

Application of unsaturated soil mechanics for agricultural conditions

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Wulfsohn, D., Adams, B.A. and Fredlund, D.G. 1996. **Application of unsaturated soil mechanics for agricultural conditions.** Can. Agric. Eng. **38**:173-181. Agricultural engineers often draw upon the classical theories of soil mechanics in their study of agricultural soil behaviour. These theories are largely based on the assumption that the soil is saturated. In an emerging theoretical framework, an unsaturated 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) becomes an important component of the unsaturated soil mechanics framework. In this paper, concepts and implications of these developments for some agricultural shear strength-based models are discussed. Experimental data highlighting these relationships are also presented. Keywords: soil suction; soil-water characteristic; shear strength.

Les ingénieurs agricoles utilisent fréquemment les théories classiques de mécanique des sols afin d'étudier le comportement des terres agricoles. Généralement, ces théories se basent sur la supposition que le sol soit saturé. Le cadre théorique qui émerge suppose que le sol non saturé est composé de quatre phases: solide, air, eau, et peau contractile (l'interphase eau-air). La peau contractile peut être comparée à une membrane de caoutchouc puisqu'une succion matricielle se produit dans les pores du sol. Il a été démontré que la succion affecte à la fois les caractéristiques de résistance et le changement de volume des sols non saturés. La relation entre la teneur en eau et la succion matricielle (caractéristique de l'eau-sol) devient une composante intrinsèque dans l'étude de la mécanique des sols non saturés. L'application de ces concepts sur deux modèles traditionnels d'interaction entre sol et machine sera présentée. Des données expérimentales seront également présentées.

INTRODUCTION

Over the years, agricultural engineers have adapted theories of classical soil mechanics as necessary to produce solutions relevant to agricultural soil conditions. The classical theories were originally developed for saturated soil. In view of the unsaturated nature of surficial soils, the extent to which desaturation affects soil behaviour needs to be understood. While similarities exist between the behavior of saturated and unsaturated soil, there are also significant differences. These differences have been found to be related to the role of matric suction as a stress variable when dealing with unsaturated soils. This paper discusses the influence of soil suction on unsaturated soil behaviour and explores the manner in which some accepted strength-based agricultural soil mechanics models can be extended for varying moisture

conditions. Some typical formulations are used to illustrate the incorporation of unsaturated soil mechanics principles.

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, an unsaturated soil is characterized by negative pore-water pressure which exerts a tensile pull at all air-water interfaces in the soil profile (Fig. 1). The surface tension on the contractile skin pulls the particles together providing additional strength to an unsaturated soil compared to a saturated soil where, in contrast, the positive pore-water pressure reduces the strength. At the air-water interface of an unsaturated soil, the pore air pressure u_a is greater than the pore water pressure, u_w . 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 in describing the behaviour of an unsaturated soil.

Soil stress state variables

The soil stress state is influenced by the number of phases

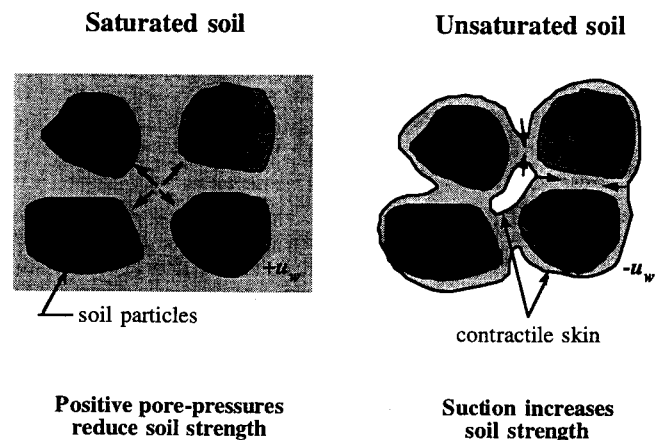


Fig. 1. Effect of pore pressures on soil strength.

present. The effective stress for a saturated soil ($\sigma - u_w$) can be 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), two independent stress variables are needed to describe unsaturated soil behaviour. Three possible combinations of stress state variables have been identified. These are:

- ($\sigma - u_a$) and ($u_a - u_w$)
- ($\sigma - u_w$) and ($u_a - u_w$)
- ($\sigma - u_a$) and ($\sigma - u_w$)

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.

