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Unsaturated Soil Mechanics for Agricultural Conditions

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SUMMARY: Over the years, fundamental theories of soil mechanics have been applied to the study of agricultural soil behaviour. These theories are largely based on the assumption that the soil is saturated. In an emerging unsaturated soil mechanics the soil is considered to have four phases: solid, air, water and *contractile skin* (the air-water interphase). The contractile skin acts like a rubber membrane as it induces a matric suction in the soil pores. Suction has been shown to affect both strength and volume change characteristics of unsaturated soils. The relationship between water content and matric suction (the *soil-water characteristic curve*) becomes an important component of the unsaturated soil mechanics framework. Concepts and implications of these developments for some agricultural soils problems are discussed. Experimental data highlighting these relationships are also presented.

KEYWORDS: Soil Suction; Soil-Water Characteristic Curve; Shear Strength; Unsaturated Soil Mechanics

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Introduction

Over the years Agricultural Engineers have used theoretical soil mechanics as a basis for their study of soil behavior and adapted models as necessary to produce solutions relevant to agricultural conditions. In general, these classical soil mechanics theories have been developed for saturated soil. Studies have revealed that while similarities exist between the behavior of saturated and unsaturated soil, there are also some significant differences. These differences have been found to be related to the use of matric suction as an independent state variable when dealing with unsaturated soils.

Some models used in agricultural situations have used classical soil mechanics theories developed for saturated soil. In view of the unsaturated nature of the surficial soils, there arises the need to investigate the extent to which desaturation affects soil behaviour. This paper investigates the influence of soil suction on agricultural soil mechanics and investigates the manner in which accepted models are affected by soil suction. Some typical formulations are reported which illustrate the incorporation of unsaturated soil mechanics principles.

An unsaturated soil and matric suction

Apart from the three independent phases namely solid, water and air usually ascribed to soil, a fourth phase has been postulated as being of importance in understanding the behaviour of an unsaturated soil. This additional phase is described as the air-water interphase (i.e., contractile skin) and provides a normal stress due to the pore-water pressure (Fredlund and Rahardjo, 1993a). While a saturated soil possesses positive pore-water pressure, unsaturated soil is characterized by negative pore-water pressure. The negative pore water pressure acts as a pull into the water at all air-water interfaces in the soil profile as shown in Figure 1. This pull creates a surface tension on the contractile skin pulling the particles together and providing additional strength to an unsaturated soil compared to a saturated soil where strength is due to the buoyancy effect of the positive pore-water pressure. At the air-water interface of an unsaturated soil, the pore air pressure u_a (assumed amtmospheric for agricultural conditions) is greater than the pore water pressure u_w (negative). The difference in these two independent pressures (u_a-u_w) is referred to as the soil matric suction. There is increasing acceptance for applying matric suction as an independent stress state variable for an unsaturated soil.

Soil stress state variable

The soil stress state is influenced by the number of phases present. The effective stress for a saturated soil (σ-u_w) has been reinterpreted as a stress state variable for saturated soil behaviour rather than a physical law (Fredlund and Rahardjo, 1993a). Because of the presence of an additional phase (the contractile skin) in an unsaturated soil, two independent stress variable are needed to describe unsaturated soil behaviour. Three possible combinations of stress state variables have been identified. These are:

$(\sigma - u_a)$ and $(u_a - u_w)$
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The first pair is generally used in practical engineering problems since it separates the effect due to changes in normal stress from the effect due to change in pore-water pressure (Fredlund, 1979).

Agricultural soil failure criterion and some strength related models

Agricultural engineers have long recognized that soil suction contributes toward soil strength; however, there has never been a rigorous framework quantifying the contribution of soil suction. Let us now consider failure conditions for a soil in light of the stress state variables and then consider the implications for practical agricultural engineering problems.

