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Estimation of unsaturated shear strength parameters using easily-available soil properties

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ABSTRACT

Unsaturated soil shear strength is an important parameter in soil erosion and management. Measurement of unsaturated shear strength at field scale is difficult, time-consuming, and very costly. This study was conducted to investigate the relationship between unsaturated shear strength parameters and soil properties, and to predict the unsaturated shear strength parameters (effective cohesion, c', angle of effective internal friction, φ' and angle of internal friction related to matric suction, φ^b) using multiple-linear regression (MLR). Direct shear tests were performed at combinations of three normal stresses of 25, 50 and 100 kPa, and four matric suctions of 0, 10, 30 and 50 kPa (i.e., 12 tests per each soil) to determine the shear strength parameters in 14 soils. Soil properties including particle size distribution (sand, silt, and clay percentages or geometric mean diameter, d_g and geometric standard deviation, σ_g), organic matter content (OM), calcium carbonate content ($CaCO_3$), compactness indices (bulk density, ρ_b and, relative bulk density, $\rho_{b\text{-rel}}$), and mean weight diameter of aggregates (MWD_{dry}, MWD_{wet}), structural stability indices (aggregate stability, AS, stability index, SI and index of crusting, I_c) were determined and used as predictors in MLR models. Strong negative correlations were found between c' and φ'. The c' positively correlated with clay content. Significant negative correlation was observed between c' and sand fractions and d_g. Significant positive correlation was obtained between φ' and fractions of sand and d_g. The φ' negatively correlated with clay, fine silt content (FSi), MWD_{dry}, and AS. The φ^b had no significant correlation with soil properties, indicating that φ^b is independent of soil properties and basically is affected by matric suction. Clay, coarse sand (CS) and very fine sand (VFS) were applied in the model for predicting c'. Clay had a positive and, CS and VFS had negative effects on c'. Pedotransfer functions (PTFs) using the fine sand (FS) and VFS as predictor could estimate the φ' accurately, so that they entered to PTFs with positive signs. In addition, the φ^b was predicted by parameter I_c only, so that it had negative effect on φ^b. Overall, better prediction models were developed for φ' than for c' and φ^b.

1. Introduction

Soil shear strength is a useful dynamic measure for evaluating soil erodibility especially in water erosion, and an important input parameter in the process-based soil erosion models (Knapen et al., 2007a, b; Léonard and Richard, 2004; Torri et al., 2013). Splash detachment processes (Nearing and Bradford, 1985; Brunori et al., 1989) and soil resistance to concentrated flow erosion (Foster et al., 1995; Knapen et al., 2007a, b) are closely linked to soil shear strength. Shear strength also affects the water movement, tilth, plant growth, biological activity of the soil (Blanco-Canqui et al., 2005; Eudoxie et al., 2012). Shear strength would also affect the load support capacity (Imhoff et al., 2004) and traction required to pull farm implements (McKyes, 1985).

Soil shear strength is the maximum shear stress that a soil can sustain before shear failure happens. Mohr–Coulomb equation is commonly used to quantify the shear strength of saturated soils (Johnson et al., 1987):

$$\tau = c + \sigma_n \tan\varphi \quad (1)$$

where τ (kPa) is the shear strength, c (kPa) is cohesion, σ_n (kPa) is the normal stress acting on the failure surface and φ (°) is the angle of internal friction. Cohesion, cohesive shear strength is due to chemical bonding between soil particles and surface tension within the water films (Knapen et al., 2007a, b; Morgan, 1986). Frictional shear strength (σ_n tan φ) is owing to internal friction between soil particles, that depends on the normal stress acting on the failure surface. However,

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Nomenclature

Abbreviations and symbols

AS	Aggregate stability (%)
$CaCO_3$	calcium carbonate content (kg 100 kg^{-1})
CS	Coarse sand (kg 100 kg^{-1})
CSi	Coarse silt (kg 100 kg^{-1})
c	Apparent cohesion (kPa)
c'	Effective cohesion (kPa)
d_g	Geometric mean diameter of Particles (mm)
FS	Fine sand (kg 100 kg^{-1})
FSi	Fine silt (kg 100 kg^{-1})
I_c	Index of crusting
MS	Medium sand (kg 100 kg^{-1})
MWD_{dry}	Mean weight diameter of dry aggregates (mm)
MWD_{wet}	Mean weight diameter of water-stable aggregates (mm)
OM	Organic matter (kg 100 kg^{-1})
SI	Structural stability index (%)
SWCC	Soil water characteristic curve
u_a	Pore air pressure (kPa)
u_w	Pore water pressure (kPa)
$(u_a$-$u_w)$	Matric suction (kPa)
VFS	Very fine sand (kg 100 kg^{-1})
ρ_b	Bulk density (Mg m^{-3})
ρ_{brel}	Relative bulk density
σ_g	Geometric standard deviation of particles
σ_n	Normal stress (kPa)
$(\sigma_n - u_a)$	Net normal stress (kPa)
σ'	Effective stress (kPa)
τ	Shear strength (kPa)
τ_f	Unsaturated shear strength (kPa)
φ'	Effective angle of internal friction (°)
φ^b	Angle of internal friction related to matric suction (°)
χ	Coefficient of effective stress

determination of the shear strength of unsaturated soil is very difficult and complicated. It can be described using the extended Mohr–Coulomb failure criterion proposed by Fredlund et al. (1978), which is written as follows:

$$\tau_f = c' + (\sigma - u_a)_f \tan\varphi' + (u_a - u_w)_f \tan\varphi^b \quad (2)$$

where τ_f (kPa) is the unsaturated shear strength, c' (kPa) and φ' (°) are the effective cohesion and effective friction angle, respectively, $(\sigma - u_a)_f$ (kPa) is the net normal stress on the failure plane at failure, $(u_a - u_w)_f$ (kPa) is the matric suction at failure, σ is the total normal stress, u_a and u_w are the pore-air and pore-water pressures, respectively, φ^b (°) is an angle indicating the rate of change in shear strength relative to changes in matric suction (Fredlund et al., 1996). Hence, total or apparent cohesion (c) in unsaturated soil consists of two components; i.e., one due to physicochemical cohesion, c' and the other due to matric suction (Zhang et al., 2001), which could be written as:

$$c = c' + (u_a - u_w)\tan\phi^b \quad (3)$$

When an unsaturated soil becomes saturated, matric suction is equal to zero, so the total cohesion approaches to the effective cohesion (Zhang et al., 2014).

Soil shear strength is affected by several soil and environmental properties such as particle size distribution (soil texture) (Gilley et al., 1993; Horn and Fleige, 2003; Knapen et al., 2007b), organic matter content (Wuddivira et al., 2013), bulk density (Gilley et al., 1993; Zhang et al., 2001), aggregation, water content/matric suction (Al Aqtash and Bandini, 2015; Gilley et al., 1993; Zhang et al., 2001; Zhou et al., 2016), network of plant roots and vegetation cover (Fattet et al., 2011; Fan and Su, 2008), and tillage systems (Knapen et al., 2007a). Soil texture is mostly used as primary indicator of soil resistance against erosion. It can affect soil shear strength either through frictional forces in coarse-texture soils or through cohesive forces in fine-textured soils (Knapen et al., 2007b; Shainberg et al., 1994). Havaee et al. (2015) reported that shear strength parameters (c and φ) strongly depended on soil particle size distribution and gravel content. They found a positive correlation between c and fine clay content. However, c was negatively correlated with sand and gravel contents. Meanwhile, significant positive correlation between φ and gravel content indicates the roughness effect of coarse particles on frictional shear strength.

The influence of soil organic matter (OM) on shear strength could be explained through mechanism of modifying the cohesiveness of soil particles and aggregate stability (Blanco-Canqui et al., 2005). Inconsistent effects of OM on soil mechanical behavior have been reported. For example, some researches showed an increase in soil shear strength with an increment in OM due to enhanced cohesive forces between the soil particles (Rachman et al., 2003; Wuddivira et al., 2013). On the contrary, OM may reduce soil shear strength because of increasing soil porosity (or decreasing bulk density) (Horn and Fleige, 2003; Kay and Angers, 1999). Rachman et al. (2003) found that the higher OM and aggregate stability resulted in greater soil shear strength. Cruse and Larson (1977) reported that c' and φ', and as a result shear strength increased with increase of bulk density and matric suction. They stated that changes in bulk density and matric suction would alter solid particle-to-particle contact, and the contact relationships between solid particles and liquid films, respectively. Soil wetting (i.e., decrease of matric suction) reduces contact relationships between solid particles and liquid films, and as a consequence reduces soil shear strength (Cruse and Larson, 1977). Horn and Fleige (2003) pointed out the shear strength parameters were also influenced by matric suction. They indicated that with an increase in matric suction, c and φ increased which is dependent to soil texture and structure. Zhou et al. (2016) determined unsaturated shear strength parameters of a silty sand soil using direct shear test and found that with increment of matric suction, total cohesion increased, φ did not change, and φ^b decreased non-linearly. They showed that shear strength significantly increased with an increase in net normal stress or matric suction.

Several techniques such as torsional shear apparatus (Johnson et al., 1987; Koolen and Kuipers, 1983), shear vane (Bradford and Grossman, 1982), drop-cone penetrometer (Bradford et al., 1992; Rachman et al., 2003; Wuddivira et al., 2013), direct shear box (Zhou et al., 2016), Zhang's method (Zhang et al., 2001), *in situ* direct shear box (Havaee et al., 2015), and tri-axial test (Nearing and Bradford, 1985; Khalili et al., 2004) are used to measure soil shear strength. However, majority of these techniques are rather complicated and time-consuming, and are difficult to use in large scale. On the other hand, some methods are not practical to determine unsaturated shear strength parameters accurately. Therefore, indirect methods, pedotransfer functions (PTFs), such as multiple-linear regression (MLR) are used to estimate the shear strength. The PTFs predict difficult-to-measure soil properties (e.g., hydraulic properties, unsaturated shear strength) using routinely-available properties as predictors (Bouma, 1989; Wösten et al., 2001).

Some PTFs have been derived for predicting shear strength parameters of saturated soil (e.g., Khalilimoghadam et al., 2009; Havaee et al., 2015). Also there are some studies on unsaturated soil shear strength in civil engineering applications (Habibagahi and Bamdad, 2003; Zhou et al., 2016). Khanlari et al. (2012), Mousavi et al. (2011) and Sudha Rani et al. (2013) predicted shear strength and engineering properties of soil using regression methods and artificial networks. However, there was no published research on prediction of the unsaturated shear strength parameters (i.e., c', φ' and φ^b) in agricultural