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Research Article

Changes in shear strength parameters in two cultivations and soil orders

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ABSTRACT- Soil shear strength is a fundamental mechanical property that influences various soil behaviors and interactions during tillage. Continuous cultivation can significantly alter soil mechanical properties, including shear strength. This study aimed to investigate changes in shear strength parameters in soils cultivated with sugar beet and canola. Eight soil profiles were excavated in fields planted with these two crops in the Gyan Plain, selected based on land suitability classifications. Each profile was described and sampled, and the physical and chemical properties of the soils were analyzed as predictors of surface shear strength across all horizons. Shear strength parameters were determined using the standard direct shear test, from which stress–shear curves were generated to calculate cohesion and internal friction angle. Correlation analysis revealed a significant positive relationship between cohesion and soil organic matter (r = 0.35, $P < 0.05$), while no significant relationship was found with clay content. Cohesion showed significant negative correlations with specific density (r = –0.37, $P < 0.05$) and internal friction angle (r = –0.70, $P < 0.01$). The angle of internal friction exhibited a significant positive correlation with both soil depth (r = 0.35, $P < 0.05$) and specific density (r = 0.56, $P < 0.01$), but a significant negative correlation with organic matter (r = –0.56, $P < 0.01$) and moisture content (r = –0.62, $P < 0.01$). Regression analysis confirmed a negative correlation between cohesion and the internal friction angle, with an R^2 of 0.53. The results indicated that shear stress was higher in soils under sugar beet cultivation compared to those under canola, while the modulus of elasticity (E) was greater in canola-cultivated soils. Overall, this study identified crop type and root system, soil moisture, specific density, organic matter content, and soil developmental stage as key factors influencing soil shear strength. To improve soil shear strength, it is recommended to adopt crop rotation strategies and avoid monoculture systems.

INTRODUCTION

Spatial variability in soil characteristics at any given field location is a natural phenomenon governed by geological and pedological factors. However, changes in soil properties can also result from cultivation practices, plant type, tillage methods, and other land management strategies (Iqbal et al., 2005). The physical properties of soil play a crucial role in root penetration, water availability, and the efficiency of water uptake by plants. These properties also affect the concentration and movement of oxygen and other gases in the soil, lateral and vertical water movement, and the growth and spatial distribution of both natural vegetation and agricultural crops (Gill & Vandenberg, 1967). Furthermore, they influence the energy required for tillage operations (Yavuzcan et al., 2002). Stott and Diack (2004) demonstrated that reducing tillage intensity enhances soil permeability while decreasing cohesion, which reflects a reduction in soil compaction. Agricultural practices can modify soil structure through mechanisms such as shear, compression, tension, and plastic flow, depending on the inherent properties of the soil. Tillage and traffic on agricultural lands exert mechanical forces, particularly tension, that can rupture soil structure (Shahangian, 2011). One key factor in developing soil cohesion is the application of compressive energy. This energy, once applied, becomes stored in the soil as potential energy, contributing to shear resistance. The compressive force leads to compaction, and the resulting structural integrity manifests as soil cohesion (Shahangian, 2011). Shear strength refers to the internal resistance of a soil mass to failure or sliding along any internal surface (Braja, 2006). It is primarily governed by cohesion between soil particles, applied stress, and the angle of internal friction (Keller et al., 2004). Various physical and chemical soil properties influence surface soil shear strength, including particle size distribution (Shahnazari et al., 2021; Eteraf et al., 2023), moisture content (Khairuddin et al., 2017; Han et al., 2020), organic matter (Khairuddin et al., 2017), bulk density (Havaee et al., 2015), soil aggregation (Khalilmoghadam, 2009), soil depth, and root structure (Khairuddin et al., 2017). Soil failure or plastic deformation occurs under a specific stress state, making shear strength a function of stress conditions rather than merely a response to failure. The theoretical basis for shear failure was established by Coulomb (1776), who proposed

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that failure occurs when maximum shear stress reaches a critical threshold (Morgan, 1996). The Mohr–Coulomb equation, a foundational concept in classical soil mechanics, defines the relationship between cohesion (c), internal friction angle (φ), normal stress (σ), and maximum shear stress (τ max) acting on a failure plane (Eq. (1)).

