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Enhancement of Slope Stability of Cover Soil of Landfills

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Introduction

The contribution to slope stability provided by fibers in a fiber-reinforced soil mass might be accounted for by using the fiber-induced tension, 't', as a discrete component in the stability analyses. The magnitude of the fiber-induced tension can be defined as a function of properties of the individual fibers (i.e. tensile strength and interface shear strength). Fiber-induced tension contributed by the fibers for the enhancement of the slope stability has been evaluated. The key assumption in this is the orientation of the fibers. The following assumptions are adopted regarding the orientation of the fibers once they mobilize tensile stresses.

- The fiber-induced tension 't' can be assumed to act, for design purposes, along the failure surface. This assumption enables the fiber-induced tensile contribution 't' can be directly added to the shear strength of the soil in a limit equilibrium analysis.

- The fiber-induced tension 't' can be assumed to act, for design purposes in a horizontal direction consistent with the design of reinforced soil structures using continuous planar reinforcements.

- The fiber-induced tension 't' can be assumed to act in a direction, which is somewhere in between the initial fiber orientation (which is at random) and the orientation of the failure plane.

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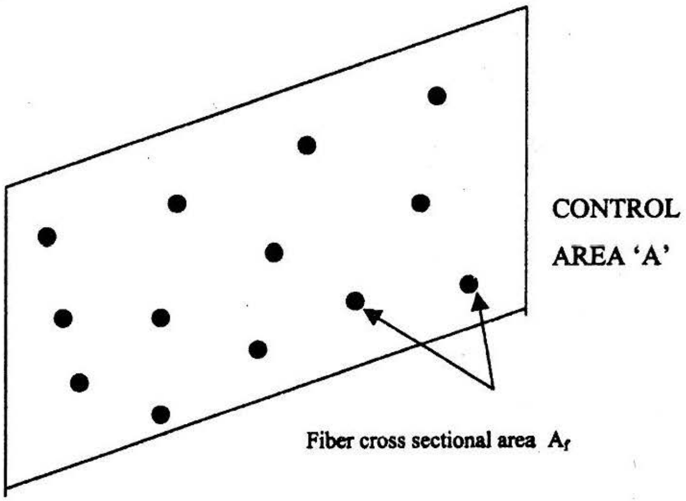

FIGURE 1 : Cross Section Showing the Cross Sectional Area of Fibres

Gray and Ohashi (1983) have provided an experimental test result, which supports the assumption that the fiber-induced tension acts along the failure surface, as the equivalent shear strength increase is independent of the orientation at which the failure plane intercepts the many randomly, oriented fibers. Though several models have been proposed in the literature to explain the behavior of randomly distributed fibers within a soil mass, here the analysis is based on a force equilibrium approach given by Maher and Gray (1990).

The shear strength model of fiber-soil composite is an important aspect, which is considered for the slope stability of the cover soil based on the study given by Gregory (1996). In the analysis two basic failure criteria are analyzed for the fiber. First, the pullout failure of the fiber and second, the breakage failure of the fiber. The conditions determining the failure criteria are also explained and used in the examples.

Failure Modes

Fiber-Induced Tension Breakage Failure Mode

The breakage failure mode here means that the failure is governed by the ultimate strength, σ_{ult}, of the individual fiber, when achieved (i.e. the fiber-induced tension at breakage). The ultimate tensile strength of the individual fiber, σ_{ult}, is determined in the laboratory. Figure 1 shows the cross section of all the fibers in a control section. If the failure is to governed by the tensile strength of fibers then the tensile force carried by the individual fibers in control section 'A' can be defined as follows:

$$\text{Ultimate Tensile Force} = t_t A = \sigma_{ult} A_f \tag{1}$$

where A_f = cross sectional area of the fiber

A = cross sectional area of control volume

t_t = fiber-induced tension for breakage failure mode

σ_{ult} = ultimate tensile strength of the individual fiber

If the volumetric fiber content $\chi = V_f/V$, then $\chi = A_f/A$ (2)

where V_f = volume of the fiber,

V = volume of the soil

Using Eqns. (1) and (2) we get,

$$t_t = \sigma_{ult}\chi$$

Fiber-Induced Tension in Pullout Failure Mode

The pullout failure mode means that the pullout resistance of the fiber, from the soil governs the failure. The interface shear resistance of individual fibers, 'f' can be determined by pullout testing of individual fiber specimens in the laboratory. The interface shear resistance of individual fibers can be defined as follows:

$$f = a + \tan\delta \times \sigma_n$$

where a = adhesive component, and

δ = interface friction angle.