Shear strength failure criterion

A common shear strength failure criterion for a *saturated* soil is called the Mohr-Coulomb equation which is expressed as follows:

$$\tau_f = c' + (\sigma_n - u_w)\tan\phi' \qquad (1)$$

where,

τ_f = shear strength

c' = effective cohesion

ϕ' = effective angle of internal friction

σ_n = total normal stress on the failure plane, and

u_w = pore-water pressure.

This relationship has proven to be satisfactory for applications where the soil is saturated and the pore-water pressures are positive. A modified Mohr-Coulomb failure criterion has been proposed by Fredlund *et al.* (1978) for an unsaturated soil:

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad (2)$$

where,

u_a = pore-air pressure

$(\sigma - u_a)$ = net normal stress

$(u_a - u_w)$ = matric suction

ϕ' = angle of internal friction relating net normal stress variable and shear stress (Note: this angle turns out to be equal to the effective angle of internal friction)

ϕ^b = angle relating rate of change in shear strength with respect to a change in matric suction.

Equation (2) can also be written as follows:

$$\tau_f = c + (\sigma_n - u_a)\tan\phi' \qquad (3)$$

where,

c = total cohesion, which can be written as

$$c = c' + (u_a - u_w)\tan\phi^b \qquad (4)$$

Eqs. (2) and (3) recognize the existence of an air-water interface and the inward pull of the pore-water.

Let us compare Eq. (3) with the form of failure equation traditionally used by agricultural engineers,

$$\tau_f = c + \sigma_n \tan\phi \qquad (5)$$

For agricultural conditions the pore-air pressure is approximately atmospheric, i.e., $u_a = 0$ (gauge). In this case, Eq. (3) and Eq. (5) are identical provided the angle of internal friction in Eq. (5) is equal to the effective angle of internal friction, i.e.,

$$\phi = \phi' \qquad (6)$$

This equality has already been established from experimental data as evident in the form of Eq. (2).

The modified Mohr-Coulomb failure criterion (i.e., Eq. 2) introduces a new shear strength parameter, namely, ϕ^b and the stress state variables, $(\sigma\text{-}u_a)$ and $(u_a\text{-}u_w)$. The angle ϕ^b, relates the change in shear strength to matric suction, $(u_a\text{-}u_w)$. While ϕ', the effective angle of internal friction, is a property related to the friction between the soil particles, ϕ^b is related to the stress in the pore fluids. The nature of the pore space in agricultural soils makes ϕ^b an important additional parameter in the determination of shear strength. The effective cohesion used for a saturated soil now takes on a different form (i.e., Eqs. 3 and 4). Eq. 4 indicates that the cohesion depends on matric suction (u_a-u_w), ϕ^b and the effective cohesion, *c'*.

Since the parameters *c* and ϕ (i.e., Eq. 5) include the effect of suction they are only applicable for the particular soil suction conditions occurring at the time of measurement. A failure criterion of the form of Eq. (2) is useful when considering varying field suction conditions.

Determination of unsaturated soil parameters

Experimentally, *c*, *c'* and ϕ' have been determined either in-situ or from laboratory tests. For in-situ determinations, field condition changes and some variables (e.g., matric suction) cannot be controlled. Laboratory tests on the other hand, can be carried out under controlled conditions. The unsaturated soil parameter, ϕ^b, can be obtained from laboratory tests.

The total cohesion *c* and unsaturated internal angle of friction ϕ (cf. Eq. 5) have traditionally been evaluated on soil specimens *in their unsaturated state*. This could be in standard laboratory tests, or in-situ, using grouser plate tests. In practice, agricultural engineers have used standard test equipment designed for *saturated* soils to determine the unsaturated parameters *c* and ϕ in the laboratory. It is more appropriate to use equipment modified to allow the matric suction of the soil specimens to be controlled while testing, such as the modified shear apparatus described by Gan *et al.* (1988) or the modified triaxial apparatus used by Wulfsohn *et al.* (1994). Rapid and simple *in-situ* techniques are available for measuring the soil parameters *c* and ϕ, such as the instrumented device described by Upadhyaya *et al.* (1993).

