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Evaluation and Comparison of Physical and Hydraulic Properties in Different Soil Structures

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ABSTRACT

Physical properties and various compounds of soil structure are reflected in different soil properties which affect the hydraulic properties of soil and consequently the flow of water and movement of contaminants. Therefore, this study was conducted to measure physical and hydraulic properties in different structures of Silakhore Bala plain located in Lorestan province of Iran. The study was conducted under laboratory conditions on nine undisturbed soil columns with three different structures of granular, blocky and massive with three replications for each column in a completely randomised design with different structures of the soil as the main factor. Physical parameters like soil particle size distribution, bulk density, total porosity, mean weight diameter and also hydraulic parameters like saturated and unsaturated hydraulic conductivity and the number of water-conducting active pores in each column were measured. Chemical properties including organic matter content were measured too in different soil samples. The results showed that soil structure had a significant effect on physical and hydraulic parameters. Due to higher organic matter content, porosity and stability of the structure, granular soils had the highest value of for saturated and unsaturated hydraulic conductivity compared to blocky and massive structures. Soils with massive structure had the weakest structure in terms of physical and hydraulic properties.

Keywords: Bulk density, hydraulic conductivity, mean weight diameter.

INTRODUCTION

Soil structure has important effects on different soil properties and these affect its performance in the environment. Soil structure cannot be considered as a direct component of plant growth but should be considered among the characteristics that are effective in plant growth factors. Robot *et al.* (2018) state that soil structure controls several soil processes such as water infiltration and storage, gas exchange, organic matter, soil nutrients, root penetration and erosion potential. Soil structure also serves as a habitat for thousands of living organisms whose variety and activities is dependent on soil structure. Researchers such as Horn *et al.* (1994), Kodešova *et al*. (2009; 2011) carried out studies on hydraulic and physical properties affecting soil structure. Soil structure affects the physical and hydraulic properties of the soil (Mohawesh *et al.* 2017). Physical properties of

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the different soil structures have an important role in the movement of water and the transport of solution which in turn affect the hydraulic properties of the soil. The formation of soil aggregates results in numerous active water-conducting pores. These pores lead to a preferential pathway of water movement in the soil and consequently alter its hydraulic properties (Jiang and Shao 2014). Karahan and Erşahin (2016) state that minor changes in soil structure have a significant effect on saturated hydraulic conductivity, which in turn is strongly controlled by soil pores (geometry, size, and direction of the pores). Soil structure significantly affects the flow of water and the transport of pollutants in the soil. Activities such as soil compaction and intensive ploughing can affect soil quality resulting in the destruction of soil structure, leading to undesirable effects on soil fertility. Therefore, it is necessary to study physical and hydraulic properties of soils in order to apply appropriate management methods on different types of soil. The purpose of this study was to investigate and compare physical and hydraulic properties of different soil structures under laboratory conditions.

MATERIALS AND METHODS

Description of Study Area

The study area was the Bayatan Village of Borujerd County in Silakhore Bala plain within the Lorestan Province of Iran. This region was chosen because of the existence of three different types of structures recognisable at different depths, but having the same climate, parent materials, and texture. Therefore, physical and hydraulic properties of the different soil structures under similar conditions were compared and evaluated quantitatively. Bayatan is located at latitude 34 ° 4' N, longitude 48 ° 39' E of Iran (Figure 1)