A concept of interaction coefficient, commonly used in the soil reinforcement literature for continuous planar reinforcement, is adopted herein to relate the components of the interface shear strength to the shear strength of the soil matrix. The interface shear strength of individual fibers can then be expressed in terms of the backfill soil shear strength as follows:

$$f = c_1 \cdot c + c_2 \cdot \tan\phi$$

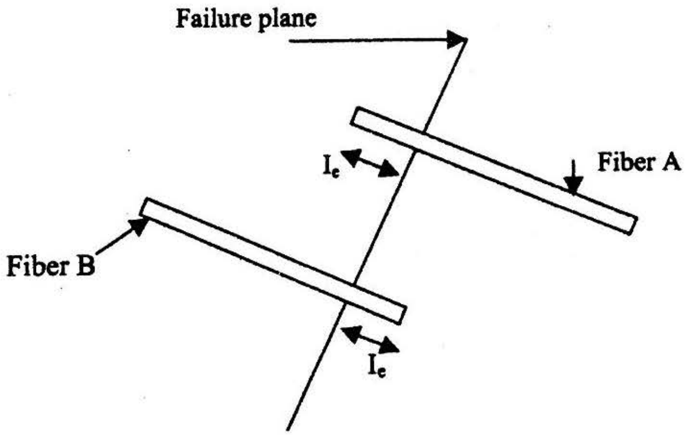

FIGURE 2 : Embedded Length of the Fiber with respect to the Failure Plane

where, c_1 and c_2 are the interaction coefficients for the cohesive and frictional components of the interface shear strength (i.e. c and $\tan\phi$) respectively. These interaction coefficients are defined as:

$$c_1 = a/c$$

$$c_2 = \tan\delta/\tan\phi$$

For the purpose of analysis the equivalent diameter for non-round cross-sectioned fiber is given by

$$d_f = \left(4A_f/\pi\right)^{1/2}$$

If l_f is the length of the fiber, then the embedded length l_e is the length of the shorter portion of the fiber on either side of the failure surface. Figure 2 shows the embedded length of the fiber on either side of the failure surface. The average embedded length of the fiber is given by (Mather and Gray, 1990)

$$l_{e\,ave} = l_f/4 \qquad (3)$$

The pullout resistance is quantified by computing the pullout resistance along the average embedded length, crossing a control surface A, instead of the actual embedded length. Hence when the pullout resistance governs the failure the tensile force carried by the individual fibers in the control section A can be defined, in case of a cohesion less soil as follows:

$$\text{Ultimate Tensile Force} = t_p A = \pi d_r l_{e\,ave} \sigma_n c_2 \tan\phi \, n \tag{4}$$

where t_p = distributed tension due to pullout resistance

σ_n = normal stress

ϕ = internal friction angle of the soil

n = number of fibers in a control section A

$$= A_{ft}/A_f = A_{ft}\Big/\left(\pi(d_f)^2/4\right) \tag{5}$$

A_{ft} = total area of fiber

A_f = area of individual fiber

The aspect ratio of the individual fiber is

$$\eta = l_f/d_f = (\text{length of the fiber/effective diameter}) \tag{6}$$

Using equations (4), (5) and (6) the distributed tension t_p can be estimated as:

$$t_p = \eta \chi c_2 \cdot \tan\phi \, \sigma_n$$

where χ = volumetric fiber content,

σ_n = normal stress, and

c_2 = interaction coefficient for frictional component of the soil

Thus the term t_p is a function of both fiber interaction properties and of the confining properties.

