Microtomography research of physical properties of urban soil

S N Gorbov*, K N Abrosimov, O S Bezuglova, E B Skvortsova and S S Tagiverdiev

1 Southern Federal University, 344090, Rostov-on-Don, Stachky prospect, 194, Russian Federation
2 V.V. Dokuchaev Soil Institute, 119017, Moscow, Pyzhevsky lane, 7, bld.2, Russian Federation
*E-mail: sngorbov@sfedu.ru

Abstract. Physical properties and their dynamics under anthropogenic impact are important for the rational use of urban soil and its fertility management. However, due to the urban soils anthropogenic transformation features some classical methods are not applicable in specific cases. Thus, the cutting ring method for determination a soil bulk density does not give objective results in horizons with a high proportion of anthropogenic inclusions. The microtomographic method allowed us to obtain new information on the parameters of the pore space of the humus-accumulative horizons of urban soils. It is shown that the value of closed porosity is the most informative diagnostic indicator of the soil structural condition. Simultaneously, anthropogenic transformation of the soil is accompanied by a significant change in the volume of closed pores. The diameter of macropores visible in tomographic sections increases in the sequence: Urbic Technosols, Technic Chernozems (Calcic), Haplic Chernozems (Calcic).

1. Introduction

Land use in cities and adjacent to city areas is characterized by increased anthropogenic impact. As a result, almost all the soils located within the city boarders are subjected to various degrees of physical degradation derived from different excessive technological loads [1, 2]. At the present stage of urban pedology development, the use of methods generally accepted in soil science in the study of urban soils is associated with a number of difficulties. Therefore, the search for additional research methods is highly relevant; it is possible to get more objective results by adapting the new methods to the study of Urbic Technosols [1].

One of the signs of physical degradation of soils is structural changes occurring at the micro level. By traditional methods (micromorphology), they can be identified, but with limitations. To study the structure and analyze the structural changes that have occurred, in fact, only non-destructive testing methods remain, namely, X-ray microtomography. The high resolution of the survey, combined with modern software data processing methods, makes it possible to restore with great confidence the volumetric structures of soil samples — the solid phase and pore space, and to establish new morphometric indicators characterizing the state of the soil structure.
2. Material and methods

2.1 Description of the study area and soil sampling sites

Objects of this study include natural and anthropogenically transformed soils of Rostov agglomeration.

The Rostov agglomeration is one of the largest agglomerations in southern Russia, which is located in the southeastern region of Rostov oblast and has pronounced monocentric indices. The first level of Rostov agglomeration, so-called Great Rostov, consists of the nucleus (city of Rostov-on-Don) and adjacent cities and rural settlements (Bataisk, Aksai, Chaltyr’) located at 10–12 km from the metropolis.

Physical properties of soils were characterized using a series of humus-accumulative A horizons sampled from 10 soil profiles, which were subdivided, depending on the land use pattern and, hence, the transformation of their morphological properties, into the following groups.

2.1.1. First group. Surface humus-accumulative horizons of soils with natural structure, which are not significantly affected by urbanization processes. These are calcareous ordinary chernozems (A–Bc–Cca) (Haplic Chernozems (Calcic) according to WRB [4]) on upland areas in the park-recreational zone of the city and fallows areas within or adjacent to the city limits.

2.1.2. Second group. Buried humus-accumulative horizons of anthropogenically transformed soils covered by asphaltic and/or other impermeable layers. Shielded urbostatozems (Asf-UR-[A-B-BC-Cca]) (Ekranic Technosols (Molic) according to WRB [4]) and shielded urbistratified chernozems (Asf-UR-[A-B-BC-Cca]) (Ekranic Chernozems (Novic Technic)) and urbostatozems UR1-UR2-[A-B-BC-Cca] (Urbic Technosols). Under the asphalt layer, shielded urban soils retain full-profile chernozems and their characteristic genetic humus-accumulative horizons. This soil type is confined to new residential regions in the peripheral part of the city, although it also can occur in residential quarters of the agglomeration center.

Figure 1. Locations of soil pits in Rostov-on-Don (№1203 - N 47.2776 E 39.7846; №1205 - N 47.2898 E 39.8332; №1401 - N 47.2410 E 39.8185; №1402 - N 47.2513 E 39.6379; №1403 - N 47.2361 E 39.6510; №1405 - N 47.2527 E 39.7696; №1406 - N 47.5045 E 40.1533; №1501 - N 47.2332 E 39.6988; №1503 - N 47.2212 E 39.6302; №1504 - N 47.2333 E 39.6482).
2.1.3. Third group. The humus-accumulative horizon of deep calcareous ordinary chernozem on loess-like loam from the northern Azov region (migration-segregation chernozem according to the 2004 Classification of Russian soils; Haplic Chernozems (Calcic) according to WRB) was used as a conventional reference material. The samples were collected in the Persianovskaya Steppe Reserve, at 52 km to the northeast of Rostov-on-Don. The reserve represents a unique massif of preserved virgin vegetation and soil cover in the Azov upland steppe.