In this framework, the matric suction becomes an essential parameter in describing the state of a soil. It is more common to determine the soil water content; however, there is an important relationship between soil suction and water content which can be determined.

Experimental nature of 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 Croney and Coleman (1954) and Olson and Langfelder (1965) showed a distinct relationship between soil suction and water content for soils compacted at various water contents. 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 Mojilaj et al. (1992) for a clay loam. In other words, different methods of compaction (i.e., impact, kneading, vibratory, or static compaction) result in significantly different fabrics in both sands and clays (Mitchell 1993).

The second form of the relationship between soil suction and water content is called the soil-water characteristic. This curve is obtained using one specimen or several "identical" soil specimens (e.g., using pressure plate apparatus or Tempe cells). The distinction between these two kinds of soil suction versus water content relationships becomes important since the soil-water characteristic characterizes a particular soil of the same structure. A variation in suction in this case is induced by wetting or drying. It is important to note that there may be considerable hysteresis of the soil-water characteristic. Thus, if the stress history of the soil is not known, knowledge of the water content only (i.e., a deformation state variable) may not be sufficient for determining the matric suction (i.e., a stress state variable).

The difference between the soil suction versus water content relationship (as compacted) and the soil-water characteristic for a glacial till is shown in Fig. 2. The "as compacted" points indicate the states for specimens which have been compacted by static compaction at different water

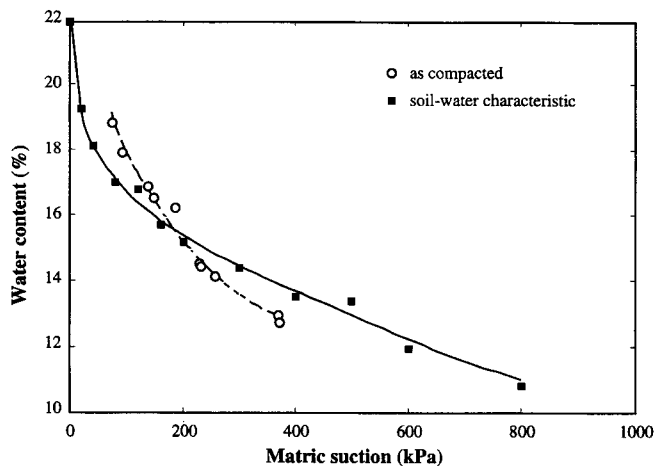


Fig. 2. Soil water content versus matric suction for a glacial till (data from Vanapalli 1994).

contents and densities. The soil-water characteristic on the other hand shows the progressive decrease in water content as a single specimen (or several identical ones) dries, as evident by the increasing matric suction.

There are benefits in using the soil-water characteristic in unsaturated soil research. It is generally easier, faster, and cheaper to determine the water content of the soil than suction, although recent advances in time-domain reflectometry and other technologies (e.g., Woodburn et al. 1993; Whalley et al. 1994) are beginning to eliminate such constraints. The relationship between soil suction and water content was originally used by soil scientists in predicting the soil water available for plant growth. It is also extensively used to empirically estimate the hydraulic conductivity function. Similarly, it has been proposed that the unsaturated shear strength may be estimated using the soil-water characteristic (Fredlund and Rahardjo 1993b).

THE AGRICULTURAL SOIL FAILURE CRITERION

Agricultural engineers and soil scientists have long recognized that soil suction contributes toward soil strength, both shear and tensile (e.g., Greacen 1960; Chancellor and Vomocil 1970; Williams and Shaykewich 1970; Koolen and Kuipers 1983; Mullins and Panayiotopoulos 1984; Mullins et al. 1990; McKyes et al. 1994); however, there has not been a rigorous theoretical framework quantifying the contribution of soil suction. In the following sections we will consider failure conditions for a soil in light of the stress state variables and implications for some practical 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:

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

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.

Equation 1 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:

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

where:

u_a = pore-air pressure,
 $(\sigma_n - u_a)$ = net normal stress,
 $(u_a - u_w)$ = matric suction,
 ϕ' = angle of internal friction relating change in shear strength to net normal stress, and
 ϕ^b = angle relating change in shear strength with respect to a change in matric suction.