$$\tau \max = c + \sigma \tan \varphi \qquad \text{Eq. (1)}$$

Cohesion is a fundamental soil property that describes the adhesive forces between soil particles. The internal friction angle, expressed in degrees (°), represents the ability of soil or rock to resist shear stress through particle interlocking and friction. Together, cohesion and internal friction angle define the shear strength of a soil, which is directly proportional to the normal stress applied. To enable practical estimation using standard laboratory equipment, φ and c are commonly used as indices derived from graphical interpretations (Shahangian, 2011). Shear strength is considered as a key indicator of overall soil quality and structural integrity (Carvalho et al., 2010; Silva et al., 2015; Havaee et al., 2015). In addition to assessing the soil's ability to bear loads, shear strength also reflects the degree of compaction (Ismael & Behbehani, 2014). Densely packed soils, with fewer voids and higher bulk density, typically exhibit greater shear strength (Bachmann et al., 2006). Shear strength arises from the combined contributions of internal friction and undrained cohesion, and it is commonly evaluated in one of three states: peak (failure), residual, or critical (softened) strength (Asadi Langrodi, 2014). Accurate estimation of shear strength parameters, and associated changes in consolidation volume, requires consideration of soil geochemistry and environmental factors. These include cation exchange capacity, the electrical charge of clay particles, and the geomorphological context of the site (Asadi Langroudi, 2014). Numerous studies have identified factors influencing shear strength, including bulk density (Havaee et al., 2015), water content (Jie et al., 2018; Han et al., 2020; Zhang et al., 2022), organic matter content (Khairuddin et al., 2017), particle size distribution (Shahnazari et al., 2021; Eteraf et al., 2023), vegetation cover, and root system characteristics (Fattet et al., 2011; Khairuddin et al., 2017). Fattet et al. (2011) showed that vegetation type significantly affects the stability of surface soil aggregates, whereas the influence is less pronounced in subsurface layers. In a study on maize with deep, dense roots, Khairuddin et al. (2017) reported that the application of palm oil mill effluent sludge increased shear strength. The amendment improved root development and enhanced soil properties such as specific gravity, porosity, and organic matter content. Han et al. (2020) found that increasing water content reduced the shear strength of paddy soils and also examined the roles of organic matter, temperature, and soil microorganisms. These findings collectively demonstrate that root system architecture, soil depth, moisture content, organic matter, and particle distribution are major factors influencing soil shear strength. In the Gyan Plain, continuous cultivation of sugar beet and canola has been practiced for many years, yet the physical and mechanical effects on soil have not been systematically studied. Canola develops deep, vertically oriented roots, while sugar beet has a shallower, more fibrous root system. This study compares these two crop types to evaluate their impact on soil shear strength across surface and subsurface layers in two soil orders, taking into account both root morphology and the nature of crop residues.

MATERIALS AND METHODS

Soil sampling

The studied area, covering approximately 1,560 hectares (87.15% of the total land), is located in the Gyan Plain of Nahavand City, Hamedan Province, Iran (Fig. 1). Geographically, it lies between latitudes 34°11′5″ to 34°12′00″ N and longitudes 48°14′56″ to 48°19′46″ E, at an elevation of 1563 meters above mean sea level. According to Banai (1997), the region exhibits a xeric soil moisture regime and a mesic soil temperature regime. Geologically, it lies within the high Zagros zone and borders the Sanandaj–Sirjan structural zone and the Zagros fold-thrust belt. The dominant physiographic units in the area include colluvial fans and piedmont plains. For this study, eight locations were randomly selected within fields cultivated with two crops, canola and sugar beet, for soil profile excavation. Soil profiles were described in accordance with Soil Taxonomy (2022), and samples were collected from all identified horizons. The soils were then classified using the keys provided by the Soil Survey Staff (2022).

Physical and chemical analysis of the soil

Several physical and chemical properties of the soil samples were analyzed. Particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986), while cation exchange capacity (CEC) was measured according to Sumner and Miller (1996). Soil organic carbon content was assessed following the method of Nelson and Sommers (1996). Gypsum and calcium carbonate equivalent (CCE) were quantified using procedures outlined by Loppert and Suarez (1996). Moisture content was determined from the saturated paste by drying samples at 110 °C for 24 hours, as described by Gardner (1986). Specific density was measured using the pycnometer method in accordance with ASTM D854-14(2004b), using 25 g of soil per test. The specific density of the samples ranged from 2.0 to 2.6 g cm^{-3}.

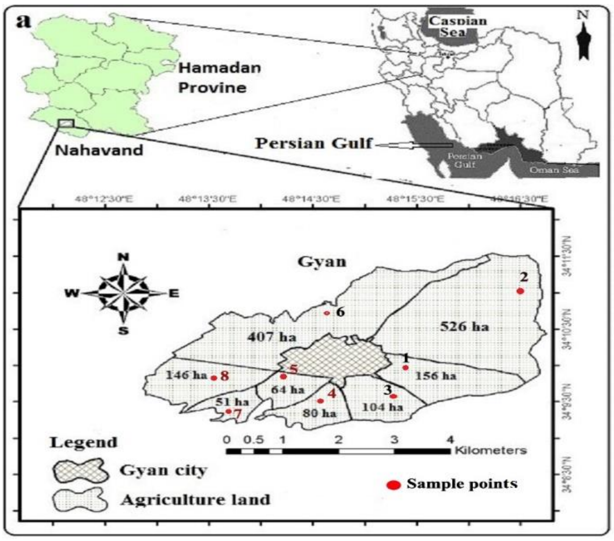

Fig. 1. The map of study area.

Shear strength

Soil shear strength parameters were determined in the laboratory using the direct shear test in accordance with ASTM D3080-04 (2004b). To ensure reliable results, three replicate samples from each soil horizon were tested under three different normal vertical stresses: 2, 4, and 8 kPa, as specified by the standard. Each sample was placed in a cubic shear box, consisting of upper and lower sections. A controlled normal stress was applied vertically, while the upper section was displaced laterally at a constant strain rate until failure occurred (Fig. 2). The applied shear load and the corresponding horizontal displacement were recorded at set intervals throughout the test. These measurements were used to generate a stress-strain curve under each normal load condition. A linear trend line was typically fitted to the resulting data (Bardet, 1997), where the y-intercept represents the cohesion and the slope corresponds to the peak internal friction angle. The tests were conducted using a shear box apparatus with internal dimensions of 6 cm × 6 cm × 2 cm (Bardet, 1997).