2.2 Analytical methods

The structure of humus-accumulative horizons of urban soils was studied by computer X-ray microtomography. To study urban soils, we used computer X-ray tomography, a method for the nondestructive analysis of the internal structure of solid objects, which is widely applied to different fields of science and industry.

Tomographic study requires a special approach to the selection of soil samples. It was decided to study soil structure in micromonoliths at the natural water content corresponding to the sampling moment. The micromonolith prepared to analysis is a hermetically closed plastic cylinder 3 cm in diameter filled with soil of undisturbed structure (figure 1, panel 4). During the sampling procedure, the soil sample is adjusted to the cylinder size, which retains the internal structure of soil undisturbed [5]. The sealing of sample with a sticky type prevents the shrinkage and closure of pores, which are inevitable at soil drying (Figure 2).

X-ray scanning on a Bruker SkyScan 1172G X-ray microtomograph with a peak energy of 100 keV (10W) and a spatial resolution of 16 µm in the Dokuchaev Soil Science Institute, Moscow. The parameters of the tomographic survey are set based on the experience of successful application in research of gray forest and sod-podzolic soils in the form of samples of a similar size (micromonoliths d = 3cm). [3] The selected resolution makes it possible to confidently detect collector pores coarser than 32 µm involved in the filtration of liquid water and solid-phase particles of analogous sizes.

Processing of tomographic data (shadow projections) and preparation of tomographic sections (reconstruction) were performed using Bruker nRecon software [6]. During the reconstruction, radiation intensity on the initial X-ray patterns is converted to CT density, the resolution of which depends on the used computer system [7].

![Figure 2. Soil sampling for tomographic study.](image)

Tomographic sections were processed and analyzed using the following Bruker software:
- CTvox for the reconstruction of a structural fragment of sample with all revealed X-ray contrast phases;
- CTvol for the reconstruction of separate 3D objects and structures of pore space; and
– CTan for the mathematical processing and calculation of 3D morphological indices of internal structure for X-ray contrast phases. The software provides results in mm³ or percentage of total sample volume. The morphometric parameters include the volume of the studied sample components (pores, aggregates), their surface areas, the sample porosity (total, open, and closed), the content of particles and structural units in the sample, and the content of contacts between linked particles or structural units [6]. The total porosity of sample is determined as the total volume of all pores visible on tomographic images under the given resolution. The open porosity consists of pores traversing the boundaries of the preset virtual cylinder within the sample; the closed porosity consists of pores contained within this virtual cylinder. The distribution of structural elements or particles by size is also available: by average diameter (2D analysis of all available tomographic sections) or by the diameter of spheres inscribed in the boundaries of volumetric structures (3D distance map).

A reliable diagnostic indicator of the structural state of soils based on tomographic data is not currently available, but studies are underway. A combination of several parameters (porosity, size and orientation of solid particles, etc.) is commonly used, often depending on the method of processing and binarization of the data. In case of processing errors, quantitative indicators suffer first of all, and the method of estimating the size of objects is extremely sensitive to point artifacts of the image, especially when measuring three-dimensional structures. As a result, with good resolution of the tomographic survey, there is a possibility of obtaining questionable results. Therefore, the ratio of open to closed porosity is the most promising indicator. (figure 6.). The measurement of porosity is based on the count of black voxels in a virtual volume structure, where the problem of noises (several dozen "wrong" white voxels within a pore space in which the number of black voxels is measured by millions) is simply insignificant. Thus, the only thing on which this indicator depends most strongly is the resolution of tomographic survey, which is determined by the tasks of the study.

In addition to closed porosity, an important diagnostic indicator may be the ratio of closed to open porosity, but in a strictly defined volume (in this case 1.82 cm³, one segment of tomographic survey at resolution 16 μm).

3. Results and discussion

Tomographic studies indicate that the physical properties of the humus-accumulative horizons of the studied urban soils retain similar characteristics regardless of the intensity of anthropogenic transformation processes. All studied samples are characterized by the presence of spherical macropores empty or filled with elastic material, as well as elongated root passages, mainly of vertical orientation. The diameter of macropores visible in the tomographic study increases in a sequence: urbostratozem (Urbic Technosols) – urbostratified chernozem (Haplic Chernozems (Calcic Technic)) – chernozem of layland (Haplic Chernozems (Calcic)) – chernozem of virgin land (Haplic Chernozems (Calcic)) – chernozem of forest-park (Haplic Chernozems (Calcic)) (table 1).

