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Shear Strength of Purple Topsoil Under Different Land Uses in the Three Gorges Reservoir Area, China

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The shear strength of topsoil indicates the resistance of surface land to external erosive forces and represents a key variable for inferring the extent and rate of soil erosion. However, the influence of land use on topsoil shear strength is poorly understood. This study aims to examine topsoil shear strength under different land uses in the purple-soiled region of the Three Gorges Reservoir area in China and explore the related factors that control the observed variability. Direct shear tests were performed to determine the shear strength of topsoil in terms of internal friction angle (φ) and cohesion (c) under 5 typical land use systems. The results showed that the topsoil shear stress increases with increasing shear displacement from 0 to 6 mm; thereafter, it remains relatively stable over a further increase of shear displacement from 6 to 10 mm. The shear stress–shear displacement curves display a hardening strain trend. Land use exerts a strong effect on the shear strength through differentiation of soil physicochemical properties. In general, topsoil from orchard land has the highest mean values for clay fraction, φ, and c and the lowest mean values for sand fraction and water content. The topsoil in abandoned land shows the highest mean values for bulk density and silt content. The bulk density and the clay and silt content are the main direct factors controlling the difference in shear strength of the purple topsoil. Organic matter content, total porosity, and sand content represent important indirect factors that contribute to the variability in c and φ values of the studied soils.

Keywords: *shear strength; purple soil; land use; fuzzy nearness degree; Three Gorges Reservoir area.*

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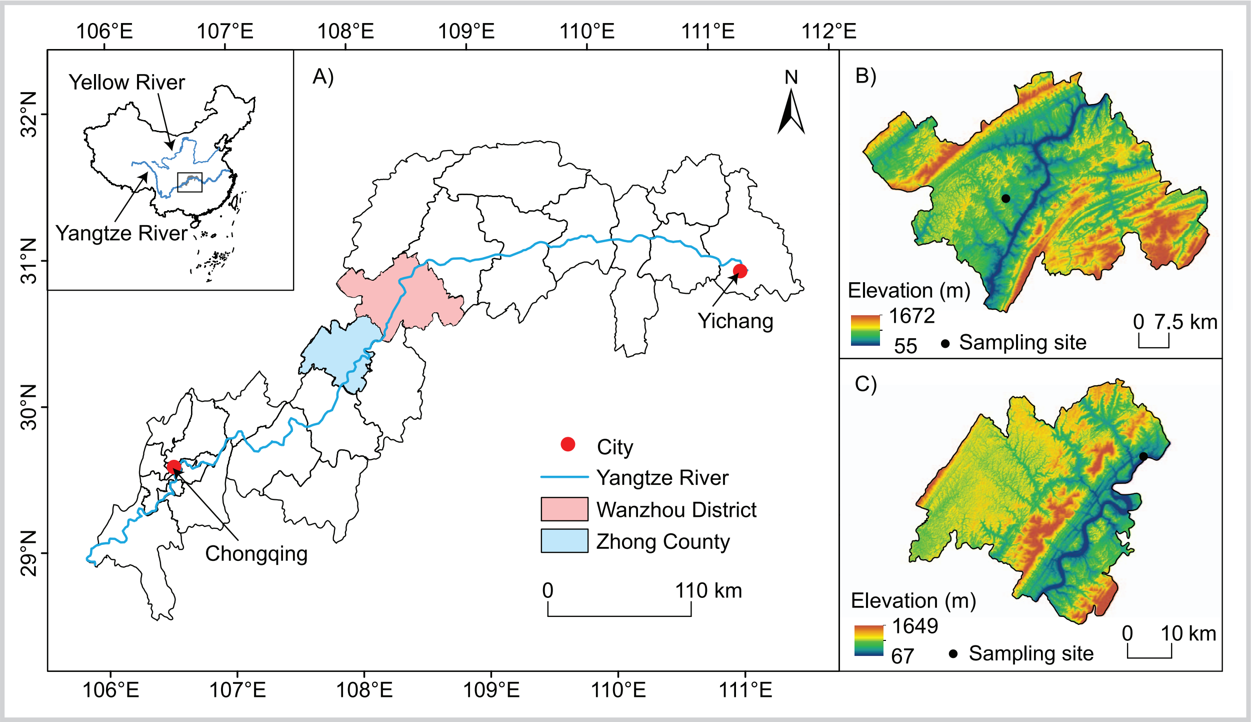
Introduction

Soil shear strength is defined as the maximum shear stress of soil before shear failure occurs. This has been widely used to evaluate soil erodibility, in particular for water erosion, and represents a key input parameter for process-based soil erosion modeling (Besalatpour et al 2012; Higuchi et al 2013; Havaee et al 2015; Singh and Thompson 2016; Khaboushan et al 2018; Zhang et al 2020). For example, knowledge of the surface soil shear strength is required to model runoff and soil erosion (Khalilmoghadam et al 2009). Shear strength has also been used to estimate slope stability and resistance to erosion (Rachman et al 2003; Wuddivira et al 2013). Léonard and Richard (2004) found that soil shear strength is the most useful soil property when predicting critical shear stress and runoff erosion. As such, the study of topsoil shear strength facilitates better understanding of soil erosion mechanisms.

Soil shear strength can be expressed using the internal friction angle (φ) and the unit cohesion (*c*) (Johnson et al 1987; Khaboushan et al 2018). Numerous studies have documented the correlation of these 2 variables with soil physicochemical properties. Hu et al (2013) reported that *c* first increased and then decreased with increasing water content, whereas φ showed a negative linear correlation with soil water content. However, other researchers have found that φ shows first-order exponential decay with increasing soil water content (Wei et al 2016). For a given water content, *c* increases as dry density increases, whereas φ shows little change (Ni et al 2012). Soil texture is used mainly as a primary indicator of soil resistance to erosion and affects the soil shear strength and frictional forces in coarse-textured soils or cohesive forces in fine-textured soils (Knapen et al 2007; Khaboushan et al 2018; Cao et al 2020). Havaee et al (2015) concluded that the shear strength parameters (*c* and φ) depend on the soil's gravel content and particle size distribution. The authors reported a positive correlation between *c* and fine clay content, whereas *c* was negatively correlated with sand and gravel content. They also reported a significant positive correlation between φ and gravel content. Other studies presented conflicting results on the effects of organic matter (OM) content on the mechanical behavior of soil. For example, Horn and Fleige (2003) reported that OM might reduce the shear strength of soil with increasing soil porosity. However, the cohesive binding forces of clay and OM in soil subjected to a range of wetting conditions cause an increase in soil shear strength with increasing OM (Rachman et al 2003; Wuddivira et al 2013). Moreover, root exudates can act as chemical stabilizing agents, affecting soil structure and enhancing soil shear strength (Tan et al 2019; Galloway et al 2020). However, the

FIGURE 1 Geographic map of (A) the Three Gorges Reservoir area, (B) Wanzhou District, and (C) Zhong County.



research discussed earlier focused primarily on the factors that influence soil shear strength.