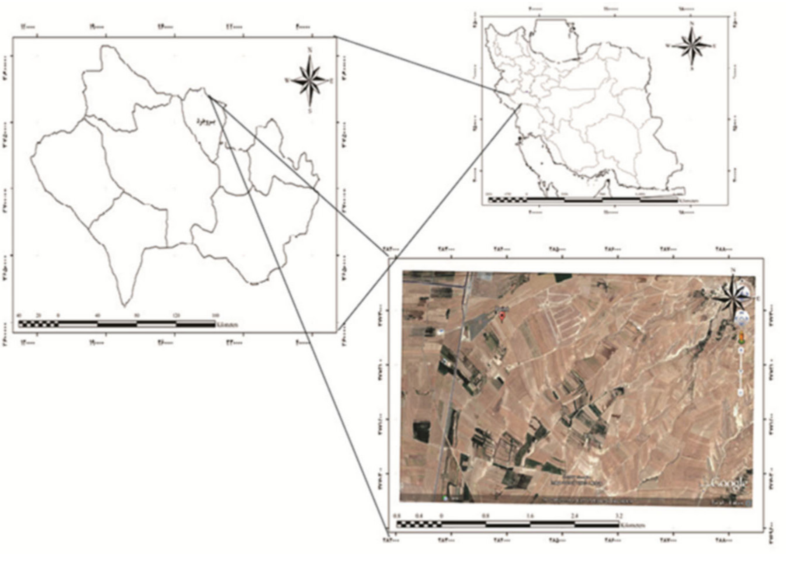

Fig. 1: Location of studied area in Lorestan- Iran

The study area has relatively cold winters and mild summers with annual precipitation and temperature of 664.09 mm (Xeric moisture regime) and 16.4°C (Mesic temperature regime), respectively. In the International Classification, the Bayatan soil series are classified as Inceptisol soils, the great group of Xerochrepts and the CalciXerollic Xerochrepts subgroup, with its counterpart class in FAO system being Calcic Cambisols.

Implementation Method

The study was conducted under laboratory conditions on nine undisturbed soil columns with three different structures namely: granular, blocky and massive with three replications for each column in a completely randomised design with different structures of the soil as the main factor. Different samples were labeled as G1, G2, G_3, B_1, B_2, B_3 and M_1, M_2, M_3. G, B and M to indicate Granular, Blocky and Massive structures respectively, and each of their subscript number represents the number of soil samples. The sampling of granular, blocky and massive structures was done from 0 to 25 cm, 25 to 50 cm and 50 to 75 cm depths respectively in the sampling area. Statistical analysis was performed using Generalized Linear Model in SAS (ver. 9.4) while mean comparison was performed using Duncan's test at a 0.05 level of significance (P <0.05). The effects of soil structure on the physical and hydraulic properties were investigated and compared.

Sampling and Preparation of Undisturbed Columns

First, the soil profile was dug to a depth of 100cm in the field, and the depth of each layer and soil structure was determined. In order to compare the physical and hydraulic properties of different soil structures under the same conditions, samples from different depths and parts of the region were kept intact. Thick polyethylene columns of 3 mm size with an inner diameter of 25 cm and a uniform height of 25 cm were established. Before the sampling, the inner wall of the columns was stained with paraffin to (i) prevent the formation of preferential flow in the soil and column surface and (ii) reduce the preferential flow between the soil and the inner wall of the column during sampling. In order to prevent soil from falling, the opening of the columns was covered with a net. The columns were transferred to the laboratory and placed on an assembly mounted on a metal tripod (Figure 2).

Measurement of Hydraulic Properties

The hydraulic properties of various soil structures were measured by a diskin filtrometer device (Soil Measurement Systems LLC, TUCSON, ARIZONA 85704 USA) that had a diameter of 20cm and matric suction of 14, 10, 4 and 1 cm. Saturated hydraulic conductivity (K_s), unsaturated hydraulic conductivity (K_h), number of water-conducting active pores (N)(average number of pores per unit area (N) in two classes of pore size: macropore (0.375 mm< radius) and mesopore (0.107<radius < 0.375 mm)) were measured based on equations previously developed (Gardner 1958; Wooding1968; Watson and Luxmoore 1986; Ankeny *et al*.1991).

