Review paper (T)

REVIEW OF PREDICTIVE MODELS FOR SHEAR STRENGTH BEHAVIOUR OF FIBRE 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 fibre reinforced soil mechanisms have been studied extensively for geotechnical engineering applications. Unlike soil structures reinforced with planar inclusions, soil structures reinforced with randomly distributed fibres are still conventionally designed using composite approaches. A number of experimental studies have been reported on fibre-reinforced soil by several researchers. Several composite models have been proposed by them to explain the contribution to shear strength from randomly distributed fibres within a soil mass. This paper presents a review of the available literature explaining the mechanisms and predictive models for shear strength behaviour of fibre-reinforced soils.

Key Words: Randomly distributed fibre, Shear strength, Reinforced soil mechanism, Composite predictive model, Geotextiles

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 conventional way by using geosynthetics (strip, geotextiles, geogrids etc.). Later on soil reinforcement with randomly distributed fibres has been incorporated successfully. There are some advantages using randomly distributed fibres (natural and synthetics) over conventionally used geosynthetics. First, the discrete fibres are simply added and mixed randomly within soil, in the same way as cement, lime or other additives.

Second, randomly distributed fibres offer strength isotropy and limit the potential planes of weakness that can develop parallel to reinforcement orientation as it doesn’t induce any clear cut potential plane of weakness due to its random orientation.

A number of laboratory testing (direct shear test, triaxial compression test, unconfined compression test, California Bearing Ratio (CBR) test) have been carried out by different researchers to investigate the behaviour of fibre reinforced soil. All these laboratory studies have predicted that the addition of fibre-reinforcement caused significant improvement in the strength and increases the stiffness of the soil. More importantly, fibre-reinforced soil exhibits greater toughness and ductility and smaller loss of post-peak strength, as compared to soil alone. Fibre-reinforced soil has become a focus of interest in recent years.

Although several experimental studies on fibre-reinforced soil have been carried out by different researchers, work on the mechanisms of fibre-reinforced soils is limited. The contribution of the fibres 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 fibre-reinforced soils. Force equilibrium mechanistic models\(^1\), deformation based model\(^2\), statistical model\(^3\), energy-based homogenization model\(^4\), discrete framework model\(^5\), theoretical model\(^6\) and several other approaches\(^7\) have been reported to analyse the fibre-reinforced soil behaviour.

**AIMS AND OBJECTIVES**

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

**DISCUSSION**

**Force equilibrium models**

Waldron\(^1\) conducted direct shear tests on 25.4 cm diameter root-permeated soil columns of 61 cm length to measure the reinforcing effect of plant roots, which stabilizes soil on slopes. The strength of soil only by Mohr-Coulomb plot has been represented as:

\[
s_f = c + \sigma_n \tan \varphi
\]

where, \(c\) = cohesion of soil, \(\sigma_n\) = normal stress acting on shear plane and \(\varphi\) = soil friction angle.

The root-reinforced soil has been analyzed as a composite material in which fibres of relatively high tensile strength are embedded in a matrix of lower tensile strength. For evaluating the tensile stress developed at the shear plane of root permeated soil, a model was presented based on force equilibrium method. The model shown in Fig. 1 of the root-soil system has been considered which is useful in applying fibre reinforcing concepts to root-reinforced soil.

It has been assumed in this model that (i) soil shearing occurs in a horizontal zone of thickness, \(Z\), which is penetrated by vertical roots (Fig. 1(a)) and \(Z\) does not change during shear (ii) the roots are flexible, of uniform diameter and are linearly elastic and (iii) the soil friction angle is unaffected by roots so that the Mohr-Coulomb equation for root-permeated soil has been expressed as:

\[
s_f = c + \Delta s_f + \sigma_n \tan \varphi
\]

\(\Delta s_f\) is the increase in shear strength due to inclusion of root in soil and has been given as:

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

where, \(a_f = A_f / A\) = fibre area ratio, \(A_f\) = area of fibre in shear, \(A\) = total area of soil in shear, \(\theta\) = root distortion angle and \(K\) = a constant.

