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In situ surface shear strength as affected by soil characteristics and land use in calcareous soils of central Iran

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ABSTRACT

Soil surface shear strength is an important input parameter in the process-based soil erosion models, but its direct measurement at the watershed scale is difficult, time-consuming and costly. This study was conducted to predict in situ shear strength of the soil surface using multiple-linear regression (MLR). The land use impact on the surface shear strength was examined as well. A direct shear box was constructed to measure in situ shear strength (cohesion, c and angle of internal friction, φ) of the soil surface in the Semirom region located in Isfahan province, central Iran. The shear device consisted of a circular shear box (with 10 cm internal diameter and height of 1 cm), an S-shaped load cell for measuring horizontal (shear) stress and an electric motor for applying the shear stress. The normal stress acting on the failure surface was adjusted by adding weights on the shear box. Soil surface shear strength was determined using the shear box at 100 locations under three land use systems of grassland, irrigated farming and dryland farming. Soil particle size distribution (clay, silt, sand and fine clay), organic matter content (OM), carbonate content, bulk density and gravel content were determined as predictors of the surface shear strength. Normalized difference vegetation index (NDVI) was also calculated using satellite images. The MLR was employed to predict the shear strength (i.e. c and φ) using two groups of input variables: i) easily-available soil properties (pedotransfer functions, PTFs) and ii) easily-available soil properties and NDVI (soil spatial prediction functions, SSPFs). A strong negative correlation ($r = -0.72$, $p < 0.001$) was found between c and φ in the studied area. Positive correlation ($r = 0.41$, $p < 0.001$) was obtained between c and fine clay content. The c was negatively correlated ($r = -0.31$, $p < 0.01$; $r = -0.37$, $p < 0.001$) with sand and gravel contents, respectively. A significant positive correlation ($r = 0.47$, $p < 0.001$) was observed between φ and gravel content, indicating the roughness effect of coarse particles on frictional shear strength. The results also showed that NDVI is an important factor indirectly explaining the variability of both c and φ in the studied soils. The land use effect on the soil properties was investigated using the $LSD_{0.05}$ test. The means of φ somehow follow the variation of gravel content among the land uses; the highest means of clay and fine clay contents and c, and the lowest means of sand and gravel contents and φ were observed in dryland farming. The c has the same trend as did clay content; irrigated farming with the highest mean of sand content and lowest mean of clay content had the lowest mean of c. The c means were significantly different between irrigated farming and dryland farming. Prediction models of in situ shear strength derived using both soil properties and NDVI as predictors (SSPFs) were more accurate than those derived using only soil properties (PTFs).

1. Introduction

Accelerated soil erosion is a serious threat to environmental sustainability (Abbaszadeh Afshar et al., 2010). In recent years, in addition to creating financial losses such as filling reservoirs of dams, diminished soil fertility and productivity, accelerated erosion has become a serious threat to human health due to its significant role in polluting surface and subsurface water resources and air (Morgan, 2005). Therefore, it is necessary to understand the important factors and take urgent steps in order to control accelerated erosion. Factors affecting the rate of erosion may be considered under three headings: energy, protection and soil erodibility. The energy group includes the potential ability of rainfall, rainsplash, runoff and wind as detaching agents. The protection group focuses on factors relating to the plant cover. Soil erodibility defines the soil resistance to detachment/transport and depends on soil texture, structural stability, shear strength, infiltrability and organic matter (OM) and chemical content (Morgan, 2005; Morgan and Nearing, 2011; Torri and Borselli, 2011). Therefore, due to dependence of soil erodibility on many factors and properties (Morgan and Nearing, 2011; Torri and Borselli, 2011; Zachar, 1982), it is difficult to generalize soil erosion findings on a specific soil type or soils of a region to other soils/regions.

