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EFFECT OF STRESS ON STEREOLOGICAL PARAMETERS OF POLISHED SECTIONS OF SOIL SAMPLES*

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A b s t r a c t. Subjecting soil to uniaxial stress causes its compaction and, at the same time, a change in its structure. So, it is important to find methods allowing to estimate such changes. The present study proposes the use of a stereological method, and estimators of a few physical values, eg. porosity and interaggregate distance, have been selelcted for the analysis. Attempts have also been made to find the answer to the question whether it is possible to determine the number of soil aggregates, which had been destroyed during sample compression, using stereological methods. The answer to this question can be obtained by analysing the changes in granulometric distribution, which ware connected with the change in the number of aggregates in individual fractions. It has been indicated that the procedure, the idea of which had been presented earlier by Rush, is fit for determination of such distribution.

K e y w o r d s: stereology, image analysis, histogram, grain size distribution, soil aggregate

INTRODUCTION

The knowledge of the structure examined materials is very important in agrophysical research. Determination and estimation of the structure changes during processing is essential for the construction and verification of physical hypotheses and theories describing the dynamic properties of the media being investigated. Thus, we pay much attention to obtain these pieces of information. They should give full and precise description of the media subjected to research. The most desirable thing here is to obtain 3D information about the shape and localization of the elements both on the surface and inside the examined medium. For the changes structure estimation, it would be very important to apply non-destructive methods which would allow for process examination on physically the same sample. Computer tomography gives a chance for fulfilling the requirement.

Stereological methods are a step torwards obtaint data for 3D media description. Stereology deals with finding value estimation methods for some statistical parameters of 3D sample structure on the basis of the information included in 2D image. So far, it was labour-consuming because of the necessity of totally manual image analysis. Nowadays, there are computer systems with special software, called image analizers, which measure in a highly automatic way. Their application can make these methods more competitive to other methods or at least can be an additional information source. In this paper, we attempt to estimate sensibility of stereological methods from the point of view of structure changes detection. Monoaggregate soil sample subjected to 1-axial compression is the examined material

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here. The aim of this paper is to determine porosity, interaggregate distances and aggregates which were crushed, i.e., divided into smaller parts.

The image analysis system was applied in this research. The aim of image analysis is to obtain one or a few parameters which would describe the examined images. In modern systems, this image analysis is automatically carried out together with presenting and storing the results in a required way. Before measurements, it is often necessary to prepare, process and elaborate an image so as to remove noise and undesirable elements.

THEORY

As it was mentioned before, owing to stereological analysis we can estimate the values of some parameters which describe space structure of a certain sample. The results obtained by image analysis are the basis for carrying out this analysis. While interpreting the results, we should remember that they are obtained by the application of some statistical laws. Because of it, the choice of certain parameters, which we want to estimate, depends on additional pieces of information on the examined material which influence the choice of a certain 3D structure statistical model and its representation on the surface of a cutting which is an object of direct observation and image analysis.

For the purpose of this paper, stereological parameters of the grained material were divided into 2 groups: structure statistical parameters of a given medium phase and the distribution of certain objects characteristic for this phase.

Structure parameters

There are 5 parameters applied in this paper:

1. Relative volume of medium grain is denoted by V_V in stereological notation. It is a measure of the coherence of a medium and is related with porosity. Some quantities, enumerated on the intersection, can be used by estimators. These quantities are related in the following way:

$$V_V = A_A = L_L = P_L \quad (1)$$

where A_A - the ratio of the sum of object surface areas to total intersection surface area; L_L - the ratio of the sum of chords random lengths of objects to the total length of all random chords; P_P - the ratio of the number of random points hitting the objects to the total number of all random points (Fig. 1).

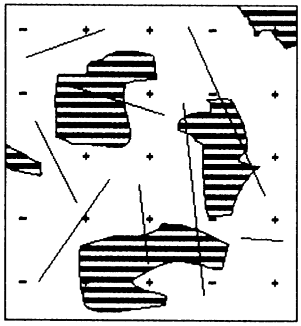

Fig.1. Intersection surface representation with objects marked in grey. + mark random points whereas lines stand for random secants.

A_A value can be obtained by image analysis. Other equalities were applied in the past, when obtaining this parameter was labour-consuming. Then, to obtain A_A, object profiles were copied into a sheet a paper and then, the paper was weighed. After that, the drawn objects were cut out and weighed again; the weight proportion was found to have A_A value.

