=== **SOIL PHYSICS** ===

Tomography of Soil Pores: from Morphological Characteristics to Structural−Functional Assessment of Pore Space

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Abstract—The development of tomographic studies of soil pore space in Russian soil science in 2011−2018 is discussed. In several years, these studies have evolved from the qualitative description of pores in some soils from the European part of Russia to the quantitative functional assessment of soil pore space on the bases of 3D tomographic models. Three stages of tomographic studies of soil pores can be distinguished: (1) qualitative analysis of pore space as a spatial-geometric characteristic of soil structure and as a component of the general analysis of soil morphology; (2) the obtaining of quantitative morphometric data on the shape, size, and orientation of soil pores and combined analysis of these tomographic data and data on the physical soil properties; and (3) the use of calculated tomographic parameters in the study of hydrological and physicomechanical properties of soils important for both theoretical and applied aspects of soil science. In recent years, the research has been focused on the assessment of the relationships between tomographic parameters of soil pore space and traditional soil hydrological constants, possibility of calculating the water retention curve and water conductivity function from the tomographic parameters of soil pore space, and on the quantitative assessment and prediction of soil degradation on the basis of tomographic data. The solution to these problems will make it possible to explain the physical phenomena controlling soil hydrological characteristics and to substantiate the use of tomographic data in applied soil science, soil hydrology, and agrophysics.

Keywords: morphology, micromorphology, micromorphometry, 3D models of pores, hydrological properties, soil functions

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INTRODUCTION

Soil pore space has always occupied a prominent place in soil studies. Soil porosity is tightly associated with the crucial soil functions in the biosphere: water supply, water conservation, water purification, gas exchanges, etc. Characteristics of the pore space are highly important in the studies of the biological activity of various soil microorganisms and in determining the role of different (geochemical, physical, hydrological, etc.) barriers in soils. Soil pores possessing the capacity of to discharge excessive gravitational water (the drainage function), to store available water and nutrients, and to contain unavailable water and nutrients have been distinguished. One of the first fundamental results in the assessment of soil pores was the idea of A.G. Doyarenko about differential porosity of soils as pore volumes belonging to separate aggregates (intraped porosity) and to interaggregate space (interaggregate porosity); pores filled with water and air were also differentiated. This idea was further developed by N.A. Kachinskii. These were the first physically substantiated quantitative characteristics of soil pore space. At present, they are actively applied in modern predictive mathematical models (often, unfortunately, without due reference to their fathers) describing the transfer of substances through macropores and fissures, or preferential flows. Such models make it possible to predict the behavior of fertilizers in soilscapes, the migration of pollutants (pesticides, heavy metals, etc.), and to assess various risks. The notion of differential porosity suggested by Russian soil scientists has contributed to the development of modern theories of the migration of water and dissolved substances lying in the basis of physically grounded mathematical models of soil behavior.

Virtually simultaneously with the ideas of Doyarenko and Kachinskii, the micromorphological method of studying soil pores in various sections under a microscope was developed. This method also played a significant role in the progress of modern functional pedology, as it was possible not only to observe volumetric porosity of soils and separate aggregates but also to analyze the shape, orientation, and mutual arrangement of the pores at the qualitative and quantitative levels [4, 12, 21, 25, 27]. Moreover, it was suggested that micromorphological data should be

used for assessing hydrological characteristics of soils [10, 11, 14, 31]. Often, this approach ensured inspiring results in the field of soil hydrology. Some new concepts and terms appeared due to the application of micromorphological method, e.g., "the architecture of soil pore space" [7].

Tomography as a nondestructive method of the study of inner structure of samples has been widely applied in geology, soil science, and biological sciences since the end of the 20th century. The advantages of tomography for direct characterization of the pore space of rocks and soils have been stressed in many publications [2, 15, 24, 29]. At present, macro- and microtomography is applied to study interactions in the soil−root system and in the solid soil phase−soil microorganisms system. It is also used to study the development and transformation of soil structure and soil aggregates in their dynamics [22, 28, 30]. There are attempts to integrate classical physical analyses of soils (the determination of soil water retention capacity and air conductivity) with the results of X-ray computed tomography [20]. The first results of tomographic studies of multiphase fluxes in simple porous media (sandstones) have been published [19]. Certainly, all these studies of pore space and mutual arrangement of solid-phase components in undisturbed samples yield much promise for solving various fundamental and applied problems of soil science.

The aim of this paper is to analyze the potential of tomographic method and its most promising directions for the theoretical and applied soil science. The particular tasks can be formulated as follows:

(1) To judge the stage of the qualitative morphological study of soil pore space with the use of tomography;

(2) To consider the structural−functional quantitative tomographic characteristics of soil pore space, their novelty, and their relevance;

(3) To assess potential advantages and limitations of the tomographic data on soil pore space in comparison with the modern physical characteristics of soil porosity; and

(4) To discuss applied target problems that might be solved with the help of modern macro- and microtomography of soil pores.

