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RESEARCH PAPER

Surface Shear Resistance of Dust Hotspot Soils on a Small Scale in Southwestern Iran

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Abstract
This research was conducted to quantify the direct and indirect effects of surface shear resistance (SSR) on dust hotspot soils in the southeast of Ahvaz city, Khuzestan, Iran. For this purpose, we measured certain parameters, including the mean weight diameter (MWD) of dry aggregates, particle size distribution (PSD), permanent wilting point percentage, soil moisture percentage, sodium absorption ratio (SAR), organic matter, calcium carbonate ($CaCO_3$), and soil electrical conductivity (EC). SSR was measured in 100 different locations of the field conditions using the modified shear device (MSD), specifically designed and manufactured to perform this project. The effects of soil properties on SSR were investigated employing path analysis and multi-linear regression approaches. SSR values (0.32-0.98 kPa) in the dust hotspot soils indicated that these soils are highly susceptible to wind erosion and have a high variability (4.26%). The best regression pedotransfer model accounted for 42% of SSR variations by soil estimating parameters. MWD and $CaCO_3$ were identified as the most sensitive parameters in SSR estimation in the dust hotspot soils in southwestern Iran. MWD and $CaCO_3$ (via PSD) showed the highest direct and indirect effects on SSR, respectively. In general, SAR on SSR represented no significant effects in this region due to high EC values.
Keywords*:* Wind erosion, Shear resistance, Dust, Shear device

Introduction

Surface shear resistance (SSR) is one of the most important soil properties used to predict soil susceptibility against wind shear force (Zhang et al., 2001). SSR is known as the best soil property for critical shear stress estimation. However, an accurate measurement of SSR and its relationship with the critical shear stress of wind requires consideration of the measurement scale (Wójciga *et al.,* 2009). Therefore, surface shear resistance, similar to soil surface roughness, is a function of scale. Römkens and Wang (1986) identified five scales for soil surface roughness, the smallest of which (<2 mm diam.) is controlled by soil particles. The largest scale of roughness (>10 cm diam.) is also controlled by agricultural activities and topographic roughness.

Since wind erosion affects soil surface without normal stress and in a state of unsaturated soil moisture, SSR measurements should be consistent with such conditions. Thus, the results of conventional SSR measurement methods, such as cone penetrometer, torsional shear boxes, and direct shear boxes, do not correspond to the reality. Accordingly, shear device (Wójciga et al., 2009) and modified direct shear apparatus (Zhang et al., 2018) have been presented for SSR laboratory measurement. Nevertheless, due to SSR variability, sample size, and measurement scale, the use of portable devices for obtaining the field data of soil resistance is more efficient (Wójciga et al., 2009).

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In several studies, the effect of soil properties on surface shear strength was investigated in areas prone to water erosion (Torri et al., 2013; Havaee et al., 2015; Farahani et al., 2020). These properties include particle size distribution (Yusefi et al., 2013), soil moisture (Knapen et al., 2007), soil structure (Baumgartl and Horn, 1991), the size and content of stones and gravel (Yusefi et al., 2013), vegetation cover and root system density (Torri et al., 2013), tillage system (Knapen et al., 2007), and CaCO3 content (Havaee et al., 2015; Khalilimoghadam et al., 2021). However, the effect of soil characteristics on SSR was less studied in areas prone to wind erosion.

A number of researchers have estimated SSR using pedotransfer functions (PTFs) from basic soil data, such as particle size distribution, bulk density, soil water content, and organic matter content, by multiple linear regression (Yusefi et al., 2013). SSR is significantly influenced by certain properties, such as soil water content, gravel, organic carbon, calcium carbonate content, and bulk density, in areas affected by wind erosion (Zhang et al., 2018; Poornazari et al., 2021). Researchers have also shown that soil water content and organic carbon (Wójciga et al., 2009) are two key parameters affecting SSR in areas susceptible to wind erosion. SSR is reduced with the increase in organic carbon; conversely, it decreases logarithmically with the rise in soil water content. Additionally, evidence has also indicated that certain parameters, like soil water content, gravel, calcium carbonate content, and bulk density, can be utilized to estimate SSR in areas sensitive to wind erosion (Wójciga et al., 2009; Zhang et al., 2018;).

Over the recent decades, dust storms have severely affected the health of the Iranian people, especially those in southwestern Iran (Abdoli et al., 2017; Khalilimoghadam and Bagheri-Bodaghabadi., 2020). The origin of these dust storms has been identified in Iran's western neighbors and southwestern Iran. The majority of the lands in this area have the smallest roughness class (<2 mm diam.). This area is susceptible to wind erosion due to flat, bare, loose, dry surfaces since most dust hotspot soils have limitations, such as salinity (5.2-103 dS/m) and SAR (1.2-91.1). Therefore, the growth of plants in dust hotspot soils has been restricted due to drought stress and toxicity effects of the elements, thereby decreasing the amount of soil organic matter. Climate change, successive droughts, and low rainfall have made the soil more susceptible to erosion. Understanding the susceptibility or resistance of dust hotspot soils to wind shear force and its contributing factors could be greatly conducive to understanding the process of soil erosion and dust control in southwestern Iran. Hence, to determine soil susceptibility to wind erosion, a portable device needs to be developed in this area so that SSR could be easily and quickly measured according to the field conditions (flat, bare, loose, dry). A few studies have been performed on SSR measurement in areas sensitive to wind erosion, and they have focused on laboratory measurements. To the best of the authors' knowledge, no studies have been conducted on SSR field measurements and the relevant influencing factors. Therefore, the present research was conducted in the dust hotspot soils of southwestern Iran (i) to determine SSR on a small scale in field conditions using Modified Shear Device (MSD) and (ii) to develop a model for estimating SSR in the saline, sodic soils.