2. Porosity of medium:

$$R = 1 - V_V . \quad (2)$$

3. Grain medium relative surface *SSUBV*. It is a proportion of the medium surface to the total volume of the medium. It can be estimated in the following manner:

$$S_V = 2P_L = \frac{4B_A}{\pi} \quad (\mathrm{mm}^{-1}) \quad (3)$$

where P_L - number of random secant intersections (Fig. 1) with object boundaries per length unit of secants; B_A - the sum of objects boundaries lengths to intersection surface.

4. Average chord length of grains of medium L_3:

$$L_3 = \frac{4V_V}{S_v} \quad \text{(mm)}. \tag{4}$$

5. Average object distance of grains of medium λ:

$$\lambda = \frac{L_3\,(1 - V_V)}{V_V} \quad \text{(mm)}. \tag{5}$$

Histograms

Grain size distribution, i.e. histogram of grain medium diameters, is an important parameter that describes an examined material. By its determination, it is assumed that grains can be described by spheres with a good approximation. The examined parameter can be obtained by image analysis of a polished section. Here the first issue is the observation that the probability of obtaining the *d*-diameter circle as the result of cutting the *D*-diameter sphere by the plane of random localization is established by the following formula:

$$dP_{D_{sphere}}(d_{circle}) = \frac{d_{circle}}{D_{sphere}\sqrt{D^2_{sphere} - d^2_{circle}}}\, d\,(d_{circle}). \tag{6}$$

This equation and Fig. 2 imply that obtaining a circle of a diameter equal to the sphere diameter is the most probable one. Thereby, the distribuant is established by the formula:

$$T_D(d) = \begin{cases} 0 \text{ for } d<0 \\ 1 - \sqrt{1 - \left(\frac{d}{D}\right)^2} \text{ for } d \in (0;D) \\ 1 \text{ for } d \geq D \end{cases} \tag{7}$$

and the probability of finding a diameter circle within the range $<d_{\min}; d_{\max}>$:

$$P_D(\Delta d) = P_D(d_{\min}; d_{\max}) = T_D(d_{\max}) - T_D(d_{\min})$$

$$P_D(\Delta d) = \sqrt{1 - \left(\frac{d_{\min}}{D}\right)^2} - \sqrt{1 - \left(\frac{d_{\max}}{D}\right)^2}. \tag{8}$$

The histogram of circle diameters presented in Fig. 2 refers to monoaggregate media, i.e., in which only spheres of one *D* diameter occur. For the non-monoaggregates, the histogram of circle diameters is formed as the sum of such histograms for all sphere fractions (Fig. 3). It is possible to obtain grain size distribution from such a summary histogram of circle diameters. One simply has to solve the equation considering:

$$NA_i = \sum_{i=1}^{n} \alpha_{ij} N_{Vj} \tag{9}$$

where N_{A_i} - number of circles of a diameter from i-th bin of circles histogram; N_{V_j} - number of spheres of D_j diameter of grain size distribution;

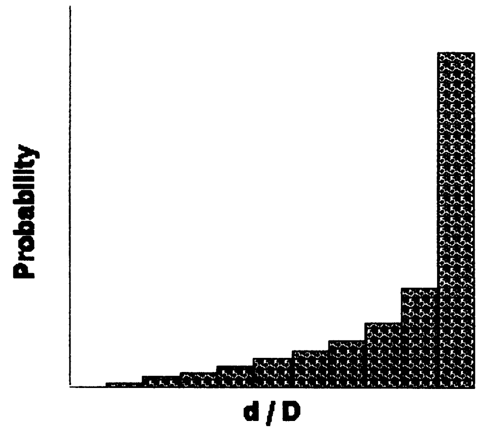

Fig. 2. Circle diameter histogram measured from intersections in monoaggregate media.

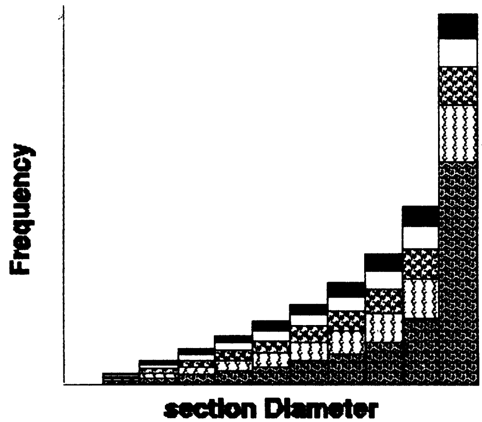

Fig. 3. Circle diameter histogram measured from intersections in non-monoaggregate media.

