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X-ray computed tomography: Validation of the effect of pore size and its connectivity on saturated hydraulic conductivity

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Abstract

Saturated hydraulic conductivity (Ks) is widely utilized in soil hydrology. Ks not only can be proportional to total porosity, but also depends on soil porous system properties such as pore size distribution, and pore connectivity. Recently, X-ray computed tomography (X-CT) is inherent in describing size, shape, connectivity, geometry, and distribution of pore space. The aim of this study was to evaluate the impact of pore connectivity including open and closed porosity on Ks values using X-CT. Moreover, the influence of pore size distribution including macroporosity and mesoporosity on Ks was validated. Ks was measured based on a constant head technique. Furthermore, the visual images of pore space structure were scanned using X-CT. Also, the percentages of open and closed porosity, as well as macroporosity and mesoporosity were calculated using CT-analysis and CT-vox programs. The results indicated that the values of Ks were sharply decreased at subsurface layers at soil depth (40-45) cm. This is attributed to increasing the percentage of closed porosity and decreasing the percentages of macroporosity and mesoporosity. The influence of mesoporosity is strongly larger than macroporosity on Ks values. There exists a positive strong correlation coefficient between mesoporosity and Ks values (r= +0.84). Moreover, the relationship between Ks values and mesoporosity can be represented by an exponential equation. The influence of closed porosity is clearer than open porosity on the values of Ks. The influence of pore connectivity may be approaching the effect of pore size distribution on Ks values for agro-soddy podzolic soil (silt loam and silty clay loam). The values of saturated hydraulic conductivity were harmonious with the calculations of pore connectivity and pore size distribution by X-CT.

Keywords: Pore size distribution; macroporosity and mesoporosity; open and closed porosity; hydraulic properties; constant head technique; podzol soil

Introduction

Saturated hydraulic conductivity (Ks) information is widely required in many agricultural management systems, as well as irrigation and drainage nets design. Ks is very important for surface soils as it regulates the partitioning of the rainfall between surface runoff, groundwater feedback and also regulates water availability for crops. Moreover, soil erosion and groundwater contamination are commonly attributed to Ks values (Jarvis *et al*., 2013). The variations of Ks values have mainly been associated with soil texture (Jabro, 1992; Jarvis *et al*., 2013; Mady and Shein, 2017; Mady and Shein, 2018a). In addition to soil texture, soil structure is the main determinant influencing soil hydrology near-saturated soils, and saturated hydraulic conductivity (Jorda *et al*., 2015). Furthermore, the effect of particle shape and surface roughness on Ks values was investigated by (Zięba, 2017). Aggregates and structure of soil have strongly affected the size, shape, geometry, connectivity, and distribution of pore space (Pires *et al*., 2017). Saturated hydraulic conductivity is primarily affected by the size, structure, connectivity, and distribution of pores (Kodešová *et al*., 2011; Nielsen *et al*., 2018). Saturated hydraulic conductivity values were usually higher in no-tilled than tilled soils, this is related to increasing pore size distribution under no-tilled soil (Bhattacharyya *et al*., 2006). The variations of pore size determine a certain function of pores in the soil according to the size of pores. Pores with an equivalent cylindrical diameter (ECD) larger than 0.05 mm represent transmission pores, they are responsible for air

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movement and drainage of excess water. Whereas pores with ECD smaller than 0.0005 mm refer to bonding pores; they are responsible for retention of water (Lal and Shukla, 2004). Pore size distribution (PSD) is indirectly calculated based on soil water retention curve (SWRC) data. Recently, PSD has been directly estimated based on X-ray computed tomography (X-CT) (Rab *et al*., 2014; Pires *et al*., 2017). Although, X-CT uses the two and three dimension models with a spatial resolution ranging from 100 to 200 µm/pixel (Pires *et al*., 2010; Helliwell *et al*., 2013). However, PSD calculated by X-CT is less accurate that calculated by SWRC data (Shein *et al*., 2016; Ivanov *et al*., 2019). X-CT is a non-destructive technique used for description of pore space structure; it has been widely utilized for scanning the whole porous media structure (Voltolini *et al*., 2017; Katuwal *et al*., 2018; Mady and Shein, 2018b). Moreover, soil porous system properties can be calculated by X-CT software analysis (Müller *et al*., 2018; Mady and Shein, 2020). X-CT has been used to evaluate the impact of agricultural practices and management systems on the soil structure and soil aggregates (Zhou *et al*., 2012; Pires *et al*., 2017). The shape, geometry, and distribution of pores can be visualized by X-CT. Also, the connectivity and its size of pores can be accurately described using X-CT (Borges *et al*., 2018). Few studies have been carried out to evaluate the impact of porous media structure visually on saturated hydraulic conductivity and its relation with the size and connectivity of pores. The aim of this work was to visually and quantitatively study the effect of soil porous system properties including open and closed pores, as well as macro and mesopores content on Ks values using X-CT images.

