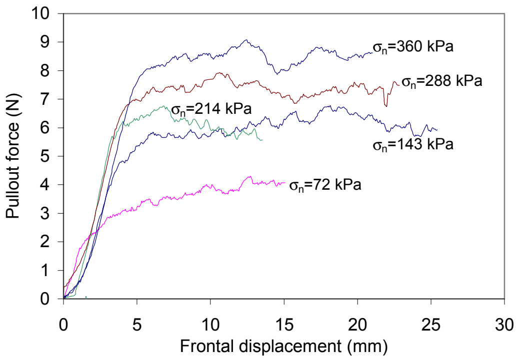

Figure 3. Pullout test results (Dr=65%)

The reinforcement can be discretized into n sections with an equal spacing between nodes Δx. The coordinate and displacement at node i are denoted as x_i and $u_{s,i}$. The equations to be solved is:

$$\sigma_n C_3 u_{s,i} \frac{u_{s,i} - C_1}{\left[u_{s,i} + C_2\right]^2} = \frac{a(u_{s,i+1} - 2u_{s,i} + u_{s,i-1})}{2\Delta x^2 \left[a + b\frac{u_{s,i+1} - u_{s,i-1}}{2\Delta x}\right]^2} \tag{20}$$

Equation (20) combines the equilibrium condition of each section, stress-strain relationship of reinforcement (Equation (17)) and interface behavior (Equation (12)). The boundary conditions to be satisfied are:

at the pullout front,

$$u_s(x_1) = u_{s,1} \tag{21}$$

at the pullout end (no shear stress at node n),

$$\frac{du_s(x_n)}{dx} = 0 \tag{22}$$

The pullout force F corresponding to the displacement at the pullout front, $u_{s,1}$, can be calculated as follows. Displacement $u_{s,i+1}$ can be solved if $u_{s,i}$ and $u_{s,i-1}$ are known. For a given value of $u_{s,1}$, the solving procedure begins with an assumed displacement at an imaginary node 0, $u_{s,0}$. The displacements at nodes 2, 3 …etc. are solved subsequently using Equation (20) until the displacement of the pullout end is solved. If the boundary condition as shown in Equation (22) is satisfied, the assumed $u_{s,0}$ is the correct solution and the corresponding pullout force F is calculated as the summation of the interface friction on each section of the reinforcement. Otherwise, $u_{s,0}$ should be reassumed and the calculation procedure is repeated until Equation (22) is satisfied. The pullout force vs. displacement curve can be obtained by calculating the pullout force corresponding to different displacement of the pullout front.

The interface shear strength parameters δ and δ_r as well as initial interface shear stiffness G_i are obtained by fitting the model-predicted pullout force vs. displacement curves with those obtained from pullout tests. Considering the difficulty in defining the surface area of fiber that is effectively in contact with the soil (especially for fibrillated fibers), the surface area of fibers is calculated using the equivalent diameter obtained by assuming the cross-section of fiber is circular. Although the surface area of tape fibers used in the pullout test is relatively easier to define than that of the fibrillated fibers, the results obtained from triaxial test show similar strength increase under comparable conditions for specimens reinforced using tape fibers and fibrillated fibers (Li and Zornberg, 2003), which indicates that both types of fibers have similar pullout resistance. Consequently, the tape fibers are considered to have a circular cross-section in the analysis herein.

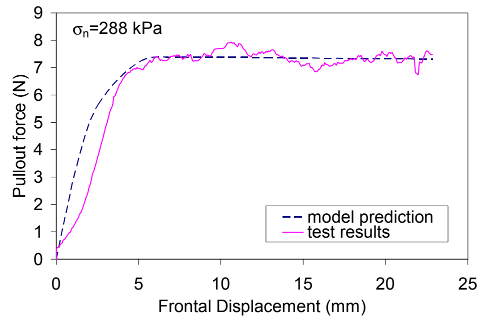

Figure 4. Fitting the pullout test result using the model

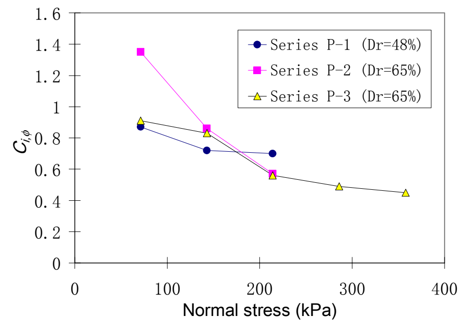

Figure 5. Coefficient of interaction as a function of normal stress

3 series of pullout tests (2 series using Dr=65%, 1 series using Dr=48%) were conducted under confining pressure varying from 72 kPa to 360 kPa. Figure 4 shows one of the curve-fitting analyses. The interface friction angles are those that lead to the best fit of pullout force vs. displacement curves. The corresponding coefficients of interaction obtained are shown in Table 1. The coefficients of interaction are found to decrease with increasing confining pressure. Similar trend was found on pullout test results using polyamide and steel fibers (Michalowski and Cermak, 2003). This is attributed to the dilatancy effect of dense soil. The soil in the vicinity of the reinforcement tends to expand when subjected to shearing during the pullout process. However, this volume expansion is constrained by the confinement of the surrounding soil. As a result, the normal stress acting on the soil-reinforcement interface is larger than the applied confining pressure, which in turn increased the pullout resistance. For tests conducted under a higher confining pressure, the normal stress increase due to the dilatancy effect becomes less significant. Consequently, the interface friction angle (or coefficient of interaction) calculated in terms of the nominal confining stress tends to decrease as the confining pressure increases. This trend is more significant for tests conducted using 65% relative density of soil, compared to tests conducted using 48% relative density (see Figure 5).