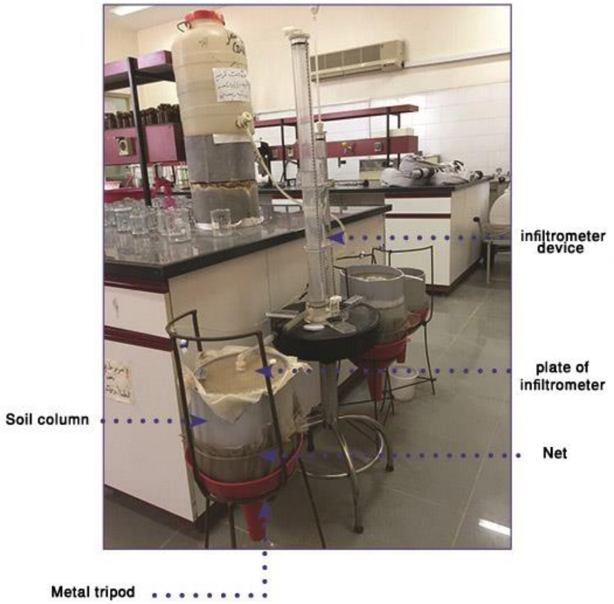

Fig. 2: Placement of infiltrometer device on the soil column

Measurement of Physical and Chemical Properties

On completion of the measurement of hydraulic properties, the infiltrometer device was removed from the soil column. After removing sand with less than 100 µm diameter from the bottom of the infiltrometer plate in each undisturbed soil column, intact samples were prepared in steel cylinders for bulk density measurements while the disturbed samples were prepared in three replications for measuring other characteristics. The disturbed samples were air dried and sieved after collection. In total, 27 samples (9 undisturbed columns with different structures) were taken in 3 replications for measuring each parameter.

Soil texture and particle size distribution were measured by the hydrometer method (Beretta *et al*. 2014). To determine bulk density and porosity, three intact samples were prepared from each depth using steel cylinders (4.5 cm in diameter and 5 cm in height (Sultani *et al.* 2007). In order to evaluate mean weight diameter (MWD) of aggregates,wet sieving was done using sieves 4, 2, 1, 0.5 and 0.25 mm in diameter (Barzegar *et al*. 2004). In order to better interpret the results, some chemical properties such as organic matter, pH and electric conductivity were measured. The percentage of organic matter was measured by oxidation with chromic acid, followed by titration with ferrous ammonium sulfate (Walkley and Black 1934). The pH (in water) of the saturated mud was measured by a pH meter and electric conductivity (EC) of the saturated mud extract was measured by the EC meter.

RESULTS AND DISCUSSION

Physical and Chemical Properties

The results did not show any significant difference between the mean distribution of particle size in different structures (Table 1). Soil texture was loam in all three types of structures (according to the soil texture triangle). The average pH of the studied soils was about neutral ranging from 7.09 to 7.56. The electrical conductivity of the studied soils was 0.4-0.5 ds/m.

There was a significant difference between the amounts of organic matter in different structures (Table 2) as indicated by a comparison of mean values of organic matter. Based on the measured values of the organic matter, granular

TABLE 1
Mean comparison of particle size between different structures

Sample	Sand (%)	Silt (%)	Clay (%)
G_1	40.00a	38.33a	21.66b
G_2	40.63a	38.39a	20.97b
G_3	40.30a	37.87a	21.82b
B_1	39.55a	34.24a	26.20a
B_2	40.32a	33.72a	26.29a
B_3	39.65a	33.75a	26.59a
M_1	40.06a	33.97a	25.96a
M_2	39.73a	33.75a	26.30a
M_3	40.23a	33.77a	25.99a

TABLE 2
Mean comparison of some chemical and physical properties between different structures

Sample	Organic matter (%)	Bulk density (Mg/m^3)	Porosity(%)	MWD(mm)
G_1	0.83a	1.32b	50.19b	0.73b
G_2	0.84a	1.12c	57.61a	0.90a
G_3	0.80a	1.13c	57.23a	0.91a
B_1	0.56b	1.24b	52.95b	0.88a
B_2	0.58b	1.25b	52.54b	0.90a
B_3	0.63b	1.23b	53.46b	0.90a
M_1	0.32c	1.39a	47.29c	0.26c
M_2	0.29c	1.44a	45.53c	0.30c
M_3	0.26c	1.47a	44.53c	0.27c