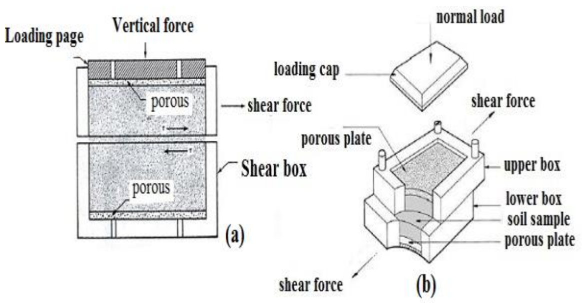

Fig. 2. Schematic diagram of the direct cutting test apparatus: (a) cross-section of the cutting box and (b) three-dimensional view of the direct cutting box with a square plan.

Statistical analysis

Statistical analyses were performed using SPSS version 21. Mean comparisons were conducted using Duncan's multiple range test at a significance level of $P < 0.05$ within a completely randomized design. Pearson correlation coefficients were also calculated in SPSS to assess relationships among variables and determine their significance. Graphical representations were prepared using Microsoft Office Excel 2019.

RESULTS AND DISCUSSION

Physicochemical characteristics

The soils in the study area were classified as Inceptisols and Entisols according to the Key to Soil Taxonomy (2022) (Table 1). The parent material in the region is calcareous, resulting in an increase in calcium carbonate content with soil depth. In contrast, surface layers showed reduced calcium carbonate due to the leaching and weathering. Calcium carbonate levels ranged between 20% and 25% (Table 1). Profiles 1 to 4, under sugar beet cultivation, exhibited an average cation exchange capacity (CEC) of approximately 18 $cmol_{(+)}\ kg^{-1}$ in the A horizon. In contrast, profiles 5 to 8, cultivated with canola, showed a higher average CEC of about 28.5 $cmol_{(+)}\ kg^{-1}$ in the same horizon. Soils under canola generally contained higher organic matter content (3.5%) than those under sugar beet (2.2%), with organic matter decreasing with depth. This increase is attributed to the incorporation of canola residues such as straw and stubble. The deeper and more extensive root system and higher biomass of canola also contribute to this difference. Soil organic carbon is a key indicator of soil quality and is useful for assessing the long-term effects of land management. Across profiles, clay and silt contents decreased with depth, while sand content increased, primarily due to the parent material exposure and a higher percentage of gravel in deeper horizons (Table 1). Correlation analysis across all soil horizons revealed a significant positive correlation between CEC and organic matter (r = 0.62, $P < 0.01$), as well as with clay content (r = 0.30, $P < 0.05$), and a significant negative correlation with sand content (r = -0.34, $P < 0.05$) (Table 2). In addition to organic matter and clay content, the mineralogical composition of clays likely plays a role in influencing CEC. Organic matter was also positively correlated with soil cohesion (r = 0.35, $P < 0.05$) and negatively correlated with the internal friction angle (r = -0.56, $P < 0.01$). In most profiles, cohesion decreased with increasing depth. Although the correlation between depth and cohesion was negative, it was not statistically significant. Soils with more developed horizons tended to show higher cohesion values. Lower cohesion values were observed in profiles 5 (15.8 kPa) and 8 (15.3 kPa), both classified as Entisols, due to the lower clay and higher sand content. Profile 7, despite its higher clay content, showed reduced cohesion due to the elevated sand and silt fractions. This was consistent with the observed negative correlation between cohesion and sand as well as the positive correlation with clay. Saturation moisture content declined with depth (r = -0.45, $P < 0.05$) and was positively correlated with cohesion, while showing a significant negative correlation with the internal friction angle (r = -0.62, $P < 0.01$) (Table 2). Specific density increased with depth (r = 0.70, $P < 0.01$), contributing to the higher internal friction angles (r = 0.56, $P < 0.01$). The highest specific density was recorded in profile 8 at the deepest horizon (2.6 g cm^{-3}), which also exhibited the highest internal friction angle (56°) (Table 1). Despite these trends, specific density showed a negative correlation with cohesion (r = -0.37, $P < 0.05$). The internal friction angle also increased with higher calcium carbonate content (r = 0.38, $P < 0.05$). Gypsum content varied from 0.1% to 3.4% across horizons without a consistent pattern, preventing any conclusive correlation between gypsum and the shear strength parameters cohesion and friction angle.

