Application of image analysis for soil macropore characterization according to pore diameter

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A b s t r a c t. Soil scientists often examine the soil structure and macroporosity by observing sections using a variety of microscopic and photographic techniques. The most frequent parameters used in the image analysis to characterize pores are: shape factors (like circularity, compactness, elongation, *etc*.), size parameters (surface area, Crofton perimeter, *etc*.) and arrangement *eg* MBR (minimum bounding rectangle) angle. The pores are usually classified according to equivalent pore diameter estimated from the area of pores.

This paper presents a proposal of a method for separating macropores according to their real diameter. Aphelion, the image analysis system, was used to prepare a procedure for splitting soil macropores and dividing them into selected fractions according to the diameter. The procedure was tested on porous and compacted soil samples which differ in their porosity, pore shape and size. The results show that the detection of macropores according to the real pore diameter is suitable for the characterization of the actual state of soil macroporosity, especially in porous soils with continuous branching macropore system.

K e y w o r d s: macroporosity, pore diameter, image analysis

INTRODUCTION

Soil macroporosity is an important indicator of soil structure conditions. Management practices in agriculture as well as meteorological factors, amelioration, and root and earthworm activity, induce changes in soil porosity (Bryk *et al.*, 2000; Pagliai and Vignozzi, 2002). Soil macroporosity is also a well-known factor influencing soil fertility, gas exchange, and water movement (Bullock and Thomasson, 1979; Gliński and Stępniewski, 1985). The importance of macropores in many soil-plant-root relations has motivated many researches to describe their features like shape, size, orientation and arrangement. To quantify soil structural changes, pore space measurements are being increasingly used. Image analyses on sections prepared from undisturbed soil samples allow precise quantification of soil macroporosity (Pagliai *et al.*, 1983; Ringroase-Voase and Bullock, 1987). Pore size distribution is often used to characterize soil pores with pore diameter as the criterion for this distribution.

The pore diameter is usually equal to an equivalent pore diameter (EPD) calculated from the surface area (*S*) of pores (Bryk, 2001):

$$EPD = 2\sqrt{(S / \pi)}. \qquad (1)$$

In fact pores have a wide range of size and shape, especially pores of soils in agricultural use (Czachor and Lipiec, 2004; Pagliai and Vignozzi, 2002). In some cases pores are rounded and they are classified as chambers, channels or spherical pores. These pores are the result of earthworm, root or gas bubble activity. In many other cases pores are irregular, with numerous links, and they develop continuous pore space around soil aggregates (Fitzpatrick, 1980; Ringroase-Voase and Bullock, 1987). Equation (1) is suitable only for such regular and oval pores. When calculating the equivalent pore diameter, the whole continuous pore space is treated as one object with an enormous area. In this case the equivalent pore diameter calculation does not make any sense.

The developments in image analysis provide a possibility of introducing more accurate methods for macropore characteristics. The aim of this study is to propose a new method for macropore identification based on real pore diameter and not dependent on the surface area of particular pores.

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MATERIALS AND METHODS

In 2005 soil samples were taken from a pot experiment located in Mydlniki near Cracow, with different levels of soil compaction as the treatment (Głąb, 2005). The pot experiment was conducted in 2003-2005. The treatment of this experiment was soil compaction in completely randomized design with four replications. The three levels of soil compaction were established according to the degree of compactness (D): 70% (D70), 80% (D80) and 90% (D90). The range of D from 70 to 90% is characteristic for agricultural soils and corresponds to results obtained by Hakansson and Lipiec (2000). The degree of compactness is defined as the dry bulk density as a percentage of reference bulk density obtained by a standardized uniaxial compression test (Proctor test) at 200 kPa (Håkansson, 1990; Håkansson and Lipiec, 2000). The reference bulk density of the soil used in the experiment was 1.65 g cm^{-3}. Table 1 reports the soil characteristics. The D70 compaction level was established using a 1 kg compaction hammer dropped from a height of 50 cm. For the D80 and D90 levels, 5 and 10 kg hammers were used, respectively. After compaction, alfalfa (*Medicago sativa*) seeds were sown at a rate of 16 plants per pot. For further analysis soil samples from two treatments: very porous (D70) and strongly compacted (D90) were taken into consideration (Table 2). The soil sections were prepared from undisturbed soil samples (Jongerius and Heintzberger, 1975; Murphy, 1989; Słowińska-Jurkiewicz and Domżał, 1988). They were taken from the 10-18 cm soil layer in a vertical position using metal boxes (80x90x40 mm). Samples were dried at room temperature for 4 weeks. Then they were saturated with polyester resin (POLIMAL 109 32K) at a tem-

perature of 20°C. The samples were put in a vacuum chamber. The pressure was cyclically (5 times) changed from -85 kPa to atmospheric pressure in order to remove any entrapped air. The hardening of the resin took approximately two months. Then the samples were cut to slices (5 mm thick) using a diamond cutting machine with a water cooling system. After cutting the surfaces of the slices were grinded to remove any scratches.