The adhesion component, a, of the pullout resistance can also be accounted for in the expression for interface shear strength of the fiber. In this case, the tensile force at failure carried by the individual fibers in the control section A can be defined as follows,

$$\text{Ultimate Tensile Force} = t_p A = \pi d_r l_{e\,ave} \left(c_1 \cdot c + \sigma_n c_2 \tan\phi\right) n \tag{7}$$

Using equations (4), (5), (6) and (7) the distributed tension t_p can be estimated as:

$$t_p = \eta \chi \left(c_1 \cdot c + \sigma_n c_2 \tan\phi\right)$$

Fiber-induced Tension and Critical Confining Pressure

The fiber-induced tension 't' to be used to account for the tensile contribution of the fibers in a limit equilibrium analysis is therefore given by

$$t = \min(t_t, t_p)$$

$$t = \min[(\sigma_{ult}\chi), (\eta\chi c_2 \cdot \tan\phi\, \sigma_n)] \text{ for cohesion less soils}$$

$$t = \min[(\sigma_{ult}\chi), \{\eta\chi(c_1 \cdot c + \sigma_n c_2 \tan\phi)\}] \text{ for cohesive soils}$$

where t_t = fiber-induced tension in breakage failure mode

t_p = fiber-induced tension in pullout failure mode

The critical confining pressure $\sigma_{n\,crit}$ that defines the change in the failure mode, which governs the behavior of the fibers, is the confining pressure at which failure occurs, simultaneously, by fiber breakage and by fiber pullout. (i.e.) at

$$\sigma_{n\,crit} = t_t/\chi = t_p/\chi$$

Therefore,

$$\sigma_{n\,crit} = \sigma_{ult}/(\eta c_2 \cdot \tan\phi) \text{ for cohesion less soils, and}$$

$$\sigma_{n\,crit} = (\sigma_{ult} - \eta\chi c_1 \cdot c)/(\eta\,\chi c_2 \cdot \tan\phi) \text{ for cohesive soils} \qquad (8)$$

The governing condition is, if $\sigma_n < \sigma_{n\,crit}$ then the mode of failure is fiber pullout and if $\sigma_n > \sigma_{n\,crit}$ the mode of failure is fiber breakage. Here the critical confining pressure is a function of the fiber geometry (η), the ultimate tensile strength of the fiber, the soil shear strength parameters and fiber-soil-interaction properties. However the critical confining pressure is not a function of the fiber content. Maher and Gray (1990) have identified the existence of a critical confining stress, at which level there is a change in the equivalent shear strength behavior of a fiber-reinforced composite. Their experimental results indicated that:

- The equivalent shear strength envelope obtained from tri-axial tests shows either a curved or bilinear shape with a transition at a certain critical confining stress

- An increase in fiber aspect ratio results in a lower critical confining pressure and higher equivalent shear strength.
- An increase in fiber content shows no apparent change in the critical confining pressure.
- The equivalent shear strength increases approximately linearly with increasing amounts of fiber and then approaches an asymptotic upper limit governed mainly by confining stress and fiber aspect ratio.
- Well-graded sands with a coefficient of uniformity (i.e. sands with comparatively higher shear strength) result in a lower critical confining pressure and higher equivalent shear strength.

Equivalent Shear Strength of Fiber-Reinforced Composite Soil

To obtain the equivalent shear strength of the fiber reinforced composite the relationship between the fiber-induced tension 't' and soil shear strength properties should be established. The important assumption made here is the orientation of the fibers to be used for design purposes for the fiber-induced tension: one, parallel to the shear plane; and two, horizontal fiber-induced tension. For the analysis here it is assumed to act parallel to the shear plane. The equivalent shear strength of the fiber-reinforced soil, S_{eq} is given by

$$S_{eq} = S + \alpha t$$

where S = shear strength of the soil alone

α = empirical coefficient for direction effect on 't' (i.e. fiber-induced tension)

If the assumption regarding the orientation of he fiber-induced tension t is correct, the empirical coefficient a will be equal to 1. Figures 3 and 4 show the schematic representation of the equivalent shear strength cohesion less soil and cohesive soils respectively.