The modified Mohr-Coulomb failure criterion introduces a new shear strength parameter, namely ϕ^b , and the stress state variables $(\sigma - u_a)$ and $(u_a - u_w)$. The proposed failure envelope in stress space is shown in Fig. 3. While the effective angle of internal friction, ϕ' , is a property related to the friction between the soil particles, ϕ^b , is indirectly related to friction through the stresses in the pore fluids. Equation 2 suggests a linear relationship between shear strength and matric suction but the experimental research by Gan et al. (1988), shown in Fig. 4, 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 suctions, the change in shear strength is controlled by ϕ' , while ϕ^b governs the change in shear strength at high matric suctions.

Fredlund et al. (1978) found that the angle ϕ' in Eq. 2 is essentially equal to the effective angle of internal friction.

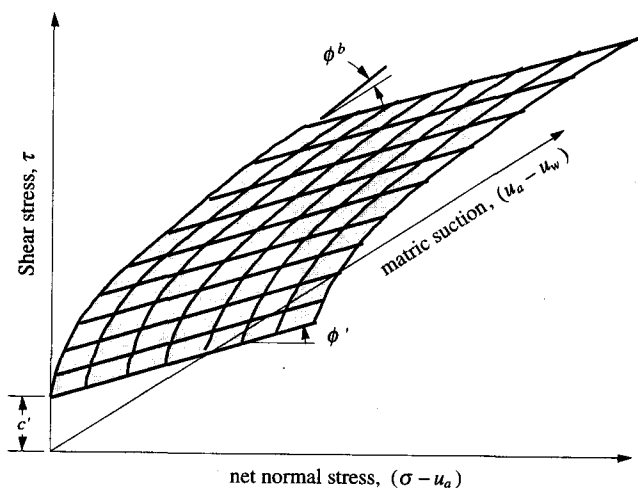


Fig. 3. Extended Mohr-Coulomb failure envelope for unsaturated soil.

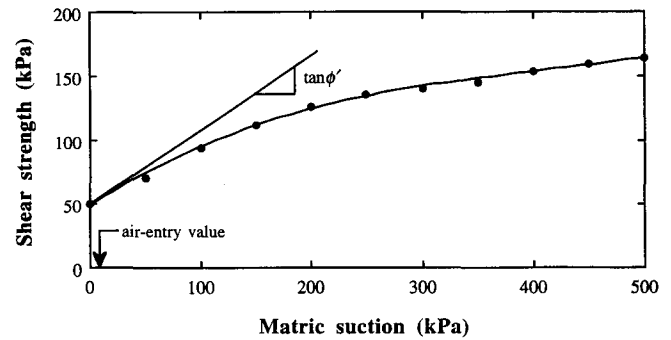


Fig. 4. Shear strength versus matric suction relationship for a glacial till (from Gan et al. 1988).

The slope, $\tan \phi^b$, is equal to $\tan \phi'$ up to the air-entry value, beyond which ϕ^b decreases with increasing suction.

Various researchers, testing a range of soil textures, have found small increases of the angle ϕ' with increasing matric suction (Escario 1980; Escario and Sáez 1986; Drumright 1989). However, Drumright (1989) showed that when variations in net applied stress were accounted for, the differences in ϕ' with respect to suction were reduced. The angle ϕ^b has been shown to be consistently equal to or less than ϕ' (Fredlund and Rahardjo 1993a).

A failure equation traditionally used by agricultural engineers is:

$$\tau_f = c + \sigma_n \tan \phi \quad (3)$$

where:

c = total cohesion, and
 ϕ = angle of internal friction.

For agricultural conditions the pore-air pressure is approximately atmospheric (i.e., $u_a = 0$, gauge). If indeed the angle of internal friction in Eq. 3 may be equated to the effective angle of internal friction, i.e., $\phi = \phi'$, then Eqs. 2 and 3 are identical provided the cohesion can be written as:

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

Equation 4 proposes that the total cohesion depends on an apparent cohesion generated due to matric suction, $(u_a - u_w) \tan \phi^b$, and effective cohesion, c' . The latter is dependent on many factors, such as chemical cementation and mineral and organic interparticle attractions (Koolen and Kuipers 1983; Mitchell 1993). The total cohesion c includes the effect of suction and can be considered to be a variable function of suction. The failure criterion given by Eq. 3 is therefore applicable only for the relevant soil suction conditions. A failure criterion of the form of Eq. 2 is useful when considering varying field suction (or moisture) conditions.