Studies show that the humus-accumulative horizon of the virgin land soil is composed of aggregates of different size divided by abundant pores of packing and large zoogenic hollows. The upper horizons of the chernozems of the forest-park area are the most similar to the chernozems of the virgin land soil, but at a depth of 10–20 cm there is a denser composition with abundant biogenic emissions. Simultaneously, the most brightly abundant zoogenic aggregates are situated in the surface horizons formed under coniferous plantations (figure 3). Generally, multi-order material aggregation and an extensive network of fissure-shaped branched pores of arbitrary orientation with an opening from 0.6 to 1.0 mm, are typical for natural soils. The diameter of the aggregates varies from 0.2 to 5.0 mm.

For natural soils the maximum values of porosity visible on tomographic sections are representative. The total visible porosity, equal to 27.58%, and the open visible porosity, 26.6%, are recorded in A horizon of the Haplic Chernozems (Calcic) of the forest-park area of the city. Nevertheless, even in this soil, which is characterized by an increased content of organic matter (7–8%), the values of porosity are lower than the total bulk porosity, which is determined by traditional
physical methods. This is due to the fact that on a tomograph only those pores that are larger than the resolution of tomographic images is to be measured.

The humus-accumulative horizons of the chernozem of the layland of the city are characterized by a more contrasting soil structure. The compacted and well-shaped soil aggregates are separated by thin fissure pores with the presence of zoogenic processing sites.

Table 1. Volumetric morphometric parameters of surface and buried humus-accumulative A horizons of urban soils (Bruker CT-analysis).

| Soils                                          | 3D model of pore space fragment (CTvol software) | Total porosity, % | Open porosity, % | Closed porosity, % | Pore space connectivity, % |
|------------------------------------------------|-------------------------------------------------|-------------------|------------------|--------------------|---------------------------|
| Haplic Chernozems (Calcic), forest-park, Rostov-on-Don | ![Image](image1.png) | 27.58             | 26.6             | 1.35               | 97.17                     |
| Haplic Chernozems (Calcic), virgin land, township Persianovskij, p.1406 | ![Image](image2.png) | 23.01             | 21.46            | 1.97               | 94.72                     |
| Haplic Chernozems (Calcic), layland, Rostov-on-Don, Botanical garden, p.1403 | ![Image](image3.png) | 13.99             | 12.23            | 2.00               | 88.69                     |
| Haplic Chernozems (Calcic Technic), residential area, Rostov-on-Don, p.1401 | ![Image](image4.png) | 17.76             | 15.19            | 3.03               | 87.29                     |
| Urbic Technosols, residential area, Rostov-on-Don, p.1405 | ![Image](image5.png) | 8.02              | 5.08             | 3.10               | 58.61                     |

It should be noted that the buried humus horizon of Haplic Chernozem (Calcic Technic) is not radically different from the soils of the layland and is not characterized by significant compaction. However, the buried humus-accumulative horizons of Urbic Technosol of residential area of the city are overly compacted and have a strong or very strong stage of degradation of the soil structure (figure 4).

As a result, the minimum values of total and open porosity visible on tomographic sections (8.02% and 3.10%, respectively) are typical for screened humus-accumulative horizons of Urbic Technosol and Haplic Chernozem (Calcic Technic).

The tomographic survey clearly illustrates the distinct individuality of the buried humus-accumulative horizons, which differ from the analogous horizons of natural soils by low aggregation
and solidity of the material. Almost all soils closed under asphalt are compacted or heavily compacted [8]. This fact is confirmed by volumetric morphometric parameters: for anthropogenically transformed soils they differ significantly for the worse (Figure 4).

The pore space is fragmented, represented mainly by the root holes. The pore connectivity into single network is much lower than of the natural soil, which indicates poor drainage properties of this soil and disturbance of its ecological functions, which is predetermined by the thickness of the urbic burial layer that exceeds 40 cm.

The buried humus-accumulative horizon of Haplic Chernozem (Calcic Technic), despite its high density (up to 1.8 g/cm³), is unlike Technosols Urbic and much more similar to Haplic Chernozem (Calcic) of the layland (Rostov-on-Don, Botanical Garden) according to many parameters. The disturbance of the granular structure is noticeably less, the pore space is represented by a multitude of pores of various shapes, the connectivity reaches 87%, which is slightly less than of chernozem of the virgin land. But there are noticeable differences from the chernozems of the layland and virgin land, which are increased closed porosity, many narrow closed pores, and the largest of all samples the surface area of the solid phase. All this may indicate a significant amount of sand in the sample or the repeated introduction of sand from the outside [1].