For the case of a cohesion less soil

$$S_{eq} = \tan\phi\left(1+\alpha\eta\chi c_1\right)\sigma_n \quad \ldots\ldots \text{ for } \sigma_n < \sigma_{n\,crit} \text{ condition}$$

$$S_{eq} = \alpha\,\chi\,\sigma_{ult} + \tan\phi\;\sigma_n \quad \ldots\ldots \text{ for } \sigma_n > \sigma_{n\,crit} \text{ condition}$$

For the case of cohesive soils

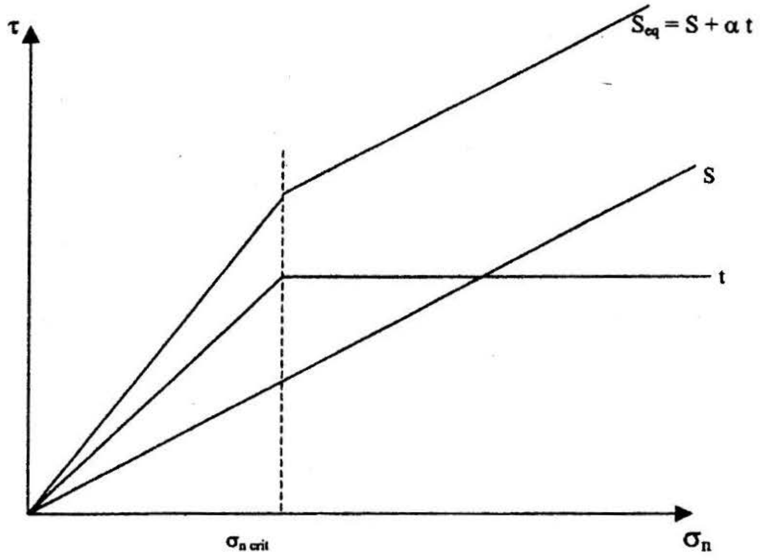

FIGURE 3 : Equivalent Shear Strength with Fiber-Induced Tension for Cohesionless Soils

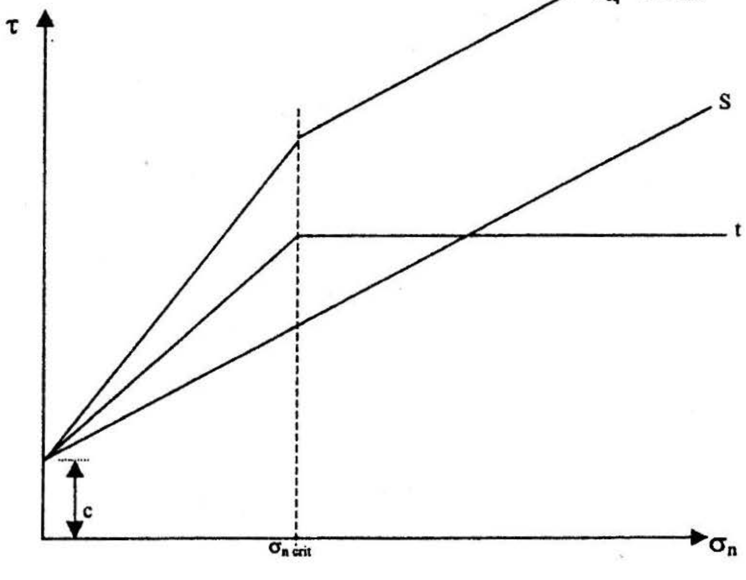

FIGURE 4 : Equivalent Shear Strength with Fiber-Induced Tension for Cohesive Soils

$$S_{eq} = c_{11} + (\tan\phi)_1 \sigma_n \qquad \ldots\ldots \text{ for } \sigma_n < \sigma_{n\,crit} \text{ condition}$$

where $c_{11} = (1 + \alpha\eta\chi c_1)\, c$, and

$$(\tan\phi)_1 = \tan\phi(1 + \alpha\,\eta\,\chi\, c_2)$$

$$S_{eq} = c_{22} + (\tan\phi)_2 \sigma_n \qquad \ldots\ldots \text{ for } \sigma_n > \sigma_{n\,crit} \text{ condition}$$