The chemical and physical properties of soils differ with land use, leading to markedly different topsoil shear strengths. Compared with grassland and forestland, the surface soil of cultivated areas is loose and porous, resulting in reduced soil compactness and topsoil shear strength (Comino and Marengo 2010; Comino et al 2010). Thus, it is important to assess the effect of land use on topsoil shear strength to understand the influence of land use on soil erodibility and erosion.

The Three Gorges Reservoir area in China experiences a high degree of soil erosion. Purple soil is widely distributed in the area (He et al 2009) and is characterized by low permeability, high hydrophobicity, and easy weathering (Zhang et al 2016). The combined impacts of natural factors (eg rainfall, geology, and lithology) and human activity (eg deforestation and farming) have led to severe erosion of these purple soils, and this has influenced the management of the Three Gorges Reservoir and the surrounding environment (Wei et al 2016, 2018). Previous studies discussed the shear strength of different soils under various conditions, but few have reported the effects of land use on the shear strength of purple topsoil. This study aims to assess the impact of land use on topsoil shear strength and determine the factors that control shear strength in the purple topsoil of the Three Gorges Reservoir area. Hence, 5 typical land use types were selected for direct shear tests, and the shear strength properties of the topsoil were investigated under the different conditions associated with each land use. This study's results provide a scientific basis for land use planning and soil conservation in the region.

Material and methods

Study area

The study area is located at Zhong County and Wanzhou District in the Three Gorges Reservoir area, China (Figure 1). This region has an elevation ranging between 55 and 1680 m and is characterized by >70% of low mountainous terrain (Wei et al 2018). The climate is dominated by humid subtropical monsoons, with an annual average temperature ranging from 17.7 to 18.2°C, annual rainfall of 1100–1400 mm, average relative humidity of 70–80%, and 340 frost-free days per year. Precipitation is unevenly distributed throughout the seasons, and a substantial proportion occurs in the period from May to September (Tang et al 2014). Purple soils, which are classified as regosols, according to the Food and Agriculture Organization taxonomy, and entisols, according to the US Department of Agriculture taxonomy (Tang et al 2014), form from Triassic–Cretaceous purple rocks (Zhong et al 2019). Their formation is enhanced by continual tillage operations, especially digging and ridging. Purple soil accounts for >70% of the soil in the Three Gorges Reservoir area (He et al 2009). The natural vegetation is subtropical evergreen broad-leaved forest, and the main crops are *Oryza glaberrima, Zea mays, Triticum aestivum, Solanum tuberosum, Brassica campestris, Ipomoea batatas,* and *Glycine max.*

Soil sampling and analysis

Five main land use types (forestland, bamboo forestland, sloping farmland, orchard land, and abandoned land) were selected for sampling around the villages of Xinzheng and Tongping during October and November 2019. For each land use system, the sample points were distributed in an S shape, and the soil samples were taken from the 0- to 5-cm layer at each sample point. Before sampling, weeds were removed and fresh bare soil was exposed. Then, a direct shear ring knife was used to collect 360 soil samples (sample diameter = 61.8 mm, sample height = 20 mm) for direct shear tests. The inner wall of the knife was lubricated with oil to minimize friction between soil and knife (Khaboushan et al 2018). The samples were sealed in plastic wrap and placed into a ring knife box. In addition, loose soil (~0.5 kg) was collected near the direct shear samples for later analysis of the chemical and physical properties of the soils. Soil bulk density was measured by the oven-drying method (105°C for 24 h). Three replicate samples were taken at each sampling site using steel rings with a diameter of 5 cm and a height of 5.1 cm (100 cm^3) (Zhang and Xie 2019). The soil water content was measured by the oven-drying method for 3 replicates for each test site using the same steel rings as used for the bulk density measurement (Zhang et al 2020). The OM content was measured using the potassium dichromate oxidation method (Yeomans and Bremmer 1989). Soil grain size distributions were tested using a Malvern Mastersizer 2000.

Test apparatus and methods

Direct shear tests were undertaken using a fully automatic quadruple direct shear apparatus (AZJ-4, Nanjing Zhilong Technology Development, China) that consisted of a testing machine, shear box, vertical load, host computer, and control system. Testing samples were 61.8 mm in diameter and 20 mm in height. The vertical load of the testing machine ranged between 0 and 400 kPa, the shear rate was from 0.001 to 2.4 mm/min, and the maximum horizontal displacement was 20 mm. The control system produced accurate shear stress, shear displacement, and shear strength parameters (c and φ), as well as Mohr–Coulomb shear failure envelopes, through full-range stepless speed regulation by a stepper motor. The test was controlled automatically, and data were captured and shown in real time (Wei et al 2018).

Based on the relevant data of the natural weight on the topsoil in the field, soil thickness, softness and hardness of the soil, and Chinese Standards for Soil Test Methods (GB/T 50123-2019) (SAC et al 2019), soil samples were placed in the direct shear apparatus, 4 vertical loads (25, 50, 100, and 200 kPa) were applied to each group of soil samples, and the shear velocity was controlled at 0.8 mm/min (Gu et al 2019). The shear strength parameters (c and φ) were calculated according to Chinese Standards for Soil Test Methods (GB/T 50123-2019). Shear strength (τ_f) was calculated as follows:

$$\tau_f = \sigma \cdot \tan\varphi + c \tag{1}$$

where c (in kilopascals) is cohesion, σ (in kilopascals) is the normal stress on the failure surface, and φ is the internal friction angle. The frictional shear strength ($\sigma \cdot \tan\varphi$) originates from internal friction between soil particles and is influenced by normal stress on the failure surface (Khaboushan et al 2018).

