Form and orientation of soil pores as indicators of a structural soil organization

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Abstract. The work is based on the idea that the shape and orientation of soil pores are among the direct indicators of the structural state of the soil. The specific features of the quantitative assessment of the shape of pores in two-dimensional sections by the degree of its difference from the circle are considered. To improve the quality of the evaluation of the pore shape, it was proposed to use a generalized index of the pore shape F, which reflects both roundness and pore isometry. Using the form factor F, the structure of thin macro pores was studied in vertical sections from the genetic horizons of the zonal loamy soils of the European territory of Russia. With the help of cluster analysis in the studied soils, 8 types of pore space specific for the main aggregative soil structures were identified. The selected types differ in shape, orientation and size of thin macro pores in micromorphological sections. By means of discriminant analysis, a system of automated morphometric diagnostics of the aggregate soil structure based on the structure of the pore space of the soil has been developed. The natural genetic divergence of the aggregate structure in virgin soils and the agrogenic convergence of the structure in the arable horizons of agro soils are shown. Morphometric criteria for diagnosing the four main stages of the degradation of the physical structure of the soil according to the shape and orientation of the soil pores are proposed.

1. Introduction

Along with the concept of soil structure as a set of aggregates of various shapes and sizes, it is becoming increasingly recognized that the soil structure refers to the physical structure of the soil substance, due to its size, shape, quantitative ratio, nature of the relationship and the location of elementary soil particles and aggregates [1]. Proposed by A.D. Voronin, this definition emphasizes the spatial and geometric nature of the soil structure. Many parameters of the system depend on how the structural elements of a dispersed body fill the volume that it occupies. One of the main spatial-geometric indicators of the soil structure is the morphological structure of soil voids. In aggregated soil, the structure of the void space reflects the shape and location of the structural units, in a soil with massive structure it serves as an independent geometric indicator of the soil structure.

Currently, methods for diagnosing and evaluating the physical structure of a soil based on the structure of its pore space are actively developing [2]. This includes the analysis of the shape and orientation of soil pores as direct indicators of the structural state of the soil in three-dimensional tomographic reconstructions and thin sections. In 3D images, the shape of soil pores is estimated by the degree of difference between the real pore and the sphere [3,4], and in 2D images by the degree of its difference from the circle [5-8]. These indicators are widely used in the practice of tomographic and
micromorphological studies, but in many cases they give distorted information about the shape of pores in soil samples.

In the present work, the specific features of the common indicator of pore roundness in flat sections

\[ R = \frac{4\pi S}{P^2} \]  

(1)

where \( S \) is the area, \( P \) is the perimeter of the pore section, are considered. A broader approach to morphometric assessment of pore shape in two-dimensional sections is proposed, the possibility of automated morphometric diagnostics of the aggregate soil structure according to the shape and orientation of inter-aggregate pores is considered, examples of the use of pore morphometry in theoretical and applied soil science are given.

2. Objects and methods

Objects of the research were pores of 0.1 < \( d < 2.0 \) mm in vertical orientated thin sections of from different horizons of virgin and arable loamy soils of the European territory of Russia (ETR): podzols, retisols, phaeozems, chernozem, developed on cover loams of different degrees of carbonate. A total of 800 thin sections were examined. Morphometric analysis of pores was performed with an increase of 15x in the field of view of 20x20 mm using the Megiscan-2 and Image-Pro image analysis programs. Measured parameters were area (\( S \)), perimeter (\( P \)), transverse (\( D \)) and longitudinal (\( L \)) dimensions of all pores visible in the field of view. The angle of deviation of the long axis of the pore from the vertical (degrees) was used as an indicator of pore orientation. Methods of cluster analysis and automatic numerical classification of objects were used for processing of the obtained morphometric data [9].

3. Results and discussion

To characterize the shape of flat discrete sections of pores, often used indicators of roundness (1) and isometry

\[ I = \frac{D}{L} \]  

(2)

The first indicator is based on the area ratio (\( S \)) and perimeter (\( P \)), the second is represented by the ratio of transverse (\( D \)) and longitudinal (\( L \)) pore dimensions. Each of these indicators has limited application: the size ratio does not consider the irregularity of the pore walls, the area-perimeter ratio does not distinguish between isometric and elongated sections (figure 1). For a more complete characterization of the pore shape in two-dimensional sections, it is necessary to consider both indicators.