Gray and Ohashi\(^2\) extended the work of Waldron\(^1\) and conducted direct shear tests on a dry sand reinforced with different types of fibres placed at both vertical and inclined orientations (Fig. 2). Both natural and synthetic fibres plus metal wires were tested. The fibre extended to equal length on both side of
potential shear plane. Shearing of soils along a shear plane was assumed to cause fibre distortion, which mobilizes its tensile resistance. The experimental behaviour was used to develop a force equilibrium model of fibre-reinforced sand. The shear strength increment, $\Delta s_f$, due to fibre reinforcement in sand has been expressed as:

For perpendicular fibre:

$$\Delta s_f = t_f (\sin \theta + \cos \theta \tan \phi)$$  \hspace{1cm} (4)

For inclined fibre:

$$\Delta s_f = t_f (\sin(90-\psi)+\cos(90-\psi)\tan \phi)$$  \hspace{1cm} (5)

where,

$t_f$ = mobilized tensile strength of fibre per unit area of soil, $\psi$ = tangent of $\tan^{-1}\left[\frac{1}{k + (\tan^{-1} i)}\right]$, $i$ = initial fibre orientation, and $k=x/z$ = shear distortion ratio. Experimental results obtained by direct shear test on different fibres (natural and synthetic) supported the proposed model.

Figure 2: Fibre reinforcement model (a) perpendicular to shear plane (b) inclined to shear plane

Maher and Gray further worked on the model proposed by Gray and Ohashi and performed triaxial compression tests on sands reinforced with discrete, randomly distributed fibres. They incorporated statistical theory of strength for composites concept to study the influence of sand granulometry (gradation, average particle size and shape) and fibre properties (aspect ratio, skin friction and modulus) on the strength-deformation response of randomly distributed fibre-reinforced sand composites. Bilinear failure envelopes with the bilinearity break occurring at a threshold confining stress was considered for the sand fibre composites (Fig. 3).

Figure 3: Failure envelope of fibre-reinforced sand
Fig. 4 shows a single fibre crossing the potential shear zone of a fibre-sand specimen under a triaxial compression load. The positions of the fibre before and after the state of shear deformation at failure are given by MNQP and MNQP', respectively.

The shear strength increment ($\Delta s_f$) due to fibre-reinforcement can be estimated by eqn. (4). Overall improvement of shear strength for fibre-reinforced soil by taking account of bilinear failure envelope has been given as

$$\Delta s_f = N_s (\frac{d_f^2}{4})[2(\sigma_c \tan \delta - \sigma_c)] \frac{l}{d_f} (\sin \theta + \cos \theta \tan \varphi) \xi$$

for $0 < \sigma_c < \sigma_{c, crit}$ (6)

$$\Delta s_f = N_s (\frac{d_f^2}{4})[2(\sigma_{crit} \tan \delta - \sigma_c)] \frac{l}{d_f} (\sin \theta + \cos \theta \tan \varphi) \xi$$

for $\sigma_c > \sigma_{crit}$ (7)

where, $N_s = \text{average number of fibres intersecting a unit area}$, $l = \text{fibre length}$, $d_f = \text{fibre diameter}$, $\sigma_c = \text{confining stress on fibre}$, $\delta = \text{soil-fibre interface friction}$, $\sigma_{c, crit} = \text{critical confining stress on fibre}$ and $\xi = \text{an empirical coefficient depending on sand granulometry i.e. average grain size ($D_{50}$), particle sphericity ($S_p$), coefficient of uniformity ($C_u$)}$.

The models proposed by Gray and Ohashi$^2$ and Maher and Gray$^3$ are valid only for extensible fibre with a frictional surface. Commonly used polymeric fibres have relatively high tensile strength and deformation modulus but relatively low interface friction. Consequently, these models may be inadequate when failure is governed by the pullout of fibres. Also the two models require determination of the thickness of the shear zone as an input parameter, which is difficult to quantify.