Example Problem No. 1: Prediction of traction

From a consideration of equilibrium, the net traction developed by a tire (or track) on a deformable soil surface is given by the sum of all horizontal components of stress in the direction of travel acting over the tire-soil interface (Fig. 1)

$$NT = \int_A [\tau\cos\theta - \sigma\sin\theta]dA \qquad (7)$$

where NT = net traction; τ = shear stress, σ = normal stress; θ = angle between surface normal and the vertical at any point on the contact surface; A = contact surface. The major contribution to net traction comes from the shear stress distribution. Therefore the maximum net traction is limited by the shear strength of the soil. Maximum tractive effort is not practically realized due to slip between tire and soil. A soil shear stress-displacement relationship is usually employed to account for this. Bekker (1960) proposed using a shear stress displacement of the form:

$$\tau = \tau_f (1-e^{-j/K}) \tag{8}$$

where,

τ = shear stress [F L^{-2}]

τ_f = shear strength [F L^{-2}]

j = soil shear deformation [L]

K = shear deformation modulus [L]

To obtain an expression for net traction for varying field conditions we may use Eq. (2) as the expression for shear strength; however, we have no knowledge of the variation of shear modulus K with varying suction. Attempts at modifying Eq. (8) based on the unsaturated soil framework may require the investigation of the effect of suction on shear modulus. Such a study will require the further investigation of the shear stress-strain family of curves in a modified direct shear box as used by Gan *et al.* (1988). It is possible to control the matric suction of the soil at desired values when using the modified direct shear box.

Example Problem No. 2: A tillage tool force prediction model

A commonly used model for tillage tool force prediction is the Universal Earth Moving Equation proposed by Reece (1965). This model can be applied for wide tools cutting the soil in a passive type failure (Figure 3). The model relates the force on the tool to soil properties, tool parameters and several dimensionless factors and can be expressed as:

$$F = (\gamma h^2 N_\gamma + c\,h\,N_c + q\,h\,N_q)\,b \qquad (9)$$

where,

γ = total unit weight of the soil [F L^{-3}]

h = tool depth into the soil [L]

c = soil cohesion [F L^{-2}]

b = tool width [L]

q = soil surcharge [F L^{-2}]

The dimensionless factors, N_γ, N_c and N_q, relate the tool rake angle to the internal friction angle and the soil tool adhesion. These factors are described as follows;

N_c = the factor for soil cohesion

N_γ = the factor taking into account the total unit weight of the soil

N_q = the factor taking into account the soil surcharge

These factors can be obtained from charts established by Hettiaratchi and Reece (1974).

By introducing the total cohesion form for an unsaturated soil (i.e., Eq. 4), this model can be appropriated for the prediction of the tillage tool force for an unsaturated soil as:

$$F = [\,\gamma h^2 N_\gamma + c'\,h\,N_c + (u_a - u_w)\,h\,N_s + q\,h\,N_q\,]\,b \qquad (9)$$

where,

$$N_s = N_c \tan \phi^b \qquad (10)$$

The dimensionless factor, N_s (i.e., the factor taking into account the soil matric suction) is implied in the suggested model (i.e., Eq. 9). The N_s factor however is a function of N_c and the unsaturated soil parameter ϕ^b (i.e., Eq. 10).

The two problems described above are commonly encountered in agricultural situations. It should be noted that the concepts applied to the above models could also be applied to other existing models used in agricultural soil mechanics. In applying the unsaturated framework to agricultural models, it may be necessary to modify the soil parameter and/or the way in which the stress state variables are applied. In the traction problem for example, the effective stress, (σ-u_w), in the traditional formulation has been modified into two independent stress state variables, net normal stress (σ-u_a) and matric suction (u_a-u_w). The soil internal friction angle, ϕ, and cohesion, c, were also redefined while a new parameter, ϕ^b, was introduced. With respect to the tillage problem, it would appear adequate to simply modify the cohesion parameter, c.

