Models for Predicting Shear Strength of Fiber-Reinforced Soils

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ABSTRACT

Soil reinforcement is an effective and reliable technique for improvement of strength and stability of soils. Traditional soil reinforcing techniques involve the use of continuous planar inclusions oriented in a preferred direction to enhance strength and stability. In the past few decades, randomly distributed fiber-reinforced soils also have been studied for geotechnical engineering applications. Unlike soil structures reinforced with planar inclusions, soil structures reinforced with randomly distributed fibers are designed using composite approaches. A number of experimental studies have been reported on fiber-reinforced soil by several researchers. Several composite models have been proposed by them to explain the contribution to shear strength from randomly distributed fibers within a soil mass. This paper presents a review of the available literature explaining the mechanisms and the models for predicting shear strength behaviour of fiber-reinforced soils.

Keywords: Randomly distributed fibers, shear strength, reinforced soil mechanism, predictive model.

1. INTRODUCTION

Several ground improvement techniques have been developed for the improvement of engineering properties of soils. This includes replacement of weak soils by desirable good quality soils, use of prefabricated drains, chemical stabilization by cement or lime, inclusion of reinforcement within soil, jet grouting etc. A number of soil reinforcement works have been carried out after the first development of the principle for reinforced earth by Vidal in 1969. Initially the reinforcement has been carried out in the conventional way by using geosynthetics (strip, geotextiles, geogrids etc.). Later on soil reinforcement with randomly distributed fibers has been incorporated successfully.

A number of laboratory studies (direct shear test, triaxial compression test, unconfined compression test, CBR test) have been carried out by different researchers to investigate the behaviour of fiber-reinforced soils. All these studies have predicted that the addition of fiber-reinforcement causes significant improvement in the strength of the soil. The contribution of the fibers is governed by the improvement in equivalent friction angle and cohesion of soil in the composite mix. Several models have been developed by different investigators to understand the behaviour of fiber-reinforced soils. Force equilibrium models [1-4], deformation based model [5-6], statistical models [7-8], energy-based homogenization model [9], discrete framework model [10], theoretical model [11] and several other models [12-13] have been reported to analyse the fiber-reinforced soil behaviour.

This paper presents a review of various mechanisms to describe the strength improvement of fiber-reinforced soils and the associated predictive models defining the shear strength behaviour.

2. FORCE EQUILIBRIUM MODELS

Based on direct shear tests, Waldron [1] evaluated the tensile stress developed at the shear plane of root-permeated soil, and presented a model based on force equilibrium method, as shown in Fig. 1. The Mohr-Coulomb equation for root-permeated soil is expressed as:

$$s_f = c + \Delta s_f + \sigma_n \tan\varphi \qquad (1)$$

where, c = cohesion of soil, σ_n = normal stress acting on shear plane, and φ = soil friction angle and Δs_f is the increase in shear strength due to inclusion of root in soil, and has been given as:

$$\Delta s_f = a_f K(\sec\theta - 1)^{1/2}(\sin\theta + \cos\theta\tan\varphi) \qquad (2)$$

where, $a_f = \dfrac{A_f}{A}$ = fiber area ratio, A_f = area of fiber in shear, A = total area of soil in shear, θ = root distortion angle, and K = a constant.

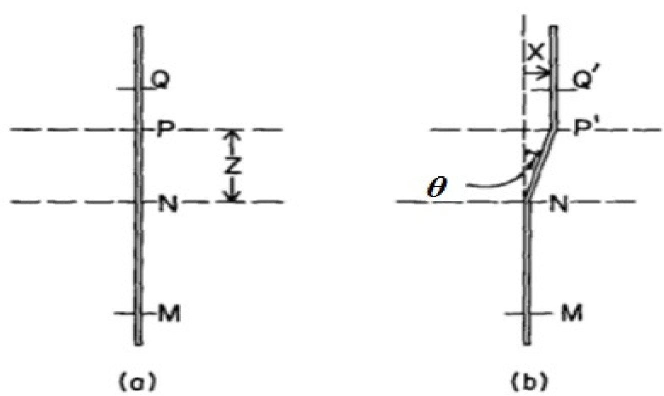

Fig. 1: Model of flexible elastic root extending vertically across horizontal shear zone (a) undisturbed soil and (b) displaced root

Gray and Ohashi [2] extended the work of Waldron [1], and developed a model of fiber-reinforced sand by conducting direct shear tests on dry sand reinforced with different types of fibers placed at both vertical and inclined orientations (Fig. 2). Shearing of soils along a shear plane was assumed to cause fiber distortion, which mobilizes its tensile resistance. The shear strength increment, Δs_f, due to fiber reinforcement has been expressed as:

For perpendicular fiber: $\Delta s_f = t_f(\sin\theta + \cos\theta \tan\varphi)$ (3)

For inclined fiber: $\Delta s_f = t_f(\sin(90-\psi) + \cos(90-\psi)\tan\varphi)$ (4)

where, t_f = mobilized tensile strength of fiber per unit area of soil, $\psi = \tan^{-1}[\frac{1}{k+(\tan^{-1} i)^{-1}}]$, i = initial fiber orientation, and $k = \frac{x}{z}$ = shear distortion ratio.

