



# Use of Tomographic Methods for the Study of Urban Soil Properties

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**Abstract.** Physical properties and their dynamics under anthropogenic impact are important for the rational use of urban soil and its fertility management. However, standard methods and procedures are hardly usable for the modern urban soil science. New methods from other areas of knowledge, such as computer microtomography widely used in geology, biology, and medicine, need to be searched and adapted.

The objects of the study are SUITMA soils of Rostov agglomeration and their physical properties, transformed under the effect of industrial, residential, and recreational zones, as well as margin city areas, which were affected by agricultural use. According to the results of studies since 1998, urban soils were grouped into morphological classes of (1) natural-structure soils without urban disturbance, (2) natural-structure soils overlaid by anthropogenic sediments, and (3) soils overlaid by water-impermeable layers.

3D scanning of soil samples was performed on a SkyScan 1172 X-ray scanner at the Dokuchaev Soil Science Institute. Image resolution was 16  $\mu\text{m}/\text{pix}$  for the study of internal structure. We used DataViewer and CTan to analyze the images. The samples had natural water content and structure during scanning. Soil samples were then placed in special plastic containers 3 cm in diameter and sealed. Modern analytical methods allow us to analyze separate structural elements, calculate their volume, surface area, amount, and orientation inside of the sample without disturbance. We also can gain data on soil pores (general porosity, open and closed porosities in  $\text{mm}^3$  or %, pore size and volume and their relationship, pore amount, connectivity).

For urban territories in the steppe zone, a comparison of humus-accumulative horizons (A, Asod, Ap, and buried [A] horizons) made it possible to trace tendencies in changes of surface soils under different technogenic and anthropogenic impacts and in the buried and sealed soils. Tomographic data allow us to acquire not only quantitative data, but also visual information.

**Keywords:** Urban soil · Urbanized area · Technosols · SUITMAs  
Calcic Chernozem · X-ray microtomography · Soil structure · Pore space

## 1 Introduction

Land use in cities and urbanized regions is characterized by increased exploitation intensity; therefore, almost all soils within the city are more or less subjected to physical degradation due to different excessive technological loads [1, 2].

Information about the physical properties of soil and consideration of their dynamics under anthropogenic impacts are necessary for the rational use of soils in urban areas and the management of their fertility. However, the use of conventional methodological approaches and procedures faces some problems at the current stage of urban soil science. Thus, search for additional investigative techniques is of current importance, and their adaptation to the study of urbostratozems and urbistratified soils can give more objective results [3].

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. Image brightness (gray gradations) in the X-ray shadow projection reflects the attenuation of X-ray radiation due to the diffusion and absorption of the signal passed through the sample. The attenuation depends on the density and effective atomic number of the substance under study [4]. Computer processing of tomographic projections makes it possible to create a 3D digital copy of internal structure of the object under study and to calculate the morphometric parameters for each visible X-ray contrast phase. Computer tomography is suitable for studying the internal structure of most natural and artificial solid bodies (hard rocks, soil particles [5], composite materials, metal parts, electronic components, etc. [6]). Exceptions are objects with high contents of lead, heavy metals from the lower part of the periodic table, or platinum-group metals. Tomographic study can be performed at different resolution levels, from hundreds of nanometers to fractions of millimeter, depending on the instrument performance.

## 2 Material and Methods

### 2.1 Description of the Study Area and Soil Sampling Sites

Objects of this study include natural and anthropo- and technogenically transformed soils of Rostov agglomeration.

The Rostov agglomeration is one of the largest agglomerations (the population is about 2 million) 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 20 soil profiles, which were subdivided, depending on the land use pattern and, hence, the transformation of their morphological indices, into the following groups:

**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–B–BC–Cca) (Calcic Chernozems according to WRB [7]) on upland areas in the park-recreational zone of the city and fallows areas within or adjacent to the city limits.

**Second Group.** Buried humus-accumulative horizons of anthropogenically transformed soils covered by asphaltic and/or other impermeable layers. Shielded urbostratozems (Asf-UR-[A-B-BC-Cca]) (Ekranic Technosols over Calcic Chernozem according to WRB [7]) and shielded urbistratified chernozems (Asf-UR-[A-B-BC-Cca]) (Novic Chernozems (Ekranic)). 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.

**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 [20]; Calcic Chernozem according to WRB [7]) was used as a conventional reference material. The profile was established 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. Studies were performed on a SkyScan 1172G X-ray microtomograph with a peak energy of 10 keV and a spatial resolution of 16  $\mu\text{m}$  in the Dokuchaev Soil Science Institute. The selected resolution makes it possible to confidently detect collector pores coarser than 32  $\mu\text{m}$  involved in the filtration of liquid water and solid-phase particles of analogous sizes.