Prediction of shear strength for varying suction conditions

Several models have been proposed to relate the shear strength of a soil to the matric suction (e.g., Greacen 1960;

Vomocil and Chancellor 1967; Fredlund et al. 1978; McKyes et al. 1994; Fredlund et al. 1996). Most of these models are based on the assumption that the contribution of suction towards the strength of the soil is related to the area of contact of water in the soil pores. Curvature of the shear strength versus matric suction envelope arises as the net area reduces with drainage (Gan 1986).

Fredlund et al. (1996), using Eq. 2 as the basis of a strength versus suction relationship, proposed a model relating $\tan \phi^b$ to the degree of saturation (or normalized water content). The relationship between the instantaneous angles of friction can be written as:

$$\frac{\tan \phi^b}{\tan \phi'} \approx S^p \quad (5)$$

where:

- S = degree of saturation (i.e., w/w_s),
- w = any gravimetric water content of the soil,
- w_s = water content at saturation, and
- p = a soil parameter related to the soil texture, and thus, to the effective area of water in the soil for a given water content.

By substituting Eq. 5 into Eq. 2, a prediction equation for the shear strength of an unsaturated soil is obtained as:

$$\tau \approx c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) S^p \tan \phi' \quad (6)$$

Equation 6 provides an estimate of the shear strength of an unsaturated soil for a given matric suction and water content using the soil-water characteristic [i.e., $S = S(u_a - u_w)$] and the effective strength parameters c' and ϕ' . At this time there are limited published data to support this relationship. Fredlund et al. (1996) tested the prediction model using a Hong Kong soil for matric suction values up to 200 kPa and found excellent agreement with measured data. A value of p equal to 1 appears to give acceptable results for sandy soils and the parameter generally increases with the plasticity of the soil and lies between $2 \leq p \leq 6$ for clay soils. The shapes of soil-water characteristic curves in the lower ranges of matric suction (where S is on the order of 10^0) would suggest that a value of p equal to 1 should be acceptable for finer textured soils as well so long as predictions are limited to the lower values of suction.

Cui and Delage (1993) found that at a high suction (i.e., 1500 kPa) the general shape of shear stress and volumetric strain versus axial strain curves was quite different than those at lower suctions (i.e., 50 to 800 kPa). Their findings show that suction has an important effect on stiffness and maximum shear strength. This emphasizes the need for precise models for the soil-water characteristic curve if the shear strength characteristics are to be estimated at elevated suctions (i.e., low water contents in fine-textured soils) with any confidence, using prediction equations such as Eq. 6.

Verification of shear strength equation for an agricultural soil

Data are presented for a sandy clay loam having the properties given in Table I. Specimens were statically compacted to the same bulk density (i.e., 1.2 Mg/m^3) at several water

Table I: Index properties of the soil used in the test program

Parameters	Values
Texture: Sand (%)	48.1
Silt (%)	23.6
Clay (%)	28.3
Specific gravity	2.65
Liquid limit (%)	32.9
Plastic limit (%)	18.8
Plasticity index (%)	14.1
Optimum water content (%)	18.0
Maximum dry bulk density (Mg/m^3)	1.65

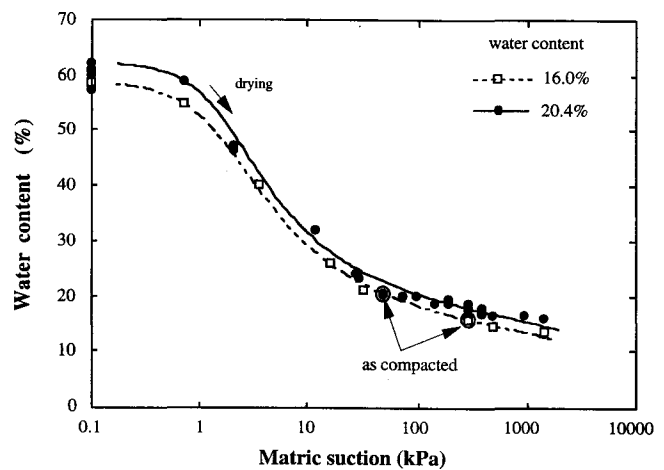


Fig. 5. Water content versus matric suction relationship for specimens compacted at water contents dry of optimum and wet of optimum, to a bulk density of 1.2 Mg/m^3 .