Overall, the results indicated that increasing sand content was associated with higher specific density, while both organic matter content and saturated soil moisture decreased across the profiles. As a consequence, soil cohesion declined. Although cohesion showed negative correlations with sand and calcium carbonate equivalent, and positive associations with organic matter and clay content, these relationships were not statistically significant. These trends are consistent with prior studies, including those by Zhang et al. (2022), Havaee et al. (2015), and Wei et al. (2019). Similarly, Khalilmoghadam et al. (2009) reported that soil cohesion tends to increase with higher clay content. This effect is partly attributed to aggregation induced by clay particles (Khalilmoghadam et al., 2009), while microstructural influences also play a critical role (Hatibu and Hettiaratchi, 1993). According to Hatibu and Hettiaratchi (1993), physical properties such as soil texture, moisture content, and microstructure significantly influence the range of mechanical behaviors observed in agricultural soils. They demonstrated that increasing clay content promotes more ductile behavior, whereas higher sand content is associated with more brittle soil responses. An upward trend in the angle of internal friction with increasing depth was observed across all profiles (r = 0.35, $P < 0.05$). The highest average friction angle (56º) was recorded in Profile 8 (Entisol), while the lowest (32.8º) occurred in Profile 4 (Inceptisol). In general, profiles with higher internal friction angles exhibited lower cohesion, a trend supported by a strong and statistically significant negative correlation between these two parameters (r = -0.70, $P < 0.01$) (Table 2). Profiles 5 and 8 (Entisols), which had the lowest cohesion, also showed the highest internal friction angles (Table 1). Profile 7, with its cambic horizons indicating limited soil development, exhibited reduced cohesion. The lowest cohesion overall was recorded in Profile 8, which also had the highest sand content.

The results indicated a positive correlation between the amount of sand in the soil and the angle of internal friction, although this relationship was not statistically significant. However, a positive and significant correlation was observed between the angle of internal friction and the amount of calcium carbonate equivalent (r = 0.35, $P < 0.05$). Shahnazari et al. (2021) demonstrated that the average internal friction angle of carbonate soils is higher than that of typical silicate sands, noting that the presence of soil carbonate, coarse particles, and other soil components significantly influences this angle. Their findings suggested that carbonate soils exhibit higher internal friction angles due to the smooth surfaces and distinct shapes of the particles. Similarly, Rasti et al. (2021) found that coarse particles contribute to higher friction angles, which, in turn, enhance the soil's shear strength. Eteraf et al. (2023) also reported that as the median diameter of soil particles increases, cohesion values decrease, while the internal friction angle increases. These results align with the findings of the current study. Additionally, the results indicated that as soil depth increased, both specific density and the friction angle also increased. Mousavi and Sharahi (2021) demonstrated that bulk density and sand content positively influence the friction angle. They also observed that at constant density, friction angle increases with particle size. Furthermore, the roundness and smoothness of sand particles were found to influence the friction angle, with larger particles generally contributing to higher shear strength. Ozelim et al. (2022) further highlighted that soil properties, including shear resistance and the internal friction angle, can be indirectly measured. The study also found that as soil depth increased, the percentage of saturated moisture decreased, resulting in a negative correlation between moisture content and the friction angle. Moisture levels influence apparent friction: at low humidity, friction is primarily due to the sliding, whereas at higher humidity, friction increases due to the enhanced cohesion. However, excessive moisture can lead to lubrication between particles, reducing friction. Ahmadi et al. (2016) demonstrated that, under various stresses, cohesion increases with rising moisture content until it peaks between 5% and 10%, after which it declines. Their study concluded that adding water to sandy soil increases its shear strength, not due to adhesion from water suction, but as a result of the enhanced internal friction angle. Notably, as soil cohesion increased, the internal friction angle decreased, a pattern that was consistent across all profiles and reflected a strong negative correlation.

Shear strength

Higher shear strength values were observed in soils under sugar beet cultivation compared to those under canola cultivation. The results from the four profiles of sugar beet cultivation indicated that their cohesion was also higher. Furthermore, the soil texture associated with sugar beet cultivation was predominantly clay (see Table 1). The cohesion in these profiles is attributed to the attractive electrostatic forces between clay plates and the water present in the very small pores, as well as the frictional resistance between soil particles (Havaee et al., 2015). Table 2 also shows a positive correlation between soil moisture and clay content with soil cohesion. Profiles 5, 6, 7, and 8, which had a higher sand content, exhibited lower cohesion (17 kPa) compared to profiles 1, 2, 3, and 4 (18.2 kPa). As soil depth increased, the friction angle increased while cohesion decreased. Fig. 3 illustrates a significant negative correlation ($R^2 = 0.53$) between these two shear strength parameters. Zhang et al. (2022) demonstrated that shear strength is influenced by several factors, including soil bulk density and moisture content. They found that the shear strength of surface soil was significantly lower than that of subsoil. The results of this study confirmed a significant negative relationship between cohesion and the internal friction angle ($R^2 = 0.53$, $P < 0.01$). Havaee et al. (2015) also reported a significant negative relationship between cohesion and the friction angle, as well as a significant positive correlation between fine clay content (0.05-0.2 µm) and cohesion (r = 0.41, $P < 0.001$). Also, they observed a significantly negative relationship between sand content and cohesion (r = -0.31, $P < 0.01$).