Fuzzy nearness degree

To study the dominant influencing factors of the shear strength of purple topsoil under different land uses, fuzzy nearness analysis was carried out between shear strength parameters (ie c or φ) and different soil properties. Fuzzy nearness degree, an important method of fuzzy recognition, mainly describes the nearness of 2 fuzzy sets based on the approaching degree principle. This approach has been used in many fields across the natural sciences and has strong practicability and reliability (Guan et al 2007). The axiomatic definition of the fuzzy nearness degree is as follows (Zeng and Li 1999; Yu et al 2019):

If mapping n: $F(X) \times F(X) \rightarrow [0,1]$, $\forall A, B, C \in F(X)$, meets the following conditions:

(1) $n(A, A) = 1$;
(2) $n(A, B) = n(B, A)$;
(3) $A \subseteq B \subseteq C \Rightarrow n(A, C) \leq n(A, C) \wedge n(A, B)$.

Then, n is the fuzzy nearness degree function of F(X), and n(A, B) is the fuzzy nearness degree between A and B (Yu et al 2019). The equations are as follows.

Hamming nearness degree (e_H):

$$e_H(C_j, D_k) = 1 - \frac{1}{m}\sum_{i=1}^{m}|c_{ij} - d_{ik}|, (j = 1, 2\cdots, p; k = 1, 2\cdots, n) \tag{2}$$

Euclid nearness degree (e_E):

$$e_E(C_j, D_k) = 1 - \frac{1}{\sqrt{m}}\left[\sum_{i=1}^{m}(c_{ij} - d_{ik})^2\right]^{\frac{1}{2}}, \quad (j = 1, 2\cdots, p; k = 1, 2\cdots, n) \tag{3}$$

Maximum and minimum nearness degree (e_1):

$$e_1(C_j, D_k) = \frac{\sum_{i=1}^{m}(c_{ij} \wedge d_{ik})}{\sum_{i=1}^{m}(c_{ij} \vee d_{ik})}, (j = 1, 2\cdots, p; k = 1, 2\cdots, n) \tag{4}$$

Arithmetic mean minimum nearness degree (e_2):

$$e_2(C_j, D_k) = \frac{2\sum_{i=1}^{m}(c_{ij} \wedge d_{ik})}{\sum_{i=1}^{m}(c_{ij} + d_{ik})}, (j = 1, 2\cdots, p; k = 1, 2\cdots, n) \tag{5}$$

Here, C_j is the comparative fuzzy set, D_K is the reference fuzzy set, c_{ij} is the set of comparative sequences, and d_{ik} is a set of reference sequences.

It is impossible to directly compare the quantity between values of different indicators. Therefore, it is necessary to normalize the original indicator value. Each data process uses the following equation:

$$Y_{ij} = \begin{cases} 0 & X_{ij} = \min X_{ij} \\ \dfrac{X_{ij} - \min_i X_{ij}}{\max_i X_{ij} - \min_i X_{ij}} & \min_i X_{ij} < X_{ij} < \max_i X_{ij} \\ 1 & X_{ij} = \max_i X_{ij} \end{cases} \tag{6}$$

From this, the corresponding new sequence is obtained, and then the 4 nearness degree equations (Equations 2–5) are used for calculation and analysis.

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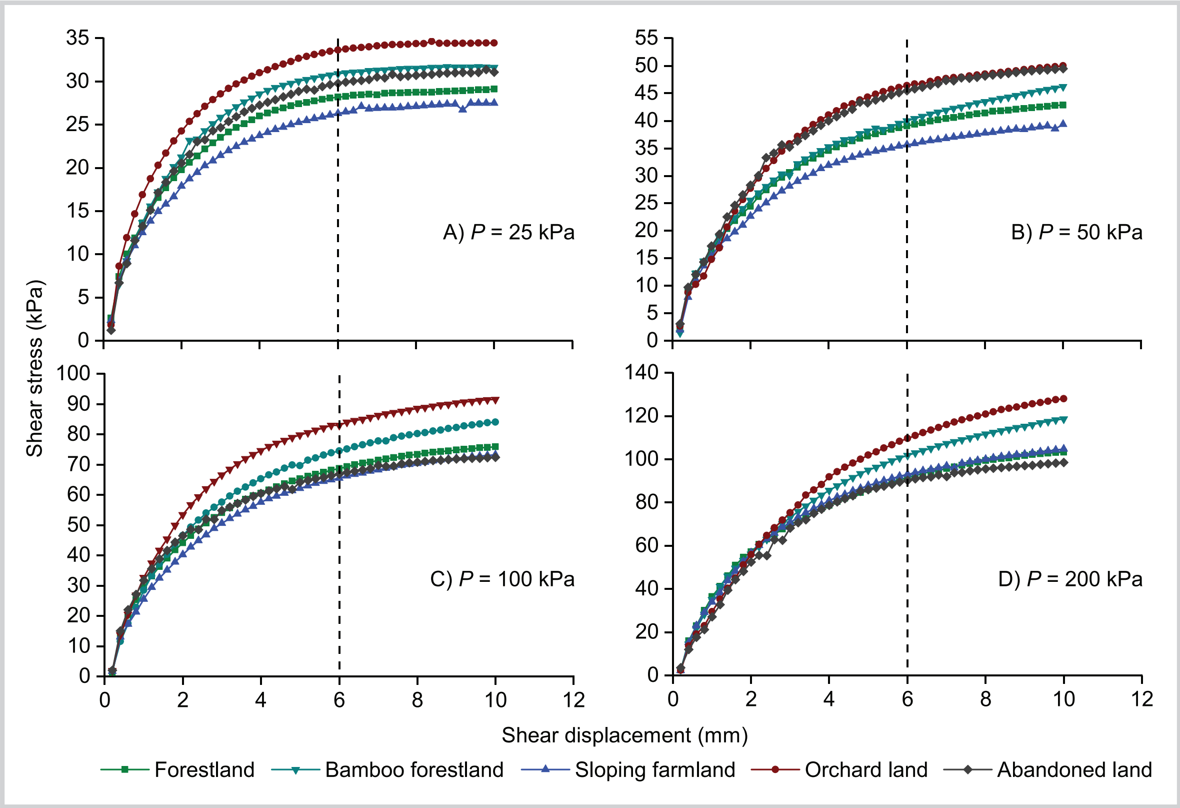
FIGURE 2 Shear stress–shear displacement curves for soil under different land uses and 4 vertical load conditions: (A) $P = 25$ kPa; (B) $P = 50$ kPa; (C) $P = 100$ kPa; (D) $P = 200$ kPa. Vertical bars indicate the maximum values of soil shear strength.



