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TOMOGRAPHY IN SOIL SCIENCE

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The main advantages of applying computed tomography to studying soil samples include non-invasiveness, independence of the moisture content in the samples and the possibility for mathematical modelling. The methodological problems of this imaging technique include restrictions of the sample size, resolution limitations and segmentation difficulties.

Key words: computed tomography, imaging, soil structure, soil pore space.

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Morphological analyses of soil samples and monoliths as well as micromorphological studies of thin sections have several limitations, the main of which is an impossibility of investigating the internal structure of an object without destroying it. The X-Ray computed tomography (CT) is a non-destructive technique of computer-based visualization and analysis of the internal structure of samples.

The first attempts at applying CT in soil science were made in the late 1980s (Crestana et al., 1986; Anderson et al., 1988). In the beginning, medical X-Ray tomographs were used for studying soil samples and later special laboratory tomographs were developed for different applications (SkyScan, General Electric, Siemens, Hitachi, etc.). At the present time, there is a growing demand for macro- and micro-tomographic analyses of soils. These analytical techniques are becoming more and more valuable with the development of interdisciplinary research **(**Taina et al., 2008; Peth, 2010; Gerke et al., 2012**;** Helliwella et al., 2013**).**

The present paper is aimed at outlining the applications and usefulness of tomographic analyses in the modern soil science.

The tomography is a procedure of creating layered images of the internal structure of different objects. A high resolution X-Ray microtomography is especially useful in soil research. This technique is based on an electronic X-Ray source, which directs a beam through an object, and an X-Ray digital camera detecting cross-section images of the object. There are hundreds of such images registered at different angles, while the object is turning. These images are integrated by a computer into a set of cross-sections of the object, with a distance of one pixel between the cross-sections. An operator can view these cross-sections layer by layer, study them at any angle without any loss of resolution, obtain digital morphometric characteristics of two- and three-dimensional images of the internal structure of a whole object or its selected part, create realistic 3-D models of the object's microstructure and virtually move within the object of study (Fig. 1).

It should be mentioned that, unlike thin section analysis and scanning electron microscopy, the tomography does not require drying of samples and can be carried out at any moisture content. This does not just make the drying pre-treatment unnecessary, but opens a broader area of application of this technique. For example, successive imag-

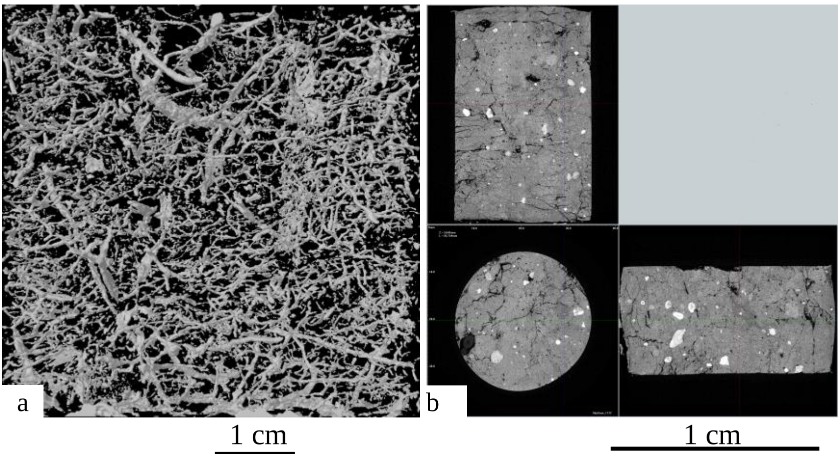

Fig. 1. Examples of microtomographic studies: a – representation of vertical and horizontal cross-sections through a cylindrical soil monolith from the plough horizon of agrogenous soddy podzolic soil (pores are black, soil mass is grey and ortsteins are white); b – 3-D computer model of pore space within the BT2 horizon of soddy podzolic soil (pores are grey).

ing of one sample at different levels of moisture content results in the tomographic representation of soil deformation at different stages of swelling and shrinking (Pires et al., 2007; Peth et al., 2010; Skvortsova et al., 2015).

The tomographic research of soil freezing and thawing processes is especially interesting (Laplante, 1998; Torrance et al., 2008). A tomograph equipped with special devices for maintaining a negative temperature of a sample during a whole period of scanning can be used for studying frozen samples of soils and sediments. Such studies were carried out using a Bruker SkyScan 1172 microtomograph with a thermoregulatory device (Fig. 2, Romanenko et al., 2016).

It should be mentioned that the tomographic analysis is a digital computer technique, which gives opportunities for a successful mathematical modelling of soil structure and properties. The input data are binarized 2-D or 3-D images of pore space, which serve as a basis for direct or indirect determinations of indices of pore shape and orientation and modelling of soil moisture transport, soil electrical properties