Material and Methods

Soil sampling

In this study, undisturbed soil samples were collected from surface and subsurface layers for estimating saturated hydraulic conductivity. The soil under study was Albic Glossic Retisols (Loamic, Cutanic) according to the WRB 2014 (update 2015) (agro-soddy podzolic soil), Moscow, Russia. Two soil profiles were dug-down as replication, and then each one divided into two horizons; horizon A (0–30 cm) at soil depths (5–10), (15–20), and (25–30) cm, and horizon B1 (30–45) cm at soil depth (40–45) cm. Undisturbed soil samples were taken from the corresponding depths (5–10), (15–20), (25–30), and (40–45) cm. Furthermore, four undisturbed soil samples were collected by plastic soil core with height 3 cm and a diameter 2 cm for scanning soil porous media structure at the saturated state using X-CT. Soil with a larger dimension lets to distorting the volumetric picture of the pore space and does not allow accurate quantitative determination of the pore space structure. That is why we used this size for the tomography images. X-CT is used to carry out binarization scanning of the soil pore for a given size, in order to distinguish between the solid phase and the soil porosity.

In the morphological field description, a well-aggregated, porous surface horizon (0–45) cm was noted; below, it turned into a dense, lamellar-prismatic, and solid finely porous in horizon B1 with large interpedial fissures.

Soil physical properties

Particle size distribution was measured using the sedimentation method (pipette method) relying on Stoke's law according to (Gee and Bauder, 1986; Mady and Shein, 2019). USDA classification was used to determine soil texture; according to sand (2–0.05 mm), silt (0.05–0.002 mm) and clay <0.002 mm. Soil texture was classified as silt loam for surface layer in horizon A, whereas it was silty clay loam for subsurface layer in horizon B1 as given in Table 1. Furthermore, soil bulk density (ρ_b) was estimated using the core method according to Klute and Dirksen, (1986). The results of particle size distribution and soil bulk density were represented in Table1, they were a part of work carried out by Mady and Shein, (2021).

Saturated hydraulic conductivity (Ks)

Because of the importance of saturated hydraulic conductivity, many direct methods have been developed for its measurement in the field and laboratory (Dawson, 2008; Head and Epps, 2011). The constant head technique is

Table 1: Particle size distribution as the percentages of sand, silt, and clay and soil bulk density, as well as soil texture

Soil depths, cm	Sand,% (2-0.05) mm	Silt, % (0.05-0.002) mm	Clay, % <0.002 mm	Soil bulk density (ρ_b), Mg m^{-3}	Soil texture
(5-10)	8.15	73.60	18.25	1.21	Silt loam
(15-20)	5.92	72.38	21.70	1.28	Silt loam
(25-30)	3.80	70.53	25.67	1.36	Silt loam
(40-45)	2.14	65.71	32.15	1.44	Silty clay loam

widely utilized for measurement of Ks.

Saturated hydraulic conductivity was determined using constant head method according to (Klute and Dirksen, 1986) based on Darcy's law:

$$\frac{Q}{A.t} = K_S \frac{\Delta H}{L} \qquad K_S = \frac{Q.L}{H.A.t}$$

where Ks is the saturated hydraulic conductivity (m day^{-1}) at T^C; Q is the volume of water passing through the soil (m^3) at time t; A is cross-sectional area of the soil core (m^2), L is the height of soil in the core (m). H is the height of soil and water in the core (m) or hydraulic head, and $\Delta H/L$ is hydraulic gradient.

Tomography of pore structure

X-CT method was used for description of the porous media structure in the soil. Three-dimensional images of pore space and two-dimensional images of soil porous system properties were obtained using a SkyScan 1172 X-CT scanner. Soil samples were scanned by X-CT with beam energy 70 kV and a resolution of 10.2 μm per pixel (Mady and Shein, 2020; Mady *et al*., 2020) at the saturated state.