Experimental Character of Soil Matric Suction and Shear Strength

While water content is easy to measure, the soil suction determination usually takes considerable time and effort. However, there is an important relationship between soil suction and water content which can be determined. The relationship between soil suction and water content was originally used in predicting the soil water available for plant growth. It can also be used to infer the shear strength properties of the soil.

Soil water content versus matric suction

Two forms of the relationship between soil suction and water content have been identified. The first form is obtained from soil specimens compacted at different densities and water contents (i.e., these specimens are unidentical in the sense that they may have different soil structures and are thus "different soils"). Studies by Olson and Langfelder (1965) showed a distant relationship between soil suction and water content. However, static and kneading methods of compaction yield different soil suction versus water content relationships as observed by Mou and Chu (1981) for an expansive clay and Mojlaj *et al.* (1991) for a clay-loam soil.

The second form of relationship between soil suction and water content is called the *soil-water characteristic curve.* This curve is obtained using one specimen or several "identical" soil specimens in the pressure plate apparatus. The distinction between these two kinds of soil suction versus water content relationships becomes important since the soil-water characteristic curve is a unique relationship for a particular soil of the same structure. A variation in suction in this case is induced by wetting or drying.

The difference between the soil suction versus water content relationship (as compacted) and the soil-water characteristic curve for a glacial till is shown in Figure 4. The 'as compacted' points indicate the states for specimens which have been compacted at different moisture contents and densities. The soil-water characteristic curve on the other hand shows the progressive decrease in moisture content as a single specimen (or several identical ones) dries out as evident by the increasing matric suction.

Some benefits abound in the use of the soil-water characteristic curve in unsaturated soil research. It is generally easier, faster and cheaper to determine the moisture content of the soil than the suction. The soil-water characteristic curve provides information about the soil suction for known water contents, which means the number of tests required for changing soil moisture conditions is reduced. It has been suggested by Fredlund and Rahardjo (1993b) that it might also be possible to estimate unsaturated soil mechnaical properties based upon the nature of the soil-water characteristic curve.

Soil shear strength versus matric suction

The shear strength of an unsaturated soil is not only affected by the friction and cohesion of the soil, but also by the amount of water in the pores. The soil-water characteristic curve relates the soil suction to the amount of water in the soil,,and the soil suction has also been shown to be related to the shear strength of the soil. The relationship between soil suction and the shear strength is quantified in terms of the soil shear strength parameter ϕ^b. Shear strength Eqs. (2) and (3) indicate the contribution of soil suction to shear strength;

$$(u_a - u_w)\tan\phi^b \tag{11}$$

The shear strength parameter, ϕ^b, relates matric suction to shear strength in a similar manner by which the coefficient of internal friction, ϕ', relates net normal stress to shear strength. Both planes of shear strength have the same cohesion intercept, c', but the same is not true for linearity (Fig. 5). Equation (11) suggests a linear relationship between shear strength and matric suction but the experimental research by Gan *et al* (1988), shown in Figure 6, shows that this relationship is linear only up to some value of suction (i.e., estimated as the air entry value of the soil), while beyond this value, the relationship becomes nonlinear. At low matric suction, the change in shear strength is controlled by ϕ' while ϕ^b controls the change in shear strength at high matric suctions.

In agricultural situations, the strength of the soil dictates its resistance to tillage tools and implements. The strength also affects root penetration and anchorage. Machine operations such as tillage, soil conditioning and seeding are carried out at field suctions which vary from time to time. Hence it is valuable to establish a soil suction versus shear strength relationship for the soil in question. The soil-water characteristic curve and the soil suction versus shear strength relationships appear to be important for the prediction of soil behavior for tillage and traction and should be extended to other conditions such as volume change and compaction.

Summary

The implication on engineering analysis of the unsaturated nature of agricultural soils has been examined. Some practical agricultural problems have been reviewed within an unsaturated soil mechanics framework. Strength based models used in traction and tillage studies may be modified to forms which will allow the models to be used for different field matric suction conditions. This approach can also be applied to other problems in agricultural soil mechanics.