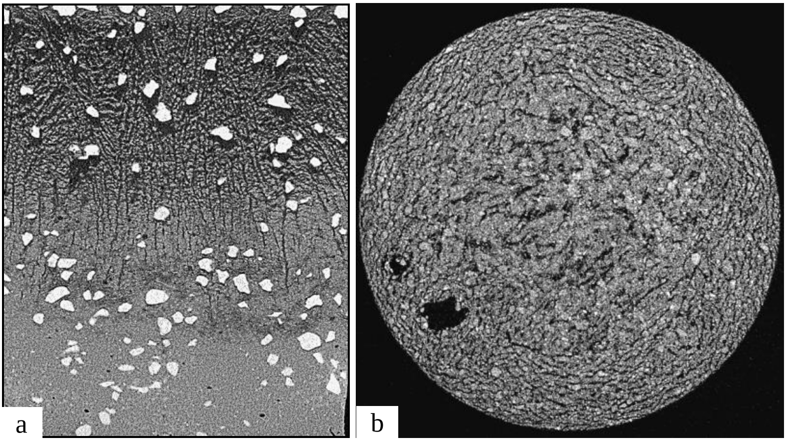

Fig. 2. a – a microtomographic image of an experimental mixture of 90% kaolinite and 10% sand in frozen state after a singe-time vertical freezing (vertical cross-section 8 mm wide): ice inclusions are black and sand grains are white. b – a microtomographic image of a ground sample from the BT1 horizon of soddy podzolic soil (passed through a 25 mm sieve) in frozen state after 20 repeated freezing-thawing cycles (horizontal cross-section 8 mm wide): pores are black, ice inclusions are dark grey, soil mass is light grey and mineral grains are white.

and resistivity, etc. (Gerke et al., 2012; Karsanina et al., 2015). Tomographic analyses of soil filtration capacity and porosity characteristics, especially, the pore configuration and distribution patterns within soil are usually in high demand.Apart from undoubted and important advantages, the tomographic analysis has some specific characteristics that complicate its application. The construction of modern tomographs implies certain limitations to the sample size and resolution level. For example, a geological macrotomograph in the Moscow State University is capable of analysing cylindrical monoliths 10 cm in diameter and 100 cm high with a resolution of 100 μm/pixel. A Bruker SkyScan 1172 universal microtomograph allows studying samples from 1–2 mm to 5 cm in diameter with resolution being higher for smaller samples, i.e., a maximum of 0.6 μm/pixel for the smallest samples.

Such limitations to the sample size and resolution level have negative implications for studies of soil porosity. For example, scanning soil monoliths 3 cm in diameter with a 16.8 μm/pixel resolution permits to confidently analyse only macropores larger than 100–150 μm, with smaller pores remaining beyond the resolution capability. To analyse the small pores, it is necessary to decrease the sample size.

It is important to take into account the aforementioned limitations while comparing the microtomographic data with data obtained by classical techniques of soil physics. The pore size distribution patterns shown in the Fig. 3 have been obtained by microtomographic analysis and calculations based on the water retention curve parameters (Shein et al., 2016). Taking into account the 16.8 μm/pixel resolution, one can make correct comparisons for only the middle and right side of the charts. Such comparisons lead to a conclusion that the two different techniques produce similar patterns of macropore size distribution. It should be pointed out that, despite their general similarity, the patterns obtained using the microtomograph and the water retention curve method can have different shapes for different horizons of soil. Moreover, the tomographic data show more significant differences between horizons. At the present time, the question still remains open as to which of these analytical techniques is more accurate. However, the tomographic analysis is undoubtedly a source of new information on the structure of soil pores.

Another problem of computed tomography is the segmentation of initial half-tone X-ray images into areas of comparable brightness.

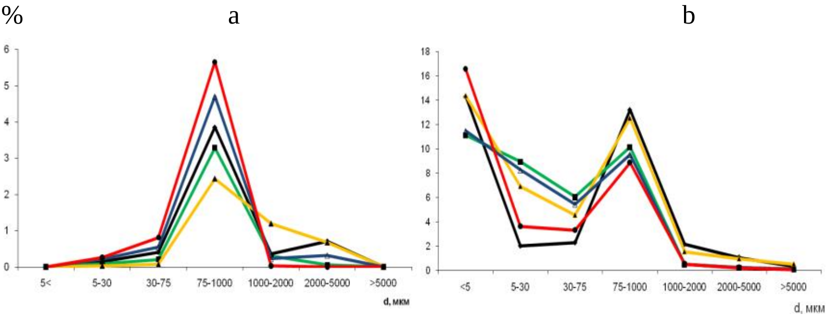

Fig. 3. (a) – The pore diameter distribution patterns obtained using a Bruker SkyScan 1172 microtomograph and cylindrical monoliths 3 cm in diameter with a 16.8 μm/pixel resolution. (b) – The pore diameter distribution patterns obtained by water-based porosimetry. The horizons are as follows: AEL (black line), EL (green line), BEL (yellow line), BT1 (blue line) and BT2 (red line).

The segmentation is a procedure of separating the objects of study (pores, salts, etc.) from the background to make them accessible for morphometric analysis as well as 2-D and 3-D modelling. Recently, many image segmentation algorithms have been developed, but none of them is universal (Muthukrishnan and Radha, 2011). The segmentation still remains a difficult and labour-consuming task, because a qualitative determination of objects' boundaries in half-tone images depends on many factors that affect the results. However, the problem of segmentation occurs not only in tomography. It arises in automated analysis of any half-tone images, including those of scanning electron microscopy samples and micromorphological thin sections.

In conclusion it should be mentioned that tomographic analysis, like many other modern high-technology methods, requires expensive equipment and powerful computer resources. Nevertheless, on account of possibility for obtaining unique data on the internal structure of undisturbed samples, the X-ray computed tomography is currently becoming a generally accepted technique of studying natural objects in geology, oil and gas industry, palaeontology and soil science.

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