The surfaces of samples were scanned, at a resolution of 600 dpi, using Epson Perfection 4870 Photo scanner and the images were saved as tiff files. The images were analysed using the APHELION software for image analysis (ADCIS SA, AAI Inc., 2002). The whole procedure of image analyses was composed of 4 main steps: filtering, segmentation, pore detection and measurements (Wojnar and Majorek, 1994). For every image two procedures of image analysis were applied. One of them was pore selection according to their real pore diameter. The real pore diameter (RPD) can be defined as the length (μm) of straight line that extends from one edge of the object (pore) to the opposite edge, through the centre of the object (circular pores), or perpendicular to the longitudinal axis of the object (elongated pores). The following Aphelion functions were used to prepare this procedure:

1. ImgColorToRGB - the input image (Fig. 1) was split into three bands: red (R), green (G) and blue (B). Because of the best contrast, grey image based on the red band (R) was prepared for further processing.

2. ImgLowPass3x3 – to perform low-pass filtering on an image using a 3x3 kernel in order to remove noise from the image.

T a b l e 1. Chosen paprameters of the investigated soil (silty loam)

Parameters	Units	Values
pH (KCl)	(-)	6.5
Total organic C	g kg^{-1}	25.8
Total N	g kg^{-1}	2.10
C/N	(-)	12.3
Reference bulk density	g cm^{-3}	1.65
Sand	g kg^{-1}	290
Silt	g kg^{-1}	670
Clay	g kg^{-1}	40

T a b l e 2. Physical parameters of tested soils

Para-meters	Density of solid phase (g cm^{-3})	Bulk density (g cm^{-3})	Total porosity (cm^3 cm^{-3})	Penetration resistance (MPa)
D70	2.53	1.20	0.526	1.1
D90	2.53	1.56	0.383	3.2
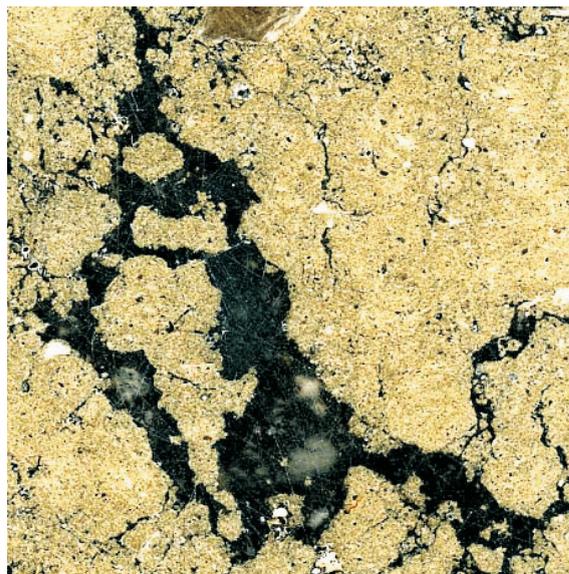
Fig. 1. Cross section of soil from 10-18 cm soil layer (fragment with dimensions of 2x2 cm, pores appear black).

3. ImgMaximumContrastThreshold – this operator picks a set of thresholds that give maximal contrast. It automatically selects thresholds that maximize the global average contrast of edges detected by the thresholds across the image (Fig. 2).

4. ImgOpen – this operator performs a morphological opening on all the regions and it was used to remove small objects with 1 pixel area.

5. ImgThinSkeleton - thinning of the objects to get a line in the middle of the object (Fig. 3).

6. ImgGraphDistance - this operator computes for every white point of a binary input image the distance to the background (distance to the nearest black point) (Fig. 4).

7. ImgDilate – this operator is used to perform a morphological dilation of the source objects due to increase of grey level filling from the centre to the border of objects (Fig. 5).