Results

Features of shear stress–shear displacement curves and shear failure envelopes

Ductile failure is the main soil behavior observed during direct shear tests. Based on Chinese Standards for Soil Test Methods (GB/T 50123-2019) (SAC et al 2019), the soil samples are deemed to have failed when the shear displacement is 6 mm, and the rate of change of the shear stress gradually decreases with increasing shear displacement. The shear stress–shear displacement curves under different vertical loads (P) are shown in Figure 2. Overall, the shear stresses in all soil samples increase as the shear displacement increases from 0 to 6 mm. The shear stresses remain stable, and the shear stress–shear displacement curves display strain hardening when the shear displacement increases from 6 to 10 mm. Specifically, at low vertical loads (25 kPa; Figure 2A), the rate of change of shear stress is highest for orchard land and relatively low for the other soil samples. When the vertical load is 50, 100, and 200 kPa (Figure 2B–D), the rate of change of shear stress is similar for all samples.

Our comparative analysis of the shear stress–shear displacement curves shows that the soil has large porosity and loose particles. During the shear process, vertical loads shift downward, soil particles are squeezed into a smaller space, the volume of the soil samples is reduced, and density increases, resulting in higher shear strength. With increasing shear displacement, shear stress quickly increases and then remains steady, and the shear stress–shear displacement curves display strain hardening.

The Mohr–Coulomb shear failure envelopes for land uses are displayed in Figure 3. Overall, the degree of fit of the Mohr–Coulomb shear failure envelopes exceeds 0.9, which could significantly reflect the failure degree of soil samples. Moreover, shear failure envelopes of the abandoned land soils have greater c and smaller slopes (or φ) than those of the forestland and sloping farmland soils. The highest mean values of φ (21.17°) and c (27.32 kPa) are observed in the fruit forestland. This indicates that land use type has a significant effect on topsoil shear strength in the study area.

Topsoil shear strength under different land uses

The mean values of the soil shear strength parameters c and φ were compared for the different land uses, using the least significant difference (LSD) test (Figure 4). Figure 4A shows a statistically significant difference ($p < 0.05$) in the mean c values between sloping farmland and other land uses. For orchard land, the mean c (27.32 kPa) is significantly greater than that of other land uses ($p < 0.05$). The average c for orchard land is about 1.22×, 1.16×, and 1.05× greater than that of forestland, bamboo forestland, and abandoned land, respectively. According to field observations, the density of orange trees is high in orchard land, and orange tree roots can absorb a large volume of soil water, resulting in reduced soil water content and increased topsoil cohesion. The mean c values show no significant differences among forestland, bamboo forestland, and abandoned land. The cohesion of the topsoil is lowest in sloping farmland and is 67.22, 70.87, 78.22, and 81.78% of that in orchard land, abandoned land, bamboo forestland, and forestland, respectively. This may be the result of plowing, which makes the soil loose and porous

FIGURE 3 Mohr–Coulomb shear failure envelopes. c, soil cohesion; τ, shear strength; φ, internal friction angle; σ, normal stress.