Table 1. Some physical and chemical characteristics of the studied profiles

Profiles	Cultivation	Soil No.	Depth (cm)	Horizon	Sand (%)	Silt (%)	Clay (%)	Texture	Gravel (%)	CEC $cmol_{(+)}\ kg^{-1}$	OM (%)	CCE (%)	$CaSO_4.2H_2O$ (%)	SP (%)	ρ ($g\ cm^{-3}$)	Tenacity (kPa)	φ (°)
1. Typic Calcixerepts	Sugar beet	1	0-20	Ap	30	31.5	38.5	Clay loam	-	19.8	1.36	24.5	0.3	63	2.0	16	42
		2	20-43	Bw1	32	25.5	42.5	Clay	10	21.5	0.39	24	0.1	59	2.1	16.9	43.2
		3	43-67	Bw2	34	21.5	44.5	Clay	20	19.3	0.58	24.5	0.1	57	2.4	18.3	43.7
		4	67-99	Bk	36	25.5	38.5	Clay loam	50	15	0.78	25	0.1	57	2.4	19.1	45.5
2. Typic Calcixerepts	Sugar beet	5	0-28	Ap	32	33.5	34.5	Clay loam	-	18.3	0.54	24	0.6	71	2.0	20.2	32.9
		6	28-51	Bw	38	27.5	34.5	Clay loam	10	20.5	0.42	24	0.3	66	2.2	16.7	38.5
		7	51-81	Bk1	36	27.5	36.5	Clay loam	30	18.9	0.35	24	0.5	56	2.3	16.8	37.4
		8	81-107	Bk2	40	25.5	34.5	Clay loam	50	15.7	0.62	25	0.5	60	2.5	16.5	38.4
3. Typic Calcixerepts	Sugar beet	9	0-17	Ap	34	25.5	40.5	Clay	-	17.3	0.42	24.5	0.4	58	2.0	18.9	36.7
		10	17-39	Bk1	32	23.5	44.5	Clay	10	19	0.42	25	0.5	57	2.1	18.4	44.7
		11	39-70	Bk2	48	15.5	36.5	Sandy clay	30	16.3	0.5	25	2.1	56	2.3	17.2	43.2
		12	70-100	Bk3	62	19.5	18.5	Sandy loam	40	13	0.1	25	2.2	55	2.5	17.0	51.3
4. Typic Calcixerepts	Sugar beet	13	0-18	Ap	56	25.5	18.5	Sandy loam	-	17	2.2	24	0.3	74	2.0	18.4	25.5
		14	18-40	Bk1	60	5.5	34.5	Sand clay	10	20.9	1.6	23	0.2	73	2.2	18.2	26.6
		15	40-60	Bk2	48	21.5	30.5	Sand clay	25	18.3	0.7	24	0.1	73	2.3	17.8	39.5
		16	>60	C	72	9.5	18.5	Sandy loam	40	13.9	0.7	24	0.2	56	2.2	17.5	39.7
5. Typic Xerorthents	Canola	17	0-23	Ap	32	39	29	Clay loam	-	26	1.4	20	0.1	70	2.0	16.2	42.3
		18	23-53	Ck1	66	21	13	Sandy loam	40	22	1.3	22	0.1	66	2.1	15.6	40.2
		19	>53	Ck2	64	17	19	Sandy loam	70	12	0.7	24	0.1	56	2.1	15.6	48.2
6. Typic Calcixerepts	Canola	20	0-15	Ap	40	37	23	Loam	-	27.6	2.2	23	0.1	73	2.1	24.5	24.4
		21	15-40	Bw	38	33	29	Clay loam	5	20.6	0.7	24	0.1	66	2.2	18.5	32.2
		22	40-64	Bk1	40	29	31	Clay loam	7	19	0.6	24	0.1	64	2.2	16.8	44.7
		23	64-97	Bk2	47.5	23	29.5	Sand clay	20	19	0.4	24	0.3	64	2.4	16.8	44.7
7. Typic Haploxerepts	Canola	24	0-15	Ap	31.5	29	39.5	Clay loam	-	31	1.9	25	0.4	67	2.1	17.5	40
		25	15-42	Bw1	35.5	33	31.5	Clay loam	10	22	0.9	25	0.1	60	2.2	16.1	46
		26	42-75	Bw2	35.5	35	29.5	Clay loam	20	14	0.6	25	0.1	59	2.5	15.6	47.7
		27	>75	Bw3	39.5	31	29.5	Clay loam	55	15	0.4	25	0.1	57	2.6	15.7	47.7
8. Lithic Xerorthents	Canola	28	0-20	Ap	55.5	17	27.5	Sand clay loam	-	30	1.5	25	0.2	73	2.3	15.7	46
		29	20-55	Ck1	51.5	21	27.5	Sand clay loam	40	17	0.9	25	0.7	60	2.4	15.4	46
		30	55-95	Ck2	67.5	17	15.5	Sandy loam	60	12	0.5	25	3.4	60	2.6	14.7	56

CEC: Cation exchange capacity; OM: Organic matter; CCE: Calcium carbonate equivalent; SP: Saturation percentage; ρ: Specific gravity; Tenacity: Cohesion force; φ: Internal friction angle.