Fig. 2. Macropores selected by ImgMaximumContrastThreshold operator (pores appear red).
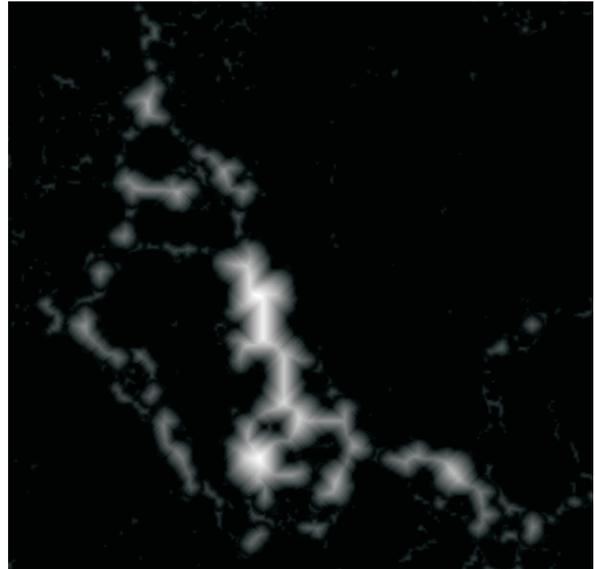
Fig. 4. Image after mgGraphDistance operator. The brightness of pixels depends on the distance between the centre and the border of objects.

Fig. 3. Skeleton of macropores after ImgThinSkeleton operator.
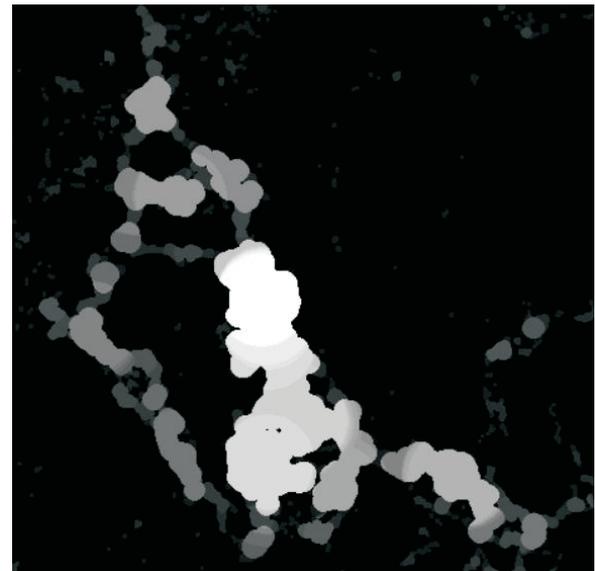
Fig. 5. Dilated pixels fill in the objects with full range grey level value.

8. ImgTreshold – to create the binary image. Using six different ranges of threshold bounds allows to get six groups of objects differing in size (Fig. 6).

9. ObjComputeMeasurements – the final operator which computes a variety of measurements for different spatial objects.

Then the second procedure for selecting pores according to the equivalent pore diameter was applied (steps of procedure described above):
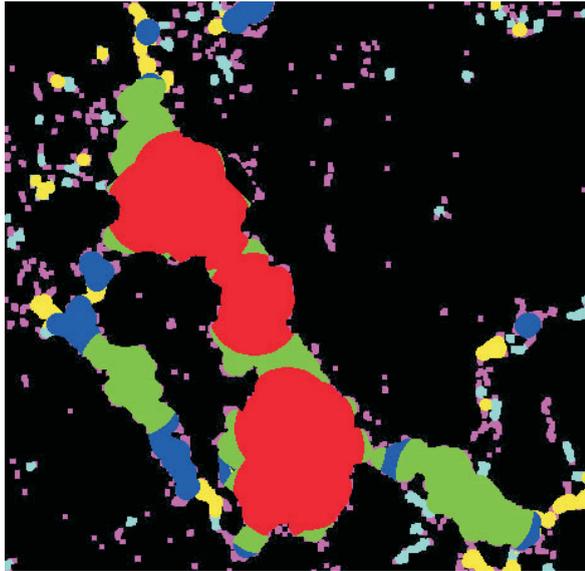
Fig. 6. Macropores divided into six fractions according to pore diameter. (>2000 µm, red; 1000-2000 µm, green; 500-1000 µm, blue; 200-500 µm, yellow; 100-200 µm, light blue; 50-100 µm, purple color).

1. ImgColorToRGB
2. ImgLowPass3x3
3. ImgMaximumContrastThreshold
4. ImgOpen
5. ObjComputeMeasurements – calculation of equivalent pore diameter based on the area of pores (Eq. 1).