As one of the possible variants of a single form factor, you can use a half-sum of roundness and isometry indicators. In this case, the pore shape factor in flat sections is determined by the formula

\[ F = \left( \frac{4\pi S}{P^2} + \frac{D}{L} \right) / 2 \]  

(3)

where \( F \) is the generalized form factor, \( S \) is the area, \( P \) is the perimeter, \( D \) is transverse, \( L \) is the longitudinal dimensions of the pores [10]. Like its components, the generalized form factor varies from \( F = 1 \) for a circle to \( F << 1 \) for fracture-like contours. Simultaneously, isometric pores, even with very rugged boundaries, do not fall into the interval with low values of \( F \). For these pores, the value of the form factor consists of close to zero values of roundness and close to unity values of isometricity, thus, the indicator \( F \) for them approaches to 0.5.

The generalized form factor was tested in the analysis of thin soil macropores 0.1 < \( d < 2.0 \) mm, characterized by a large variety of forms. In Figure 1, the dashed lines show the boundaries that divide the pores into five classes according to the magnitude of the form factor: 0 < \( F \leq 0.2 \); 0.2 < \( F \leq 0.4 \); 0.4 < \( F \leq 0.6 \); 0.6 < \( F \leq 0.8 \); 0.8 < \( F \leq 1.0 \) (classes 1, 2, 3, 4, 5). Fracture pores fall into the first class, pores with rounded and isometric cuts close to them fall into the fifth class. The middle classes are more heterogeneous in composition. However, the pore distributions in these five classes reflect the main structural features of the pore space of soils: fracture, the presence and content of openwork pores in the
packaging of lumpy aggregates, the presence and content of smooth-walled channels and weakly rugged pores trapped in the non-aggregated soil mass.

800 vertical thin sections of the main types of EPR (European Part of Russia) loamy soils were analysed using the generalized form factor $F$. Basing on pore distributions in terms of $F$, as well as considering their orientation and longitudinal dimensions, 8 types of pore space structure with a level of similarity within the types of not less than 70% were identified using cluster analysis in the aggregate of these sections (figure 2). These eight types are isolated from larger groups with a lower level of internal similarity.

Each of the types coincides with one of the following soil structures in thin sections: 1 - massive (not divided into aggregates), 2 - fissured-massive, 3 - massive-fissured, 4 - lumpy, 5 - granular, 6 - walnut, 7 - lamellar, 8 - massive-lamellar (figure 3). Thanks to discriminant analysis, an automatic morphometric diagnostic program of the soil structure was created based on the structure of the pore space of the soil. Under this program, the studied section, represented by the parameters of the structure of thin macropores, automatically belongs to the closest type of soil structure. To assess the quality of the developed system, a comparison was made of the results of automated diagnostics of the soil structure in thin sections and its expert visual assessment. On average, with a sample size of 10 sections, more than 75% coincidence of estimates was noted. Moreover, with a massive, lumpy, lamellar and massively lamellar structure, the coincidence of visual and automatic assessments was equal to or exceeded 90%. Less pronounced convergence of results with fissured-massive, granular and walnut structures. However, in most cases, the scatter of estimates does not go beyond the boundary types.

The study of both the pore space and the soil structure can have theoretical and application value. Thus, in the zonal series of virgin loamy soils of the EPR, automated morphometric diagnostics revealed a natural genetic divergence of the types of pore space in the upper soil horizons (Figure 4).

Accordingly, there is a natural genetic divergence of the aggregate soil structures. Since the studied soils are developed in soil-forming rocks of similar structure and are located in similar autonomous geomorphological positions, the divergence of the pore space and aggregate structure can be associated with changes in modern and ancient bioclimatic factors.
During tillage and agricultural cultivation of loamy soils, there is an agrogenic convergence of the shape of the pore space and the aggregate structure of non-degraded arable horizons. Convergence processes are due to the uniformity of the anthropogenic impact on arable soil, which aims to increase soil fertility. The similarity is most pronounced at a depth of 0–10 cm, where the influence of agrotechnical treatment and the effect of plant roots have a stronger effect (figure 5).