Materials and Methods

General site description

The study site is located in the dust hotspot of southeastern Ahvaz, the southwest of Iran (45°30´ - 31°15´ N and 48°47´- 49°17´ E), with an area of approximately 112636 hectares (Fig. 1). According to the nearest rain gauge and synoptic station, the average precipitation, mean evaporation, along with the maximum and minimum long-term average temperature of the study site are 218 mm, 3000 mm, 27.7 ˚C, and 24.4 ˚C, respectively. The average annual precipitation shows a decreasing trend, and the average long-term annual temperature is estimated to be 26.6 ˚C. According to the De Martonne climatic method, this region has a hyper-hot dry climate. Due to climate change, drought, and land use change over the past decades, the dominant land use of this area is poor rangeland (> 75%) and its vegetation cover is less than 10% (Institute Research of Forests and Rangelands, 2017). The study area has two land types, namely River alluvial plain and low land with heavy soil texture, massive structure, and low permeability (Table 1). Most of the soils in this area, due to the shallow water table, have limited salinity and sodicity. Salt accumulates on the soil surface, and secondary salinization occurs because of the capillary rise and evaporation of water from the soil surface. The soils include *Typic Haplosalids*, *Aquic Haplosalids*, *Typic Torriorthents* (Soil Survey Staff, 2006), *Calcaric Regosols*, and *Haplic Solonchak* (World soil resources reports, 2006).

Table 1. Soil surface (<20 cm) properties of different land type and land unit in the study area

Land type	Land unit	Area (ha)	Texture	Soil permeability (cm h^{-1})	EC (dSm^{-1})	OM (%)	SAR	Vegetation cover (%)
5	5.1.1	190	C	<0.5	5.2	0.29	2.1	8
	5.1.2	214	L	6-12	19	0.25	53.6	10
	5.1.3	493	C	<0.5	35	0.38	105.2	5
	5.1.4	322	L	6-12	16	0.38	90.4	8
	5.1.5	954	CL	<0.5	35	0.30	61.7	8
	5.1.6	4946	CL	<0.5	50	0.32	41.5	8
	5.1.7	663	C	<0.5	75	0.34	73	8
	5.1.8	2230	L	6-12	79.5	0.27	1.2	8
	5.1.9	2669	CL	<0.5	62	0.40	65	5
	5.1.10	1755	CL	<0.5	15.5	0.43	52.1	5
	5.1.11	906	CL	<0.5	62	0.28	56.3	5
	5.1.12	638	SiL	0.5-6	21.5	0.30	15	5
	5.1.13	421	SiL	0.5-6	64.5	0.40	46	5
	5.1.14	1496	CL	<0.5	34.5	0.08	18	5
	5.1.15	1562	CL	<0.5	85	0.43	60	5
	5.1.16	1428	CL	<0.5	103	0.41	21	5
	5.1.17	5471	CL	<0.5	30	0.14	62.1	10
	5.2.1	2394	CL	<0.5	22	0.55	4.2	5
	5.2.2	13303	C and CL	<0.5	64	0.28	55.3	22
	5.2.3	675	CL	<0.5	75	0.28	38.7	5
	5.2.4	230	SiCL	<0.5	75	0.28	91.8	5
6	6.1.1	1107	CL	<0.5	95	0.29	28	10
	6.1.2	1855	CL	<0.5	43	0.36	65	8
	6.1.3	3137	SiCL	<0.5	21.5	0.27	4.1	8
	6.1.4	2379	CL	<0.5	28	0.57	48	8
	6.1.5	2065	L	6-12	97	0.23	66.6	13
	6.2.1	11667	CL	<0.5	78	0.40	21	25

5: River Alluvial plain; 5.1: Kupal river Alluvial plain with slope less than 0.02%; 5.2: Jarahi river Alluvial plain with slope less than 0.02%; 6: Low Land; 6.1: Sharifieh wetland with high salinity and no vegetatation cover; 6.2: Mansouri wetland with high salinity and halophyte cover

Experimental design

The study area was initially divided into several similar land unit tracts (LUTs). Each land unit had attributes sufficiently uniform and distinct from those of the neighboring areas (Abbasi, 2021). The maps of the land capability, wind erodibility, geology, topography, and land use were stratified using Arc GIS 9 software, and 27 land units (Abbasi, 2021) were produced (Fig. 1). In each land unit, at least three points were randomly selected, and a total of 100 locations were determined according to the level of each land unit. At each point, soil samples were taken from the soil surface (0-10 mm) in three replications, which were transferred to the laboratory. The sampling took place in the fall and winter of 2018.