Finally two sets of objects (pores), resulting from both methods of pore selection, were divided according to their shape and size. The pores were divided into six fractions according to their diameter:
– >2000 µm,
– 1000-2000 µm,
– 500-1000 µm,
– 200-500 µm,
– 100-200 µm,
– 50-100 µm.

The pores of every fraction were also divided according to their shape as expressed by circularity (Eq. 2) as the shape factor (Pagliai, 1983):

$$c = 4\pi\, A/P^2 \qquad (2)$$

where: c – circularity, A – area, P – perimeter.

The macropores were divided into three shape classes:
– regular – circularity of 0.5-1.0,
– irregular – circularity of 0.2-0.5,
– elongated – circularity of 0.0-0.2.

RESULTS

Two methods of splitting macropores, according to EPD and RPD, were compared for two kinds of soils differing in their macroporosity. The results showed that for porous soil with large continuous pore space (Fig. 7) the
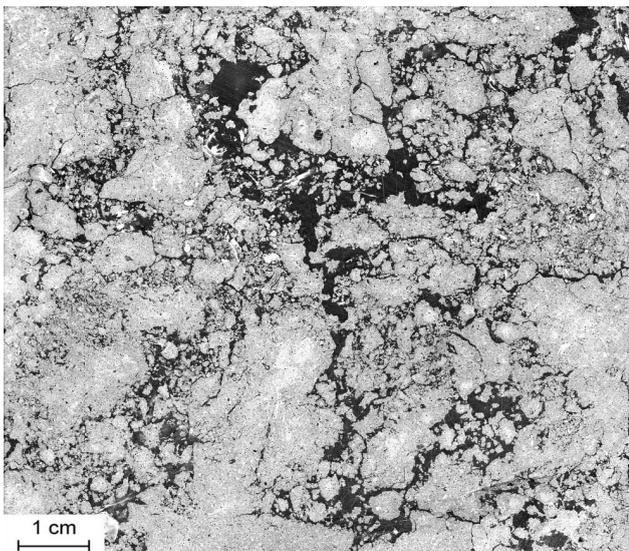
Fig. 7. Example of porous (D70) soil sample (pores appear black).
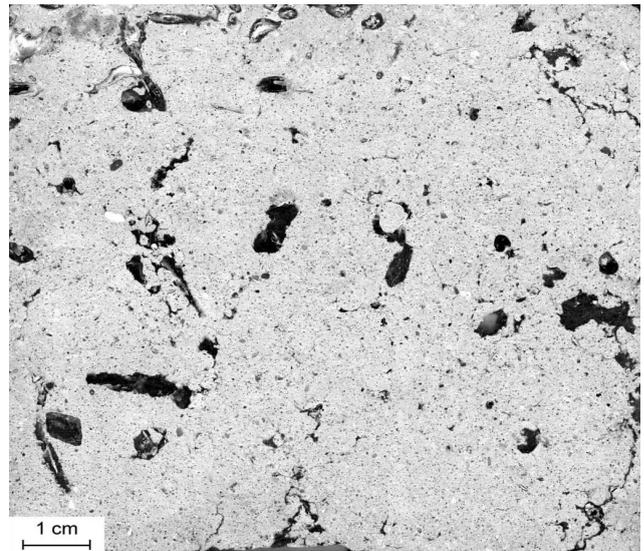
Fig. 8. Example of compacted (D90) soil sample (pores appear black).

method of splitting pores based on the RPD provides better characterization of their geometry. Pore characterization according to the EPD treated all connected pores as one pore with big area and it yielded an enormously big pore diameter (Fig. 9). The final result showed considerable participation of pores with >2000 μm in diameter, approximately 9% (42% of the total pores area). All of these pores were in 100% recognized as elongated. Whereas, the pores with >2000 μm in diameter, determined according to the RPD, were only 5% of total macroporosity. There was different participation of regular, irregular and elongated pores, 81, 11, and 8% respectively. For other fractions of pores similar relationships were noticed.

As the compacted soil was considered, the results were very similar for both methods of pore quantification. This soil was characterized by discrete, separated and rounded pores, usually produced by earthworms and roots (Fig. 8). For this kind of pores there were no significant differences between the compared methods of pore quantification in the participation of different pore fractions, in terms of both shape and diameter classification (Fig. 10).