contents, four dry of optimum and one wet of optimum (Table II). Under these conditions, the 'dry of optimum' specimens are expected to all have similar structures and the 'wet of optimum' specimen to have a somewhat different structure. Soil-water characteristics were determined using a pressure cell (University of Saskatchewan design) for specimens statically compacted at 16.0% and 20.4% to represent specimens dry and wet of optimum, respectively (Fig. 5).

Unsaturated shear strength parameters for the soil were determined using direct shear box tests. Net normal stresses ($\sigma - u_a$) from 25 kPa to 150 kPa in 25 kPa intervals were used for the specimens at each water content. The specimens were sheared at a rate of 0.9 mm/min. In addition, the effective strength parameters were obtained from triaxial tests on saturated specimens, using the apparatus described by Wulfsohn et al. (1994). Results of the strength tests are presented in Table II. The results verify that, for this soil, the unsaturated internal friction angle ϕ can be taken as equal to the effective internal angle of friction ϕ' . The total cohesion c shows no trend with water content.

With c' and ϕ' and the soil-water characteristic curves

Table II: Properties of sandy clay loam soil specimens prepared by static compaction to 1.2 Mg/m³ bulk density

As-compacted conditions				Unsaturated strength parameters ^c	
Water content (%)	Void ratio	Degree of saturation (%)	Matric suction (kPa)	<i>c</i> (kPa)	ϕ (degrees)
dry of optimum					
3.5	1.29	7.2	- ^a	6.5	35.8
9.2	1.41	17.3	- ^a	5.3	37.4
14.6	1.53	25.3	595	8.3	35.8
16.9	1.58	28.3	195	6.2	36.8
wet of optimum					
21.1	1.67	33.4	35 ^b	1.3 ^d	35.8 ^d
			saturated strength parameters ^e		
			0	~0	36.5

^a Lies outside range of suction for which experimental data falls

^b From null pressure plate test

^c Parameters of Eq. 3, determined from shear box test data

^d Based on linear regression through 3 data points at low normal stresses (see Fig. 7)

^e From triaxial test data for specimens compacted at 20.4% water content

known, the unsaturated shear strength was then calculated using Eq. 6. The predicted shear strength envelope is plotted versus matric suction and versus net normal stress in Figs. 6 and 7, respectively. The value of *p* used in these predictions was 2.6. The shear strength of the soil did not increase much with reduced water content (increasing suction) in the experiments and this trend was predicted by the model (Fig. 6).

Samples at all water contents developed similar strengths (also see Table II). Figure 7 supports the conjecture that all samples compacted dry of optimum were of similar structure. The data also indicate that the sample wet of optimum had a similar structure. If the soil-water characteristics (Fig. 5) are replotted with degree of saturation on the vertical axis, the curves almost overlap. Nevertheless, the strength of the wet of optimum specimen (*w* = 21.1 %) dropped off significantly at higher net stress levels. This type of behaviour was also observed by Greacen (1960). It is suggested that the strength