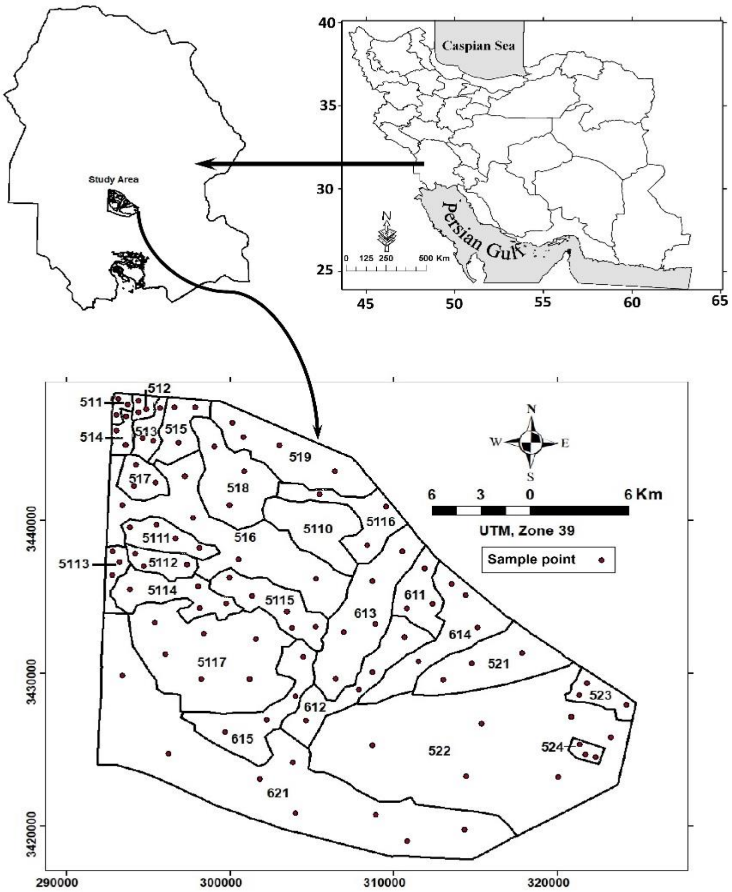

Figure 1. Location and the general landscape of the study area

Physicochemical attributes

Particle size distribution (PSD) was determined by sieving and sedimentation (Gee and Bauder, 1986), and aggregate stability was measured through dry sieving. Soil moisture percentage and moisture content at permanent wilting point (PWP) were measured employing the gravitational method and the pressure plate apparatus, respectively. Organic matter and calcium carbonate contents were investigated with the Walkley – Black procedure (Nelson and Sommers, 1986) and titration with NaOH (Nelson, 1982), respectively. Acidity reaction was utilized by a glass electrode in a water-saturated paste, and an electrical conductivity (EC) meter was used to measure electrical conductivity in a soil-saturated extract. Sodium adsorption ratio (SAR) was calculated via the standard method (Page et al., 1986).

Modified Shear Device (MSD)

Due to the spatial and temporal variations in SSR, it is necessary to measure SSR under natural conditions in the field. Therefore, the Modified Shear Device (MSD) was designed and manufactured based on the Wójciga shear device (Wójciga et al., 2009). Through the use of MSD, we measured SSR under field conditions on a small scale. The MSD set (Fig. 2) includes framework, shear container (with abrasive material), balance (force measurement), transparent perspex plate, handwheel, spring and winding cord, and display cable. The shear container (Ø = 68 mm) was placed in a special place on the transparent perspex plate so that the sandpaper (P-40) adhered to the bottom of the container could be placed on the top of the soil. The spring and winding cord connected to the balance and the transparent perspex plate were used to rotate the handwheel slowly (up to a maximum of 1 turn/sec) in order to move the transparent perspex plate into the special rail. This balance logged the maximum applied force until the movement of shear container for 5 seconds.

The sandpaper created friction in contact with the soil surface (2 mm), depending on the soil properties. The force applied to this movement was the friction force between the soil and the sandpaper, which was recorded by the balance and transferred to the laptop via a USB cable. The data were recorded at 0.01s intervals via the MSD set. Surface shear resistance (SSR) values were calculated using the Ordenio-defined software. Since the normal stress is negligible during wind erosion, the vertical load was not applied to the shear container. The sandpaper was considered as the wind stress applied to the soil surface, and the adhesion between the sandpaper and the soil (<2 mm diam.) was measured as the surface-shear resistance on a small scale. Accordingly, the SSR of the soils tested (S, kPa) was calculated using Equation 1.

$$S = \frac{F_C}{A} \tag{1}$$

where F_c denotes the maximum shear stress recorded by balance and A represents the cross-sectional area.