X-CT studies are based on image analysis steps which widely related to the thresholding step and the segmentation method. Gackiewicz *et al*. (2019) found that the errors related to the thresholding step lead to uncertainty in the estimation of soil pore system properties and saturated hydraulic conductivity. They reported that the means of the errors associated with the thresholding step were between 15 to 40% at the calculation of visible total porosity.

The thresholds were automatically determined to focus only on the pore structure. The segmentation technique is widely utilized to transfer X-CT images into discrete sections which tend to distinguish between the solid phase and soil porosity for the quantitative description of porous media structure. The image was turned out to multi-segmented (4 segments in vertical). The segmentation process was carried out according to Otsu technique (Otsu, 1979). The images were observed to increase the quality of the segmentation processes.

Pore connectivity and pore size distribution

X-CT is widely used for estimation of pore size distribution and pore connectivity. The programs of CT-analysis and CT-vox are commonly used for calculating the number and visible volume of open and closed pores, as well as pore size distribution. The classification of pore size was proposed by Brewer (1964) according to equivalent cylindrical diameter (ECD). Pores with ECD larger than 0.075 to 1 mm refer to macropores, they are responsible for air movement and drainage of excess water. While pores that have ECD smaller than 0.075 to 0.03 mm represent mesopores; they have a great effect on water flow and saturated hydraulic conductivity.

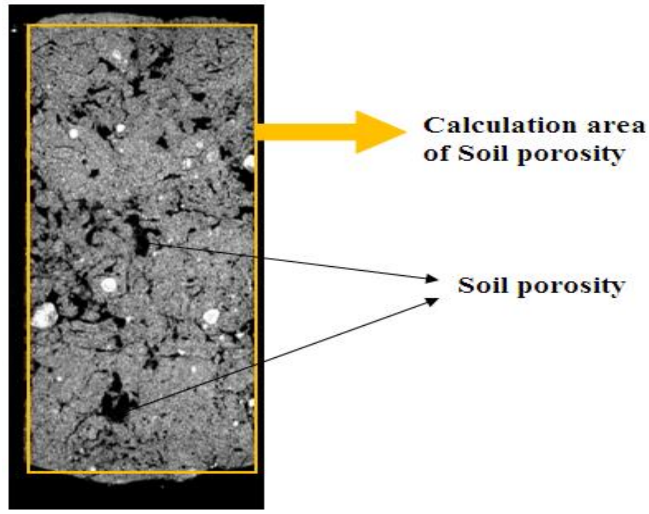

Figure 1: The two-dimensional tomography image for soil and the yellow frame marks the border refers for calculation of equivalent cylindrical diameter (ECD)

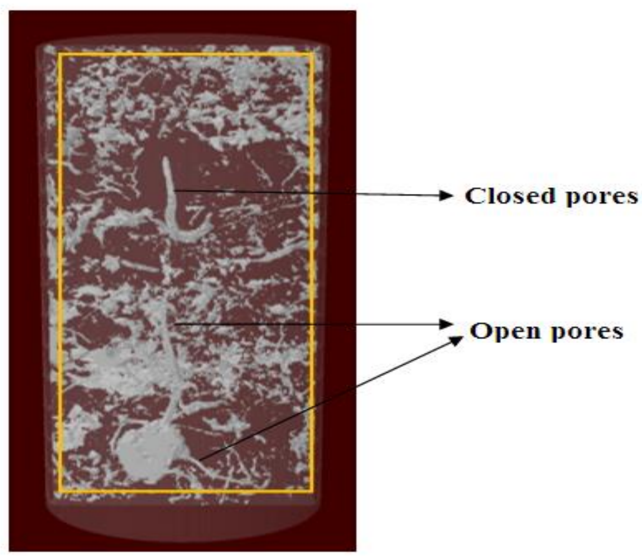

Figure 2: The three-dimensional tomography image of soil sample by X-CT at soil depth (15-20) cm

The percentages and visible volumes of open and closed pores were calculated using CT-analysis software according to Shein *et al*. (2016), Mady and Shein, (2020) and Mady *et al*. (2020). Furthermore, the percentages of