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Several studies showed that shear strength of the surface soil is an appropriate dynamic index for evaluating soil erodibility (Foster et al., 1995; Franti et al., 1985; Higuchi et al., 2013; Knapen et al., 2007a,b; Léonard and Richard, 2004; Luk and Hamilton, 1986; Torri and Poesen, 2014; Torri et al., 2013). Soil shear strength is the maximum shear stress a soil resists before shear failure happens. It is quantified by the two-component Mohr–Coulomb equation (Johnson et al., 1987; Koolen and Kuipers, 1983):

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

where τ is the shear strength, c is the cohesive shear strength or cohesion due to intrinsic bonds between soil particles/aggregates, σ_n is the normal stress acting on the failure surface and φ is the angle of internal friction. Frictional shear strength ($\sigma_n \tan\varphi$) is due to internal friction between soil particles/aggregates and depends on the normal stress acting on the failure surface.

Soil shear strength (τ) is considered as a key property to characterize soil detachability by raindrop impact (Al-Durrah and Bradford, 1982a; Bradford et al., 1992; Cruse and Larson, 1977; Nearing and Bradford, 1985; Torri et al., 1987a,b) and soil resistance to concentrated flow erosion (Foster et al., 1995; Knapen et al., 2007a,b). Rainsplash detachment processes are linked to shear strength of the surface soil (Brunori et al., 1989; Watson and Lafflen, 1986). Detachment is due to a combination of compression and shear under raindrop impact (Al-Durrah and Bradford, 1982a,b). Al-Durrah and Bradford (1982a) observed stronger linear regression between rainsplash weight and ratio of rainfall kinetic energy and undrained soil shear strength than any other soil property. It is reported that detachment decreases in a nonlinear manner with increment of shear strength (Bradford et al., 1992; Cruse and Larson, 1977; Torri et al., 1987b). Léonard and Richard (2004) found that saturated shear strength could be considered as the best soil property to predict critical shear stress (i.e. minimum shear stress of flowing water required to move soil particles) and runoff erosion. Critical shear stress, a measure of soil resistance to water erosion, is an important parameter governing soil detachment by runoff in several erosion models. Rauws and Govers (1988) noticed that the soil conditions at which rill flow becomes erosive are governed by shear strength of the surface soil.

There are evidences for the importance of φ in soil detachment/erosion processes as well. Al-Durrah and Bradford (1982b) concluded that rainsplash weight and angle are influenced by c and φ, and by soil deformability. Nearing and Bradford (1985) found that shear strength (measured using a fall-cone penetrometer) overestimated overall soil resistance against splashing. A correction term including φ was suggested to develop a unique linear relation between soil detachment and ratio of waterdrop kinetic energy and fall-cone shear strength. Thus, φ should also be considered in soil strength measurements/predictions for erosion researches.

Most frequently soil physical properties that could affect shear strength of the surface soil are particle size distribution (Knapen et al., 2007b; Shainberg et al., 1994), water content/matric potential (Bradford and Grossman, 1982; Cruse and Larson, 1977; Knapen et al., 2007b), aggregation (Baumgartl and Horn, 1991), stone size (Léonard and Richard, 2004), network of plant roots and vegetation cover (Franti et al., 1999; Knapen et al., 2007b; Torri et al., 2013) and tillage systems and time (Knapen et al., 2007a). Gilley et al. (1993) reported that soil shear strength could be related to texture, OM and bulk density. Soil texture (mean particle size or clay content) plays a key role in soil structure and/or erodibility, and is usually used as primary indicator of soil resistance to erosion (Knapen et al., 2007b; Line and Meyer, 1989). Based on WEPP dataset, Knapen et al. (2007b) observed linear relation between soil detachment capacity and flow shear stress which differed among the soil textural classes. Poesen (1992) obtained a relation between soil erodibility factor and geometric mean diameter of primary particles and found that medium (silt loam) soils are most susceptible to erosion with coarse- and fine-textured soils having lower erodibility factors. Knapen et al. (2007b) analyzed the WEPP dataset and found a trend of higher critical flow shear stresses for clayey soils. They combined the concentrated flow erodibility and critical flow shear stress data to present a texture-based erodibility ranking. The results indicated that silt loam and clayey soils have high and low erodibilities, respectively.