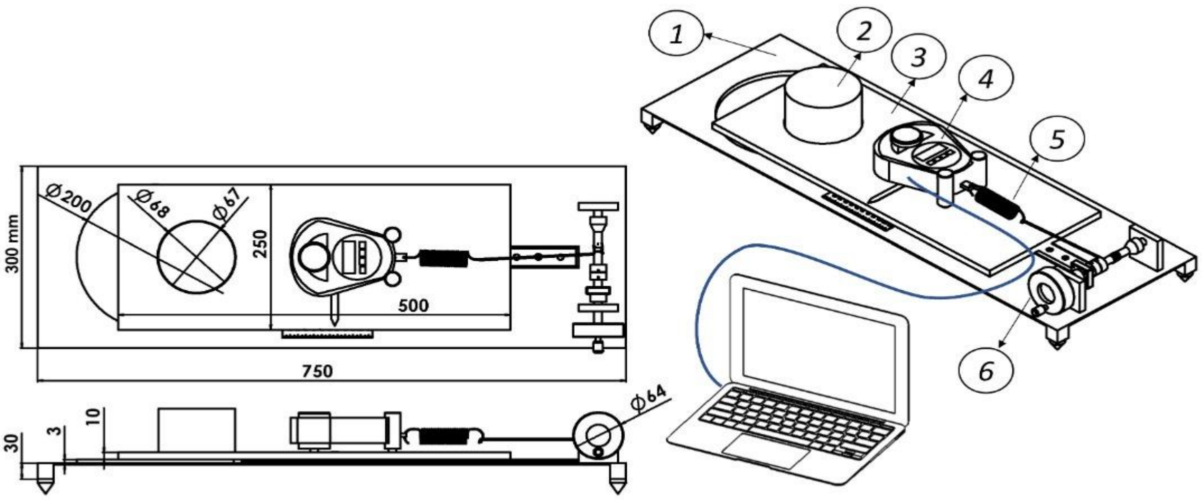

Figure 2. Schematic view of the Modified Shear Device (MSD) and the insertion of the device and sediment collection. 1) Framework; 2) Shear container (with abrasive material); 3) Transparent perspex plate; 4) Balance; 5) Spring and winding cord; 6) Handwheel

Statistical analyses

In this study, the descriptive statistics, mean, minimum, maximum, and standard deviation related to soil properties versus SSR were specified using SPSS version 16 software. The stepwise multiple regression (MLR) method was applied for the stabilization of regression pedotransfer functions (PTFs) of the independent variables (organic matter, calcium carbonate, electrical conductivity, sodium absorption ratio, clay contents, silt and fraction, soil moisture, constant wilting point, and aggregate mean weight diameter) versus the dependent variable (SSR). The data were statistically normalized with the Kolmogorov–Smirnov (K–S) test in Minitab software and logx transformation. Subsequently, the outliers were eliminated, and regression equations between the independent (x) and dependent (y) variables were established. Coefficients of determination (R^2) and root mean square error (RMSE) were utilized for evaluation of the equations, and the equation with the largest correlation ($0 \leq R^2 \leq 100$) and the smallest mean squared error (the highest correlation and the least error) was selected as the most appropriate one. All the predictor variables in the regression models were used for path analysis. The path analysis method was employed in order to determine the share of the direct and indirect effects of an independent variable on the dependent variable. The path models described had an error or a residual term for each variable. This error reflects the effects of extraneous variables that do not exist in the model and represents the portion of the variance of the dependent variables, which is unexplained (Rougoor et al., 1997), as given by ($1 - R^2$).

Results and Discussion

Soil properties

Table 2 depicts the statistical summary of the studied soil properties. The results demonstrated that among the soil chemical properties, sodium absorption ratio has the highest coefficient of variation (47%) compared to the other properties. The mean values of soil electrical conductivity (70.68 dS/m) and sodium adsorption ratio (98.28) indicated the salinity and sodicity of these soils. The salinity is due to the existence of soluble chemicals in the two formations of Mishan and Gachsaran in the study area. Moreover, the shallow water table in some areas has caused high solubility chemicals, such as sodium chloride, to accumulate on the soil surface due to the evaporation process. The average organic matter in the soils (0.34%) implied that these soils are poor in organic matter. Soil salinity and drought stress inhibit the growth of plants and the activity of soil organisms, thereby reducing soil organic matter. Furthermore, the percentage of $CaCO_3$ was found to have a wide range, with its maximum and minimum being 51.5 and 9%, respectively. The average amount of $CaCO_3$ in the region was 19.65%, showing that these soils are calcareous. Soil pH showed the least variability compared to the other parameters, ranging from 6.82 to 8.2. The results of soil physical and mechanical properties showed that SSR was 0.32-0.98 kPa in the study area and that the soil was highly sensitive to wind erosion (Fig. 3). The highest and lowest coefficient of variation belonged to SSR (4.26%) and the mean weight and diameter (0.196), respectively. The predominant textures of the soil were loam and sandy loam, and among the soil particle components, the highest variability belonged to sand particles (Saeedavi et al., 2017; Karami et al., 2018)