In support of the proposed formulations, aspects of unsaturated soil behaviour such as soil strength experiments are described and reported. The concepts described above are advantageous under varying field situations. It will coonsiderably reduce the number of in-situ tests required. These concepts are relevant to agricultural soil as it is prone to desaturation and changing field conditions.

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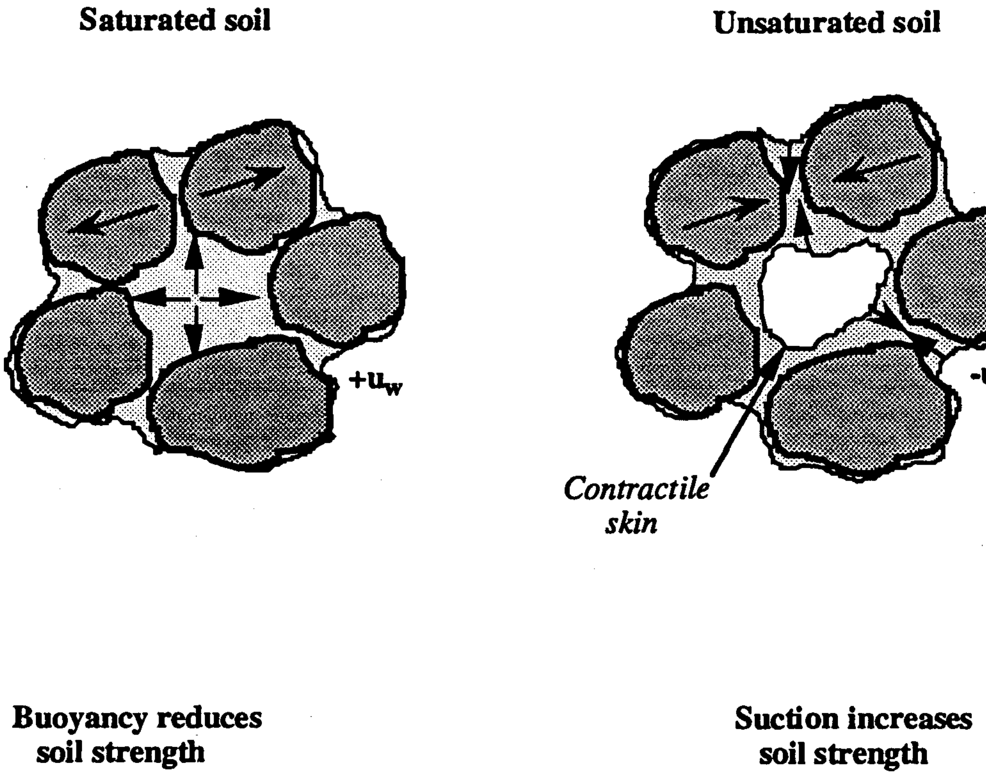

Fig. 1 Effect of pore pressures on soil strength.

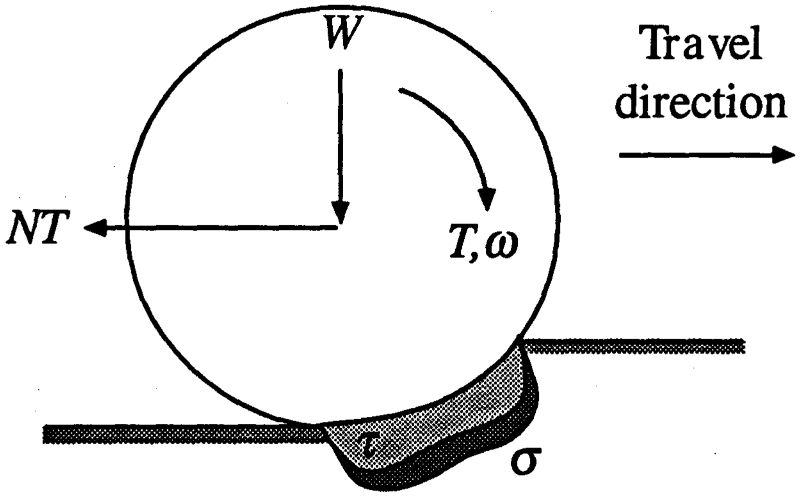

Fig. 2 Traction model for the interaction between tire and soil.

