Soil & Tillage Research 178 (2018) 1–10

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Estimation of surface shear strength of undisturbed soils in the eastern part of northern China's wind erosion area

Chunlai Zhang, Xuesong Wang*, Xueyong Zou, Jinlu Tian, Bo Liu, Jifeng Li, Liqiang Kang, Hong Chen, Yongqiu Wu

State Key Laboratory of Earth Surface Processes and Resource Ecology, MOE Engineering Research Center of Desertification and Blown-sand Control, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Keywords:
Unsaturated soil
Undisturbed soil
Surface shear strength of surface soil
Prediction equation

ABSTRACT

Shear strength of surface soil that is unsaturated and undisturbed is an important soil mechanical property to predict its resistance against the shear force created by the wind. However, measurement of this property was always complicated and time-consuming. In this work, we obtained unsaturated (soil moisture < 13%) and undisturbed surface soil samples, collected in the eastern part of northern China's wind erosion area, and determined the relationships between surface soil shear strength (SSS) and soil properties (root density; the moisture, SM; gravel content, GC; clay, organic matter, OM; calcium carbonate contents, $CaCO_3$; and bulk density, ρ_b) to provide a function for predicting surface shear strength. Although roots generally strongly influence surface shear strength, the root density was not a proper soil property to reflect the relationship between plant roots and soil surface shear strength. For future study, we suggest that a new definition of root density which merely describe the quantity of the roots penetrating through the shear surface, to replace the conventional one. Surface shear strength decreased logarithmically with increasing water content. Several soil properties were strongly correlated with surface shear strength: the contents of gravel ($r = 0.793$, $p < 0.001$), organic matter ($r = 0.771$, $p < 0.001$), and calcium carbonate ($r = 0.669$, $p < 0.05$) and the soil bulk density ($r = 0.793$, $p < 0.001$). Based on these results, we developed a prediction equation for surface shear strength of surface soil: $SSS = -(0.103\ GC + 7.76\ \rho_b - 8.88) \times \ln(SM) + 0.131\ GC + 1.655\ OM + 2.192\ CaCO_3 + 19.467\ \rho_b - 27.39$. The predicted and observed values were strongly and significantly correlated ($r = 0.83$, $p < 0.001$) and fell close to the 1:1 line, with relatively small root-mean-square and mean absolute errors (1.32 and 0.97, respectively).

1. Introduction

Increasing soil erosion is a severe threat to global environmental sustainability, and has also become a serious threat to human health due to its role in air pollution (suspended particulate matter) and pollution of surface and subsurface water (Morgan, 2005). Therefore, it is necessary to be able to predict soil erosion so that appropriate measures can be adopted to control it. Much fruitful research has been performed to predict soil erosion. For example, models like USLE (Wischmeier and Smith, 1965), RUSLE (Renard et al., 1997), and WEPP (Ascough et al., 1997) have been developed to simulate soil erosion by water. Similarly, models such as WEQ (Woodruff and Siddoway, 1965), WEPS (Hagen, 1991), and RWEQ (Fryrear et al., 1998) have been developed to simulate soil erosion by the wind.

In both groups of models, soil erodibility is a key factor because it determines the vulnerability of a soil to water and wind. In studies of wind erosion, erodibility was successfully predicted based on the content of soil particles with a diameter < 0.84 mm (Chepil, 1953). In addition, the contents of calcium carbonate ($CaCO_3$), organic matter (*OM*), and clay have been used to calculate the erodibility of cultivated soil (Chepil, 1954, 1955, 1956b). However, when it comes to steppe soils, whose structure is stable and compact, the previously used methods are impractical (Zou et al., 2014). In addition, if loose surface soil particles are completely blown away, the stable and compacted soil mass will be exposed to the wind; as a result, the content of soil particles (< 0.84 mm) does not reflect the soil's erodibility.

For a stable and compacted soil mass, wind erosion occurs when the shear force exerted on the particles by the wind and the impact force

Abbreviations: OM, organic matter; ρ_b, soil bulk density (g cm^{-3}); RD, root density (kg m^{-3}); RMSE, root-mean-square error; SM, soil moisture in gravity, %; (GC), gravel content, %; SD, standard deviation; CV, coefficient of variation; MAE, mean absolute error; SSS, surface shear strength

* Corresponding author at: State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University No. 19 Xinjiekouwai Street, Beijing 100875, China.
E-mail address: 201631480002@mail.bnu.edu.cn (X. Wang).

https://doi.org/10.1016/j.still.2017.12.014
Received 28 May 2017; Received in revised form 10 October 2017; Accepted 13 December 2017
0167-1987/