Table 2. Summary of statistics (maximum, minimum, mean and coefficient of variations, CV) for soil properties

Property	Minimum	Maximum	Mean	SD	CV
SAR	7.98	227	98.28	68.34	47.53
OM (%)	0.01	0.82	0.34	0.19	0.1
$CaCO_3$(%)	9	51.5	19.65	6.25	1.98
EC(dSm^{-1})	1.8	134	70.68	33.83	16.19
pH	6.82	8.2	7.4	0.27	0.01
sand(%)	13.5	66.5	43.26	10.23	2.42
silt(%)	7	61	37	8.49	1.94
clay(%)	9	51.5	19.65	6.25	1.98
MWD(mm)	2.14	6.68	4.63	0.95	0.196
PWP(%)	6.01	24.02	15.62	4.24	1.15
SM(%)	2.86	7.91	4.78	1.08	0.24
SSR(hPa)	32.2	98.5	55.28	15.34	4.26

SSR: surface shear resistance, MWD: mean weight diameter of dry aggregate,SAR: sodium absorption ratio, OM; organic matter, EC: electrical conductivity, PWP: permanent wilting point, SM: Soil moisture

Figure 3. A view of the study area (Institute Research of Forests and Rangelands, 2017) showing the general landscape and vegetation cover in the rangeland (September 2018)

Regression pedotransfer functions

Both of the data normality distribution (dependent variable: SSR) and the independence of the errors (the difference between the real values and those predicted via the regression equation) are the multiple regression assumptions. The logarithm transform was used to normalize SSR in view of its abnormal distribution. The Durbin-Watson test was also utilized to detect the presence of autocorrelation. If the value of this statistic is in the range of 1.5 to 2.5, there is a discrepancy between the errors and the possibility of using linear regression. SSR had the value of 1.75. The variance inflation factor (VIF) and the tolerance factor were used to investigate the assumption of the alignment of independent variables in linear regression (Table 3). The lower the tolerance, the lower the variance of the regression coefficients of the variables; the regression method is thus inadequate. There is a close relationship between the VIF factor and tolerance. As the VIF factor increases, the variance of the regression coefficients rises and the regression estimation is inadequate. A tolerance of less than 0.1 and a VIF factor greater than 10 indicate a lower likelihood of linearization. The obtained results revealed that the values of VIF and tolerance for all the independent variables were in the range of 1.05 to 1.52 and 0.657 to 0.950, respectively (Table 3). The distribution of errors (the third assumption) was approximately normal, the mean value presented was very small (approximately zero), and the standard deviation was near one, which confims that the regression can be used.

Table 3. Evaluation criteria of multicollinearity among the predictor variables

Index	Property								
	EC	$CaCO_3$	OM	SAR	SM	PWP	Clay	Sand	MWD
Variance Inflation Factor (VIF)	1.28	1.18	1.09	1.36	1.09	1.05	1.52	1.51	1.21
Tolerance	0.77	0.84	0.91	0.73	0.91	0.95	0.65	0.66	0.82

Correlation coefficient between the independent and dependent variable(s)

Table 4 exhibits the values of the Pearson's linear correlation coefficient between different soil variables. Our findings showed that among the independent variables, aggregate mean weight diameter, silt percentage, soil moisture percentage, organic matter, salinity, sodium absorption ratio, and calcium carbonate had a positive effect on the dependent variable (SSR). Meanwhile, variables like sand percentage, clay percentage, and permanent wilting point percentage had a negative effect on the dependent variable (SSR). Among the independent variables studied, only the parameters of aggregate mean weight diameter and calcium carbonate showed a significant effect ($P<0.01$) on SSR. In fact, due to the low organic matter content and the high percentage of sodium absorption ratio in the soils studied, which reduces the effect of organic matter on aggregation, this parameter did not have a significant effect on SSR. Ekwue (1990) stated that soils containing less organic matter were more susceptible to degradation and dispersion, resulting in lower SSR in these soils. However, the high percentage of calcium carbonate in these soils makes both aggregation and cementation increase the resistance of soil particles to wind shear force. Furthermore, soil calcium carbonate had a significantly positive effect on the aggregate mean weight diameter and increased with the rise in the amount of calcium carbonate. The findings reported by other researchers, such as Zhang et al. (2018) and Nikokar et al. (2016), are consistent with those of this study. Zhang et al. (2018) reported a significant positive correlation ($R^2 = 0.447$, $p < 0.05$) between SSR and calcium carbonate content of soil. Mirmozen et al. (2013) found that by adding calcium carbonate to soil containing 85% organic matter, soil shear strength improved. Their results showed that adding 3 and 6% calcium carbonate to soil increased soil cohesion and calcium carbonate-stabilized soil comapred to the control (non-stabilized) soil by 300 and 450%, respectively. Nevertheless, Nikokar et al. (2016) used 3, 6, 9, 12, and 15% calcium carbonate over 7, 14, 28, and 90 days for the restoration of pith soils and found that the optimum amount of calcium carbonate for the stabilization of these soils is between 9 and 12%.