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 sealed plastic cylinder 3 cm in diameter filled with soil of undisturbed structure (Fig. 1, panel 4). During the sampling procedure, the soil sample is adjusted to the cylinder size, which retains undisturbed the internal structure of soil [3, 8]. The sealing of sample with a sticky type prevents the shrinkage and closure of pores, which are inevitable at soil drying (Fig. 1).

Processing of tomographic data (shadow projections) and preparation of tomographic sections (reconstruction) were performed using Bruker nRecon software [9]. 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 [10].

Tomographic sections were processed and analyzed using the following software:

- Data Viewer for the preparation and scanning of tomographic sections under the required angle;



**Fig. 1.** Soil sampling for tomographic study.

- CTvox for the reconstruction of a structural fragment of sample with all revealed X-ray contrast phases [11];
- 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  $\text{mm}^3$  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 [12]. 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 [13].

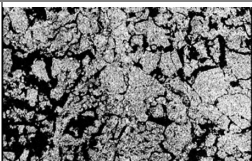
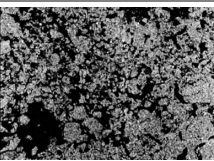
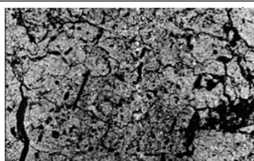
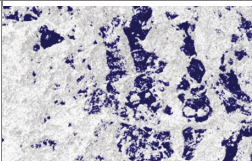
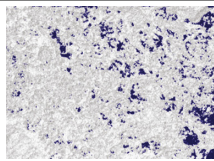
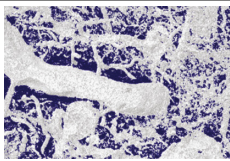
### 3 Results

The morphometric parameters determined in tomographic studies (porosity, pore space connectivity, the number of objects, etc.) are actual only for the resolution used. Some authors [14, 15] showed that the total tomographic porosity of separate chernozem aggregates exceeded 70% under a resolution lower than  $1 \mu\text{m}$ . In our case,

interaggregate porosity (packing pores of structural units, channel pores, and crack pores) becomes the main object of calculation under a resolution of 16  $\mu\text{m}$ . Interaggregate porosity looks like a small closed volume within the soil aggregate and composes only a small portion of the total tomographically-determined volume of pore space. From the obtained data, the total porosity for virgin and forest-park chernozems is 23–28%, and their closed (mainly interaggregate) porosity is 1.3–2%.

Similar imaging conditions allow assessing the scale and details of structural changes in urban soils against virgin chernozem. 3D morphometric data for each object of study, as well as fragments of the vertical tomographic section of sample and the 3D structural model of its pore space, are given in Tables 1 and 2. Scanning and analysis were performed using identical scanning and reconstruction settings.

**Table 1.** 3D morphological parameters of humus-accumulative A horizons of Calcic Chernozem (virgin soil and forest-park).

	Calcic Chernozem, forest-park, Rostov-on-Don	Calcic Chernozem, forest-park, Rostov-on-Don	Calcic Chernozem, virgin, settlement of Persianovskii
Vertical tomographic section (black pores)			
3D model of pore space fragment			
Solid phase volume, $\text{mm}^3$	1322.55	1327.78	1406.02
Solid-phase object surface area, $\text{mm}^2$	22223.96	27137.24	28605.61
Number of solid-phase objects in $1 \text{ mm}^3$	287.58	233.15	221.95
Total number of solid-phase objects	525202	425803	405349
Number of solid-phase contacts in $1 \text{ mm}^3$	460.63	571.56	678.77

(continued)

**Table 1.** (continued)

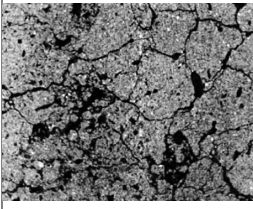
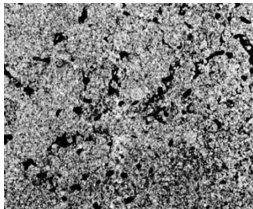
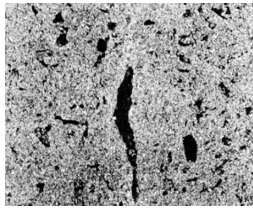
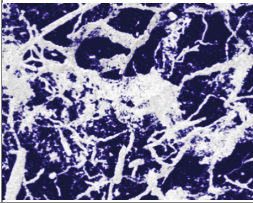
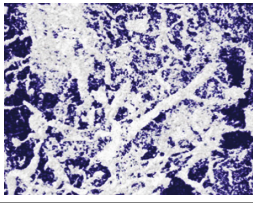
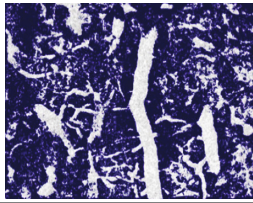
	Calcic Chernozem, forest-park, Rostov-on-Don	Calcic Chernozem, forest-park, Rostov-on-Don	Calcic Chernozem, virgin, settlement of Persianovskii
Total number of solid-phase contacts	841252	1043829	1239631
Number of pores in 1 mm <sup>3</sup>	1227.13	1302.90	1544.39
Number of closed pores in 1 mm <sup>3</sup>	489.79	965.95	1492.52
Total porosity, %	27.58	27.3	23.01
Open porosity, %	26.60	26.09	21.46
Closed porosity, %	1.35	1.64	1.97
Closed pore surface area, mm <sup>2</sup>	4459.58	5191.39	6612.08
Pore space connectivity, %	97.17	96.71	94.72