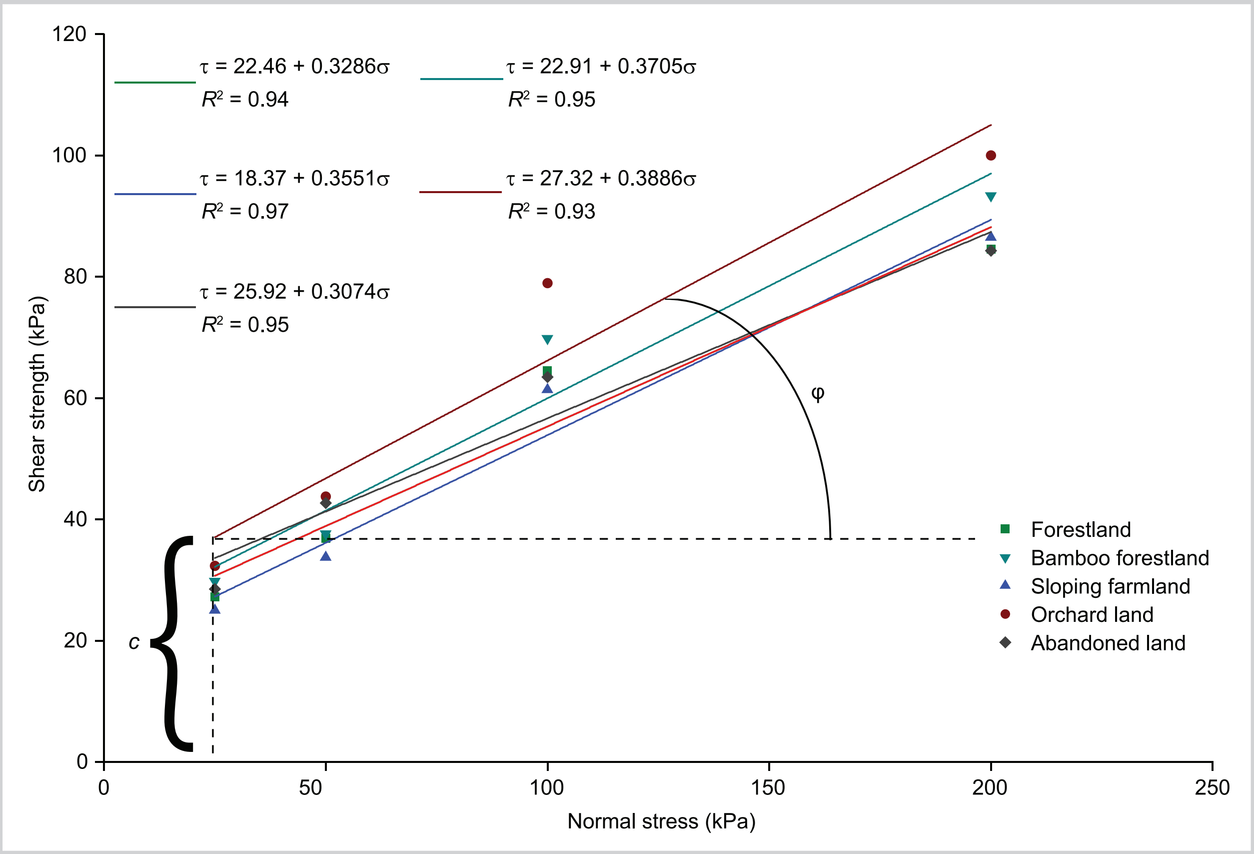


FIGURE 4 Comparisons of mean soil shear strength parameters among the land uses in the studied region: (A) soil cohesion (c); (B) internal friction angle (φ). Values with different letters in each group are significantly different (LSD, $p < 0.05$).

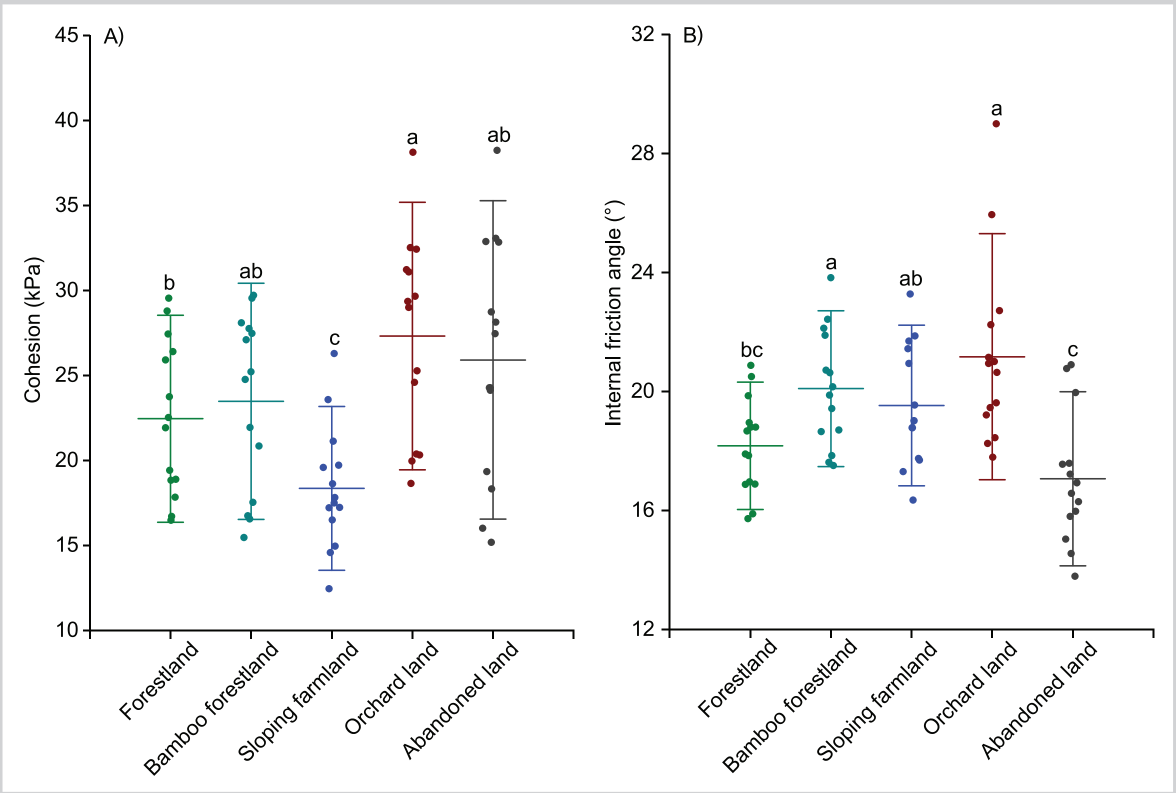


TABLE 1 The physicochemical properties of tested soils under different land uses in the study area.

Variable	Land use				
	Forestland	Bamboo forestland	Sloping farmland	Orchard land	Abandoned land
Bulk density (g/cm^3)	1.37 ± 0.12 ab	1.24 ± 0.12 c	1.38 ± 0.09 ab	1.33 ± 0.07 b	1.41 ± 0.08 a
Water content (%)	28.07 ± 3.23 a	29.14 ± 3.16 a	23.03 ± 2.99 bc	22.23 ± 1.70 c	24.55 ± 1.42 b
OM (%)	2.41 ± 0.52 bc	3.66 ± 0.77 a	1.76 ± 0.40 d	2.61 ± 0.76 b	2.12 ± 0.34 cd
Total porosity (%)	48.01 ± 4.60 bc	53.25 ± 4.33 a	47.78 ± 3.28 bc	49.84 ± 2.65 b	46.77 ± 3.16 c
Clay (%)	10.49 ± 1.65 ab	9.33 ± 2.02 b	11.29 ± 1.26 a	11.30 ± 1.28 a	11.03 ± 1.55 a
Silt (%)	69.77 ± 3.45 ab	67.077 ± 5.4 b	70.31 ± 6.20 ab	72.83 ± 2.85 a	72.86 ± 2.53 a
Sand (%)	19.73 ± 4.20 ab	23.60 ± 6.81 a	18.40 ± 6.87 b	15.88 ± 3.28 b	16.12 ± 3.22 b

Note: Mean ± SD. Values with different letters in each group are significantly different (LSD, $p < 0.05$). OM, organic matter.

and reduces soil compactness, leading to lower cohesion of the topsoil.