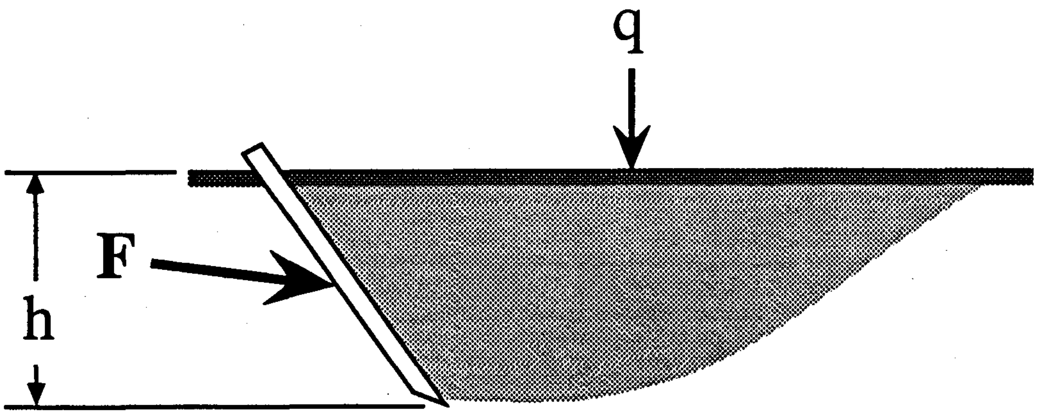

Fig. 3 Tillage tool and soil failure pattern.