OBJECTS AND METHODS

The results of macro- and microtomographic studies of soil samples performed in Russia in the recent years are analyzed. Soddy-podzolic soils (Albic Glossic Retisols (Loamic, Cutanic) according to the WRB 2014 (update 2015) system) have been the major object of these studies. A SkyScan 1172 (Belgium) X-ray microtomograph installed in the Dokuchaev Soil Science Institute and a macrotomograph installed in the Geological Faculty of Lomonosov Moscow State University have been used.

RESULTS AND DISCUSSION

Numerous experiments have demonstrated that the tomographic method cis applicable for studying various soil components. However, the soil pore space is one of the most suitable objects for tomographic analysis. In contrast to the solid-phase soil components, the pores are easily permeable to X-rays, so that the pore space is clearly separated from the main soil mass on the X-ray images. In fact, the first tomographic studies of soils in the 1980s were mainly devoted to the soil pore space [13, 23].

Computed 3D models of soil pores represent one of the major results of the tomographic analysis. Such models are highly informative; their interpretation is important in terms of the genesis of soils. Thus, 2D images of thin sections from the soddy-podzolic soil demonstrate the abundance of round voids in the EL and BC horizons (Fig. 1a). The transition to 3D microtomographic images (Fig. 1b) indicates that such round voids in thin sections from the EL horizon represent isolated vesicles, whereas analogous voids in thin sections from the BC horizon actually represent modern and relict root channels [3].

The genesis of vesicular porosity in the eluvial horizons is still open to argument. However, it is probable that the formation of vesicles is explained by the modern processes: seasonal biogenic release of gases and their pressing out by water in the periods of the high soil moistening, freeze−thaw processes in winter and spring, and by some physicochemical processes.

Along with distinct images, the tomographic analysis makes it possible to obtain specific morphometric data on the studied objects (second stage of the development of tomographic studies). Thus, quantitative characteristics of sizes, shapes, and spatial orientation of soil pores can be obtained. These characteristics are measured in 2D virtual sections of the 3D computed tomographic reconstruction of soil samples (Fig. 2).

The morphometric analysis of 2D tomographic sections is based on various programs developed for the analysis of plane images and on the indices that were earlier applied in the study of soil porosity in micromorphological thin sections [4, 21, 25, 27]. The description and reconstruction of the pore space of soils with the use of correlations functions [1, 18] represent a promising direction in this area of research.