A simple analytical model has been developed by Shukla et al.$^4$ for predicting the shear strength behaviour of fibre-reinforced granular soils under high confining stresses, where it can be assumed that pullout of fibres does not take place. The model shown in Fig. 5 presents an analytical expression derived from the...
force-equilibrium consideration incorporating several significant parameters describing the characteristics of the granular soil (specific gravity, angle of shearing resistance and void ratio), fibres (fibre content, aspect ratio, modulus of elasticity, specific gravity, soil-fibre friction, initial orientation with respect to shear plane) and normal confining stress. The shear strength \( s_f \) of fibre-reinforced granular soil has been expressed as:

\[
 s_f = c_f + \sigma_n \tan \phi 
\]

where, \( c_f \) = apparent cohesion developed due to fibre inclusion and \( \sigma_n \) = improved confining normal stress on fibre-reinforced soil and is given as:

\[
 c_f = \sigma_c [2 \frac{A}{A_i} (1 - \sin \phi (2)) \cos \phi \sin \phi] \tan \phi \sin \phi 
\]

\[
 \sigma_n = \sigma_i [1 + 2 \frac{A}{A_i} (1 - \sin \phi (2)) \cos \phi \sin \phi] \tan \phi \sin \phi 
\]

The shear strength improvement of the granular soil due to inclusion of fibres has been defined in terms of a dimensionless ratio, called Shear Strength Ratio (SSR), as:

\[
 SSR = \frac{s_f}{s} 
\]

where, \( s_f \) = shear strength of reinforced soil, \( s \) = shear strength of unreinforced soil

The developed expression shows that fibres inclusion in the granular soil induces cohesion, as well as increase in normal stress on the shear failure plane. This induced strength parameters are proportional to the fibre content and aspect ratio, implying that increase in shear strength is also proportional to the fibre content and aspect ratio.

**Deformation-based model**

Earlier methods developed by Waldron\(^1\) and Gray and Ohashi\(^2\) assumed a simple shear deformation pattern for the developed tensile stress in reinforced soil and the corresponding strength increment of soil (Fig. 2). The thickness of shear zone has major importance for the prediction of the strength of reinforced soils as it affects both the mobilized resistance of reinforcement due to stretching or bending.

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. 6). This deformed shape has been defined as:

\[
 X_1 = B - Be^{-4[\phi]} 
\]

where, \( X_1 \) = axis parallel to shear direction, \( X_2 \) = axis perpendicular to the shear direction with origin at the centre of shear zone, \( B \) = one-half of the externally applied shear

Fig. 5: Fibre-reinforced model extending across shear zone of thickness \( z \)
displacement and \( b \) = a deformation decay constant depending on reinforcement concentration, reinforcement stiffness and soil-reinforcement bond strength. Later, Shewbridge and Sitar\(^6\) developed a model has been by based on the above deformation pattern (Fig. 6) to investigate the influence of soil and reinforcement properties on the work to deform the soil. A rigid-plastic model was chosen to define the stress-strain relation for the soil. Reinforcement deformation results in the storing of elastic energy in reinforcement due to stretching and bending and change in normal stress in shear zone.

\[
W = 2\int_{0}^{l(B)} A\sigma_{c}(be^{-ibX})\tan\varphi_{c}\beta dX_{2} + 2N_i\int_{0}^{1/b} ([be^{-ibX}][l(B) - X_i]r_{i}\cdot\pi d_{j} \cos i\tan d\beta dX_{2} + N_i\frac{1}{2}E_{f}I_{b}^{2}b^{3} + \frac{N_i[4\pi^2\pi[l(B)]^{3}]}{3E_{f}} \tag{13}
\]

where, \( \varphi_{c} \) = friction angle of soil at critical state, \( l(B) \) = length of reinforcement in tension as function of one-half shear displacement, \( E_{f} \) = elastic modulus of reinforcement and \( A \) = cross-sectional area of shear

In eqn. 13, the first term describes the amount of frictional work to shear the soil due to the normal stress acting on the shear plane. The second term describes the amount of frictional work to deform the soil due to an increase in the normal stress acting on the shear planes caused by tension in the reinforcements. The third term describes the amount of work required to bend the reinforcements. The fourth term describes the amount of work to stretch the reinforcements as determined from the elastic stretching of the reinforcements. All of the terms are positive and decrease in magnitude with decreasing \( b \) in eqn. 12.