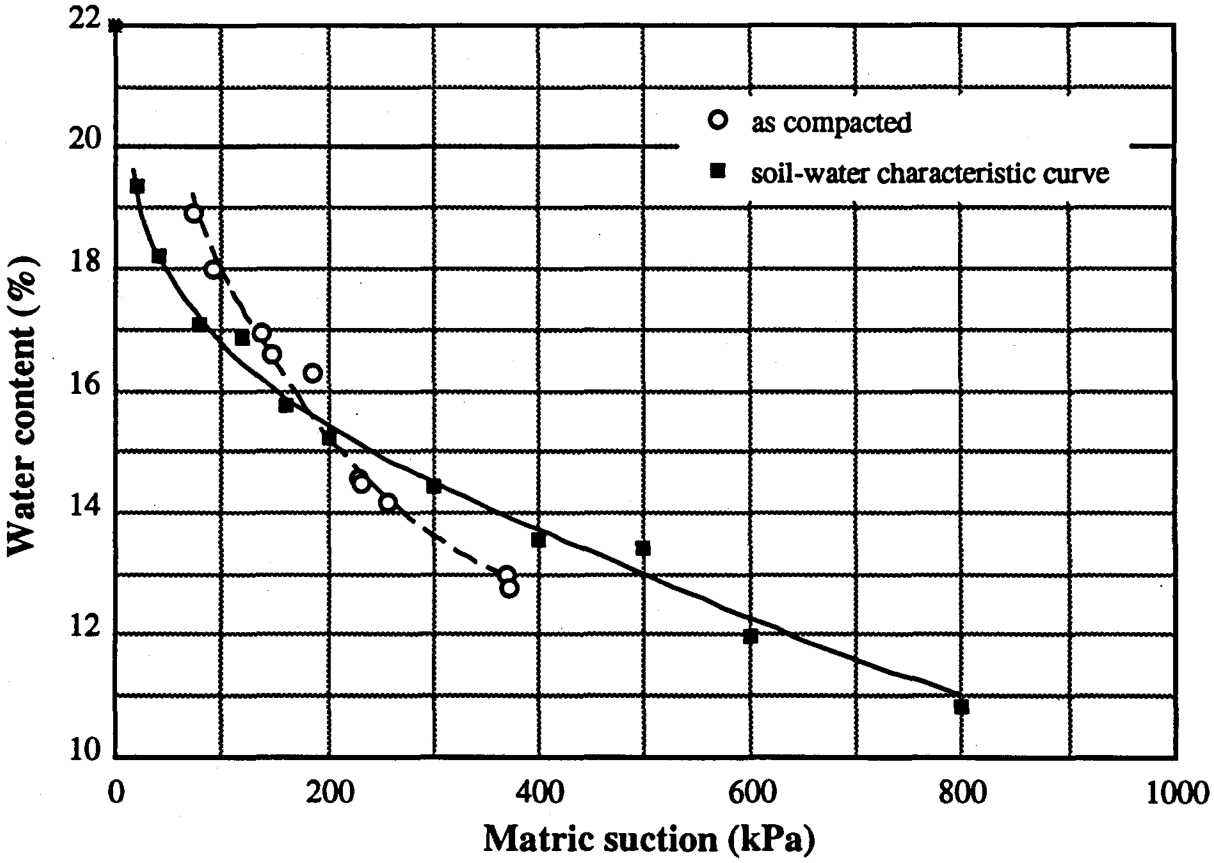

Fig. 4 Soil water content versus matric suction for a glacial till.

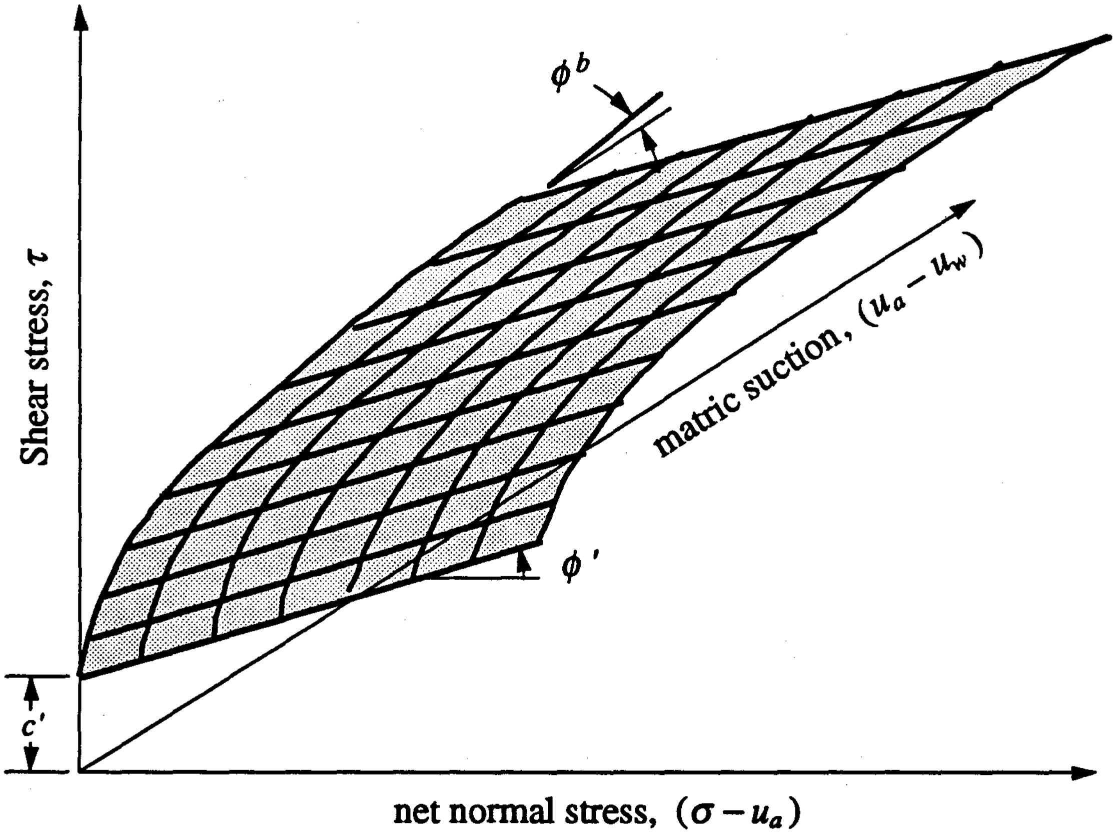

Fig. 5. Extended Mohr-Coulomb failure envelope for unsaturated soil.