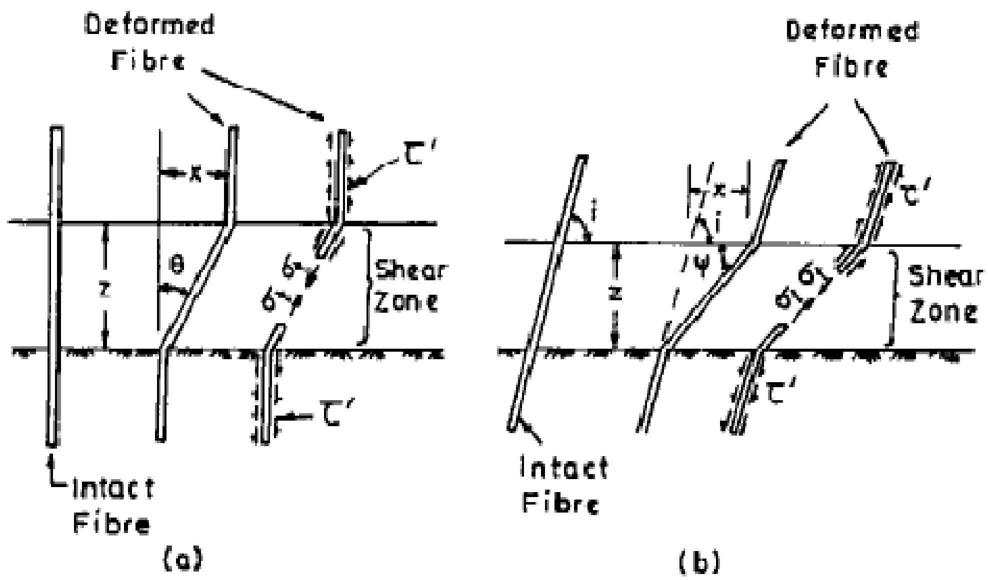

Fig. 2: Fiber reinforcement model
(a) perpendicular to shear plain (b) inclined to shear plane

Maher and Gray [3] further worked on the model proposed by Gray and Ohashi [2], and developed a model incorporating statistical theory. Triaxial compression tests on sands reinforced with discrete, randomly distributed fibers were conducted. They incorporated a bilinear failure envelope with the bilinearity break occurring at a threshold confining stress (Fig. 3).

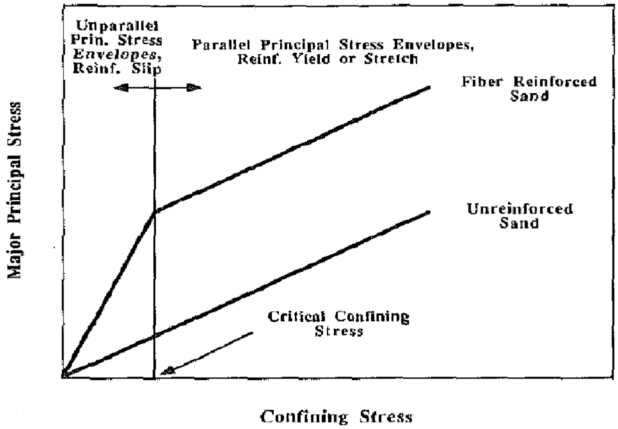

Fig. 3: Failure envelope of fiber-reinforced sand

Shukla et al. [4] developed a simple analytical model (Fig. 4) for predicting the shear strength behaviour of fiber-reinforced granular soils under high confining stresses, where it can be assumed that pullout of fibers does not take place. The shear strength (s_f) of fiber-reinforced granular soil has been expressed as:

$$s_f = c_f + \sigma_{n,f} \tan \varphi \quad (5)$$

where, c_f = apparent cohesion developed due to fiber inclusion and $\sigma_{n,f}$ = improved confining normal stress on fiber-reinforced soil.