Summarizing the above considerations it was found that proposed method of splitting macropores according the RPD is suitable for all types of soil structure. Particularly for branching pores system, the results reflect the real pore arrangement. In fact most of the soils in agricultural use (including grasslands and forests) are characterized by such a type of structure. The proposed method would be recommended for structure analysis in the investigation of the influence of tillage, crop rotation, organic fertilization, etc.
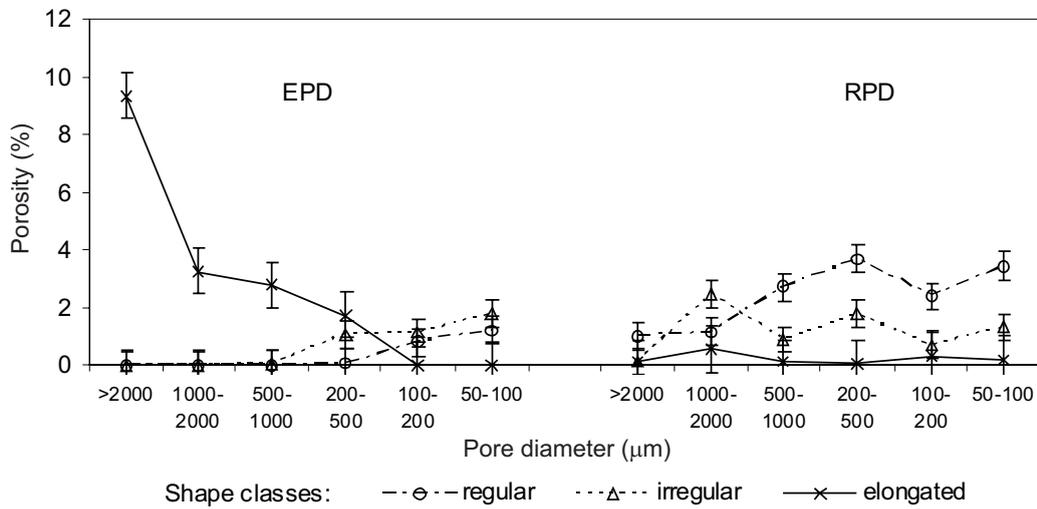
Fig. 9. Pore distribution of porous soil (D70) according to EPD and RPD detection. Bars represent standard error.
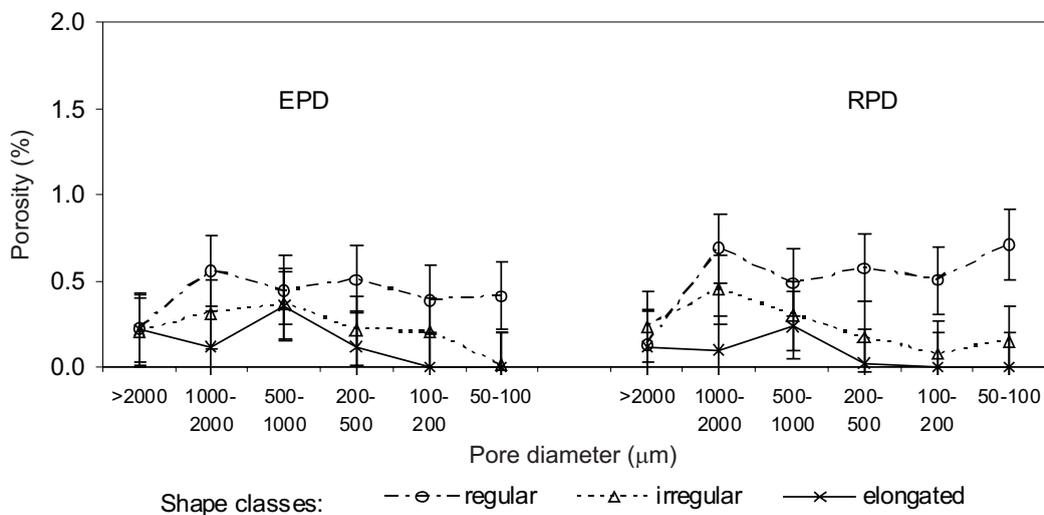
Fig. 10. Pore distribution of compacted soil (D90) according to EPD and RPD. Bars represent standard error.

CONCLUSIONS

1. Application of presented image analysis procedure in soil structure characterization allows to separate the pore classes according to their real diameter

2. Soil macropore classification based on equivalent pore diameter does not reflect the real macropore arrangement, especially in porous soil with continuous branching macropore system.

3. The detection of macropores according to the real pore diameter is a proposition for the characterization of the actual state of soil macroporosity corresponding with air-water properties of soil.

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