Soil salinity had a minor but positive effect on SSR. Qajar and Hemmat (2014) investigated the effect of salinity stress on soil shear strength at three salinity levels of 4, 9, and 14 dS/m. In agreement with the present study, they reported that with an increase in salinity from 4 to 9 dS/m, soil cohesion decreased, but with an increase in salinity from 9 to 13 dS/m, soil cohesion rose significantly.

Table 4. Variance–covariance matrix of inputs and outputs dataset

Variables	SSR	MWD	Sand	Silt	Clay	PWP	SM	SAR	OM	$CaCO_3$	EC
SSR	1	**0.6	0.019-٠	0.064	0.056-	0.009-	0.026	0.118	0.148	**0.37	0.05
(mm) WD		1	0.193-	0.147	0.015	0.045	0.156	0.11	0.015	**0.342	0.036
(%)Sand			1	**0.793-	**0.56-	0.047	-0.041	-0.033	0.035	-0.103	-0.007
(%)Silt				1	0.061-	-0.013	-0.016	-0.038	0.018	0.124	-0.008
(%)Clay					1	-0.06	0.089	0.106	-0.082	0.001	0.022
(%)PWP						1	-0.137	0.064	-0.048	-0.071	-0.051
(%)SM							1	-0.053	0.143	0.067	0.036
SAR								1	**0.205	0.087	**0.437
(%)OM									1	0.056	0.116
(%)$CaCO_3$										1	0.091
EC(dSm^{-1})											1

Significance levels: *, $p < 0.05$; **, $p < 0.01$

Model developing

To investigate the effect of the independent variables on SSR and develop different regression models, the independent variables were divided into seven groups. Table 5 presents different types of regression models between the independent variables and SSR. The results showed that Model 1 has the highest R^2 among the other models with the following variables: aggregate mean weight diameter, sand percentage, clay percentage, permanent wilting point percentage, soil moisture percentage, SAR, organic matter, calcium carbonate, and soil electrical conductivity. R^2 and MSE for this model were 0.426 and 0.0084, respectively. As the number of independent variables decreased from Model 1 to 7, the R^2 of the models decreased. With the deletion of the aggregate mean weight diameter parameter, there was a sharp decrease in R^2 in the regression models, and this coefficient decreased from 0.383 to 0.017. Fig. 4 illustrates the comparison between the measured and the estimated soil SSR.

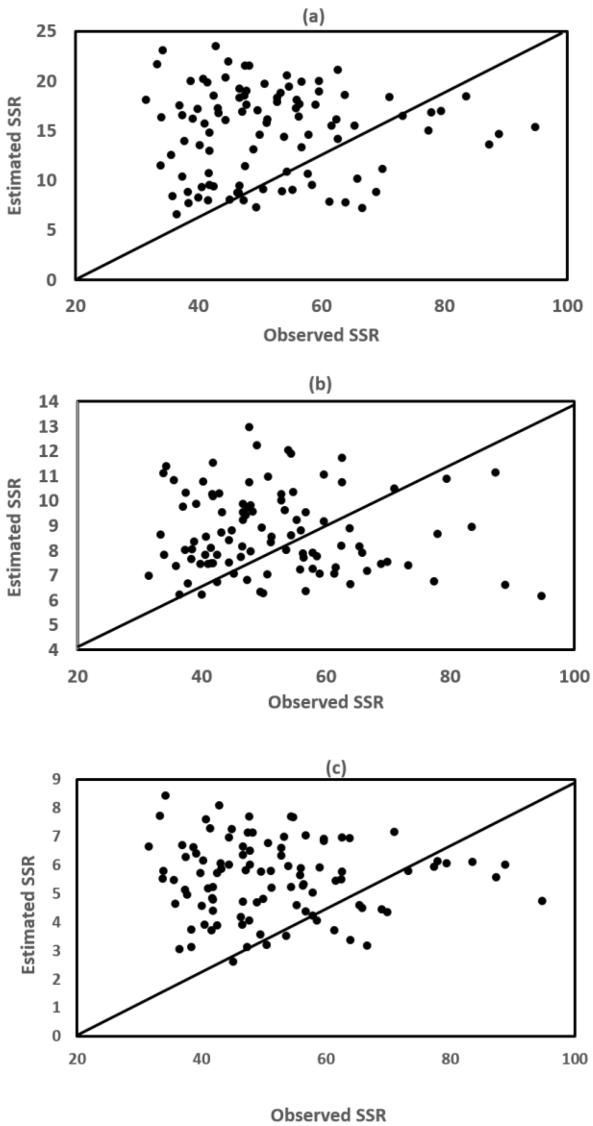

Figure 4. This figure shows the comparison between the measured and estimated soil surface shear resistance of Model 1(a), Model 2(b) and Model 3(c)

The mean weight diameter aggregate and calcium carbonate percentage had the most positive effect on SSR. In fact, as the aggregate stability increases, soil resistance to shear stress and soil failure threshold rise, resulting in a decrease in soil erodibility. The greater the mean weight diameter and the stability aggregate, the greater the random roughness at the soil surface, and the severity of the wind erosion is reduced due to the effect of roughness on the reduction of wind velocity. Research has indicated that surface aggregates play an important role in controlling random roughness (Li et al., 2003; Six et al., 2001). Since soil surface aggregate reduces wind velocity to a significant degree above the ground level, any changes in random roughness makes a significant difference in wind erosion severity (Zhang et al., 2001). Mahmood Abadi et al. (2011) stated that with increased soil aggregate size, resistance to soil particle detachment is enhanced due to particle weight force; thus, erodibility decreases.