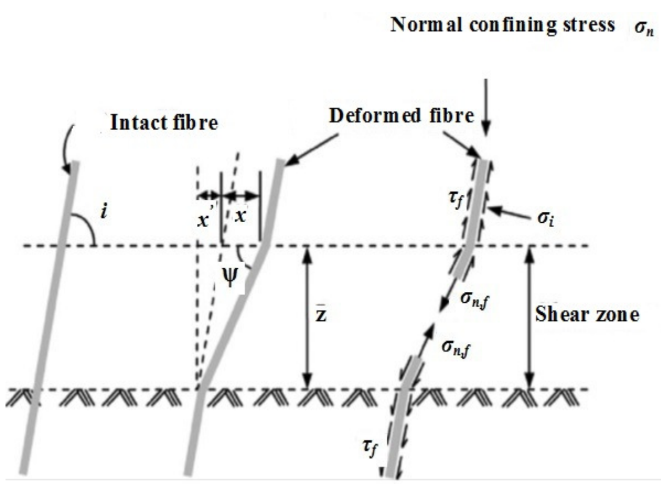

Fig. 4: Fiber-reinforced model extending across shear zone of thickness z

3. DEFORMATION-BASED MODEL

Shewbridge and Sitar [5] investigated the shear zone development and shear zone deformation pattern of reinforced soil mixtures by large direct shear tests. It has been found that the deformation of reinforced soil is not confined to discrete region undergoing linear simple shear as shown earlier in Fig. 2. The deformation pattern is found to be curvilinear and symmetric about the centre of the shear zone (Fig. 5). Later, Shewbridge and Sitar [6] developed a model, to investigate the influence of soil and reinforcement properties on the work to deform the soil.

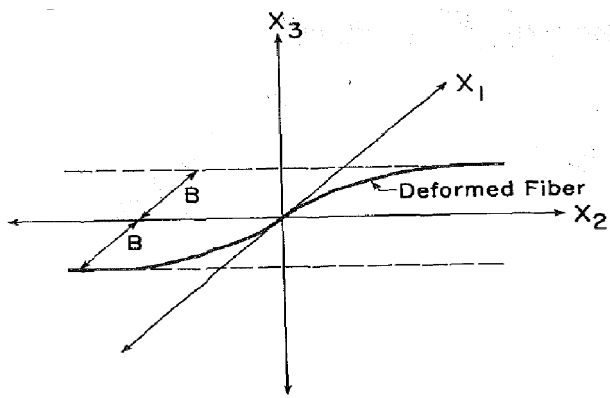

Fig. 5: Schematic geometry of deformation pattern of reinforcement in soil

4. STATISTICAL MODELS

Based on triaxial tests on cohesionless soils, Ranjan et al. [7] developed a mathematical model to define the strength characteristics of fiber-reinforced soil. The test results indicate that the failure envelopes of soil-fiber composites have a curvilinear failure envelope, with a transition occurring at a certain confining stress, termed as critical confining stress, below which the fibers tend to slip. The model is represented mathematically as a function of weight fraction of fiber, fiber aspect ratio, surface friction coefficient, coefficient of friction and confining pressure.

A statistical model has been developed by Sivakumar Babu and Vasudevan [8] using regression for prediction the strength of fiber-reinforced soil. Conventional triaxial testing of soil mixed with coir fiber were carried out to study the effect of various fiber parameters on strength and stiffness of soil. The statistical model is capable of quantifying the major principal stress at failure, cohesion, friction angle and initial stiffness of coir fiber-reinforced soil.

5. ENERGY-BASED HOMOGENIZATION MODEL

Michalowski and Zhao [9] used an energy-based homogenization technique to calculate the macroscopic (average) failure stress of fibrous granular composite materials at failure. The fiber-soil mixture was considered as isotropic. The deformation pattern of fibers was assumed as in Fig. 6, in which slip takes place at both ends of the fibers whereas tensile rupture occurs in the middle of the fibers. The strength of the granular matrix is quantified by the internal friction angle, whereas fibers are characterised by volumetric concentration, aspect ratio, yield point and fiber-soil interface friction angle.