Table 2: Saturated hydraulic conductivity and the volumes of open, closed pores corresponding to the percentages of open and closed porosity

Soil depths, cm	Ks, m day^{-1}	Open porosity, %	Closed porosity, %	Volume of open pore, mm^3	Volume of closed pore, mm^3
(5-10)	0.91	11.97	1.19	657.42	57.40
(15-20)	0.30	10.36	1.56	547.34	73.79
(25-30)	0.13	5.28	1.08	289.88	56.35
(40-45)	0.08	11.96	1.40	656.52	67.58

Table 3: Saturated hydraulic conductivity and each of Macroporosity % and Mesoporosity %

Soil depths, cm	Ks, m day^{-1}	Macroporosity,%	Mesoporosity,%
(5-10)	0.91	1.30	0.60
(15-20)	0.30	1.77	0.55
(25-30)	0.13	1.15	0.39
(40-45)	0.08	0.83	0.31

macroporosity and mesoporosity were determined according to ECD by Brewer (1964) using CT-analysis. Also, the volumetric structure of soil porous system properties was estimated using CT-vox software. The pore size distribution and its connectivity were calculated from the center of the image as Figure 1 using CT analysis and CT vox software. Figure 1 is showing the two-dimensional image of porous media structure and pore connectivity by X-CT; the visible pores are represented by black color. While, in three-dimensional image the visible pores are represented by gray color as Figure 2.

Results and Discussion

Effect of pore connectivity on Ks

Saturated hydraulic conductivity is a critical parameter in soil hydrology which determining the water balance on the soil surface. Ks values are based not only on soil physical properties, but also on pore connectivity, and pore size distribution (Shein *et al*., 2015; Zięba, 2017). Two and three dimensions tomography images of X-CT are used for scanning soil porous media structure. Moreover, the percentages of open and closed porosities were calculated by X-CT software. X-CT data analysis can be used to explain water and solute movement in the soil by scanning the porous media structure and calculating it quantitatively. Table 2 shows the results of saturated hydraulic conductivity, as well as the percentages and volumes of open and closed pores. Ks value at soil depth 15–20 cm (0.30 m day^{-1}) was larger than its value (0.13 m day^{-1}) at depth 25–30 cm. This is strongly associated with the percentage and volume of open pores which were at 15–20 cm larger than their values at depth 25–30 cm as in Table 2. Although the percentage and volume of open pores at depth 5–10 cm were approaches the percentage and volume of open pores at 40–45 cm as given in Table 2. However, Ks value at soil depth 5–10 cm (0.91 m day^{-1}) was larger than its value at 40–45 cm equal to 0.08 m day^{-1}. The reason of that is mainly attributed to increasing the percentage and volume of closed pores, at 40–45 cm (1.40% and 67.58 mm^3) were larger than their values at 5–10 cm (1.19% and 57.40 mm^3), respectively. In addition to increasing the percentage and volume of closed pores at 40-45 cm, the percentage of clay content and soil bulk density were increased at the same depth 40–45 cm; they were 32.15% and 1.44 Mg m^{-3}, respectively. Furthermore, soil texture was silty clay loam at soil depth 40–45 cm. The closed pores are usually restricting water and liquid flow in pores, the values of saturated hydraulic conductivity were decreased by increasing the percentage of closed porosity (Table 2). On the other hand, Ks values were increased by increasing the percentage of open porosity. Ivanov *et al*. (2019) reported that the value of saturated hydraulic conductivity was reduced by decreasing open porosity at agro-soddy podzolic soil. Although, open porosity has a huge effect on saturated hydraulic conductivity, however, the variations of saturated hydraulic conductivity values were clearly related to closed porosity and soil texture. In general, the mean values of open porosity were larger than closed porosity for agro-soddy podzolic soil (silt loam and silty clay loam). In addition to a quantitative description of open and closed porosity, the visual analysis of the X-CT image clearly explains the reasons of changes in Ks values. Figure 3 shows that porous media structure is represented by black color; it is referring to soil total visible porosity (Mady and Shein, 2020). Analysis of visual images of X-CT for soil samples observed that total visible porosity at soil depth (5–10) cm was close to total visible porosity at soil depth (40–45) cm. While the visual images of total visible porosity at soil depth (25–30) cm was less than at soil depth (15–20) cm as Figure 3 which explains the results in Table 2. Ks values don't depend on total porosity only, but their values are in harmony with open and closed porosity calculated using X-CT.