Highly relevant morphometric characteristics are the total area of pores in the visual field, the dimensions and areas of individual pores, their perimeter values, the indices of pore orientation, and the shape of the pores in 2D images. The informativeness of 2D analysis of the shape of pores in tomographic reconstructions is high. Thus, Fig. 3 displays the dendrogram of similarities and differences of the major genetic horizons of a soddy-podzolic soil calculated for the shape of the interaggregate pore space. The shape of the pores was estimated according to quantitative ratios between their perimeter and lengthwise
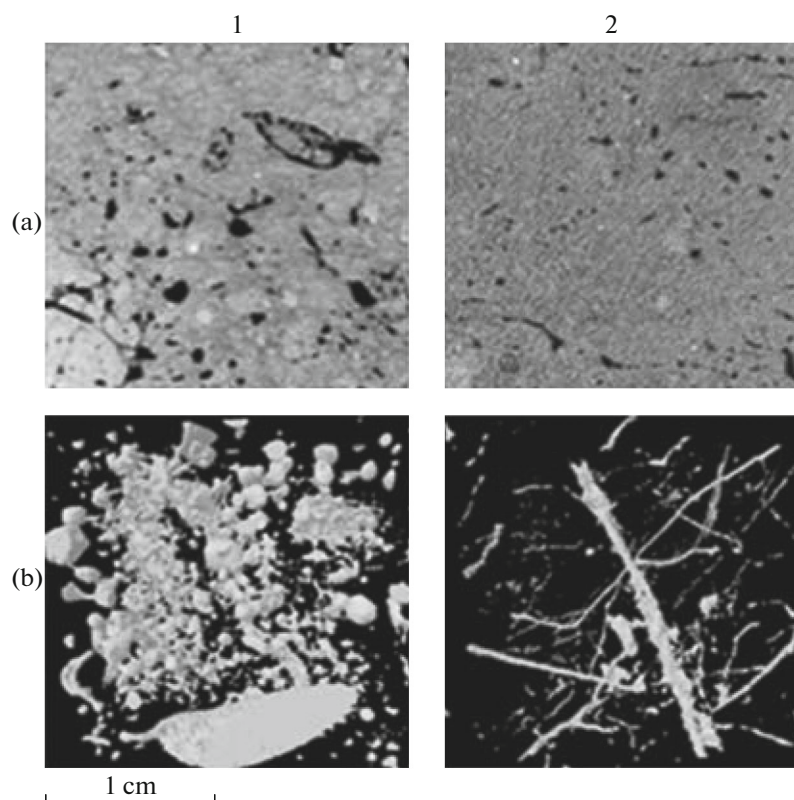
Fig. 1. Pore space of the (1) EL and (2) BC horizons of a soddy-podzolic soil (Albic Glossic Retisol): (a) thin sections (the pores are black) and (b) 3D microtomographic reconstructions (the pores are light) [3].
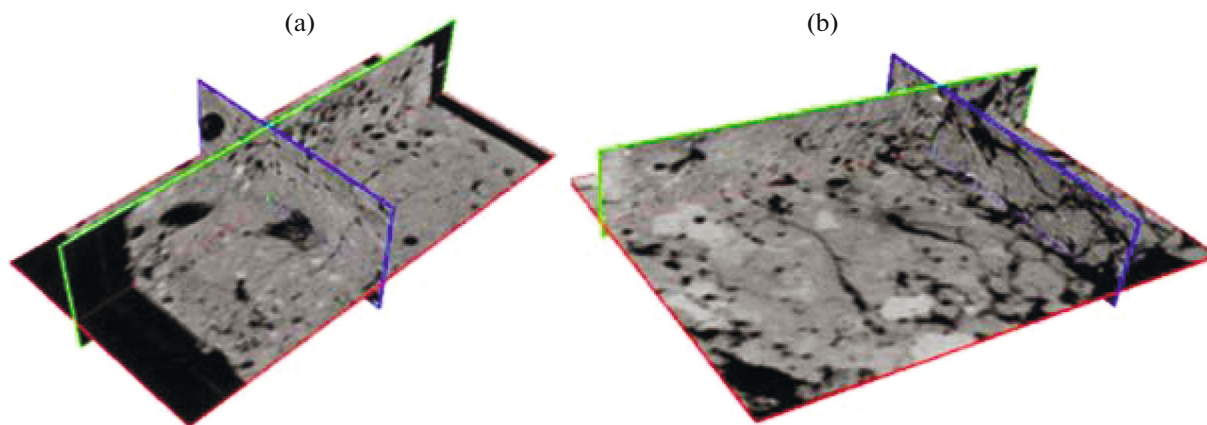
Fig. 2. Lengthwise and transverse sections of tomographic reconstructions of the samples from the (a) EL horizon of a soddy-podzolic soil and (b) AEL horizon of the gray forest soil [2].

and transverse dimensions [4]. Cluster analysis revealed a high level (about 80%) of similarity between the horizons with clear eluviation features (the AEL, EL, and BEL horizons). At the same time, the soil profile contains the horizons with a low level of similarity (<45%). These are the humus horizon and the textural BT2 and BT1 horizons. The horizons with low similarity levels are characterized by a specific pore shape

differing from that in the other horizons; their pore shape corresponds to the crumb–powdery, angular blocky–platy, and massive structure of the samples.

Along with the solution of various morphogenetic problems, the tomographic visualization of soil pores actually creates a novel approach towards the traditional analysis of pore-size distribution important for soil physics. Pore-size distribution is a highly informa-

tive soil characteristic, but it is difficult to obtain it with the help of traditional methods [8]. In soil physics, the methods of water or mercury porosimetry are applied for this purpose. The volume of liquid contained in the pores of corresponding diameter is considered to be bound by capillary forces, and its pressure can be calculated according to Jurin's equation. However, the tomographic images of the pore space allow direct determination of the distribution of pore volumes by pore diameters. For this purpose, the binarized tomographic images are used. Various programs have been suggested to measure areas (in 2D sections) or volumes (in 3D images) of tomographically visible pores of different diameters.

It is important that the results of quantitative measurements of the soil pore space on tomographic images do not agree with the results of traditional methods of determination of total porosity. The total porosity calculated with the use of tomograms is always considerably smaller than the total porosity calculated on the basis of data on the bulk and solid-phase densities of soils. In some cases, the tomographic porosity is six–nine times lower than the porosity determined by the classical methods. This is explained by the fact that the tomographic method has a certain lower resolution limit, the value of which depends on sample size and on the model of tomograph. As a rule, the larger the sample, the lower the resolution of tomographic scanning. Various macrotomographs have the resolution of up to 100–200 μm/pixel. In the high-resolution X-ray microtomographs, this resolution is up to 0.6–0.8 μm/pixel. Taking into account the resolution of tomographic scanning, it is reasonable to operate with the notion of tomographically visible porosity (TVP) with indication of the tomographic resolution. In this context, it is desirable to find the method of image analysis, which would be potentially suitable for all the necessary soil scales. Recently, a new method of multiscale image fusion based on separate images obtained with the use of different tomographs with different spatial resolutions has been suggested [17]. This method yields much promise for multiscale scale soil studies, though it has not found wide practical application so far.