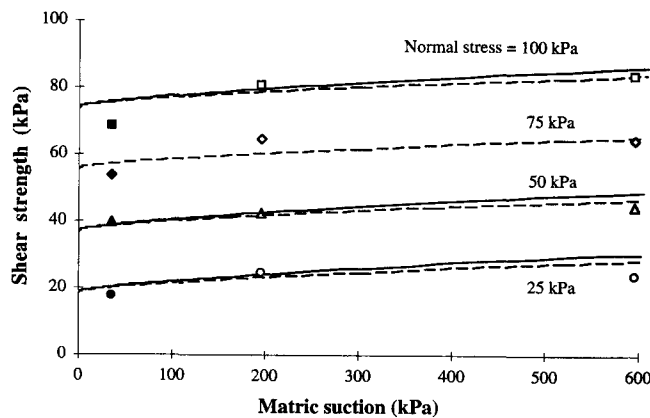


Fig. 6. Predicted and measured shear strength versus matric suction for a sandy clay loam soil. Predicted relationships based on Eq. 6 and soil-water characteristic curves for (---) dry of optimum and (—) wet of optimum specimens (Fig. 5). Open symbols are for specimens compacted at water contents dry of optimum (*w* = 9.2, 14.6, and 16.9%), filled symbols represent specimens wet of optimum (*w* = 21.1%).

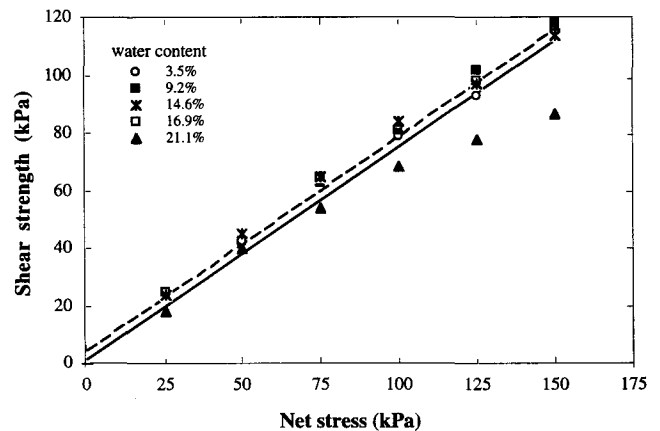


Fig. 7. Predicted and measured shear strength versus net normal stress for a sandy clay loam soil. Predicted relationships are based on Eq. 6 and soil-water characteristics curves for (---) dry of optimum and (—) wet of optimum specimens (Fig. 5).

decreases when normal loads exceeding some critical value greater than the soil suction are applied (see Croney and Coleman 1953; Larson and Gupta 1980). Above this value the tension in the soil water will rapidly decrease, and the pore-water pressure increase, as the “contractile skin” is distorted. Thus, a reduction in strength is observed for the wet of optimum specimen ($u_a - u_w = 38$ kPa) but not for the drier specimens which all had suction values well exceeding the range of normal loads applied in the shear box tests.

APPLICATION TO SOME AGRICULTURAL STRENGTH RELATED MODELS

The strength of soil is of fundamental importance in agricultural soil-engaging processes. The shear strength prediction equation presented above is based on parameters (i.e., effective strength coefficients and the soil-water characteristic) that need only be determined once for a given soil structure, providing a means to simulate the behaviour of strength dependent processes under different moisture conditions. Two examples will be presented here.

Example Problem No. 1: Estimation of traction To illustrate the role of unsaturated soil strength, a simplified model of traction is used in this example. 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. 8):

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

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, and
- 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 (1957) proposed using

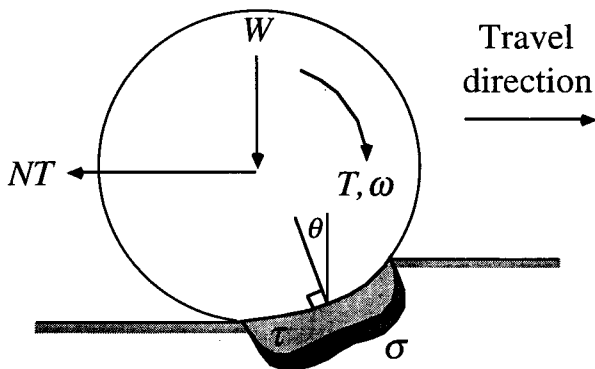


Fig. 8. Traction model for the interaction between tire and soil.

a shear stress-displacement relation of the form:

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

where:

- τ = shear stress [F/L²],
- τ_f = shear strength [F/L²],
- j = soil shear deformation [L], and
- K = shear deformation modulus [L].