3D tomographic model of pore space is a good index of soil structural state. It is free from some disadvantages of the planar (2D) analysis of pores and aggregates in thin sections or isolated tomographic sections. The tomographic study easily distinguishes channel pores from bubble pores [16, 17]. In our study, the pore system under a resolution of 16  $\mu\text{m}$  represents a coupled system in which liquid and gas flows move. A very high pore space connectivity (usually >95%) is noted in soils of natural texture. This parameter increases from 94.72 to 97.15% in the series virgin chernozem–chernozem of the forest-park zone, which is primarily related to the higher biogenesity of the latter soil. In the upper horizons of fallow chernozem, connectivity slightly decreases (to 88.69%), which largely agrees with the parameter value for buried humus-accumulative horizon of shielded urbistratified chernozem (Novic Chernozem (Ekranic)): 87.29%. However, pore space connectivity in shielded urbostratozem (Ekranic Technosol over Calcic Chernozem) with strongly deformed structure varies significantly, its filtration properties are disturbed, and connectivity significantly decreases compared to the natural state, as confirmed by our studies.

## 4 Discussion

The obtained results indicate that the humus-accumulative horizons of urban soils, regardless of their anthropo- and technogenic transformation, retain some similar indices, including the presence of spherical macropores, empty or filled with fragmental

**Table 2.** 3D morphometric parameters of surface and buried humus-accumulative A horizons of urban soils.

	Calcic Chernozem, virgin, Botanic garden, Rostov-on-Don	Novic Chernozem (Ekranic), residential zone, Rostov-on-Don	Ekranic Technosol over Calcic Chernozem, residential zone, Rostov-on-Don
Vertical tomographic section (black pores)			
3D model of pore space fragment			
Solid phase volume, mm <sup>3</sup>	1570.76	1501.94	1679.79
Solid-phase object surface area, mm <sup>2</sup>	20932.36	32754.83	17226.98
Number of solid-phase objects in 1 mm <sup>3</sup>	150.03	134.88	96.66
Total number of solid-phase objects	273996	246322	176521
Number of solid-phase contacts in 1 mm <sup>3</sup>	424.01	671.62	310.20
Total number of solid-phase contacts	774361	1226569	566526
Number of pores in 1 mm <sup>3</sup>	1832.05	2199.50	1949.63
Number of closed pores in 1 mm <sup>3</sup>	1303.40	1359.37	1465.78
Total porosity, %	13.99	17.76	8.02
Open porosity, %	12.23	15.19	5.08
Closed porosity, %	2.00	3.03	3.10
Closed pore surface area, mm <sup>2</sup>	7719.96	11335.75	10461.97
Pore space connectivity, %	88.69	87.29	58.61

material, as well as elongated, predominantly vertical, root holes. The diameter of tomographically visible macropores increases in the series of urbostratozem–urbis-tratified chernozem to fallow chernozem to virgin chernozem to forest-park chernozem. Therefore, the parameters of virgin and forest-park soils are close to those of the reference soil. The structure on the tomographic section is seen as undisturbed. Small differences can be due to the features of mesorelief, vegetation, and moisture in the moment of sampling. The humus horizon of virgin chernozem is characterized by multiordinal aggregation with aggregates of 0.02 to 1–1.5 cm in size, as well as a network of fine crack-like pores of random orientation penetrating the entire sample. Crack-like pores reach 0.4 mm in width (diameter). The upper horizons of forest-park chernozems are closest to those of virgin chernozem from suburbs. This is confirmed by the multiordinal aggregation of material and the vast network of branched crack-like pores of random orientation with openings of 0.6 to 1. mm. The aggregate diameter varies from 0.5 to 5 mm (Table 1).