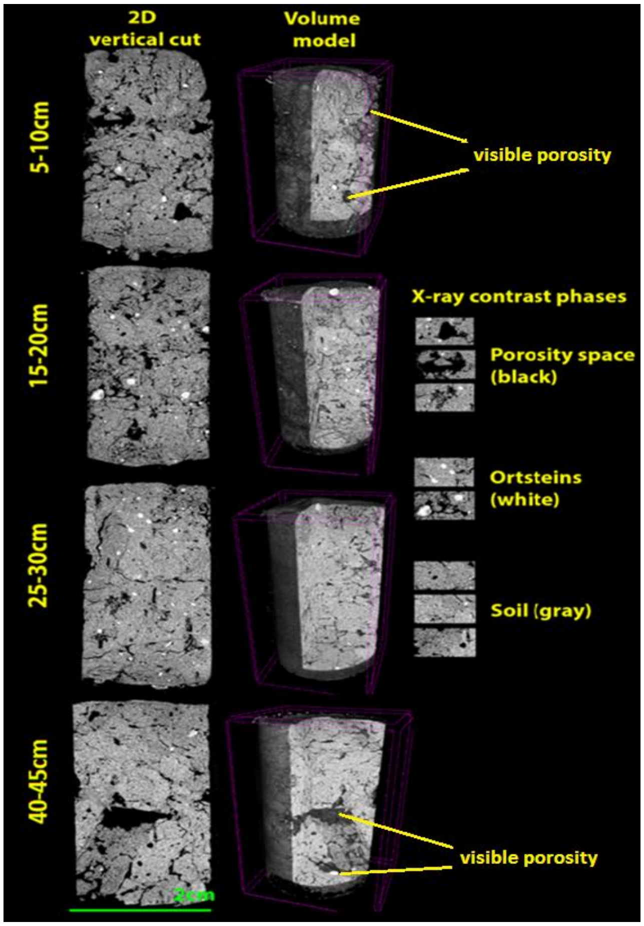

Figure 3: The 2D–3D images of soil samples for different soil depths

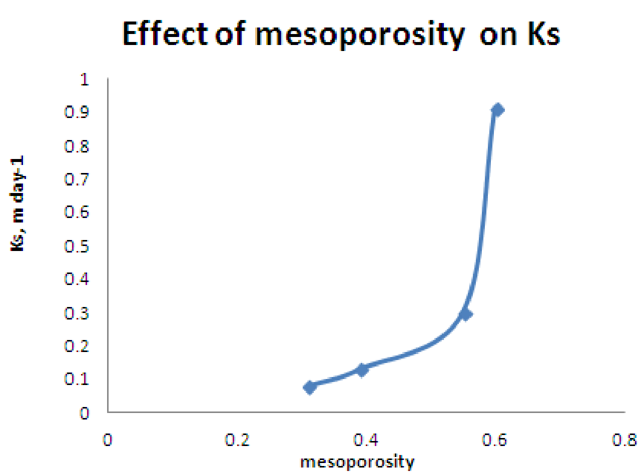

Figure 4: Effect of mesoporosity, % on saturated hydraulic conductivity Ks (m day^{-1})