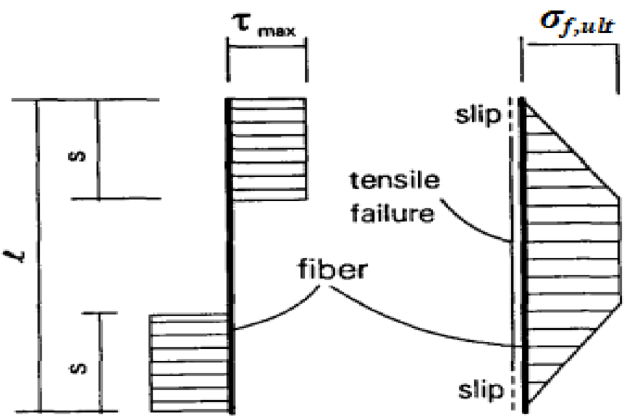

Fig. 6: Deformation pattern of fiber-reinforced soil

6. DISCRETE FRAMEWORK MODEL

Zornberg [10] proposed a design methodology for fiber-reinforced soil slope to characterize the contribution of randomly fiber reinforcement using discrete framework approach. In this approach, the reinforced mass is characterised by the mechanical properties of individual fibers and of the soil, rather than by the mechanical properties of the fiber-reinforced composite material. Fibers have been considered as discrete elements that contribute to stability by mobilizing tensile stresses along the shear plane. The main objective of the discrete framework was to avoid the need of conducting non-conventional shear strength testing programmes on fiber-reinforced specimens in order to perform limit equilibrium analysis. The mode of failure of fibers has been defined by a critical stress at which failure changes from fiber pullout to fiber breakage. When failure is governed by fiber breakage, the fiber-induced distributed tension is a function of the volumetric fiber content and tensile strength of individual fibers. For pullout failure, the fiber-induced distributed tension is a function of the volumetric fiber content, interface shear strength and fiber aspect ratio.

7. THEORETICAL MODEL

Rifai and Miller [11] developed a theoretical model to describe the mechanism of tensile strength improvement of fiber-reinforced soil undergoing desiccation. The model includes a distinctive effective stress combination acting on the fiber strings due to the generated matric suction by desiccation. Mohr-Coulomb failure criterion at the interface area between fibers and the surrounding soil has been considered in this model. Matric suction is generated within the soil mass by the desiccation process of the soil under given stress condition. Soil-water characteristic curve, Mohr-Coulomb parameters, and unsaturated soil parameters have been used as the basic components for this model formulation. Random distribution of fibers has been assumed with single fiber under the combined effect of overburden soil pressure and lateral earth pressure in addition to matric suction. Tensile strength of the fiber-soil composite increases significantly by fiber inclusion and the increase is a function of fiber content and soil-water content.

8. OTHER MODELS

Michalowski and Cermak [12] developed a model by introducing the concept of macroscopic internal frictional angle to describe the failure criteria of fiber-reinforced sand. Drained triaxial compression tests on fiber-reinforced sand were conducted The benefit of fiber reinforcement (increase of failure stress, drop of the initial stiffness and increase of the failure strain) increases with increase in fiber concentration and aspect ratio and is also dependent on relative size of the grains and fiber length. The prediction of failure stress in triaxial compression tests is based on frictional interaction of fibers and sand. This model is limited to cylindrical monofilament fibers with an isotropic distribution of their orientation. The failure of fiber is governed by a critical confining stress. For a soil subjected to confining pressure less than critical value, slip of fiber occurs and beyond that critical limit, rupture of fiber occurs.

Michalowski [13] worked on the development of an anisotropic yield condition for fiber-reinforced sand and on the application of the kinematic approach of limit analysis for solving problems with anisotropic materials. In anisotropic yield condition for fiber-reinforced sand, ellipsoidal distribution of fibers is developed. It is found that the maximum shear stress can be represented as a function of the inclination of the principal stress direction and the in-plane mean stress. Internal friction angle of anisotropic material has been represented as a function of the major principal stress or major principal strain rate direction and not just a function of the orientation of the shear surface.

9. CONCLUSIONS

Soil reinforcement with randomly distributed fibers as tension material has been accepted for the improvement of geotechnical behaviour of weak soils. Improvement of strength of the soil by reinforcement is achieved in terms of apparent cohesion developed or in increase in soil friction angle. The strength improvement depends on the shear strength of soil, tensile strength and distribution pattern of reinforcement. The stress-strain response of fiber-reinforced soil composite depends on fiber content, fiber aspect ratio, fiber-soil interface friction, strength characteristics of fibers, soil-reinforcement bond strength and internal friction angle of soil.

The predictive models for shear strength behaviour have been developed for low fiber concentration (<10%) to neglect fiber-fiber interaction. Estimation of fiber contribution in soil strength is mainly based on the concept of isotropic distribution of fibers within soils. But in actual field conditions due to decomposition technique of fiber-reinforced soils (mixing, rolling, compacting), fiber orientation has a defined bedding plane giving anisotropic mechanical properties of mixture. The influence of scale effects on the stress-strain characteristics of fiber-reinforced soils has not been investigated fully on large scale. Further detailed studies based on anisotropic concept and large scale tests can explain the behaviour of fiber-reinforced soils in a better way.

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