where $c_{22} = c + \alpha\,\chi\,\sigma_{ult}$ and

$$(\tan\phi)_2 = \tan\phi$$

Design Methodology for Cover Soil Slope Stability using Fiber-Reinforced Soil

Limit Equilibrium approach for fiber-reinforced slopes of cover soil for landfills will be analyzed. The orientation of the fiber-induced tension 't' is assumed parallel to the failure surface. Figure 5 shows a schematic view of a fiber-reinforced infinite soil veneer. The orientation of the fiber-induced

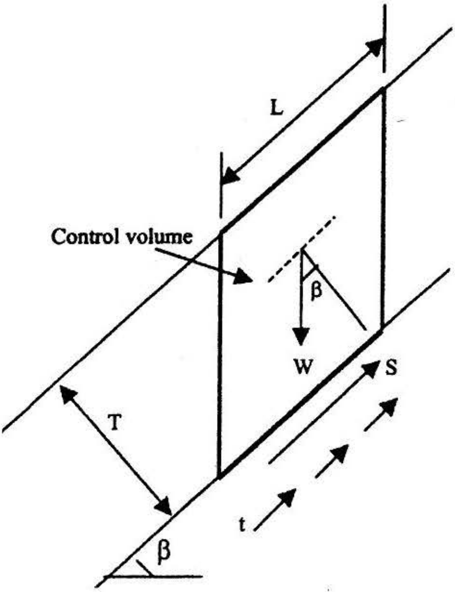

FIGURE 5 : Shear Strength of Cover Soil and Fiber-Induced Tension in a Control Volume

tension 't' is assumed parallel to the failure surface. The stability of the soil veneer is established by calculating the factor of safety (FS) as follows.

$$\text{Factor of Safety, FS} = \frac{c + (N/L)\tan\phi}{S/L - \alpha t}$$

where $N = W\cos\beta$

c, ϕ = shear strength parameters of the soil

t = fiber-induced tension

L = length of the control section along the slope

S = equivalent shear strength of the soil-fiber composite

α = coefficient of orientation

β = side slope angle

Even though the coefficient α is equal to unity as per the assumption it is included for completeness. Using limit equilibrium the FS becomes

$$FS = \frac{c + W\cos\beta\tan\phi}{W\sin\beta - \alpha t L} \tag{9}$$

where W = weight of the soil in control volume

L = length of the control volume

β = side slope angle

ϕ = internal friction angle of the soil

$W = \gamma L T$

where γ = unit weight of the soil

T = thickness of the cover soil

Therefore Eqn.(10) becomes

$$FS = \frac{c + \gamma T\cos\beta\tan\phi}{\gamma T\sin\beta - \alpha t} \tag{10}$$

For a targeted FS value the required fiber-induced tension 't_{req}' can be obtained from Eqn.(10) as,

$$t_{req} = \gamma T \sin\beta / (\alpha FS)\{FS - c/(\gamma T \sin\beta) - \tan\phi/\tan\beta\}$$

The critical normal stress is given by Eqn.(8). The normal stress at the base of the veneer is defined as,

$$\sigma_n = \gamma T \cos\beta$$

If $\sigma_n < \sigma_{n\,crit}$, the dominant mode of failure is the fiber pullout. In this case, the convenient expression can be obtained to define the fiber content. 'χ_{req}' required to satisfy the target FS value.

Equating $t_p = t_{req}$ for $\sigma_n < \sigma_{n\,crit}$ we get,

$$\chi_{req} = \frac{FS - [c/(\gamma T \sin\beta) + \tan\phi/\tan\beta]}{\alpha FS \eta [c_1 c/(\gamma T \sin\beta) - c_2 \tan\phi/\tan\beta]} \tag{11}$$

Similarly, if $\sigma_n > \sigma_{n\,crit}$, the dominant mode of failure is fiber breakage. Again a convenient expression can be obtained to define the fiber content. 'χ_{req}' required to satisfy the target FS value.