**Statistical models**

Ranjan et al.,\(^6\) carried out a series of triaxial compression tests on cohesionless soils reinforced with discrete, randomly distributed fibres, both synthetic and natural, to study the influence of fibre characteristics (weight fraction, aspect ratio and surface friction) soil characteristics and its density and confining stress on the shear strength of reinforced soils. The test results indicate that the failure envelopes of soil-fibre composites have a curvilinear failure envelope with a transition occurring at a certain confining stress, termed as critical confining stress, below which the fibres tend to slip. The magnitude of the critical confining stress is affected by the fibre aspect ratio. Shear strength of soil has been significantly increased by the fibre inclusion. The increase in strength is a function of fibre characteristics.

A regression analysis of test results has been carried out to develop a mathematical model to bring out the effect of these factors. The model estimates the strength of soils reinforced with
any type of fibre and under given stress environment. The model is represented mathematically as a function of weight fraction of fibre \((f_c)\), fibre aspect ratio \((1/d_f)\), surface friction coefficient \((f^*)\), coefficient of friction \((\phi)\) and confining pressure \((\sigma_3)\) as follows:

\[
\sigma_f = f(f_c, \frac{l}{d_f}, f^*, \phi, \sigma_3)
\]

(14)

The shear strength relationship has been developed as:

\[
\sigma_f = 12.3(f_c)^{0.14}(\frac{l}{d_f})^{0.28}(f^*)^{0.27}(\phi)^{1.1}(\sigma_3)^{0.68}
\]

for \(\sigma_3 > \sigma_{crit}\)

(15)

\[
\sigma_f = 8.78(f_c)^{0.35}(\frac{l}{d_f})^{0.26}(f^*)^{0.06}(\phi)^{0.64}(\sigma_3)^{0.73}
\]

for \(\sigma_3 > \sigma_{crit}\)

(16)

These proposed models give accurate result for shear strength of uniformly graded cohesionless soils.

Sivakumar Babu and Vasudevan have developed a statistical model using regression for prediction the strength of fibre-reinforced soil. Conventional triaxial testing of soil mixed with coir fibre has been carried out to study the effect of various fibre parameters on strength and stiffness of soil. From experimental results, they have analysed that the inclusion of coir fibres result in the improvement in shear strength parameters, failure deviator stress, stiffness and energy absorption capacity of soil. A statistical model to quantify the major principal stress at failure, cohesion, friction angle and initial stiffness of coir fibre-reinforced soil is as follows:

\[
\sigma_{f,ult} = 159.1 + 3.96\sigma_3 - 0.0083\sigma_3^2 - 2959 d_f + 4866.5d_f^2 - 37.01 f_c + 17.35 f_c^2 + 58.8 l
\]

(17)

\[
c = 76.5 + 156.4d_f - 102.2d_f^2 + 1261f_c - 303.3f_c^2 - 202 d_f f_c
\]

(18)

\[
\phi = 23.1 - 7.85d_f + 191.1d_f^2 + 7.08f_c + 23.8f_c^2 - 15.02d_f f_c
\]

(19)

\[
E_i = 8992.2 + 64.94\sigma_3 - 0.14\sigma_3^2 - 94612 d_f + 186594d_f^2 - 1744.9 f_c + 1167.8 f_c^2 + 1765.1 l
\]

(20)

\[
l < 2s \quad \text{or} \quad \eta < \frac{\sigma_{f,ult}}{2\sigma_n\tan\delta}
\]

where, \(\sigma_{f,ult}\) = major principal stress at failure, \(\sigma_n\) = confining pressure, \(f_c\) = fibre content in % by dry weight, \(d_f\) = diameter of fibre, \(l\) = length of fibre, \(c\) = cohesion, \(\phi\) = angle of internal friction and \(E_i\) = initial stiffness modulus of coir fibre-reinforced soil.