The elongation of fiber calculated by the model is also compared with the test results (Figure 6), which is determined from the difference between data recorded by LVDTs 1 and 2. The test result is slightly larger than the model prediction. This may be due to initial slack of fiber before the pullout process.

Table 1. $c_{i,\phi}$ determined from fiber pullout tests

Normal tress σ_n (kPa)	Series P-1 (Dr=48%) $c_{i,\phi}$	Series P-2 (Dr=65%) $c_{i,\phi}$	Series P-3 (Dr=65%) $c_{i,\phi}$
71.5	0.87	1.35	0.91
143	0.72	0.86	0.83
214	0.70	0.57	0.56
286			0.49
358			0.45

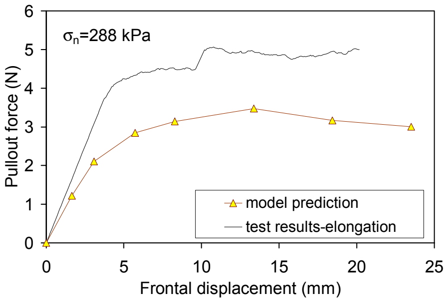

Figure 6. Comparison of model calculated fiber elongation and results from pullout test

The discrete framework yields a bilinear shear strength envelope for fiber-reinforced soil, which is the result of the change of failure modes (Zornberg, 2002). However, a nonlinear shear strength envelope of fiber-soil composite can also be due to the change of interface friction angle with varying confining pressure even though the tensile stresses within fibers are still well below the tensile strength of the fibers. Figure 7 shows a shear strength envelope obtained from triaxial tests conducted using a wide range of confining pressure. The fibers used were 102 mm long 360 denier polypropylene tape fibers and were placed at a gravimetric fiber content of 0.1%. For the range of confining pressure applied, the failure mode is fiber pullout since the tensions within the fibers are still well below the tensile strength of fibers. The friction angle of the fiber-soil composite is found to decrease with increasing confining pressure. Given the friction angle corresponding to each confining pressure, the coefficient of interaction can be back calculated using Equation (8). The friction angle shows a decreasing trend with increasing confining pressure, which is consistent with the trend found in the pullout tests (Figure 8). This experimental result shows that nonlinear interface behavior can lead to nonlinear shear strength behavior of the fiber-soil composites.

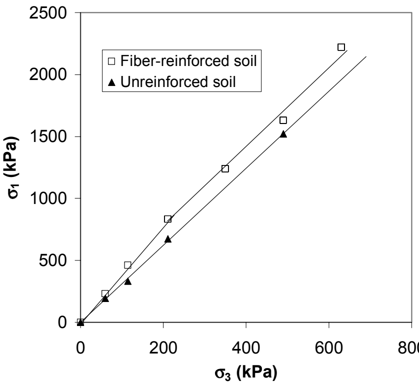

Figure 7. Shear strength envelope of fiber-reinforced soil tested under wide range of confining pressure (0.1% 100 mm long 360 Denier fibers)

The nonlinear shear strength behavior within a range of confining pressures can be ignored for simplicity. Since the interface friction angle is not constant, a representative coefficient of interaction in this normal pressure range should be selected. The shear strength results obtained from a higher confining pressure usually carry more weight in the curve-fitting. Consequently, using a coefficient of interaction corresponds to the higher confining pressure in the discrete framework will yield a prediction closer to the test results. At confining pressure of 140 to 210 kPa (20 to 30 psi), the coefficient of interaction obtained from the pullout test varies between 0.6 to 0.9. For confining pressures less than 30 psi, a coefficient of interaction of 0.8 and an equivalent diameter calculated from the circular cross-section assumptions, is adequate for use in the discrete framework.

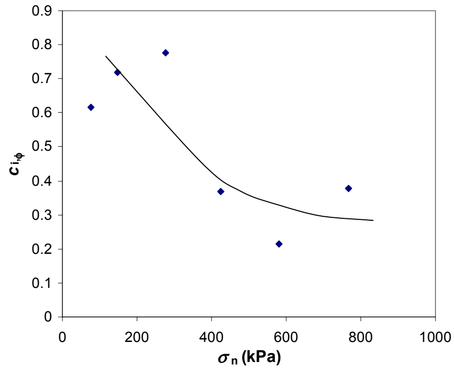

Figure 8. Coefficient of interaction back-calculated from triaxial test results

5 SUMMARY AND CONCLUSION

A specially-designed pullout test was conducted to study coefficient of interaction useful for prediction of equivalent shear strength of fiber-soil composites using the discrete framework. The coefficient of interaction was found to decrease with increasing confining pressure due to soil dilatancy. For confining pressure less than approximately 200 kPa, a coefficient of interaction of 0.8 and an equivalent diameter calculated from the circular cross-section assumption was found to be an adequate selection for the discrete framework. For a wider range of confining pressure, nonlinear interface behavior can lead to nonlinear shear strength behavior in fiber-soil composites. Therefore the coefficient of interaction should be selected considering the level of confining pressure.

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