The φ reflects the friction between granular materials, and changes in this parameter within a given range of suction values do not affect the size or size distribution of soil particles (Gu et al 2019). Figure 4B shows that the internal friction angles of the topsoil under different land uses differ significantly ($p < 0.05$). The φ of orchard land is the largest at 21.17°, which is 1.24× that of abandoned land. The topsoil internal friction angle of abandoned land (17.07°) is significantly lower than that of bamboo forestland, sloping farmland, and orchard land ($p < 0.05$). These differences might arise partly because abandoned land has higher soil moisture content and higher bulk density, so the water film attached to the soil particles is relatively thick, which will weaken the bite force and reduce the internal friction angle.

Physical and chemical properties of soil under different land uses

Land use has a strong effect on soil properties, and unsuitable land use practices can lead to soil degradation and broader environmental harm (Papini et al 2011; Olorunfemi et al 2020). Bulk density and porosity are the basic physical parameters that describe soil, and they play a key role in soil water conservation. The bulk density shows a statistically significant difference ($p < 0.05$) for all samples in the study region (Table 1). The highest soil bulk density is in abandoned land (1.41 g/cm^3), followed by sloping farmland (1.38 g/cm^3), forestland (1.37 g/cm^3), and orchard land (1.33 g/cm^3), and the lowest mean soil bulk density is in bamboo forestland (1.24 g/cm^3). The range of soil total porosity is from 46.77 to 53.25%, and soil total porosity follows the opposite trend of soil bulk density. Bamboo forestland has the highest mean soil total porosity, and orchard land and sloping farmland have the intermediate and lowest values, respectively (Table 1). The soil water content shows no significant difference between forestland and bamboo forestland ($p < 0.05$).

The highest (3.66%) and lowest (1.76%) mean OM contents are observed in bamboo forestland and sloping farmland, respectively (Table 1). This difference may be related to the existence of a thicker humus layer and more litter in bamboo forestland, whereas cereals are typically grown with little addition of OM to the soil on sloping farmland. In addition, the OM content may differ among the different land uses, but this factor was not evaluated in this study.

Particle size is an important control on the stress, strain, and strength responses of granular materials (Horn et al 2005; Li 2013). There is no significant statistical difference among the mean proportions of clay and silt in soils of forestland, sloping farmland, orchard land, and abandoned land. Moreover, the highest mean sand content (23.60%) is recorded in bamboo forestland (Table 1).

Correlation between shear strength parameters and soil properties

To determine the relationship between shear strength parameters and soil physical and chemical properties, we used fuzzy nearness degree to identify the main controls on c and φ in the studied region. Soil shear strength is affected by numerous factors, including soil texture, OM, water content, particle shape, and soil structure. Bulk density (x_1), water content (x_2), and total porosity (x_3), as well as the proportions of OM (x_4), clay content (x_5), silt content (x_6), and sand content (x_7), are identified as the factors with the greatest influence on cohesion (c). These factors were listed as a series of sets, and the fuzzy nearness degree equations (Equations 2–5) were used to calculate the 4 nearness degrees between each factor and c after dimensionless processing of the original data (Table 2). The 4 nearness degrees between clay content and c are the greatest, followed by bulk density in forestland and sloping farmland. In bamboo forestland, the order of the 4 nearness degrees between each factor and c are as follows: $^{e}(x_6,c) > {}^{e}(x_4,c) > {}^{e}(x_1,c) > {}^{e}(x_5,c) > {}^{e}(x_2,c) > {}^{e}(x_3,c) > {}^{e}(x_7,c)$. The nearness between silt content and c is greatest, followed by OM and bulk density, and the nearness degree between sand content and c is the lowest. In orchard land, the nearness degree between bulk density and c is the highest, followed by sand content and water content, and the nearness degree between total porosity and c is the lowest. In abandoned land, the nearness degree between bulk density and c is greatest, and the silt and sand contents are ranked second and third, respectively. This could be caused by the chemical and physical properties of soils under differing land uses with markedly different topsoil shear strength parameters. The nearness degrees of the clay and silt contents to c are relatively large, mainly because the clay and silt contents are not only the fundamental factor affecting

TABLE 2 Nearness degree for the factors that influence topsoil cohesion (*c*) under the different land uses.

Land use type	Sort	$^e(x_1,c)$	$^e(x_2,c)$	$^e(x_3,c)$	$^e(x_4,c)$	$^e(x_5,c)$	$^e(x_6,c)$	$^e(x_7,c)$
Forestland	e_H	0.6754	0.5791	0.5796	0.5894	0.6838	0.6333	0.6394
	e_E	0.5966	0.5081	0.5103	0.4869	0.5718	0.5645	0.5440
	e_1	0.4658	0.3637	0.4182	0.2889	0.5504	0.4901	0.4084
	e_2	0.6355	0.5334	0.5898	0.4483	0.7100	0.6578	0.5799
Bamboo forestland	e_H	0.6317	0.5285	0.5466	0.6875	0.6045	0.6957	0.5312
	e_E	0.5763	0.4485	0.4567	0.6289	0.5033	0.6325	0.4485
	e_1	0.5120	0.3966	0.3690	0.5246	0.4084	0.5853	0.3465
	e_2	0.6772	0.5680	0.5391	0.6881	0.5800	0.7384	0.5147
Sloping farmland	e_H	0.7240	0.5811	0.6612	0.7370	0.8124	0.6560	0.6604
	e_E	0.6439	0.5007	0.5846	0.5727	0.7610	0.5654	0.5994
	e_1	0.5619	0.4551	0.4395	0.4163	0.6542	0.5238	0.4007
	e_2	0.7195	0.6256	0.6106	0.5879	0.7910	0.6875	0.5721
Orchard land	e_H	0.7169	0.6570	0.5741	0.7234	0.6660	0.6188	0.6675
	e_E	0.6588	0.5998	0.5268	0.5663	0.5622	0.5525	0.6044
	e_1	0.5513	0.5023	0.3638	0.4776	0.4639	0.3542	0.5037
	e_2	0.7108	0.6687	0.5335	0.6465	0.6338	0.5231	0.6700
Abandoned land	e_H	0.7309	0.5679	0.5736	0.7332	0.4945	0.6959	0.6680
	e_E	0.6942	0.5191	0.5130	0.5272	0.4493	0.6281	0.5881
	e_1	0.5782	0.3738	0.3860	0.4250	0.2479	0.4898	0.5061
	e_2	0.7327	0.5442	0.5570	0.5965	0.3973	0.6575	0.6721

Note: e_H, Hamming nearness degree; e_E, Euclid nearness degree; e_1, maximum and minimum nearness degree; e_2, arithmetic mean minimum nearness degree; *c*, cohesion (kPa); x_1, bulk density (g/cm^3); x_2, water content (%); x_3, total porosity (%); x_4, OM (%); x_5, clay content (%); x_6, silt content (%); x_7, sand content (%).

soil shear strength but also the internal factor that determines the distribution of the soil stress field, the state of relative movement between particles, and the degree of particle fragmentation during the process of shearing.