To obtain an expression for net traction for varying field moisture conditions, Eq. 6 may be used as the expression for shear strength along with the soil-water characteristic to relate suction to water content; however, the variation of shear modulus K with varying suction is not known. The shear modulus, K , is itself a composite parameter (i.e., it is not a fundamental soil property) which depends on the distribution of shear deformation with depth beneath a traction device. There have been relatively few studies on strain in the ground beneath traction devices. A more complete analysis would require the investigation of the effect of suction on soil deformation characteristics.

Figure 9 shows the effect of water content on traction coefficient, NT/W , where W is the dynamic axle load, for the sandy clay loam soil for a normal stress of 135 kPa, $L/K = 8$ and two slip levels. The experimental data shown were obtained from grouser plate tests with two plate sizes in the Department of Agricultural and Bioresource Engineering soil bin. The soil was prepared by compacting it at 20% water content using a sheep-foot roller followed by a smooth roller, and then allowed to dry out to various water contents. Under these conditions similar soil structures are expected to those for which soil-water characteristics were determined. For rigid grouser plates $j = iL$ was substituted in Eq. 6, where $i =$ slip and $L =$ plate length. Predicted and measured data agree fairly well.

Example Problem No. 2: A tillage tool force prediction model A commonly used model for tillage tool force predic-

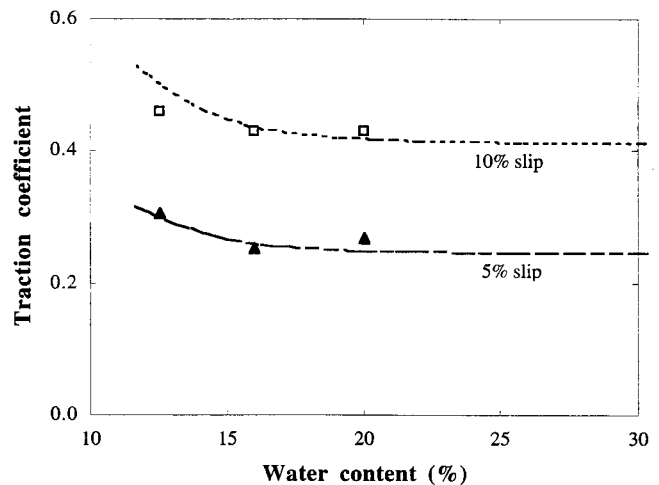


Fig. 9. Variation of traction coefficient, NT/W , with soil water content for two levels of slip, $L/K = 8$, $\sigma_n = 135$ kPa, in a sandy clay loam soil.

tion is based on the Universal Earth Moving Equation proposed by Reece (1965). The model was originally developed for wide tools cutting the soil in a passive type failure (Fig. 10) (Hettiaratchi et al. 1966). The approach has since been extended by others to narrow tools (Hettiaratchi and Reece 1967; Godwin and Spoor 1977; McKyes and Ali 1977; Perumpral et al. 1983). The force on the tool is related to soil properties, tool parameters, and several dimensionless factors by:

$$F = (\gamma h^2 N_\gamma + c h N_c + q h N_q + c_\alpha h N_{c\alpha})b \quad (9)$$

where:

- F = soil force [F],
- γ = total unit weight of the soil [F/L^3],
- h = tool depth into the soil [L],
- c = soil cohesion [F/L^2],
- c_α = soil-tool adhesion [F/L^2],
- b = tool width [L], and
- q = soil surcharge [F/L^2].

The dimensionless factors, N_γ , N_c , $N_{c\alpha}$, and N_q relate the tool geometry to the internal friction angle and the soil-tool friction angle and can be obtained from established charts.

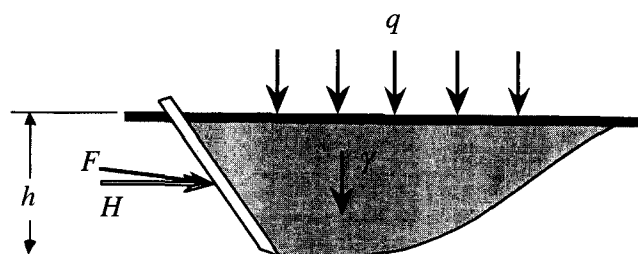


Fig. 10. Tillage tool and soil failure pattern.