In each column, the dis-similar letters indicate significant difference and same letters show non-significant difference between various structures ($p<0.05$ Duncan). (G, B and M indicate Granular, Blocky and Massive structure respectively, and each of their subscript number represents the number of soil samples) structure had the highest amount of organic matter and was significantly different compared to the amounts of organic matter in soils with blocky and massive structures. The lowest percentage of organic matter was observed in massive soils. Blocky soils had a higher percentage of organic matter than massive soils, indicating improved and higher stability of blocky structures in comparison to massive structures. Martinez *et al.* (2008) observed that plant debris increases organic matter especially on soil surface, which can lead to a more stable layer of soil. Ahad *et al.* (2015) showed that organic matter plays an important role in the nutrition cycle by contributing to an improved soil structure.

The difference in mean bulk density and total porosity was significant among treatments with granular, blocky and massive structures (Table 2). Soil structure had a significant effect on bulk density. The trend of soil bulk density was as follows: granular < blocky <massive. Total porosity percentage of soils was as follows: granular > blocky> massive structures. This indicates that soil structure has an effect on bulk density and porosity percentage of total soil. G_2 and G_3 soils, which had the highest soil porosity, had the lowest bulk density. As the textures in the studied soils were the same, it can be concluded that soil structure is independent of its texture in its effects on soil hydraulic properties. Kelishadi *et al*. (2014) showed that high values of bulk density of arable soils are associated with a weak structure and the degradation of the soil pore system. The presence of the highest amount of organic matter in G_2 and G_3 with granular structure (0.82) justifies the high porosity (57.42%) and low bulk density (1.125 Mg/m^3) in this structure compared to other structures. Ahad *et al*. (2015) noted that bulk density depends on the amount of soil organic matter, particle size distribution and soil porosity. There was a significant difference in the values of bulk density and soil porosity between G_1 and two other granular soil structures (G_2 and G_3). Due to the position of the G_1 soil and the fact that this soil sample was taken near the road, the probability of passing tractors and agricultural machinery could have led to soil compaction and increased bulk density and reduced soil porosity relative to the other two granular (G_2 and G_3) structures. According to Behfar *et al.* (2012), compaction resulting from the passage of tractors and agricultural machinery leads to reduced porosity and number of soil pores, as well as increased bulk density and soil resistance.

As shown in Table 2, there is a significant difference in average mean weight diameter (MWD) of the aggregates in the granular structures (G_2 and G_3) and blocky (B_1, B_2, B_3) compared to massive structures (M1, M2, M3). Soils with massive structures (M_1, M_2, M_3) had the lowest MWD index. There was no significant difference between granular and blocky structures. The presence of organic matter has a significant effect on the improvement and formation of the soil structure. Aziz and Karim (2016) stated that the percentage of clay and organic matter plays a very important role in the stability of the soil structure. Due to the presence of organic matter, M_1, M_2, M_3 soils had low soil stability and a weak structure with a minimum MWD of about 0.3 mm. The development of soil structure in granular (G_2 and G_3) and blocky structures (B_1, B_2, B_3) was completely visible and the MWD of the aggregates at 0.73-0.91 mm indicates the good stability of these soils. In granular structure, a significant difference was obtained between G1 and the other two granular soils of G_2 and G_3 (Table 2). The position of the G1 soil near the road and the passing of agricultural machinery could have led to the breakdown of aggregates and a decrease in the MWD of the aggregates. Barzegar *et al.* (2004) reported that passing agricultural machinery, especially when the soil is dry, could lead to the collapse of aggregates and the formation of smaller sized aggregates.

Hydraulic Properties

The results of statistical analysis showed that structure had a significant effect on hydraulic properties (Table 3). As the textures in the studied treatments were the same (Table 1), it can be concluded that soil structure affects soil hydraulic properties, independent of its texture. Kelishadi *et al*. (2014) studied soil hydraulic properties in different landuse management systems and concluded that hydraulic properties such as saturated and unsaturated hydraulic conductivity and macroscopic capillary length were not influenced by soil texture. They also showed the significant difference in different landuse patterns that was independent of soil texture.