In our studies, a Bruker SkyScan 1172B laboratory microtomograph was used to compare classical physical and tomographic methods for the analysis of soil pore space. The X-ray tube of this device has a power range from 40 to 130 keV; the scanning resolution can vary from 0.6 to 50 μm/pixel. Soil monoliths of 2.5 cm in height and 3 cm in diameter were subjected to the tomographic scanning with the beam energy of 100 keV and the resolution of 8.75 μm/pixel. Under these conditions, meso- and macropores with diameter $d > 30$ μm can be quantitatively determined. In the obtained tomographic reconstructions, we measured the distribution of the volumes of tomographically visible pores by their diameters. Then, the same samples
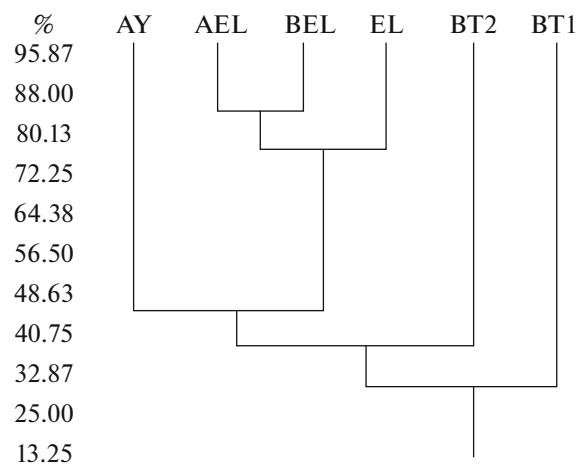

Fig. 3. Dendrogram of similarity of the genetic horizons of soddy-podzolic soil according to characteristics of their pore space [5].

were used to determine pore-size distribution according to the water retention characteristics (the method of water porosimetry). The existence of a resolution limit on the tomograms led to a mismatch of the obtained empirical distributions of pore volumes by their diameters (Fig. 4). The major differences were observed in the range of pore diameters $d < 30$ μm, i.e., in the area inaccessible to tomographic studies. At the same time, in the area of meso- and macropores ($d > 30$ μm), the shapes of both distribution curves were close to one another. The peaks on both curves were observed in the area of fine macropores ($d = 75$–1000 μm); the volume of the pores of larger diameters was much smaller. Judging from published data, the results of mercury porosimetry also satisfactorily coincide with tomographic characteristics in the range of meso- and macropores [16, 26].

Thus, it may be concluded that direct tomographic studies of the pore space of soils confirm the fitting of the classical capillary physical model to the real size distribution of soil meso- and macropores. However, the total porosity calculated according to this model is much greater than the porosity determined from the tomograms, which attests to the need in further soil-hydrological studies coupled with tomography of a higher resolution.

The next step in using quantitative tomographic is to try apply them for calculation of soil permeability, e.g., the filtration coefficient. According to the theory of water filtration in soils, this characteristic of the movement of water should be related to soil porosity, pore-size distribution, and sinuosity of the pores. Attempts to find the filtration coefficient from traditional data on soil porosity have already been made [6]. However, most of them have not been successful and have not found practical application because of the difficulties in quantifying the sinuosity of the pore
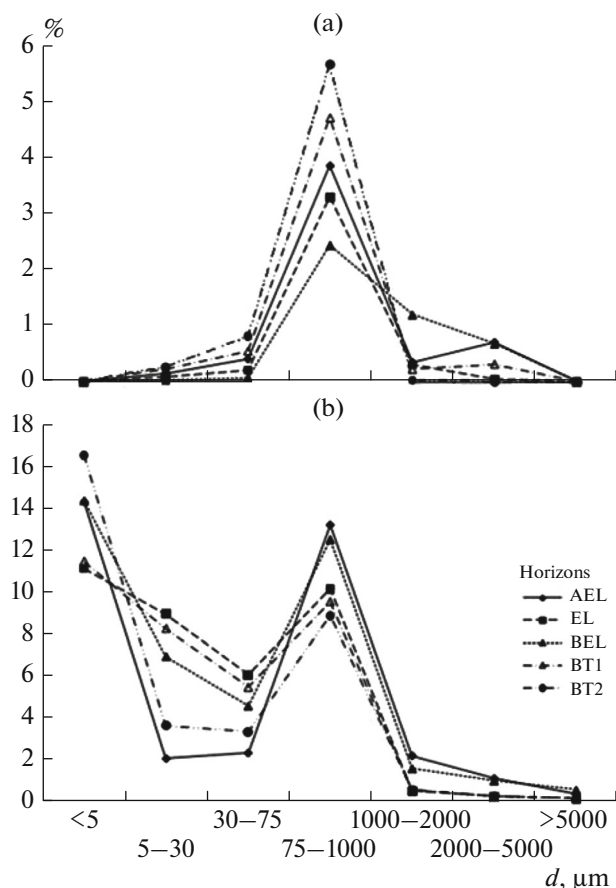
Fig. 4. Distribution of the volumes of the pores (% of the total pore volume) by their diameters (d, μm) obtained by the (a) tomographic method (mean values) and (b) water porosimetry method (from the water retention curve) [9].

space, the presence of pinched (dead-end) pores, and the inability to assess the connectivity of the pores in the porous soil system.