Figure 3. Schematic images of 8 types of pore space in thin sections from different horizons of loamy soils on the European territory of Russia. The pores are black.

Figure 4. Occurrence of pore space types in zonal virgin loamy soils of EPR.
The presence of agrogenic convergence allows us to adopt a single standard for the optimal spatial-geometric organization of arable horizons for all loamy soils of the European Russia. This standard implies an abundance of lumpy aggregates separated by isometric rugged pores of a package without preferential orientation (Figure 6).

Figure 5. Types of pore space of virgin (A) and arable (B) loamy soils in the coordinates of principal components. Depth is 0-10 cm. The contribution of the first two components to the total dispersion for virgin soils (A) is 88%, for arable soils (B) - 80%.

The main factor in the convergence of the shape and orientation of the inter-aggregate pores in the arable horizons of the soils of different natural zones is the similarity of agricultural development methods. In this regard, the uniformity of inter-aggregate pores is observed not only in cultivated, but also in degraded soils. The study of arable sod-podzolic, gray forest soils and chernozem in various agricultural conditions made it possible to identify the general stages of agrogenic degradation of the

Figure 6. Non-degraded lumpy structure and variants of degraded structures in the arable horizons of the loamy soils of EPR. Pores are white.
porous-structural state of loamy soils: 1 - compaction of the soil mass without changing the shape and orientation of pores; 2 - the appearance of angular aggregates and cracked pores between them; 3 - the appearance of both angular aggregates and fissure-like pores with a horizontal orientation; 4 - complete disappearance of aggregates and the formation of a massive structure with pinched round pores (figure 6, 1-4).

The listed stages can be characterized by generalized quantitative indicators for pores 0.1 <d <2.0 mm, which diagnose the degradation of the aggregate structure of the soil in arable horizons (table 1).

Table 1. Indicators of transformation of the inter-aggregate pore space of the arable horizons during the degradation of loamy soils.

| Transformation stage | Pore content, % of total porosity | Pore form factor, F | Horizontal orientated |
|----------------------|----------------------------------|--------------------|-----------------------|
|                      |                                  | 0.4<F≤0.6          | 0.6<F≤1.0             | ≤40   | <40   | >40   | N/A   |
| 1                    | >40                              |                    |                      |
| 2                    | ≤40                              | <30                |                      |
| 3                    |                                  |                    |                      |
| 4                    | ≤20                              | ≥40                |                      |
|                      |                                  |                    |                      |

5. Conclusion

The shape and orientation of soil pores are among the direct indicators of the structural state of the soil. Currently, the relevance of a quantitative assessment of the shape of pores according to the degree of their roundness and isometry in two-dimensional sections remains. However, the separate use of indicators of roundness and isometry can significantly distort the results. To improve the quality of the pore shape assessment, you can apply the generalized index (3) where F is the generalized form factor, S is the area, P is the perimeter, D is transverse, and L is the longitudinal dimensions of the pore slices.

In the loamy soils of the EPR, 8 types of pore space specific to the main aggregative soil structures are distinguished. The selected types differ in shape, orientation and dimensions of thin macropores in thin sections. Thanks to discriminant analysis, a system of automated morphometric diagnostics of the aggregate soil structure based on the structure of the pore space of the soil has been developed. The results of automated diagnostics of soil structure in thin sections by more than 75% coincide with its expert visual assessment.

The method of automated diagnostics revealed the natural genetic divergence of the structure of the pore space and the aggregate structure in virgin soils and the agrogenic convergence of these indicators in the arable horizons of agrosoils. Agrogenic convergence is observed not only in cultivated, but also in degraded soils. In this regard, morphometric criteria are proposed for the diagnosis of the four main stages of the degradation of the physical structure of the soil according to the shape and orientation of the soil pores.

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