Consequently, wind velocity at soil contact surface is significantly reduced, as a result of which wind erosivity declines.

Despite high SAR (a mean of 98.2) in the studied soils, it had a small but positive effect on SSR. In fact, with the growth in sodium absorption ratio, the surface crust formation in soils increased, which resulted in a rise in soil resistance to stresses. As the SAR increased, soil salinity increased as well. As the salinity and concentration of soluble chemicals in the soil increase, the dispersant effect of high sodium concentration decline, and chemicals act as a cementing agent and enhance aggregation and soil resistance to mechanical stress. In arid regions, due to the lack of organic matter and weak soil structure, less stable and coarse aggregates remain on the surface of these soils. These conditions exacerbate erosion in these areas; nonetheless, with appropriate surface soil management, dust could be significantly controlled in these areas.

Calcium carbonate is also an important factor affecting shear strength and soil erosion in arid regions (Mossadeghi et al., 2006). It increases bond formation between soil particles (Chou et al., 2011 and Chu et al., 2012), thereby increasing the resistance (Al Qabany and Soga, 2013) and hardness (Mortensen et al., 2011) of soil aggregates.

Soil moisture was also inversely proportional to SSR, and SSR decreased with the increase in soil moisture content. Similarly, Sharma and Bora (2003) reported a reverse relationship between soil moisture and soil shear strength. However, Zhang et al. (2018) found that as soil moisture increased, SSR was logarithmically reduced. The relationship between soil water content and shear strength is negative and significant (Sadek et al., 2011; Ferreira et al., 2015; Zydron et al., 2016) and has been reported positive in some cases (Luk and Hamilton, 1986). The results herein showed that when the soil moisture content is low, the surface tension of the water between the soil particles is maximized, and as a result, the SSR increases. Nonetheless, as soil water content rises, chemicals and other cementation materials are washed between the soil particles, and surface shear strength (SSS) is reduced (Zhang et al., 2018); moreover, water acts as a lubricant and reduces the cohesion between the soil particles. In agreement with the present study, Wójciga et al. (2009) stated that there is a nonlinear relationship between soil moisture and SSS. Therefore, air-dried soil samples had the lowest SSS, but with increased soil moisture, SSS increased gradually, peaking at a certain percentage of moisture and then gradually decreasing with the increase in SSS moisture.

The soil moisture regimen studied is mainly aridic and the soil thermal regimen is hyperthermic; hence, the study area is highly susceptible to wind erosion. In the study area, due to detachment after rainfall, crust is formed on the soil surface, which has high shear resistance and is a natural barrier to dust production. If this crust breaks, the dust source becomes active (Fig. 3). Thus, livestock should be prevented from entering these areas to inhibit crust loss.

Organic matter showed a positive effect on the SSR of the soils studied. Research has shown that organic matter has different effects on SSS. Some researchers have argued that organic matter increases SSS due to the increased adhesion force between soil particles (Rachman et al., 2003). Conversely, others have suggested that organic matter may decrease surface shear strength on account of increased soil porosity (Horn and Fleige, 2003). Moreover, organic matter, by increasing soil water retention, binds to further soil particles through surface tension and increases the adhesion strength of soil particles (Khaboushan et al., 2018). Other researchers' findings are consistent with those of this study. Soane (1990) and Arthur et al. (2013) stated that the effect of organic matter on soil mechanical properties depends on soil type, soil water content, soil porosity, as well as the type and decomposition condition of organic matter. In addition, Ekwue (1990) found that grassland organic matter significantly increased soil surface shear strength while organic matter derived from peat had the opposite effect.

Table 5. Performance of different Multiple Linear Regression (MLR) models(1-7) in predicting SSR(surface shear resistance)

Dependent Variable	Model	Independent Variable										Evaluation criteria	
		Intercept	MWD	Sand	Clay	PWP	SM	SAR	OM	$CaCO_3$	EC	R^2	MSE
SSR	1	1.50	0.55	0.04	-0.06	-0.05	-0.07	0.05	0.11	0.15	0.05	0.43	0.008
	2	1.50	0.57	-	-	-0.04	-0.07	-0.01	0.12	0.15	0.05	0.42	0.008
	3	1.54	0.62	-	-	-0.06	-0.08	0.01	0.12	-	0.02	0.40	0.008
	4	1.56	0.62	-	-	-0.06	-0.06	0.04	-	-	0.03	0.38	0.008
	5	1.68	-	-	-	-0.02	0.05	0.12	-	-	0.01	0.02	0.013
	6	1.69	-	-	-	-0.02	0.04	-	-	-	0.06	0.01	0.013
	7	1.71	-	-	-	-0.02	0.04	-	-	-	-	0.01	0.013