The closed visible porosity is an essential diagnostic parameter of urban soils. The chernozems of the virgin land and the chernozems under woody vegetation have the value of closed visible porosity of under 10% of the total porosity. The chernozems of the layland and Haplic Chernozem (Calcic) Technic have this value within range from 10 to 15%. The anthropogenically transformed soils have
the value of closed porosity of more than 15% and it can reach almost 40% of the total tomographic volume of the pore space.

The obtained data allowed to plot a curve of distribution of the relative volumes of the closed pore space depending on the content of large-sized aggregates in the soil. This curve is well approximated by a quadratic polynomial and makes it possible to regard the relative value of closed porosity as diagnostic parameters of physical soil degradation (figure 5).

![Figure 5. Relative volume of closed pore under the various blocky aggregate content.](image)

When processing tomographic data of urban soils, such an index as the ratio of open to closed porosity is obtained much more informative and contrasting than simply closed porosity and particle size of solid phase (according to tomography). In soils Haplic Chernozems (Calcic) this indicator reaches 20, in samples of soil from urban areas with moderate anthropogenic load decreases almost twice to 10, and in repackaged blackearths like Urban Technologies decreases to 3. It should be considered that this indicator is new and has not yet been tested when working with different types of soils. The main difference from the indicator of closed porosity is the difference between the soil of the Persianovskij steppe in the suburbs (p. 1406) and the soil of the city botanical garden (p. 1403), where comparable values of closed porosity but different volumes of pore space are (figure 6).

4. Conclusion

Microtomography method allows obtaining information about the parameters of the pore space - the physical characteristics of the soil, which is not studied by traditional methods. Information about the pore space is especially relevant for soils under increased loads, in which there are anthropogenic inclusions that significantly change the physical properties of the soil.

The value of closed porosity that reflects the presence of pores isolated from the rest of the pore space is an informative diagnostic parameter of the structural condition of the soil. The ratio of open to closed porosity in urban soils is a more contrasting indicator than closed porosity and over time can be used in further studies of soil structure as a major one.

Using the example of the Rostov urban agglomeration, it is shown that the anthropogenic transformation of the soil is accompanied by a significant change in the volume of closed pores. The relative volume of closed pores can reach 40% under severe physical degradation.
The diameter of macropores visible in the tomographic study increases in a sequence: urbostatozem (Urbic Technosols) – urbostratified chernozem (Haplic Chernozems (Calcic Technic)) – chernozem of the layland (Haplic Chernozems (Calcic)) – chernozem of the virgin land (Haplic Chernozems (Calcic)) – chernozem of the forest-park (Haplic Chernozems (Calcic)).

Figure 6. Ratio of open to closed porosity and some tomographic values (number of pores in volume 1.82 cm$^3$), closed porosity and average particle size of solid phase (mm).

Acknowledgment
This research was supported by project of Ministry Education and Science of Russia, no. 6.6222.2017/8.9. Analytical work was carried out on the equipment of Centers for Collective Use of Southern Federal University "Biotechnology, Biomedical and Environmental Monitoring" and using the instruments of the Center for collective use of scientific equipment “Functions and properties of soil and soil cover” of the V.V. Dokuchaev Soil Institute.

References
[1] Gorbov S N, Abrosimov K N, Bezuglova O S, Skvortsova E B, Romanenko K A and Tagiverdiev S S 2018 Use of Tomographic Methods for the Study of Urban Soil Properties Urbanization: Challenge and Opportunity for Soil Functions and Ecosystem Services. Proceedings of the 9th SUITMA Congress Moscow Publisher Name: Springer Cham pp 249-59
[2] Lehmann A and Stahr K 2007 Nature and Significance of Anthropogenic Urban Soils J. Soils Sediments 7 (4) 247–60
[3] Gerke K M, Skvortsova E B and Korost D V 2012 Tomographic method of studying soil pore space: Current perspectives and results for some Russian soils Eurasian Soil Sci. 45 (7) 700-09
[4] World References Base for Soil Resources 2006. First update 2007, World Soil Resources Reports, 103, FAO, Rome

[5] Gorbov S N, Bezuglova O S, Abrosimov K N, Skvortsova E B, Tagiverdiev S S and Morozov I V 2016 Physical properties of soils in Rostov agglomeration Eurasian Soil Sci. 49 (8) 898-07

[6] SkyScan NRecon User Guide 2016 (Bruker microCT) p 27

[7] Cullity B D and Stock S R 2001 Elements of X-ray Diffraction 3rd Edition Upper Saddle River (NJ: Prentice-Hall) p 697

[8] Prokof’eva T V, Gerasimova M I, Bezuglova O S, Bakhmatova K A, Gol’eva A A, Gorbov S N, Zharikova E A, Matinyan N N, Nakvasina E N and Sivtseva N E 2014 Inclusion of Soils and Soil-Like Bodies of Urban Territories into the Russian Soil Classification System Eurasian Soil Sci. 47 (10) 959–67