Equating $t_p = t_{req}$ for $\sigma_n < \sigma_{n\,crit}$ we get,

$$\chi_{req} = \gamma T \sin\beta / (\alpha FS \sigma_{ult})\{FS - c/(\gamma T \sin\beta) - \tan\phi/\tan\beta\} \tag{12}$$

Note that the above equation is for both cohesive and cohesion less soils. For cohesion less soils the term containing c will become zero.

A computer program was developed to obtain the values of χ_{req} for various side slope angles and cover soil thickness. The results are shown in Figs.6, 7 and 8 for 25, 37.5 and 50 mm fibers respectively. The gravimetric is the ratio of weight of fibers to the dry weight of soil.

Conclusions

The utilization of fiber reinforced composite soil in the side slope of landfill over the barrier liner (geosynthetic liner) provides innovative and cost effective designs for veneer cover soil. The methodology proposed for the stability analysis of fiber reinforced soil slope is generic and treats the fibers as discrete reinforcing elements, which contribute stability by developing tensile stresses.

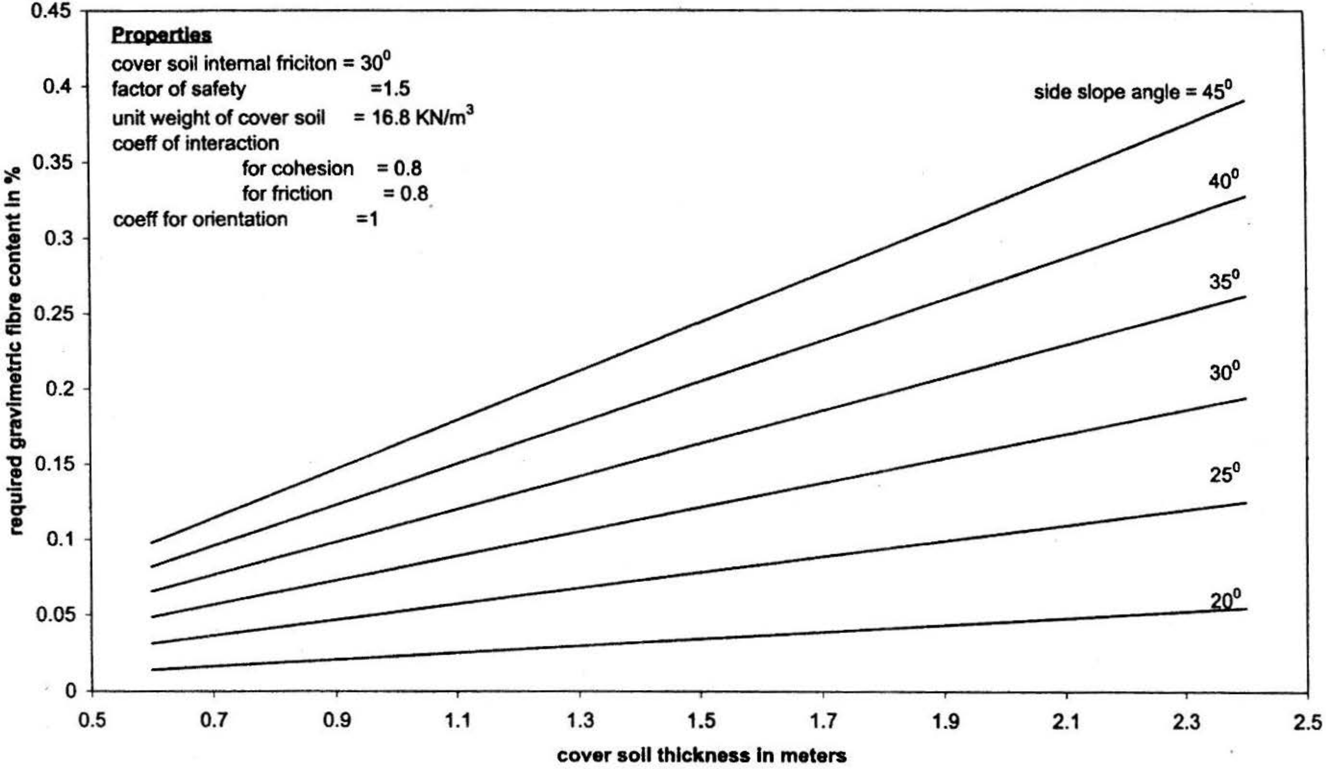

FIGURE 6 : Required Gravimetric Fiber Content for 2.5 cm Fiber

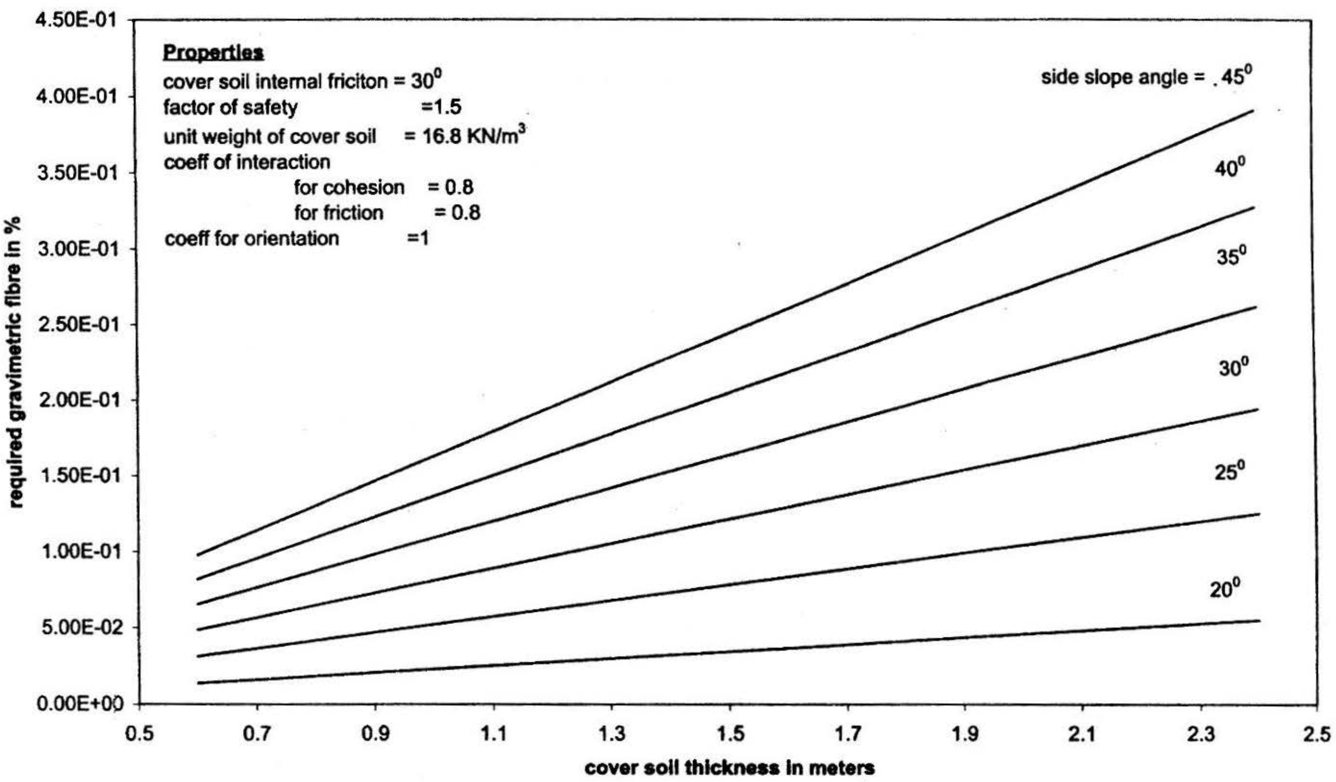

FIGURE 7 : Required Gravimetric Fiber Content for 3.75 cm Fiber

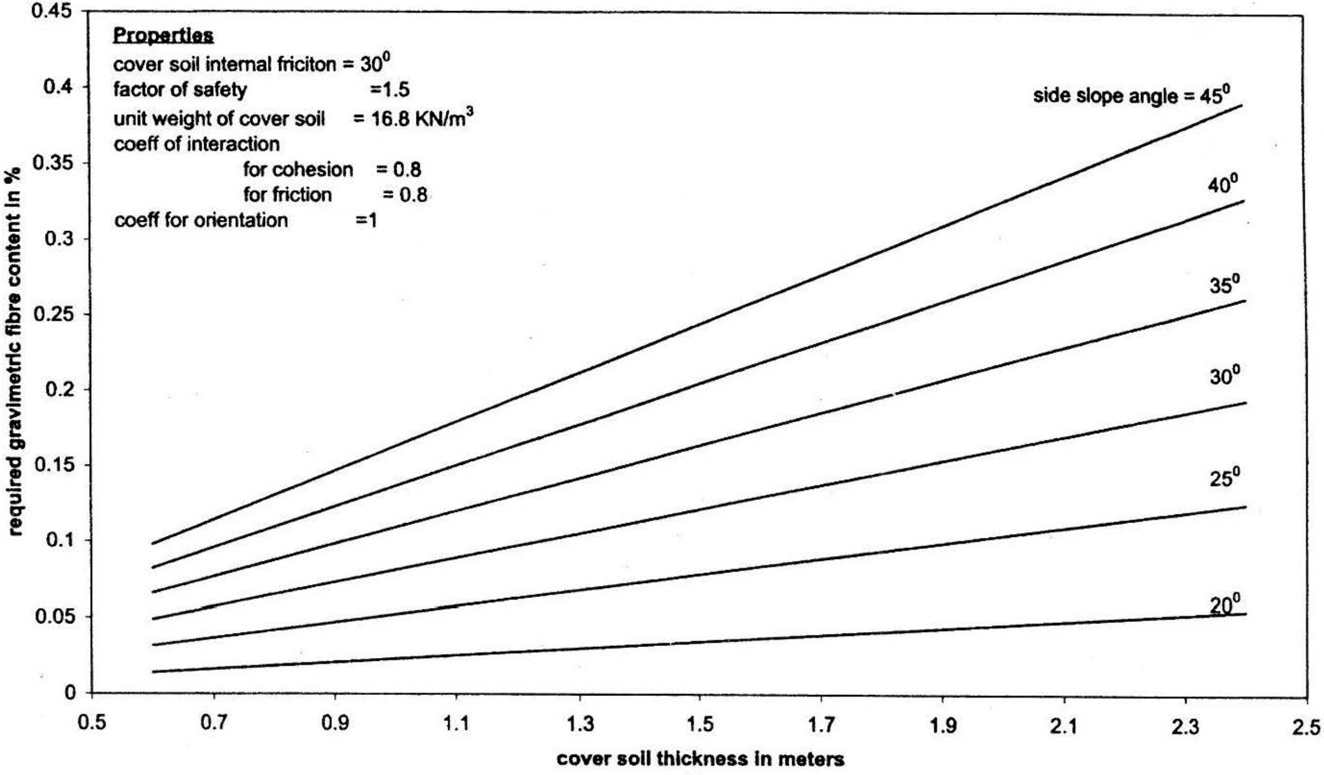

FIGURE 8 : Required Gravimetric Fiber Content for 5 cm Fiber

The fiber-induced tension is a function of fiber content. It is also a function of ultimate tensile strength of individual fibres or fiber aspect ratio and interface shear strength of individual fibers if governing mode of failure is by individual fiber breakage or by fiber pullout respectively. The critical confining pressure at which there is a change in the fiber reinforced soil behavior form fiber pullout to fiber breakage can be defined using the individual fiber and soil matrix properties.

The proposed design methodology for fiber reinforced soil structures using a discrete approach is consistent with current design guidelines for the use of continuos planar reinforcements and with the actual soil improvement mechanism.

The proposed discrete design methodology can lead not only to a more accurate design but also to the development of more adequate field specifications, standard of practice, and quality control guidelines.

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