Overall this regression analysis is very useful to quantify the effect of various fibre parameters on shear parameters, major principal stress at failure and initial stiffness modulus for fibre-reinforced soil over a wide range of confining pressures and fibre parameters.

**Energy-based homogenization model**

Michalowski and Zhao have used an energy based homogenization technique to calculate the macroscopic (average) failure stress of fibrous granular composite materials at failure. The fibre-soil mixture was considered as isotropic. The deformation pattern of fibres was assumed as in Fig. 7, where fibres slip at both ends of the fibres and tensile rupture takes place in the middle of the fibres. The expected distribution of the shear stress on the fibre surface and the axial stress in the fibre is also shown. An energy-based homogenization system has been used to achieve the macroscopic failure stress of fibrous granular composite. The strength of granular matrix is quantified by the internal friction angle \((\phi)\) and fibres are characterised by volumetric concentration \((x = v_f/v)\), aspect ratio \((\eta=l/d_f)\), yield point \((\sigma_{f,ult})\) and fibre-soil interface friction angle \((\delta)\).

Failure of a single fibre in a deforming composite can occur due to fibre slip or tensile rupture. Tensile rupture is modelled here as incipient plastic flow of fibres. However, even if a tensile rupture occurs, the end of the fibre slips as the tensile strength of fibre material cannot be mobilized throughout the entire fibre length. At tensile rupture failure of fibre, slip at the end of fibre occurs up to a distance \(s\) as follows:

\[
s = \frac{d_f\sigma_{f,ult}}{4\sigma_n\tan\delta}
\]

while pure slip failure occurs when fibre length

\[
l < 2s \quad \text{or} \quad \eta < \frac{\sigma_{f,ult}}{2\sigma_n\tan\delta}
\]
A failure criterion of fibre-reinforced matrix has been given as:

\[ \bar{\sigma}_1 - \tan^2(\frac{\pi}{4} + \frac{\varphi}{2})\bar{\sigma}_1 = \frac{2\sigma_{f,ult}}{3}M(1 - \frac{\sigma_{f,ult}}{4\eta p \tan \delta}) \]

(21)

where, \( p = \frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2} \) and \( M = (\frac{1}{2} + \frac{\varphi}{\pi})\tan^2(\frac{\pi}{4} + \frac{\varphi}{2}) - \frac{1}{2} - \frac{\varphi}{\pi} + \frac{1}{\cos \varphi} \)

The failure criteria derived is directly applicable in numerical methods for solving boundary value problems, but is limited to isotropic mixtures.

**Discrete framework model**

Zornberg\(^10\) proposed a design methodology for fibre-reinforced soil slope to characterize the contribution of randomly fibre reinforcement using discrete framework approach. In this approach the reinforced mass is characterised by the mechanical properties of individual fibres and of the soil, rather than by the mechanical properties of the fibre-reinforced composite material. Fibres 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 fibre-reinforced specimens in order to perform limit equilibrium analysis. The mode of failure of fibres has been defined by a critical stress at which failure change from fibre pullout to fibre breakage. **Fig. 8** shows the bilinear representation of the fibre induced distributed tension. When failure is governed by fibre breakage, the fibre-induced distributed tension is a function of the volumetric fibre content and tensile strength of individual fibres. For pullout failure, the fibre-induced distributed tension is a function of the volumetric fibre content, interface shear strength and fibre aspect ratio. Equivalent shear strength of fibre-reinforced soil for fibre pullout failure has been defined as:

\[ s_{eq,p} = c_{eq,p} + (\tan \varphi)_{eq,p} \sigma_n \]