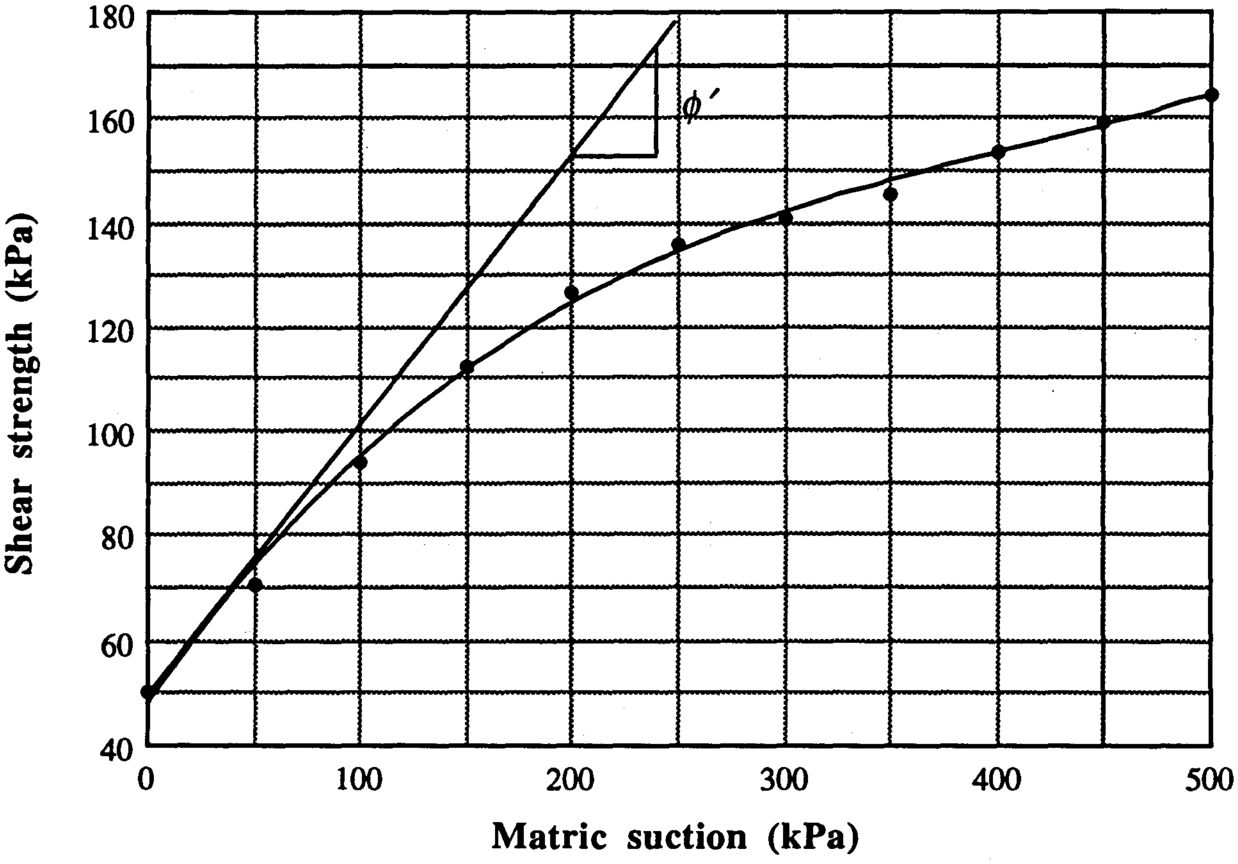

Fig. 6. Matric suction versus shear strength relationship for a glacial till (Gan *et al.*, 1988).