TABLE 3

Statistical analysis of structure effect on some hydraulic parameters

Souce of variation	df	F value						
		K_{14}	K_{10}	K_4	K_1	K_s	$N_{macropore}$	$N_{mezopore}$
Soil structure	8	462.43^{ns}	137.02^{**}	842.29^{**}	1505.26^{**}	3088.04^{**}	3231.62^{**}	51959^{**}

Notes: Letter K shows hydraulic conductivity; subscripts display various matric suctions; letter N" indicates number of pores.

The average number of pores per unit area (N) in two classes of pore size including mesopore and macropore of each are given in Table 4. In calculating the number of pores in each class, the smallest radius in each class was used in two successive matric suctions to calculate the maximum number of pores in each class. Our results of statistical analysis show the effect of soil structure on both pore size classes to be significant.

The number of mesopores was manifold higher than the macropores in all treatments. The highest number of macropores and mesopores was observed in G_3 and G_2 and the lowest was seen in massive M_1, M_2 and M_3 soils. The number of macropores and mesopores in G_1 soil was significantly less than in the G_3 and G_2 soils. Despite its high organic matter content and granular structure, G_1 had a significantly lower number of pores compared to the two other granular structures due to soil compaction resulting from passing agricultural machinery. The passing of agricultural machinery and a significant increase in bulk density,

TABLE 4.
Mean comparison of macropore and mesopore number per square meter in different structures

Sample	Pore size	
	Macropore 0.375 (mm) < radius	Mesopore 0.107< radius<0.375(mm)
G_1	140c	20167b
G_2	216a	27261a
G_3	214a	27306a
B_1	147b	18430c
B_2	148b	18552c
B_3	149b	18554c
M_1	14d	2429d
M_2	14d	2489d
M_3	15d	2425d

Notes: In each column, the dissimilar letters indicate significant difference between various structures ($p<0.05$ Duncan). (G, B and M indicate Granular, Blocky and Massive structure respectively, and each of their subscript number represents the number of soil samples)

with its consequent decrease in the porosity of the total soil, led to a significant decrease in the number of pores. In G_1, the number of macropores and mesopores were respectively 35% and 26% lesser compared to the number of pores in the G_3 and G_2. As compaction increased, macropores were more affected than mesopores despite their lesser quantity. Lipiec and Håkansson (2000) showed that the compaction caused by the transport of agricultural machinery affects the volume of macropores (the pores that are active in the saturation flow) more than micropores (μm>30). The presence of greater organic matter, low bulk density (high porosity) and more stable aggregates in the granular class indicate that this class has a higher number of macropores and mesopores than the other two soil structures. Dorner *et al*. (2010) who studied the role of soil structure on pore performance stated that unstructured soils have a smaller number and less continuous pores than the structured soils.

The effect of structure on saturated and unsaturated hydraulic conductivity in various potentials is shown in Figure 3.

In all structures, saturated and unsaturated hydraulic conductivity increased with matric suction reduction (from 14 to 1 cm). By reducing the matric suction to near-saturation conditions, the macropores involved in the water flow

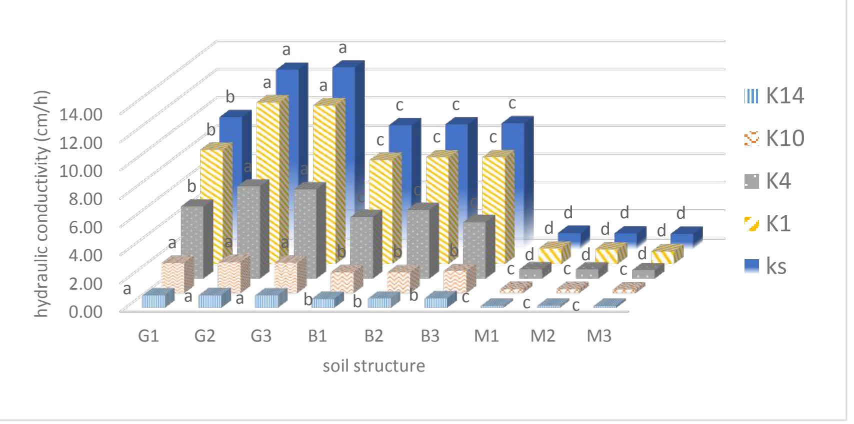

Fig. 3: Mean saturated and unsaturated hydraulic conductivity in different matric suctions and various structures