At present, at the third stage of tomographic studies, we recognize the fact that computed tomography is, in essence, a quantitative numerical method. Branded programs for constructing and analyzing tomographic 3D images make it possible to calculate the following characteristics of porous samples: total porosity, open porosity, closed porosity, pore connectivity, the number of contacts, and some other geometric characteristics of the pore space.

It is interesting to establish relationships between the tomographically calculated parameters and practically important hydrological soil properties, including, first of all, the filtration coefficient. In this context, several questions arise: (1) how "physical" are the indicated tomographic parameters (e.g., what is the open/close porosity in physical terms? Are these notions analogous to the physically understandable conductive/dead-end porosity?); (2) how exactly do the indicated tomographic parameters influence the

filtration coefficient? (what kind of dependence—linear, nonlinear, continuous, or discontinuous—exists between the tomographic parameters and the filtration coefficient?); (3) as tomographically determined parameters are, obviously, not strictly constants, and their values depend on the sample volume and on the methods of tomographic reconstruction and segmentation, how should we study these dependences and which form of the distribution parameter (median, mean, or spread) should we use?; and (4) how representative are the tomographic images and tomographic parameters of the pore space? Indeed, tomography provides data on the pore space of some limited soil monolith, which only to a certain extent reflects hydrologically important paths in soils (obviously, not all of them), as any monolith "cuts off" a significant part of the pores. In particular, it cuts off a part of the pores with a horizontal orientation. As we know, soil flows are not only vertical; horizontal flows are no less important. This can be seen from morphological data on the diversity of boundaries between soil horizons and layers: pocket-shaped, tonguing, blurry, serrate, etc.), which are associated with preferential flows both in the vertical and horizontal directions.

To answer these and many other questions, experiments are needed, in which the filtration coefficient and the tomographic characteristics are determined in the same samples. It is probable that only such thoroughly conducted experiments will allow to find adequate relationships between the filtration coefficient and the tomographic parameters (or to reject the existence of such relationships).

It is evident that only large undisturbed soil samples should be used to fine the relationships between the physical soil characteristics (water conductivity, filtration, etc.) and the tomographic characteristics. Special tomographs should be used for this purpose. To study the structure of macropores in the soil samples, a macrotomograph at the Geological Faculty of Moscow State University was applied. The study of large cylindrical soil monoliths ($h = 50$ cm, $d = 10$ cm) made it possible to obtain new macrotomographic data on the structure of solid phase and pore space in the postagrogenic soddy-podzolic soils. Three-dimensional tomographic reconstructions of soil macropores ($d > 1$ mm) for six such vertically oriented monoliths sampled in the field with a spacing of 50–100 cm between them were obtained. Their analysis indicates that these monoliths are characterized by the moderate spatial variability of the connectivity of pores and by the moderate to high spatial variability of the total tomographic porosity and the volumes of open and closed pores.