Table 2. Correlation coefficient between mechanical and some physico-chemical properties of soils in the studied profiles

	Tenacity	**φ (°)**	**OM (%)**	**Clay (%)**	**Depth**	**Sand (%)**	**$CaCO_3$ (%)**	**ρ (g cm^{-3})**	**CEC $cmol_{(+)}$ kg^{-1}**	**SP%**
Tenacity	1	-0.7^{**}	0.35^{*}	0.26^{ns}	-0.24^{ns}	$-0.27^{n.s}$	-0.15^{ns}	-0.37^{*}	0.26^{ns}	0.34^{ns}
φ (°)		1	-0.56^{**}	-0.1^{ns}	0.35^{*}	0.15^{ns}	0.38^{*}	0.56^{**}	-0.36^{*}	-0.62^{**}
OM (%)			1	0.22^{ns}	-0.6^{**}	0.08^{ns}	-0.36^{*}	-0.46^{*}	0.62^{**}	0.7^{**}
Clay (%)				1	-0.13^{ns}	-0.8^{**}	0.25^{ns}	-0.14^{ns}	0.33^{*}	0.17^{ns}
Depth					1	0.16^{ns}	0.27^{ns}	0.7^{**}	-0.54^{**}	-0.45^{*}
Sand (%)						1	-0.15^{ns}	0.23^{ns}	-0.34^{*}	0.02^{ns}
$CaCO_3$ (%)							1	0.49^{**}	-0.35^{ns}	-0.47^{**}
ρ								1	-0.46^{*}	-0.42^{*}
CEC									1	0.6^{**}

* and **: significant at 5% and 1% probability level, respectively; ns: not significant. CEC: Cation exchange capacity; OM: Organic matter; ρ: Specific gravity; Tenacity: Cohesion force; φ: Interna friction angle.

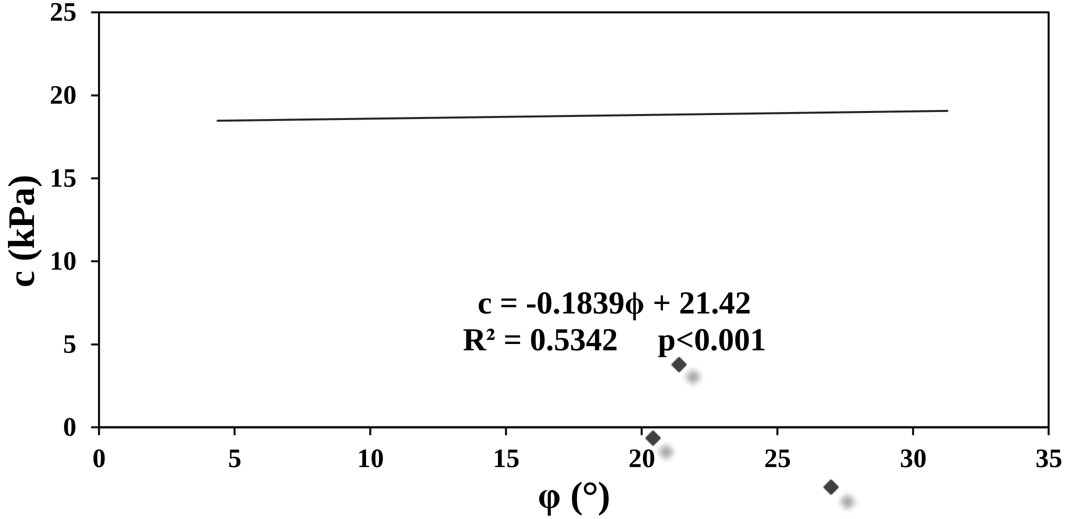

Fig. 3. The regression between soil cohesion (c, kPa) and the angle of internal friction (φ, °) the studied soils.

The mean comparison of specific characteristics in the soil horizons, including the angle of internal friction and soil cohesion, is shown in Fig. 4. As illustrated, cohesion is greater in the horizons with higher clay content and lower sand content. During sugar beet cultivation, the clay content was higher, significantly differing from the clay content observed in canola cultivation. In contrast, the sand content was greater in canola cultivation, with a significant difference compared to the sugar beet cultivation. However, this difference was not observed in profile 4. Additionally, a significant difference in organic matter content was noted between the profiles of the two crops, as shown in Fig. 4. The cohesion levels in the four profiles under sugar beet cultivation were higher and significantly different from those under canola cultivation. Despite this, no significant difference was found in the internal friction angle or moisture content when comparing the profiles. The results of shear stress in relation to horizontal displacement across all studied soil profiles are presented in Fig. 5. Vertical pressures ranging from 0 to 90 kPa were applied. Overall, shear stress values were higher in the sugar beet land use compared to canola land use, as shown in Fig. 5. With increasing soil depth, the percentage of saturated soil moisture decreased (see Table 2), while the amount of shear stress increased. This suggests that, under uniform applied stress, a higher initial suction rate in the soil corresponds to greater maximum shear resistance. As the soil sample becomes saturated, the shear stress value decreases. In other words, as the degree of saturation increases, the shear resistance of the soil diminishes. Furthermore, when soil moisture content exceeds a certain threshold, the cohesive force decreases as water content increases (Al-Shayea, 2001). Additionally, a higher degree of soil saturation leads to a decrease in the internal friction angle, as noted by Zangh et al. (2022). This negative correlation is also evident in Table 2. In all profiles, as soil depth increased and water content decreased, the amount of soil shear stress increased to some extent. Han et al. (2020) showed that shear stress increases with increasing shear displacement, particularly at lower water contents. Higher vertical pressure results in higher shear stress. In general, the cohesive force of soil is the result of cohesive forces between soil particles and is influenced by several factors, including van der Waals forces, cementation, osmotic pressure due to the concentration differences, the types of clay minerals present in the soil, Coulomb forces, and the adhesive forces of the water film (Al-Shayea, 2001).