Notes: The dissimilar letters in each suction indicate significant difference between various structures (p<0.05 Duncan). (G, B and M indicate Granular, Blocky and Massive structure respectively, and each of their number represents the number of soil samples. Letter K shows hydraulic conductivity and numbers display various matric suctions).

increased the rate of saturated and unsaturated hydraulic conductivity in the soil. The difference in the values of all three parameters measured at the matric suction of 1 cm was higher than that of the matric suction at 14 cm among the different structures. This is due to the difference between macropores and their non-uniformity in near-saturated suction in different structures. Moosavi and Sepaskhah (2012) reported that the higher coefficient of variation of Ks is related to the size, the number and heterogeneity of macropores compared to unsaturated hydraulic conductivity values. They also stated that the low coefficient of variation of the flow and hydraulic conductivity parameters in the higher matric suction in related to the smaller and uniform sizes of these pores. The highest rate of flow and saturated and unsaturated hydraulic conductivity through macropores and mesopores were observed in granular structures (G_3 and G_2) and the lowest value of the mentioned parameters was calculated in massive structures (M_1, M_2, M_3) (Figure 3), which had the lowest number of active water-conducting pores. The presence of high organic matter and low bulk density in granular soils resulted in more active water conductive pores, which consequently resulted in saturated and unsaturated hydraulic conductivity in these soils.

In G_1 soil, there was a significant difference between the values of saturated and unsaturated hydraulic conductivity compared to G_3 and G_2 soils. The position of G_1 near the road and the passing of tractors led to increased bulk density and reduced porosity which resulted in a significant reduction in the flow rate and consequently a decrease in the saturated and unsaturated hydraulic conductivity relative to G_3 and G_2. Changes in bulk density resulted in saturated hydraulic conduction changes which indicate soil structure sensitivity in soil management practices. Soracco *et al*. (2015) who studied the effects of agricultural machinery movement on the shape and distribution of soil pores, stated that soil compaction, by decreasing the number of soil pores, significantly changed physical and hydraulic properties, especially hydraulic conductivity. In soil structure, continuity and distribution of pore size, especially the volume and continuity of conductive active pores (macropores and mesopores), have a major effect on soil hydraulic conductivity. According to Verwoort and Cattle (2003) a meaningful relationship exists between the continuity of pores and hydraulic conductivity which indicates the importance of soil structure and the continuity of pores in water movement and transport of solutes in the soil. In near-zero matric suction, the water and solute flow occur mainly in the macropores and mesopores, which are the preferred water paths in the soil. Due to the presence of a high number of macropores and mesopores, soils with G_3 and G_2 granular structures have preferential pathways and are more likely to have a more preferential flow than other soils.

CONCLUSION

Our study showed that soil structure has significant effects on hydraulic and physical properties. Considering physical and hydraulic properties, granular soils had the best structure compared to blocky and massive soils. Blocky soils ranked second in terms of physical and hydraulic conditions, followed by massive soils. Massive soils had the weakest structure in terms of physical and hydraulic properties. In general, the presence of organic matter, as one of the important factors in aggregation, caused the formation of more stable aggregates and a lower bulk density in granular soils. The formation of more active water conductive pores in these soils led to more saturated and unsaturated hydraulic conduction, which increased the preferential flow in this structure compared to the blocky and massive structure.

Compaction had a significant effect on soil structure. The passing of agricultural machinery resulted in reduced porosity and number of pores and increased bulk density, which resulted in significant changes in the physical and hydraulic parameters in compacted soils compared to other soils.

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