Using the data on these monoliths as an example, we examined the relationship between the filtration coefficient (Kf, cm/day) and tomographic parameters of the macropores in individual fragments of the soil profile at the depths of 0–10, 10–20, 20–30, 30–40,
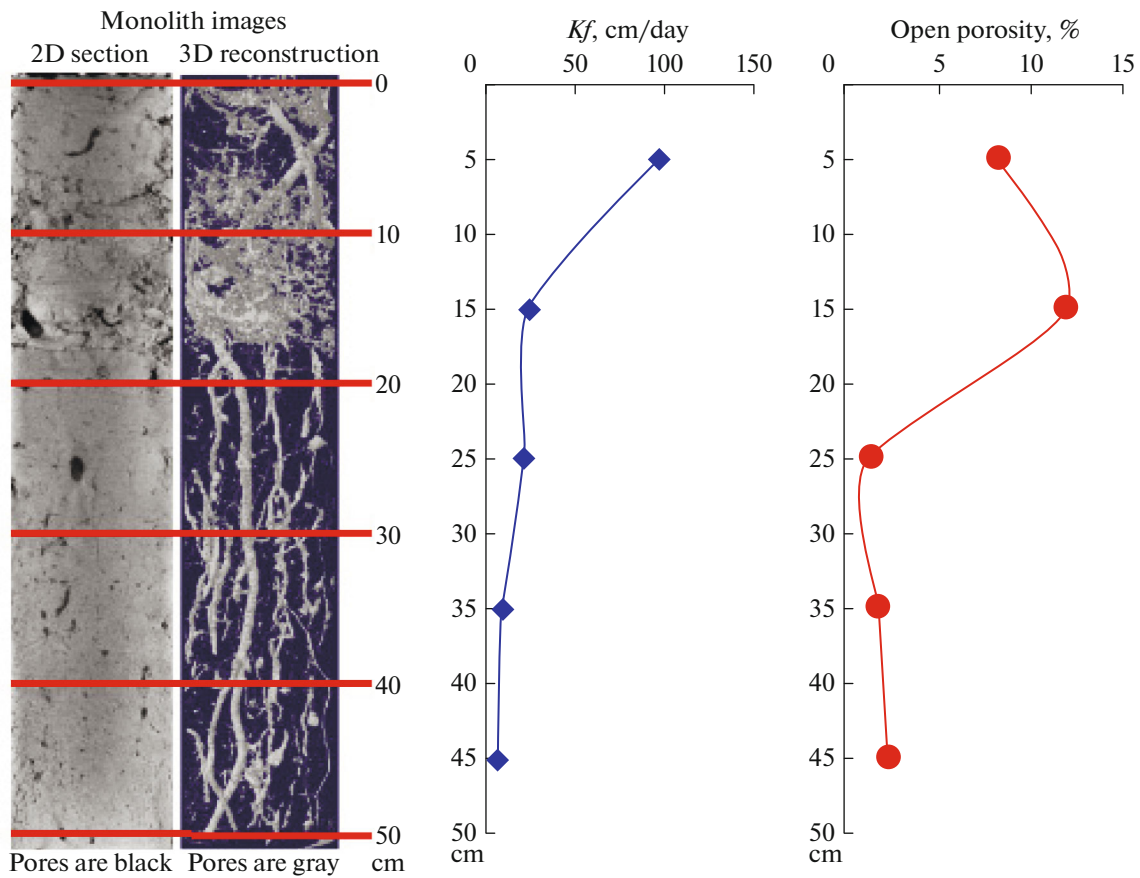
Fig. 5. Changes in the filtration coefficient (Kf) and open tomographic porosity in the profile of a soddy-podzolic soil. The tomographic resolution was 100 μm/pixel.

and 40−50 cm (Fig. 5). It was found that the patterns of changes in Kf and in the volumes of tomographically visible pores along the profile were close to one another, when the tomographic resolution was 100 μm/pixel. A sharp drop in the value of the filtration coefficient (from 100 to 20 cm/day) at the depth of 10−20 cm was due to the presence of a plowpan in the lower part of this layer. The presence of this plowpan could be easily judged from the data on tomographic porosity (Fig. 6).

Interesting results were obtained for the relationships between Kf and open and closed tomographic porosities. As seen from Fig. 6, the closed porosity does not play a significant role in changes of the filtration coefficient. The major role in the fivefold decrease of the filtration coefficient at this depth is played by the open porosity and connectivity of the pores.

A question arises: what are the filtration patterns in such a complex system upon the decrease in the volume of open pores and connectivity of the pores by four−seven times? Can we expect water stagnation at the upper boundary of the layer with the decreased open porosity and connectivity of the pores? To answer these questions, additional experimental stud-

ies are required. Obviously, in the study of large objects (such as the considered soil monoliths), it is desirable to use powerful macrotomographs with the high resolution capacity. The application of such tomographs should help us to solve the problem of using larger (and more representative) samples without detriment to the detail of the study.

It should be noted that the tomographic method allows us to measure the volumes of the pores of particular diameter (or radius). This means that we may estimate the content of capillary water in soil capillaries responsible for the soil water retention at the field
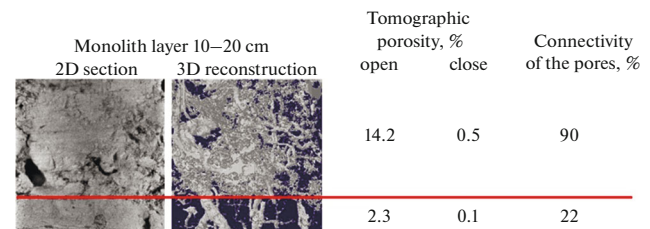

Fig. 6. Differentiation of the pore space of the studied monolith in the layer of 10−20 cm.

soil water content. On other words, tomographic data may be helpful for determination of water retention (water storage) properties of the soils. This opens new possibilities for soil hydrology, as the tomographic method of the study of soil pore space allows us to verify the existing concepts of soil-hydrological constants and their physical substantiation.

The tomographic method may also help us to gain better understanding of soil water stability. The tomographic study of a well-aggregated soil with following calculations may provide data on the contacts of solid-phase particles in soils, including the determination of their number per unit volume and of the surface area of closed pores. These parameters (especially, the number of contacts) are important in terms of the assessment of the water stability of soil structure. Nearest studies should either confirm this theoretical precept of soil rheology, which will make it possible to predict water stability of soil structure from tomographic data, or introduce new knowledge to our understanding of the nature of a number of soil physical phenomena, such as the water stability, mechanical strength, etc.