Elasticity module

The modulus of elasticity for the samples was determined by creating a stress-strain diagram using Excel software and calculating the slope of these diagrams (Table 3). As shown in Table 3, the modulus of elasticity for the first four profiles (soils numbered 1 to 16) ranged from 26 to 66 kg cm^{-2}. In contrast, for soils numbered 17 to 30, the modulus of elasticity varied from 39 to 70 kg cm^{-2}. The highest modulus of elasticity was observed in soils with low organic content and greater depth. Entisols cultivated with canola exhibited higher modulus of elasticity values. This may be attributed to the abundance of canola plant residues and the relatively low moisture levels in these soils.

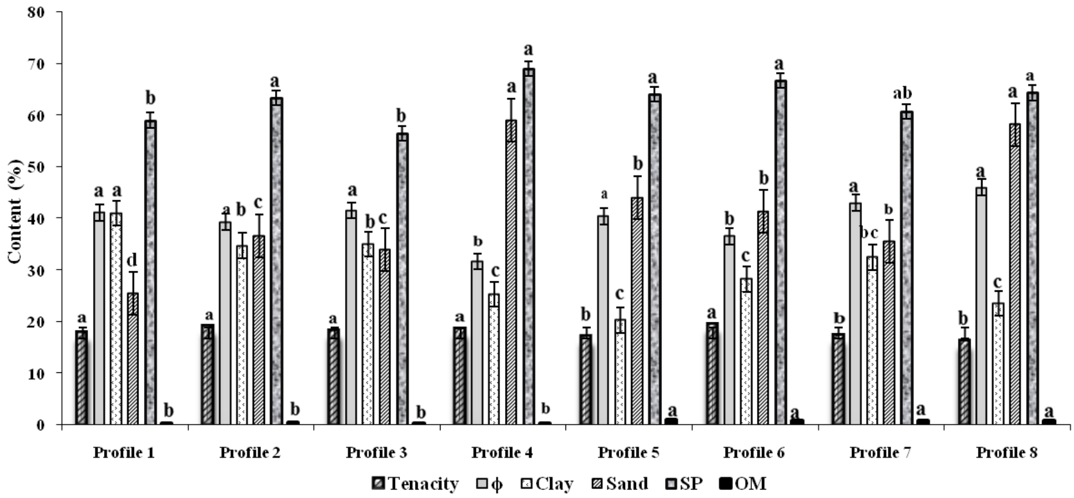

Fig. 4. Mean compression of some soil properties in different soil profiles. (ϕ: Internal friction angle; SP: Saturation percentage; OM: Organic matter).