(22)

where, \( c_{eq,p} = c(1 + \alpha \eta \varphi c_{i,\varphi}) \) and \( (\tan \varphi)_{eq,p} = (1 + \alpha \eta \varphi c_{i,\varphi}) \tan \varphi \)

\( c_{i,\varphi} \) and \( c_{i,\phi} \) are interaction coefficients defined as:

\[ c_{i,\varphi} = \frac{a}{c} \quad \text{and} \quad c_{i,\phi} = \frac{\tan \delta}{\tan \varphi} \]

where, \( a = \) adhesive component of the interface shear strength between soil and fibre. Equivalent shear strength of fibre-reinforced soil for fibre tensile breakage is given as:

\[ s_{eq,t} = c_{eq,t} + (\tan \varphi)_{eq,t} \sigma_n \]

(23)

where, \( c_{eq,t} = c + \alpha \eta \sigma_{f,ult} \) and \( (\tan \varphi)_{eq,t} = \tan \varphi \)
Theoretical model

Rifai and Miller\(^1\) developed a theoretical model to describe the mechanism of tensile strength improvement of fibre-reinforced soil undergoing desiccation. The model includes a distinctive effective stress combination acting on the fibre strings due to the generated matric suction by desiccation. Mohr-Coulomb failure criterion at the interface area between fibres 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 fibres has been assumed with single fibre under the combined effect of overburden soil pressure and lateral earth pressure in addition to matric suction. Tensile strength of the fibre-soil composite increases significantly by fibre inclusion and the increase is a function of fibre content and soil-water content. The apparent increase in tensile strength of a unit volume of fibrous soil due to fibre inclusion has been given as:

\[ \Delta \sigma_t = \frac{f_d}{2G_s f} \left[ \sigma_v - u_w \right] + \left[ \frac{\left( K_0 - 1 \right) K_0 u_w}{\gamma_d} \right] \tan \phi \] (24)

where, \( \gamma_d \) = dry unit weight of soil, \( w_f \) = weight of fibre, \( G_s \) = specific gravity of fibre, \( \sigma_v - u_w \) = effective vertical stress on fibre, \( K_0 = 0.75 \) \( K_0 + 0.25 \) = effective lateral earth pressure coefficient, \( K_0 \) = lateral earth pressure coefficient at rest, \( u_w - u_r \) = matric suction, \( \Theta \) = normalize volumetric water content and \( K \) = fitting parameter.

Other approaches

Michalowski and Cermak\(^2\) developed a model for the prediction of the failure stress in triaxial compression. Drained triaxial compression tests on fibre-reinforced sand have been conducted. It is found that the addition of a small amount of synthetic fibres increases the failure stress of the composite, drops the initial stiffness and increases the failure strain. The benefit of fibre reinforcement increases with increase in fibre concentration and aspect ratio and is also dependent on relative size of the grains and fibre length.

The concept of macroscopic internal frictional angle \( (\phi) \) has been introduced to describe the failure criteria of fibre-reinforced sand in this model. The prediction of failure stress in triaxial compression test is based on frictional interaction of fibres and sand. This model is limited to cylindrical monofilament fibres with an isotropic distribution of their orientation. The failure of fibre is governed by a critical confining stress. For a soil subjected to confining pressure less than critical value, slip

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**Fig. 8**: Fibre induced distributed tension as per discrete approach
of fibre occurs and beyond that critical limit, rupture of fibre occurs.

In the model, fibre-reinforced soil has been replaced by a granular material characterized with equivalent friction angle \( \Phi \) given as:

\[
\Phi = 2 \tan^{-1} \left( \frac{N \eta \tan \delta + 6K_p}{6 - N \eta \tan \delta} \right) - \frac{\pi}{2}
\]

(25)

where, \( \Phi \) = macroscopic internal friction angle, \( K_p = \tan^{-1} \left( \frac{\pi}{4}, \frac{\Phi}{2} \right) \), \( N = K_p \sin \theta_p, \Phi = \tan^{-1} \left( N \eta \right) \)