CONCLUSIONS

Three major stages in the development of tomographic studies of soil porosity can be distinguished: (1) the stage of qualitative examination of the soil pore space, its spatial patterns, and its architecture in relation to the genesis of soils; (2) the stage of quantitative examination of the soil pore space (distributions of the pores by their size, shape, and orientation) with comparison of tomographic data with data on the water retention curve in the capillary range); and (3) the stage of mathematical analysis of tomographic images with a search for the ways of practical application of tomographic parameters. At the current (third) stage, the problems of correspondence of the classical physical structural−functional parameters of the soils to the parameters of tomographic reconstructions of the theoretically and practically important hydrophysical soil properties (such as the filtration coefficient, the water retention curve, and the water stability of the soil structure) come to the forefront of studies in this field. It is necessary to take into account the fact that tomographic data on the pore space characterize just a limited volume of the examined soil monolith, which contains only a part of hydrological paths in the soil. In any monolith, some horizontal pores are "cut off." Thus, as well as in many other fields of soil science, the problem of the representativeness of tomographic images arises.

It can be concluded that the tomographic method as a physically substantiated and nondestructive method of the study of the soil pore space, its volumes, structure, and architecture yields much promise. In particular, it may help us to understand the role of the particular parameters of the soil pore space in the depository and conductive functions of the soils. One can be sure that such studies will provide new data for various fields of soil science, including, in particular, better knowledge of the traditional soil-physical and soil-hydrological characteristics and constants.

REFERENCES

1. K. M. Gerke, M. V. Karsanina, and E. B. Skvortsova, "Description and reconstruction of the soil pore space using correlation functions," Eurasian Soil Sci. **45**, 861−872 (2012).

2. K. M. Gerke, E. B. Skvortsova, and D. V. Korost, "Tomographic method of studying soil pore space: current perspectives and results for some Russian soils," Eurasian Soil Sci. **45**, 700−709 (2012).

3. E. B. Skvortsova, K. M. Gerke, D. V. Korost, and K. N. Abrosimov, "The pore space arrangement in podzolic horizons of loamy soils (analysis of 2D and 3D images)," Byull. Pochv. Inst. im. V.V. Dokuchaeva, no. 71, 65−79 (2013.

4. E. B. Skvortsova and D. R. Morozov, "Micromorphological classification and diagnostics of the pore structure of soil," Pochvovedenie, No. 6, 49−56 (1993).

5. E. B. Skvortsova, V. A. Rozhkov, K. N. Abrosimov, K. A. Romanenko, S. F. Khokhlov, D. D. Khaidapova, V. V. Klyueva, and A. V. Yudina, "Microtomographic analysis of pore space in a virgin soddy-podzolic soil," Eurasian Soil Sci. **49**, 1250−1258 (2016).

6. I. I. Sudnitsyn, *Regularities of Soil Water Migration* (Nauka, Moscow, 1964) [in Russian].

7. A. B. Umarova, *Preferential Water Flows in Soils: The Pattern of Formation and Role in Soil Functions* (GEOS, Moscow, 2011) [in Russian].

8. E. V. Shein, *Lectures on Soil Physics* (Moscow State Univ., Moscow, 2005) [in Russian].

9. E. V. Shein, E. B. Skvortsova, A. V. Dembovetskii, K. N. Abrosimov, L. I. Il'in, and N. A. Shnyrev, "Pore-size distribution in loamy soils: a comparison between microtomographic and capillarimetric determination methods," Eurasian Soil Sci. **49**, 315−325 (2016).

10. J. Bouma, A. Jongerius, O. Boersma, A. Jager, and D. Schoonderbeek, "The function of different types of macropores during saturated flow through four swelling soil horizons," Soil Sci. Soc. Am. J. **41**, 945−950 (1977).

11. J. Bouma, A. Jongerius, and D. Schoonderbeek, "Calculation of hydraulic conductivity of some pedal clay soils using micromorphometric data," Soil Sci. Soc. Am. J. **43**, 261−264 (1979).

12. S. Carnicelli, G. A. Ferrari, and M. Pagliai, "Pore space degradation in Zimbabwean crusting soils," in *Proceedings of the IX International Working Meeting on Soil Micromorphology "Soil Micromorphology: Studies in*

Management and Genesis," Townsville, Australia, July, 1992, Developments in Soil Science vol. 22 (Elsevier, Amsterdam, 1994), pp. 677–686.

13. S. Crestana, R. Cesareo, and S. Mascarenhas, "Using a computed tomography miniscanner in soil science," Soil Sci. **142**, 56–61 (1986).