Model 1: Variables (MWD, sand, clay, PWP, SM, SAR, OM, CaCO3, EC); Model 2: Variables (MWD, PWP, SM, SAR, OM, Caco3, EC); Model 3: Variables (MWD, PWP, SM, SAR, OM, EC); Model 4: Variables (MWD, PWP, SM, SAR, EC); Model 5: Variables (PWP, SM, SAR, EC); Model 6: Variables (PWP, SM, EC); Model 7: Variables (PWP, SM)

Table 6. Path analysis direct effects and indirect effects for variables in predicting SSR(surface shear resistance)

Variables	r_p	Direct effect	Indirect effect									
			1	2	3	4	5	6	7	8	9	10
MWD (mm)	0.61	0.60	-	0.41	-0.28	-0.17	-0.001	-0.001	0.002	0.001	0.005	0.001
Sand(%)	-0.02	0.02	-0.11	-	0.14	0.82	-0.001	0.004	-0.007	0.006	-0.016	0.001
Silt(%)	0.06	0.018	0.09	1.74	-	0.08	0.002	0.002	-0.001	0.003	0.019	0.001
Clay(%)	-0.06	-0.001	0.072	1.23	0.11	-	0.001	-0.008	0.002	-0.012	-	0.001
PWP(%)	-0.01	-0.02	0.024	-0.11	0.019	0.087	-	0.003	0.001	-0.007	-0.011	0.001
SM(%)	0.03	-0.09	0.096	0.088	0.037	-0.13	0.003	-	-0.001	0.02	0.011	0.001
SAR	0.12	0.023	0.066	0.066	0.075	-0.16	-0.001	.0050	-	0.03	0.014	0.001
OM(%)	0.15	0.15	0.006	-0.088	-0.037	0.11	0.001	-0.013	0.004	-	0.01	0.001
$CaCO_3$(%)	0.37	0.16	0.20	0.22	-0.22	0.001	0.002	-0.006	0.002	0.009	-	0.001
EC(dSm^{-1})	0.05	0.001	0.024	0.022	0.018	-0.03	0.001	-0.004	0.01	0.001	-0.014	-
Residual							0.52					

Path analysis

More accurate and reliable information could be provided by examining the direct and indirect effects of parameters through path analysis and its interpretation; meanwhile, based on regression and correlation analysis, it is not possible to introduce an appropriate index. If the correlation between the dependent variable and an independent one is due to its direct effect, a real relationship exists between them. Therefore, the independent variable can be selected so that the dependent variable be estimated. However, if this correlation is due to the indirect effect of the variable through another independent variable, the selection operation must be performed on the variable that caused the indirect effect.

Table 6 demonstrates the results of path analysis variables affecting SSR. The mean weight diameter of aggregate and sand percentage had the highest positive direct effect (0.6) and the highest negative direct effect (-2.2) on SSR, respectively. The most positive indirect effect on SSR was silt percentage (1.74) through sand percentage whereas the highest indirect negative effect was calcium carbonate through sand percentage. Furthermore, the least positive direct effect on SSR was soil salinity and the lowest negative direct effect was permanent wilting point. In addition, the least positive indirect effect on soil SSR was the percentage of clay through soil calcium carbonate while the least negative direct effect was the percentage of sand and silt through soil salinity.

Conclusion

In this study, the effects of different soil physicochemical properties on surface shear resistance (SSR) of dust hotspot soils in saline and sodic soils were investigated. Aggregate mean weight diameter and percentage of calcium carbonate had a significant and positive correlation with SSR. Aggregate mean weight diameter, sand percentage, clay percentage, organic matter percentage, soil moisture percentage, calcium carbonate percentage, sodium adsorption ratio, and soil salinity accounted for 42% of SSR changes, and 60% of SSR changes depended on other variables that were not examined in this study. Moreover, despite the high percentage of salinity and sodicity, the soils studied did not have a significant effect on SSR due to the neutralizing effect of the parameters interaction. However, a high percentage of calcium carbonate in soils (an average of 20%) had a significant effect on SSR both directly and through the influence of other independent variables. The highest positive direct effect on SSR belonged to aggregate mean weight diameter whereas soil texture had the highest negative direct effect. In addition to its effect on soil texture, calcium carbonate had a bigger indirect effect on SSR compared to its direct effect. The percentage of calcium carbonate in the soil, compared to other variables, showed the most indirect effect on SSR by affecting aggregate mean weight diameter. In general, on account of the considerable influence of aggregate mean weight diameter on increasing soil SSR, one of the effective strategies for controlling wind erosion in southwestern Iran is, vegetation cover restoration and enhancing organic matter. This minimizes the severity of erosion in dust hotspots by influencing soil aggregate size distribution and creating random roughness at the surface.

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