Using the fuzzy nearness degree equations (Equations 2–5), the 4 nearness degrees were also calculated for the influencing factors and φ (Table 3). The results for forestland show that the nearness degree between silt content and φ is greatest, followed by clay content and bulk density. In bamboo forestland, the trend of the 4 nearness degrees is as follows: $^e(x_7,\varphi) > {}^e(x_1,\varphi) > {}^e(x_2,\varphi) > {}^e(x_5,\varphi) > {}^e(x_4,\varphi) > {}^e(x_3,\varphi) > {}^e(x_6,\varphi)$. For sloping farmland, the nearness degree is greatest between bulk density and φ, followed by silt and clay contents, whereas the nearness degrees are relatively small between OM and φ and between water content and φ. In orchard land, the trend of the calculation results for the 4 nearness degrees is as follows: $^e(x_3,\varphi) > {}^e(x_6,\varphi) > {}^e(x_5,\varphi) > {}^e(x_7,\varphi) > {}^e(x_4,\varphi) > {}^e(x_2,\varphi) > {}^e(x_1,\varphi)$. For abandoned land, the nearness degree between total porosity and φ is greatest, followed by sand content, and the nearness degree between OM and φ is the smallest.

Water content is thought to be the decisive factor affecting the shear strength (Wei et al 2016). In this study, the water content of the sampled soils was close to saturation, which can be seen as a fixed factor. The preceding fuzzy nearness degrees in Tables 2 and 3 showed that the bulk density and the clay and silt contents are the main direct factors affecting the variation of soil shear strength for the purple topsoil and that other indirect factors, in terms of the OM content, total porosity, and sand content, contribute to the variability of *c* and φ values for the case soil.

Discussion

Soil shear strength is closely connected with land use. Topsoil roughness, plant roots, and the physical and chemical properties of soils differ under various land uses, leading to differences in *c* and φ for a given soil type. Table 4 shows the results of related research into soil shear strength under different land uses. Overall, in forestland and sloping farmland, the purple soil has relatively low shear strength. This differs from the results of Bi et al (2006), Chen et al (2007), and Ni et al (2012, 2013), possibly because the purple soil was thin, there was significant soil erosion, and the OM and clay contents were lower (Zhang et al 2016), factors that lead to lower soil shear strength. In addition, the type of test can affect the values obtained for the shear strength of a particular soil sample (Lin et al 2015; Gu et al 2019).

In this study, the shear strength of surface soil is highest in orchard land. That is because plowing and application of fertilizer contribute to the development of soil structure, which enhances the cementation and aggregation of soil

TABLE 3 Nearness degree for the factors that influence topsoil internal friction angle (φ) under the different land uses.

Land use type	Sort	$e(x_1,\varphi)$	$e(x_2,\varphi)$	$e(x_3,\varphi)$	$e(x_4,\varphi)$	$e(x_5,\varphi)$	$e(x_6,\varphi)$	$e(x_7,\varphi)$
Forestland	e_H	0.6725	0.6358	0.6074	0.6625	0.6831	0.7059	0.5935
	e_E	0.6035	0.5538	0.5565	0.5855	0.5905	0.6544	0.5293
	e_1	0.4709	0.4337	0.4537	0.3874	0.5559	0.5755	0.3673
	e_2	0.6403	0.6050	0.6242	0.5584	0.7146	0.7306	0.5372
Bamboo forestland	e_H	0.6714	0.6505	0.6009	0.6030	0.6293	0.5257	0.7387
	e_E	0.5743	0.6064	0.5179	0.5284	0.5530	0.4636	0.6585
	e_1	0.5010	0.4574	0.3511	0.3630	0.3607	0.3612	0.5136
	e_2	0.6676	0.6277	0.5197	0.5326	0.5301	0.5307	0.6787
Sloping farmland	e_H	0.7161	0.5227	0.6356	0.6281	0.6323	0.6625	0.6334
	e_E	0.6437	0.4656	0.5561	0.5465	0.5708	0.5894	0.5756
	e_1	0.5632	0.4136	0.4245	0.3923	0.4329	0.5409	0.3849
	e_2	0.7205	0.5852	0.5960	0.5635	0.6042	0.7021	0.5558
Orchard land	e_H	0.5196	0.5125	0.7648	0.5767	0.6660	0.7509	0.5860
	e_E	0.4530	0.4447	0.7070	0.4940	0.6104	0.6532	0.4836
	e_1	0.2696	0.2931	0.5316	0.3415	0.3940	0.4492	0.3520
	e_2	0.4247	0.4534	0.6942	0.5091	0.5652	0.6199	0.5207
Abandoned land	e_H	0.5971	0.6357	0.7880	0.5622	0.6183	0.6329	0.6634
	e_E	0.5057	0.5637	0.7178	0.5258	0.5613	0.5277	0.5984
	e_1	0.4262	0.4426	0.6374	0.3174	0.3718	0.4126	0.4990
	e_2	0.5977	0.6136	0.7785	0.4819	0.5421	0.5842	0.6658

Note: e_H, Hamming nearness degree; e_E, Euclid nearness degree; e_1, maximum and minimum nearness degree; e_2, arithmetic mean minimum nearness degree; φ, internal friction angle (°); x_1, bulk density (g/cm^3); x_2, water content (%); x_3, total porosity (%); x_4, OM (%); x_5, clay content (%); x_6, silt content (%); x_7, sand content (%).