For a given surcharge, the largest contributions to draft are from the cohesion and weight terms. Soil-tool adhesion arises almost entirely from soil suction (Fountain 1954, and others) and may vary considerably with soil moisture. However, it has a relatively small contribution to the overall draft (i.e., $N_{c\alpha}$ is small compared with N_c and N_γ). By introducing the total cohesion form for an unsaturated soil (i.e., Eq. 4) and Eq. 5 to relate ϕ^b and degree of saturation, this model can be appropriated to predict the variation in tillage tool force for variable moisture conditions, as:

$$F = \left\{ \gamma h^2 N_\gamma + [c' + (u_a - u_w) (S)^p \tan \phi'] h N_c + q h N_q \right\} b \quad (10)$$

where the adhesion component has been neglected. The variation in soil unit weight with water content can also be computed using the basic volume-mass relationship:

$$Se = wG_s \quad (11)$$

where:

- e = void ratio,
- w = gravimetric water content, and
- G_s = specific gravity of soil solids.

Equation 10 was used to predict the variation of draft with water content in the sandy clay loam soil for two tool configurations: (1) wide blade $b = 750$ mm; (2) narrow blade $b = 30$ mm, both operating at a depth $h = 150$ mm and a 40° rake angle, and having a soil-tool friction angle of 24° (Fig. 11). Values of the N-factors were obtained from charts in McKyes (1985). In these predictions, the cohesive term accounted for over 90% of the draft for water contents up to 14%. The contribution of the weight term gradually increased with increasing water content, so that at a water content of 25% the weight term accounted for 52% and 48% of the draft for the wide and narrow tools, respectively.

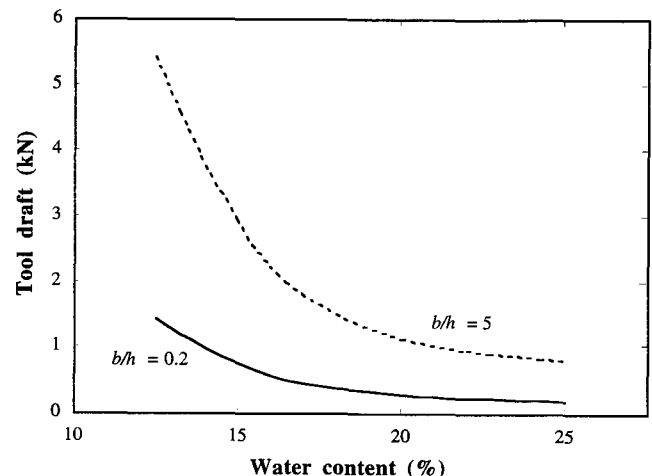


Fig. 11. Predicted variation of draft, H , with water content for a wide ($b/h = 5$) and a narrow ($b/h = 0.2$) tool operating at 150 mm depth, 40° rake angle in a sandy clay loam soil (1.04 Mg/m^3 dry bulk density).

CONCLUSIONS

The above examples illustrate how the principles discussed in this paper can be used with some elementary strength-based models. The experimental data obtained for a sandy clay loam soil supported the use of the soil-water characteristic combined with saturated strength parameters to estimate shear strength over a wide range of suctions. The modified forms of prediction relationships for traction and tool draft should be valid for all water contents for a given soil. Their particular advantage is that they provide a means to estimate tractive ability and tillage forces in a given soil without having to determine in-situ strength parameters for every water content encountered in the field. However, the use of the soil-water characteristic to relate matric suction and water content or degree of saturation to soil strength is only valid for the soil structure for which the soil-water characteristic was obtained. Variable factors in soil structure such as aggregate size distribution, cracks, macropores, fabric anisotropy, bulk density, and moisture status influence soil strength and volume change tendencies. If the structure alters significantly under wetting or drying or due to mechanical disturbance, the saturated strength parameters as well as the soil-water characteristic will all change. Predicting these structural changes requires an understanding of the

effect of the stress variables on the soil deformation characteristics and the soil-water characteristic. Most real agricultural problems, however, engage the shear and compressive strengths and deformation responses of soil simultaneously. For the full effectiveness of the unsaturated framework to be realized it will be necessary to adapt unified models of soil behaviour by incorporating matric suction and the soil-water characteristic.

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