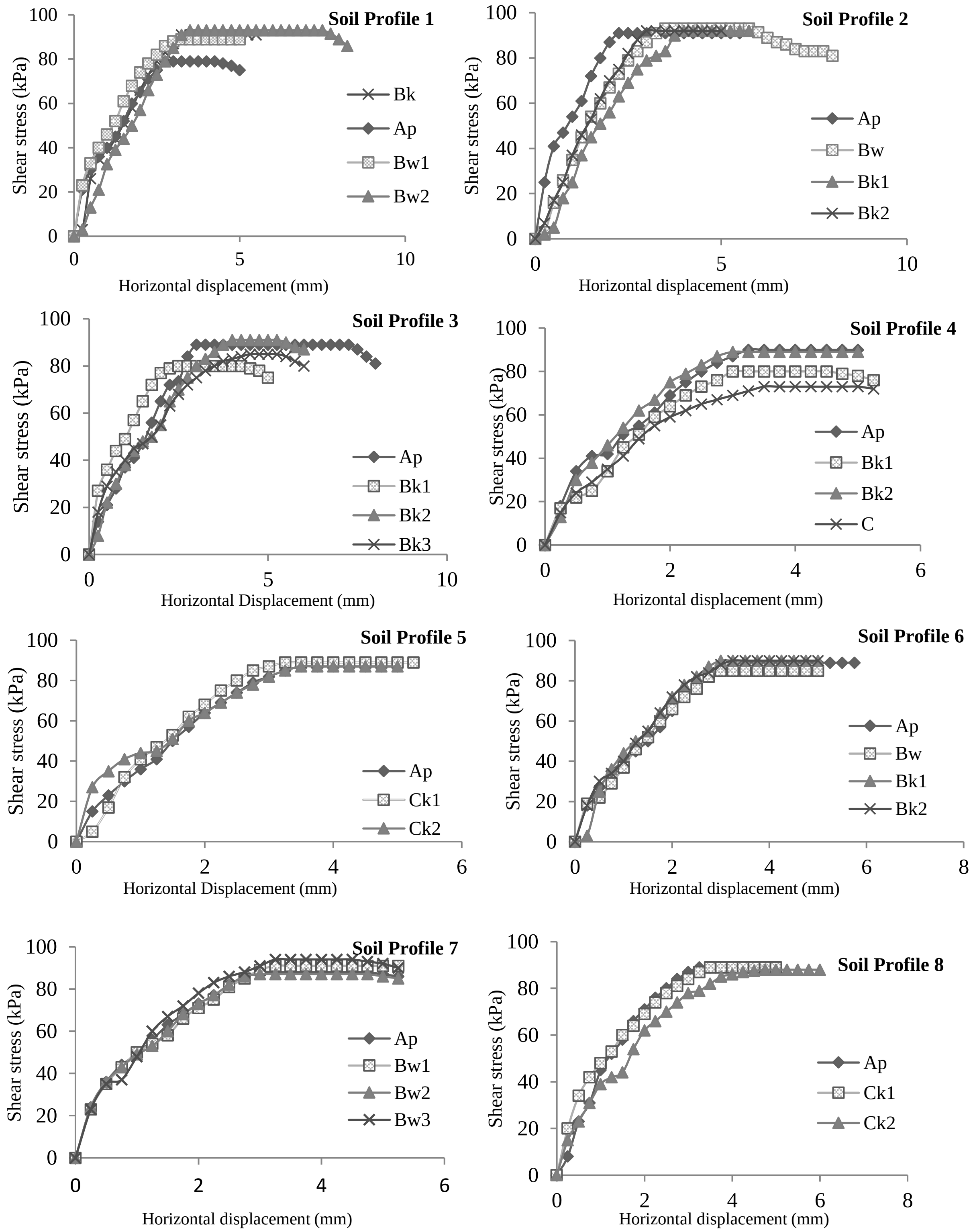

Fig. 5. The shear stress curves in terms of horizontal displacement against vertical stress in all soil profiles.

Table 3. Elasticity module of the studied soils

Soil No.	E Module (kg cm^{-2})	Soil No	E Module (kg cm^{-2})
1	53	17	43
2	57	18	56
3	27	19	40
4	51	20	56
5	63	21	44
6	36	22	59
7	16	23	45
8	34	24	39
9	36	25	43
10	56	26	64
11	42	27	58
12	46	28	56
13	46	29	56
14	44	30	66
15	52		
16	46		

The modulus of elasticity is defined as the slope of the stress-strain curve in the elastic region of a material's behavior. The results indicated that increased humidity and higher organic matter content enhance the soil's flexibility, thereby reducing the modulus of elasticity. Profiles 5, 7, and 8, which contain the highest sand content and exhibit minimal soil development, demonstrated the highest modulus of elasticity at 70 kg cm^{-2}. This suggests that less developed soils, when subjected to a canola cultivation system, exhibit higher modulus values in the desired test. Ka’ab Omeir et al. (2019) demonstrated that the addition of sand to a soil-calcium carbonate mixture moderately enhances both compressive strength and modulus of elasticity over three storage periods. However, the incorporation of fine and medium sand leads to a reduction in the strength and modulus of elasticity of the soil-calcium carbonate mixture. In general, the results indicated that both the type of cultivation and consistent cultivation practices influence changes in the cohesion and shear resistance of the soil. The presence of high root density in sugar beet may enhance shear strength due to the increased cohesion. Another study demonstrated that roots contribute to increased shear strength and enhance the internal friction angle by reducing cohesion (Khairuddin et al., 2017). Fattet et al. (2011) also showed that the resistance of soil aggregates in the surface layer is significantly influenced by the type of cultivation. Additionally, properties such as calcium carbonate equivalent, particle size distribution, and degree of development affect shear strength, with the highest resistance observed in Inceptisols compared to Entisols.

CONCLUSION

The primary conclusions of this study highlight that shear strength parameters, such as cohesion and the angle of internal friction, were measured in surface soils under sugar beet and canola cultivation. A negative correlation was observed between cohesion and friction angle in the soil data. These shear strength parameters were influenced by factors such as soil particle size distribution, moisture content, and bulk density. The type of land use was found to affect surface soil shear stress, with sugar beet cultivation exhibiting the lowest average sand and gravel content and the highest average clay content. This type of cultivation also showed the highest cohesion and the lowest friction angle. The highest soil elasticity modulus was observed in the canola cultivation profiles, which had the greatest moisture content, sand proportion, and bulk density, alongside the least soil development. The type of cultivation, plant root system, specific density, humidity, particle size distribution, and overall degree of soil development were found to significantly influence the shear strength and stress of the soil. Continuous canola cultivation, due to its direct root system, impacts soil cohesion and shear strength. However, to maintain soil health and avoid the detrimental effects of monoculture, it is advisable to incorporate a crop rotation system into agricultural practices.

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Conceptualization: Soheila Sadat Hashemi, Zahra Khedri., and Hanie Abbaslou; Methodology: Soheila Sadat Hashemi., and Zahra Khedri; Software: Soheila Sadat Hashemi, Zahra Khedri., and Hanie Abbaslou; Validation: Soheila Sadat Hashemi., and Zahra Khedri; Formal analysis: Soheila Sadat Hashemi, Zahra Khedri., and Hanie Abbaslou; Investigation: Soheila Sadat Hashemi., and Zahra Khedri; Resources: Soheila Sadat Hashemi., and Zahra Khedri; Data curation: Soheila Sadat Hashemi., and Zahra Khedri; Writing—original draft preparation: Soheila Sadat Hashemi; Writing—review and editing: Soheila Sadat Hashemi; Visualization: Soheila Sadat Hashemi; Supervision: Soheila Sadat Hashemi; Project administration: Soheila Sadat Hashemi; Funding acquisition: Soheila Sadat Hashemi, Zahra Khedri, and Hanie Abbaslou.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

The readers are encouraged to contact the corresponding author via email to gain access to the data used in this study.

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