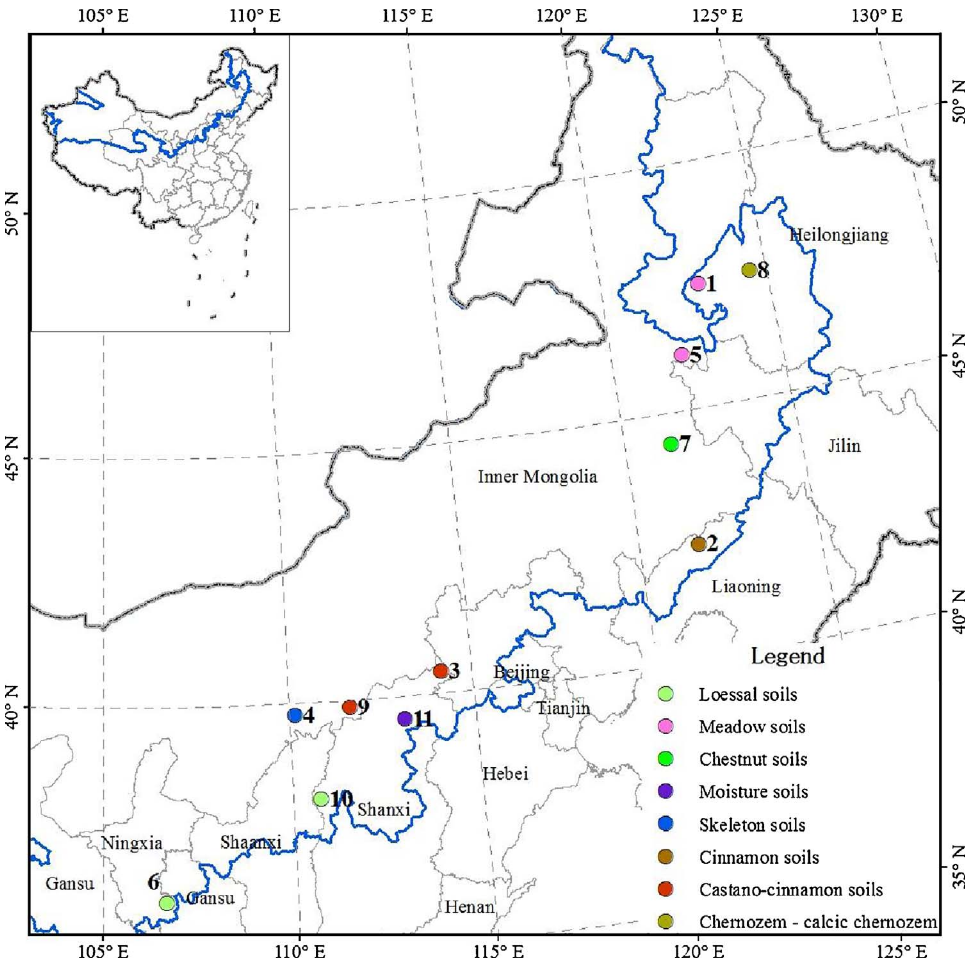

Fig. 1. Locations of the sampling sites within the wind erosion area of northern China.

created by saltating particles together overcome the force of adhesion among the soil particles. The forces created by saltating particles are relatively well understood (Jasper et al., 2012). However, the effects of shear strength are less well understood. As a result, understanding the soil's resistance to the shear force (it's *shear strength*) is an important component of predicting its resistance to erosion, particularly if surface shear strength can be determined easily using simple mechanical properties. Research on soil erosion by water has provided a relatively high level of theoretical and practical understanding of how runoff scours and shears the soil surface (Liu, 1997); as a result, surface shear strength has been selected as a dynamic indicator of a soil's resistance to water erosion (Franti et al., 1985; Luk and Hamilton, 1986; Torri et al., 2013). For instance, Léonard and Richard (2004) stated that soil surface shear strength was the soil property that best predicted the critical shear stress value required to resist runoff. Therefore, based on these findings for water erosion, we hypothesized that the surface soil's surface shear strength could also be used to predict its resistance against the surface shear strength created by the wind (since moving air is also a fluid).

Soil shear strength is the maximum shear stress a soil resists before shear failure happens. To introduce soil shear strength into water erosion research, a series of techniques have been developed to directly measure it; these include the cone penetrometer, torsional shear boxes, and direct shear boxes (Franti et al., 1985; Rauws and Govers, 1988; Havaee et al., 2015). However, because wind erosion is generated from surface soil which is generally dry and unsaturated and there is no normal stress applied to the soil surface during wind erosion (Zou et al., 2014), soil surface shear strength measured by means of conventional test methods (applying several levels of normal stress to the surface) cannot reliably reflect the soil's ability to resist the wind's lateral force. Only the surface shear strength of unsaturated surface soil measured with no normal stress makes sense. The methods and techniques for measuring the surface shear strength of such soils are still underdeveloped. A wide range of measurements is even more difficult due to its complexity and high time consumption.

One solution would be to estimate soil surface shear strength using routinely available data as inputs for predictive equations or models (Bouma, 1989; Mayr and Jarvis, 1999; Tomasella et al., 2000; Minasny and Mcbratney, 2002; Minasny et al., 2004; Lagacherie and Mcbratney, 2006). The most common factors and soil properties that affect the surface soil's shear strength are its particle size distribution (Shainberg et al., 1994; Knapen et al., 2007b), water content (Cruse and Larson, 1977; Bradford and Grossman, 1982; Knapen et al., 2007b), degree of aggregation (Baumgartl and Horn, 1991), size and content of stones and gravel (Léonard and Richard, 2004), vegetation cover and root system density (Franti et al., 1999; Knapen et al., 2007b; Torri et al., 2013), tillage system and time of tillage (Knapen et al., 2007a), and calcium carbonate content (Mosaddeghi et al., 2006). It is difficult to obtain enough data to include all of these factors within a single equation or model, particularly since the dominant factors often differ among areas. Therefore, selecting the most useful factors and eliminating the least useful ones will improve the efficiency of prediction. An additional problem is that current research on these factors and current estimates of soil surface shear strength are mainly based on data from studies of water erosion; in contrast, there have been few studies of wind erosion, particularly in areas such as northern China, where wind erosion is serious. Our literature review found only three studies of the relationships between wind erosion and soil surface shear strength, and they were preliminary and qualitative (Wilson and Gregory, 1992; Shen et al., 2004; Lu, 2005). Besides, there has been insufficient research in