14. V. Hallaire and P. Curmi, "Image analysis of pore space morphology in soil sections, in relation to water movement," in *Proceedings of the IX International Working Meeting on Soil Micromorphology "Soil Micromorphology: Studies in Management and Genesis," Townsville, Australia, July, 1992*, Developments in Soil Science vol. 22 (Elsevier, Amsterdam, 1994), pp. 559–567.

15. J. Helliwell, C. Sturrock, K. M. Grayling, S. R. Tracy, R. J. Flavel, I. M. Young, W. R. Whalley, and S. Mooney, "Applications of X-ray computed tomography for examining biophysical interactions and structural development in soil systems: a review," Eur. J. Soil Sci. **64** (3), 279–297 (2013). http://dx.doi.org/. doi 10.1111/ejss.12028:1-19

16. J. H. Jin, J. Kim, J.-Y. Lee, and Y. M. Oh, "Correlative multiple porosimetries for reservoir sandstones with adoption of a new reference-sample-guided computed-tomographic method," Sci. Rep. **6**, 30250 (2016). doi 10.1038/srep30250

17. M. V. Karsanina, K. M. Gerke, E. B. Skvortsova, A. L. Ivanov, and D. Mallants, "Enhancing image resolution of soils by stochastic multiscale image fusion," Geoderma **314**, 138–145 (2018). doi 10.1016/j.geoderma.2017.10.055

18. M. V. Karsanina, K. M. Gerke, E. B. Skvortsova, and D. Mallants, "Universal spatial correlation functions for describing and reconstructing soil microstructure," PLoS One **10** (5), e0126515 (2015). doi 10.1371/journal.pone.0126515

19. L. Leu, S. Berg, F. Enzmann, R. T. Armstrong, and M. Kersten, "Fast X-ray micro-tomography of multiphase flow in Berea sandstone: a sensitivity study on image processing transport in porous media," Transp. Porous Med. **105**, 451–469 (2014). doi 10.1007/s11242-014-0378-4

20. M. Naveed, P. Moldrup, E. Arthur, D. Wildenschild, M. Eden, M. Lamand, et al., "Revealing soil structure and functional macroporosity along a clay gradient using X-ray computed tomography," Soil Sci. Soc. Am. J. **77** (2), 403–411 (2013). doi 10.2136/sssaj2012.0134

21. M. Pagliai, "Soil porosity aspects," Int. Agrophys. **4** (3), 215–232 (1988).

22. S. Peth, "Applications of microtomography in soils and sediments," in *Synchrotron-Based Techniques in Soils and Sediments* (Elsevier, Amsterdam, 2010), Vol. 34, pp. 73–101.

23. A. M. Petrovic, J. E. Siebert, and P. E. Rieke, "Soil bulk density analysis in three dimensions by computed tomographic scanning," Soil Sci. Soc. Am. J. **46**, 445–450 (1982).

24. L. F. Pires, J. A. R. Borges, O. O. S. Bacchi, and K. Reichardt, "Twenty-five years of computed tomography in soil physics: A literature review of Brazilian contribution," Soil Tillage Res. **110**, 197–210 (2010).

25. R. Protz, M. J. Shipitalo, A. R. Mermut, and C. A. Fox, "Image analysis of soil—present and future," Geoderma **40**, 115–125 (1987).

26. S. P. Rigby, P. I. Chigada, J. Wang, S. K. Wilkinson, H. Bateman, B. Al-Duri, J. Wood, S. Bakalis, and T. Miri, "Improving the interpretation of mercury porosimetry data using computerized X-ray tomography and mean-field DFT," Chem. Eng. Sci. **66** (11), 2328–2339 (2011). doi 10.1016/j.ces.2011.02.031

27. A. J. Ringrose-Voase and P. Bullock, "The automatic recognition and measurement of soil pore types by image analysis and computer programs," J. Soil Sci. **35**, 673–684 (1984).

28. I. A. Taina, R. J. Heck, W. Deen, and E. Y. T. Ma, "Quantification of freeze—thaw related structure in cultivated topsoils using X-ray computed tomography," Can. J. Soil Sci. **93**, 533–553 (2013).

29. I. A. Taina, R. J. Heck, and T. R. Elliot, "Application of x-ray computed tomography to soil science: a literature review," Can. J. Soil Sci. **88**, 1–19 (2008).

30. J. K. Torrance, T. Elliot, R. Martin, and R. J. Heck, "X-ray computed tomography of frozen soil," Cold Reg. Sci. Technol. **53**, 75–82 (2008).

31. H. J. Vogel and V. Babel, "Experimental relationship between the morphological pore-size distribution and the soil water-retention characteristic," in *Proceedings of the IX International Working Meeting on Soil Micromorphology "Soil Micromorphology: Studies in Management and Genesis," Townsville, Australia, July, 1992*, Developments in Soil Science vol. 22 (Elsevier, Amsterdam, 1994), pp. 591–600.

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