Plant roots could reinforce soils; mechanical properties of the root–soil system are regulated by a combination of soil strength, single root strength, and the interface strength between soil and roots (Comino et al, 2010). Waldron (1977) and Wu et al. (1979) considered the root contribution to soil shear strength as a cohesion term added to the Mohr–Coulomb equation (Eq. (1)). Stokes et al. (2009) reported that the presence of plant roots physically reinforce the shear zone. Moreover, root exudates, as chemical stabilizing agents, could affect soil structure and erodibility (Angers and Caron, 1998; Morgan, 2005).

Several laboratory and field methods are used to measure soil shear strength (Bowles, 1978; Bradford et al., 1992; Brunori et al., 1989; Koolen and Kuipers, 1983; Léonard and Richard, 2004; Zimbone et al., 1996). Torsional shear apparatus is used to measure c and φ in the field. However, shear stress and soil failure are not uniformly distributed over the shear surface under the shear ring (Johnson et al., 1987; Koolen and Kuipers, 1983). Although Zimbone et al. (1996) suggested torvane and hand vane tester as most appropriate and simple devices for quick measurement of soil cohesion, in situ measurement of shear strength using small-size shear vane and torvane might not be reliable and a larger measuring volume is preferred (Léonard and Richard, 2004). The shear vane test underestimated the shear strength of frictional low-strength soils like loams and silt loams (Bradford and Grossman, 1982). Torvane might underestimate the resistance of sealed soils to raindrop splash because insertion of the vane blades into soil breaks the crust and measures lower soil strength. Moreover, torvane measurement in frictional sandy soils is highly susceptible to uncontrolled vertical force exerted on the vane while shearing (Bradford et al., 1992). Fall-cone penetrometer was used as a simple and rapid test for in situ measurement of near-surface shear strength in soil erosion studies (e.g. Al-Durrah and Bradford, 1982a; Bradford and Grossman, 1982; Bradford et al., 1992; Nearing and Bradford, 1985). However, two major limitations of this test are: 1) dependency of empirical calibration constant, needed for translating depth of cone penetration to shear strength, on cone angle and soil type/texture (Bradford et al., 1992; Towner, 1973), and 2) uncontrolled variable depth of cone penetration which ultimately affects the measured soil layer (Bradford and Grossman, 1982; Bradford et al., 1992). Collis-George et al. (1993) introduced a quick/easy resin-impregnated plate method to measure the surface shear strength. However, the shear surface is not easily detectable and is wavy-like at the edges of the shear plate. Shear device proposed by Zhang et al. (2001) for measuring the surface shear strength is interesting and promising but the measured c and φ are not intrinsic (internal) soil strength parameters but depend on the sandpaper–soil interface properties.

Direct measurement of soil shear strength parameters (c and φ) at large scale is difficult, time-consuming and costly. Researchers have used indirect methods such as pedotransfer functions (PTFs) to predict difficult-to-measure soil properties (e.g. hydraulic properties) using easily-available properties as predictors (Bouma, 1989; Wösten et al., 2001). In a first attempt, Horn and Fleige (2003) provided class PTFs for c and φ in terms of soil texture, structure and matric suction in Germany. Goktepea et al. (2008) estimated shear strength of plastic clays using PTFs that were derived by statistical and neural network approaches. An artificial neural network (ANN) framework was employed by Habibagahi and Bamdad (2003) to predict mechanical behavior of unsaturated soils. Hirata et al. (1990) employed multiple regression analysis between the mechanical and physical properties of cohesive soils. Khalilmoghadam et al. (2009) and Besalatpour et al. (2012) developed the ANN-based and ANFIS-based PTFs to predict c, measured by a shear vane, using easily-available data in Zagros region of Iran.

High rate of land use change from pasture to dryland farming is reported in Iran (Abbaszadeh Afshar et al., 2010). Previous reports on