Effect of pore size distribution on Ks

The quantitative pore size distribution has reflected the morphology of soil and porous media structure and its effects on saturated hydraulic conductivity. Table 3 illustrates the influence of pore size distribution including macroporosity and mesoporosity on Ks. Soil macroporosity was calculated using X-CT according to ECD larger than 0.075 to 1 mm based on the classification of Brewer (1964). Ks value (0.13 m day^{-1}) at depth (25–30) cm was smaller than its value (0.30 m day^{-1}) at depth (15–20) cm as shown in Table 3. This is due to the reason that soil macroporosity at depth (25–30) cm was smaller than its value at depth (15–20) cm. They were 1.15% and 1.77% at soil depths (25–30) and (15–20) cm, respectively. Ks value at soil depth (5–10) cm was larger than its value at depth (40–45) cm as in Table 3. The reason of that is attributed to reducing soil macroporosity at depth (40-45) cm which reaches 0.83 %, while it was larger 1.30% at depth (5-10) cm. This result agrees with Amer *et al*. (2009) and Schlütera *et al*. (2018); They found that Ks values were reduced by decreasing macroporosity. Nielsen *et al*. (2018) reported that the variations of Ks values were related to soil macroporosity. In the same context, mesopores which have ECD smaller than 0.075 to 0.03 mm, it is defined as storage pores because of the ability of it to store water available to plants and crops. Furthermore, mesopores don't have capillary forces too large to restrict the water uptake by the plants and runoff of water. Table 3 is showing that the largest value of Ks (0.91 m day^{-1}) at depth (5–10) cm was corresponding to the largest value of soil mesoporosity (0.60%) at the same depth. Whereas, the smallest value of Ks (0.08 m day^{-1}) at depth (40–45) cm was corresponding to the smallest value of mesoporosity (0.31%) at the same depth. The variations of Ks values are strongly affected by mesoporosity. The reason of that is attributed to the size of mesopores with ECD smaller than 0.075 to 0.03 mm; it can be given the ability to retain water and drainage the excess water above the field capacity. This result agrees with Bittelli *et al*. (2015) who found that mesoporosity has a huge influence on Ks. Furthermore, there exists a positive strong correlation coefficient between Ks and mesoporosity (r= +0.84). But, there is no correlation coefficient between Ks and macroporosity (r=+0.40) less than 0.5. Figure 4 shows that the relationship between Ks and mesoporosity can be described by an exponential equation. This description agrees with (Wösten *et al*., 1999; Mady and Shein, 2018a), they calculated Ks as a function of soil physical properties by pedotransfer functions (PTFs) with an exponential equation with a little estimation error. Figure 5 shows that the mean values of macroporosity were larger than the mean values of mesoporosity in agro soddy podzolic soil with soil texture silt loam and silty clay loam. This is due to soil texture effect and agriculture management such as tillage.

Bahmani (2019) found that tillage practices affected the porosity and total available water. Moreover, Schlütera *et al*. (2018) reported that the plowed horizon in the conventional tillage has higher macroporosity and higher saturated hydraulic conductivity than the soil beside the cultivator soil at depth (13-23) cm. The value of Ks was the highest at soil depth (5-10) cm because of increasing macroporosity and mesoporosity, as well as open porosity. Whereas the value of Ks was the lowest at soil depth (40-45) cm, it was associated with decreasing the values of macroporosity and mesoporosity and increasing closed porosity.

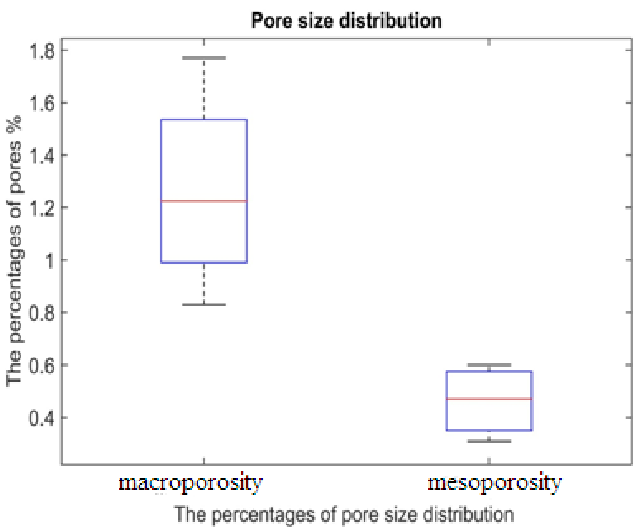

Figure 5: Statistical analysis of macroporosity and mesoporosity for silt loam and silty clay loam soils

In addition to the effect of pore size and it connectivity on Ks, Ks values have been strongly affected by soil texture. Ks value was larger (0.91 m day^{-1}) at surface layer with soil texture silt loam, whereas it was smaller (0.08 m day^{-1}) at subsurface layer with soil texture silty clay loam. Figure 6 is showing the effect of soil depth on the percentages of macropores and mesopores. In general, the mean values of macroporosity and mesoporosity at surface layer (5-10) cm were larger than their values at subsurface layer (40-45) cm. This is due to the percentage of clay content and bulk density at the surface layer (5-10) cm were smaller than their values at the subsurface layer (40-45) cm as Table 1. The main soil physical properties such as particle size distribution, bulk density, and organic matter can directly affect size, shape, and connectivity of pores affecting saturated hydraulic conductivity (Bittelli *et al*., 2015). Furthermore, X-CT calculation of the pore size distribution was approaching to the visual images of the pore space structure.