particles, leading to higher *c* and φ values. Moreover, compared with other land uses, orchard land has higher soil bulk density (1.33 g/cm^3) and lower water content (22.23%), and the interaction between bulk density and water content caused *c* and φ to increase (Ni et al 2013). The main component of the OM inputs to the soils of bamboo forestland is higher-quality bamboo residue and litter. Such OM would increase the soil frictional strength and enhance the cohesion between soil particles (Hartge 1975). Furthermore, bamboo roots can reinforce soils, and root exudates have a remarkable impact on soil structure and soil shear strength (Ma'ruf et al 2012). Figure 4 shows that the shear strength of soil in abandoned land is greater than that in forestland. Field observations indicate that the root system of the eucalyptus is stout and extends into deep soil layers. However, the density of grassroots is high in the topsoil of abandoned land, and these grassroots are finer and combine closely with the surface soil to create a complex system. When comparing the same volume of roots and soil, the incremental effect of thicker roots on topsoil shear strength is poor compared with that of finer roots. This finding is consistent with the results of Comino and Marengo (2010) and Comino et al (2010). In this study, we found that the topsoil shear strength of sloping farmland was lower than that of fruit forestland and bamboo forestland, in contrast to the findings of Li et al (2017). They reported that the shear strength of topsoil was higher in sloping farmland than in orchard land, coniferous and broad-leaved mixed woodland, abandoned land, and shrub forest. This difference may be related to the differences in slope positions, crop types, and soil types. However, identification of the internal cause requires a comprehensive study of the biological characteristics of the site and the environmental characteristics of crops on sloping farmland.

Orchard land shows better soil properties and water conservation than abandoned land. Hence, we strongly recommend that abandoned land be converted to fruit forestland to control soil erosion. Purple soils on sloping farmland are the main carrier of agricultural production in the Three Gorges Reservoir area. Under the influence of human activity and natural factors, soil erosion is a serious problem. Biological or engineering measures should be introduced in terraced agricultural land, such as planting hedgerows, building soil bunds, or reducing slope angles, to improve the resistance of the topsoil to erosion in such sloping farmland.

Particle size is a key control on the strength behavior of granular materials (Li 2013; Silva et al 2020). The parameters *c* and φ are strongly influenced by the gravel content of soil and particle size distribution (Havaee et al 2015). In this

TABLE 4 Effects of land use on soil shear strength.

Soil type	Source of soil sample	Test type	Particle composition (%)			Shear strength index		Data source
			Clay	Silt	Sand	c (kPa)	φ (°)	
Yellow soil	Forestland	Triaxial shear test	52.6	15.1	32.3	58.5	42.4	Ni et al (2013)
	Slope	Direct shear test	17.1	69.4	13.5	73.1	29.5	Shen et al (2009)
Yellow brown earth	Farmland	Triaxial shear test	10.3	53.6	36.1	37.0	28.6	Chen et al (2007)
Red soil	Collapsing	Direct shear test	38.2	29.5	32.3	32.6	35.3	Zhang et al (2012)
			44.78	31.60	23.62	34.09	20.06	Zhang et al (2020)
	Farmland		—	—	—	59.0	13.6	Bi et al (2006)
Loess	Grassland	Direct shear test	—	—	—	13.7	24.4	Xiao et al (2013)
	Shrub		—	—	—	14.3	26.6	
	Bare land		—	—	—	17.5	27.1	
Purple soil	Farmland	Triaxial shear test	59.1	20.8	20.1	80.0	28.3	Ni et al (2012)
	Forestland	Direct shear test	10.49	69.79	19.73	22.46	18.18	This study
	Bamboo forestland		9.33	67.08	23.60	23.48	20.10	
	Sloping farmland		11.30	70.31	18.39	18.37	19.53	
	Orchard land		11.29	72.84	15.88	27.32	21.17	
	Abandoned land		11.03	72.86	16.12	25.92	17.07	

Note: — indicates no relevant data in the cited studies.

study, the nearness degrees are comparatively large for the clay content and c of the soils from forestland and sloping farmland. This reflects the relatively high clay content in these soils, because the clay particles have strong interparticle bonds and aggregate as a result of their high surface area, colloidal size, and many chemical bonds (Horn and Fleige 2003; Cao et al 2020). The nearness degree between sand content and c was relatively high in orchard land, possibly because the coarser sand particles affect soil cohesion by inhibiting soil aggregation and separating finer soil particles (Khalilmoghadam et al 2009). Casini et al (2011) indicated that the strength and deformation of soil depend on particle shape, compactness, and variation in the mass fraction of fine particles. The highest nearness degree to φ is the sand content in bamboo forestland. Coarser sand is likely to have increased internal (interparticle) friction in these soils (Wang et al 2010, 2020). In addition, φ is affected by other factors, such as the type of clay minerals, the soil particle components, and compaction.

Many factors influence soil shear strength, and the interaction mechanism is complex in the natural state. In this paper, we have only compared the relative contribution of 7 factors that strongly influence soil shear strength and of the surface shear strength characteristics of 5 land uses in the Three Gorges Reservoir area. For further study and discussion, the influence of other factors (eg root systems, soil aggregates, and slope angle) on topsoil shear strength should be examined. Furthermore, as many field experiments as possible should be conducted in future research. The results have increased our understanding of the mechanisms of surface soil loss and provide a theoretical basis for controlling soil erosion in the Three Gorges Reservoir area.

Conclusions

This study examines shear strength under typical land uses in the Three Gorges Reservoir area and explores prevailing factors in determining the observed variances. When the shear displacement increases from 6 to 10 mm, the shear stresses remain stable, and the shear stress–shear displacement curves display a strain hardening trend. Land uses have a significant effect on topsoil shear strength parameters, as well as on the physical and chemical properties of the soils analyzed ($p < 0.05$). Compared with other land uses, the mean values of c, φ, and clay content for orchard land are the highest, and the mean sand and water contents are the lowest. Finally, the fuzzy nearness degrees show that the shear strength of the purple topsoil is controlled mainly by the bulk density and the clay and silt contents, whereas the OM content, total porosity, and sand content are important indirect factors that affects the shear strength of the purple topsoil. In all, orchard land has relatively high shear strength of topsoil in 5 typical land use types; therefore, it is beneficial for soil conservation and should be favored in land use planning for the area.

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