The tomographic imaging data most clearly demonstrate the individuality of buried humus-accumulative horizons of anthropo- and technogenic transformed soils, which differ from other soils by the low degree of aggregation and integrity of material. According to Prokof'eva et al. [18], almost all soils sealed under asphalt are compacted or strongly compacted. This is confirmed by the significantly worse 3D morphometric parameters of anthropogenically transformed soils than those of natural soils (Table 2). Before overlapping the surface horizons of chernozems in city undergo intensive anthropogenic impact. As a result the A horizons structure of Calcic Chernozem, which will become the basis for the formation of Ekranic Technosol were seriously disturbed. Clear signs of overcompaction are observed, as well as lower porosity than in forest-park and virgin chernozems. The pore space is fragmented and mainly consists of root holes, including those of relic roots. Pore space connectivity is significantly lower than in natural soils. This indicates poor draining properties of this soil and disturbance of its ecological functions, which is due to the burying urbic horizons more than 40 cm thick. Almost no granular structure is present, or there are its compacted rests (smaller solid-phase surface area, smaller number of aggregates in the same volume, closed porosity double that of virgin chernozem); therefore, water and gas transfer occurs only in the rests of root hole network.

The buried humus-accumulative horizon of shielded urbistratified chernozem (Novic Chernozem (Ekranic)), despite its high density (up to 1.8 g/cm<sup>3</sup>), is significantly closer to fallow chernozems (Botanic garden, Rostov-on-Don) than to shielded urbostratozem (Ekranic Technosol over Calcic Chernozem). The disturbance of granular structure is appreciably lower; the pore space consists of numerous pores, including aggregate packings; connectivity reaches 87%, which is insignificantly lower than the analogous parameter of virgin chernozem. However, there are distinct differences from fallow and virgin chernozems: increased closed porosity, numerous fine closed pores, and the largest solid-phase surface area. All this can indicate a significant content of sand in the sample or repeated input of sand from outside [19].

From the results of study, fallow chernozems have an extremely diverse structure. The parameters of deep calcareous ordinary chernozem are close to those of undisturbed virgin and forest-park soils, but differences are visible on the sections. The natural structure is partially preserved; a part of volume is occupied by compacted



structures with low porosity but high fracture density. Humus-accumulative horizons on virgin areas are characterized by abundant unioordinal aggregates and their agglomerates separated by fine crack-like pores. Coarse biogenic voids of different shape up to 1 cm in diameter are also common in the soil (Table 2).

Change in the 3D parameters of humus-accumulative horizons should be considered separately for each studied urban soil:

- **Porosity parameters** (total porosity, open porosity, pore space connectivity) decrease in the buried A horizons of anthropogenically transformed soils (Technosols), while closed porosity can increase due to the degradation of channel-pore network and the separation of pore space segments.
- **Surface area** (pore–solid phase interface) changes less significantly when going from the natural to the anthropogenically transformed soil. The amount of inter-aggregate pores decreases and a tendency of soil cracking appears under overcompaction.
- **The number of pores**, especially closed pores, in buried horizons of anthropogenically transformed soils is 2 times higher than in forest-park chernozem and 1.5 times higher than in the humus-accumulative horizon of virgin chernozem. However, the pores are significantly smaller.
- **Solid-phase parameters** (the number of grains, microaggregates, and other particles) also significantly vary between natural and anthropogenically transformed soils and depend on changes in particle size distribution. Under compaction, the aggregated structure disappears, and coarser dense soil particles separated by resting interaggregate pores and cracks remain.
- **The number of objects and contacts** between them in urbostratozem (Ekranic Technosol over Calcic Chernozem) decrease in 2–3 times compared to virgin soil. However, these parameters can increase significantly at the addition of coarse sand to the soil.

From the obtained data, the minimum values of total and open porosity (8.02 and 3.10%, respectively) are typical for the buried humus-accumulative horizons of shielded urbostratozem and shielded urbistratified chernozem. The surface A horizon of virgin chernozem and the buried A horizon of urbistratified chernozem have close values of total and open porosity, which proves the high self-remediation capacity of the entire chernozem type. The maximum parameter values (total visible porosity of 27.58% and open visible porosity of 26.60%) were recorded for the A chernozem of calcareous ordinary chernozem in the forest-park zone of the city. However, in this soil characterized by increased content of organic matter (7–8%), the porosity values are also lower than the total porosity determined by conventional physical methods, because the tomograph determines only visible porosity.

## 5 Conclusions

Tomographic analysis data clearly demonstrate that the A horizon in the forest-park zone is characterized by high aggregation and the presence of aggregates of different diameter (from 0.2 to 5 mm), loose texture, and high tomographically distinguishable

total (27.58%) and open (26.60%) porosity. The buried humus-accumulative horizons of anthropogenically transformed soils are characterized by unpronounced aggregation and integrity. As a result, they have the minimum values of tomographically distinguishable total and open porosity (8.02 and 3.10%, respectively). The diameter of tomographically distinguishable macropores increases in the series: urbostratozem–urbistratified chernozem–fallow chernozem–virgin chernozem–forest-park chernozem.

The surface A horizon of virgin chernozem and the buried A horizon of urbistratified chernozem have close values of 3D morphometric parameters, which proves the high self-remediation capacity of the entire chernozem type.

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