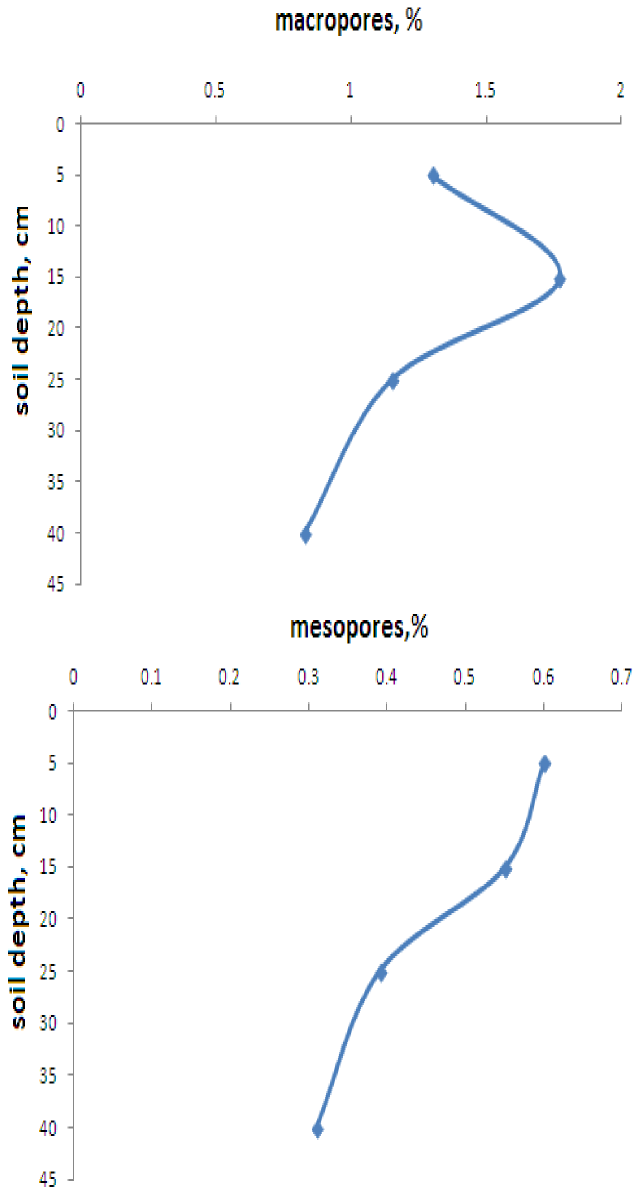

Figure 6: Effects of soil depth on pore size distribution on a) macropores, % and b) mesopores, %

Conclusions

Saturated hydraulic conductivity has a huge effect on modeling water flux and contamination of groundwater. X-CT is commonly used for scanning of pore space structure visually. It can be provided information about quantitative of the open and closed porosity, as well as pore size distribution. In general, the mean values of macroporosity and open porosity were larger than mesoporosity and closed porosity for agro-soddy podzolic soil (silt loam and silty clay loam). The values of macroporosity and mesoporosity are in harmony with Ks values (positive relationship). The percentages of macroporosity and mesoporosity were larger at the surface layer than the subsurface layer. The effect of mesoporosity was larger than macroporosity on Ks values. There exists strong correlation coefficient between mesoporosity and Ks values (r= +0.84), whereas there is no correlation coefficient between macroporosity and Ks values (r=+0.40). Also, Ks can be calculated as a function of mesoporosity by an exponential equation. On the other hand, there is a negative relationship between closed porosity and Ks values. It means that with increasing the percentage of closed porosity, the value of Ks was decreased. The influence of closed porosity was clearer than open porosity on Ks values. The values of saturated hydraulic conductivity were affected by pore size distribution and its connectivity along with soil texture and soil physical parameters. Soil physical properties have affected the values of saturated hydraulic conductivity by affecting soil porous system properties. X-CT can be used for explaining the reasons of the change in *Ks* values based on visually and quantitative description of pore space structure. The quantitative pore size distribution and pore connectivity estimated by X-CT have reflected the values of saturated hydraulic conductivity.

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