Michalowski\(^{13}\) has worked on the development of an anisotropic yield condition for fibre-reinforced sand and on the application of the kinematic approach of limit analysis for solving problems with anisotropic materials. In anisotropic yield condition for fibre-reinforced sand, ellipsoidal distribution of fibres 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. The angle of internal friction for an anisotropic material is dependent on the spatial direction. The yielding of an anisotropic composite is described with a circular trace of the yield surface in space \( \tau_{pq}, p, q \) (Fig. 9) and this surface is shifted to the origin by distance \( Q \) along \( q \)-axis. The internal friction angle (\( \varphi_a \)) for anisotropic material has been described by the expression

\[
\sin \Phi_a = \frac{R_o}{R} \sqrt{1 - \frac{1}{R_c^2 \sin^2 \omega} - \frac{Q}{R_c^2 \cos 2 \omega}} \sqrt{1 - \frac{1}{R_c^2 \sin^2 2 \omega}}
\]

(26)

where, \( \omega \) = angle of inclination to major principal stress to axis \( x \), \( \zeta \) = angle made by major principal strain rate with axis \( x \), \( R_o \) = radius of circular cross section, \( Q \) = offset of circular cross section at \( \Omega \), \( \tau_{pq} = \frac{\sigma_{pq}}{2} = \text{in-plane mean microscopic stress} \), \( \tau_{pq} = \frac{\sigma_{pq}}{2} = \text{shear stress} \).

Fig. 9: Trace of the yield condition on plane \( p \) for anisotropic soil

Ibraim et al.\(^{14}\), Ibraim and Maeda\(^{15}\) and Maeda and Ibraim\(^{16}\) developed a two-dimensional DEM (Distinct Element Method) for micromechanical analysis under biaxial compression condition of sand-fibre mixture for understanding the bond generation by randomly distributed flexible fibres within soil and its effect on kinematics of granular matrix. Macro and micro behaviour of composite material have been studied. The analysis implies that fibres completely separate the sand particles. The dilation phenomena of mix are not inhibited by fibres and increase with fibre content. The interaction mechanism between fibres and matrix is not mobilized at small and medium strain domains. Beyond this axial strain, the tensile strength in reinforcement increase with strain level and
the maximum value is found with higher fibre content. The effect of reinforcement is higher for fibre oriented in the direction of minor principal strain. Local micro fabric and local structural rearrangement have an important effect on the interaction mechanism between fibres and the original matrix. The presence of fibres increases micro-confinment for the granular matrix.

Bourrier et al.,17 developed a numerical model of direct shear tests of non-rooted and rooted granular soils based on the Discrete Element Method (DEM) to analyse the influence of the roots on the shear resistance of the soil. Numerical simulations have been carried out for different soils (frictional and cohesive granular) and root properties (tensile strength, bending modulus, root–soil interfacial friction angle, number of roots).18-20 This model takes into account of the root tensile loading until breakage, the root bending loading, the root–soil adhesive links until adhesion breakage and the root slippage associated with a frictional resistance at the root–soil interface.21-24 The results show that the effect of the roots strongly depends on the shear strain for any soil type. Shear strain range associated with the different processes strongly depends on the relative rigidities of the roots and soil matrix.25 The approach developed can also be used to analyse the resistance of rooted soils under different loading conditions.

CONCLUSION

Soil reinforcement with randomly distributed fibres 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 fibre-reinforced soil composite depends on fibre content, fibre aspect ratio, fibre soil interface friction, strength characteristics of fibres, soil-reinforcement bond strength and internal friction angle of soil. The models developed have been for low fibre concentration (<10%) to neglect fibre-fibre interaction. Estimation of fibre contribution in soil strength is mainly based on the concept of isotropic distribution of fibres within soils. But in actual field conditions due to decomposition technique of fibre-reinforced soils (mixing, rolling, compacting), fibre orientation has a defined bedding plane giving anisotropic mechanical properties of mixture. The influence of scale effects on the stress-strain characteristics of fibre-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 fibre-reinforced soils in a better way.

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