$\alpha_{ij} = P_{D_j}(\Delta d_i)$ - probability of obtaining the circle of a diameter from the range by cutting of D_j-diameter sphere (Eq. 8); n - number of histogram bins and grain size distribution bins.

Coefficients matrix α_{ij} is a top-diagonal. It results from the fact that there cannot be a circle formed by sphere cutting the diameter of which would be bigger than the diameter of this sphere. Thus, the substitution method can be applied to solve the Eq. (9) and present the recurrent formula:

$$N_{V_j} = \alpha_{ij}^{-1}\left(N_{A_i} - \sum_{i=j+1}^{n} \alpha_{ij} N_{V_i}\right). \qquad (10)$$

The recurrence starts from $j=n$ and aims to $j=1$.

The formula (9) determines grain size distribution on the basis of diameter object histograms. Another way of determining this characteristic is the application of area and perimeter length histograms. Only circle diameters must be calculated from areas and perimeters length (for all objects) to utilize the known relations:

$$d_A = 2\sqrt{\frac{A}{\pi}} \qquad d_L = \frac{L}{\pi} \qquad (11)$$

where A - object area; L - object perimeter length; and then create appropriate histograms and solve matrix Eq. (9).

MATERIALS AND METHODS

A test on monoaggregate soil sample was carried out to determine the influence of stress on the stereological quantities presented in the previous chapter. Brown soil of the grain size distribution of medium loamy clay was applied in the research.

The sample was taken from the arable horizon of the soil and after drying to the air dry state it was sifted out by sieves to obtain narrow aggregate fractions of 2 mm diameter. Next, the soil was poured into 4 metal cylinders of a volume of 100 cm^3 and was subjected to the following 1-axial stress, respectively 0, 100, 200 and 300 kPa. The samples prepared in this way were saturated with methyl methacrylate and the process of polymerization was started to fix soil structure. After that, the samples were cut, ground and polished. This method of sample preparation is applied in the Strata Mechanics Research Institute.

IPS-512 image analysis system was applied to carry out stereological analysis. Since the aim of the research was to determine 2 kinds of stereological quantities then the sample processing was carried out by two methods adequate to obtaining the required result.

To obtain structure stereological parameters, the polished section surface was arbitrarily devided into 17 non-touching areas of the surface equal about 62 mm^2. After that, every area of the polished sections was introduced to the image analysis system. The number of areas was optimum, considering both statistically assumed sufficient number of repetitions and the adequâte number of objects on every area. Processing of individual images was mainly focused on the most reliable detection of aggregates boundary line - a point of pores touching. Neither object segmentation nor area determination precision was a critical factor in this approach. It resulted from the fact that image number of objects was not measured and that possible relative error at the area estimation was wery little because of considerable object image sizes.

It was necessary to possess an image of great object number to determine sphere histograms in sample volume. The object number was at least 1000. Because of it, these made up one big photo enclosing the whole sample surface. While working out individual images one had to care about precise segmentation of aggregates, determination of aggregate areas and shapes (it is not the same as a boundary line) since these were the input quantities for further work. The aggregate shape is essential because of the precision of average aggreagate diameter determination.

Before starting image analysis, all the images had been subjected to processing consisting in the elimination of noise and heterogenity of illumination as well as increase of contrast. The black and white camera was applied here.

RESULTS

The results of stereological analysis are presented below in tables and charts. Complying with our expectations, the sample denoted as '4' (load 0 kPa) has the biggest porosity (Table 1). The samples denoted '118' and '906' had similar parameter values, but the latter is packed more densely, which indicates that the soil has reached its highest density at the load of 200 kPa and further increase of load has not changed anything. The only difference was the drop of the number of aggregates in the '906' sample. This effect can be explained in two ways: either the aggregates were so close to one another that they merged in the images or they, had been destroyed. This doubt can be explained by the investigation of granulometric distribution.

Grain size distributions have been obtained from the Eq. (9) by substitution methods (described by Eq. (10)). Table 2 includes Eq. (9) coefficients. Histograms are presented in Figs 4 nd 5. The graphs (Figs 6 and 7), presenting grain size distributions, show that there are no essential differences between the samples '4' and '118'. This indicates that, within the range of loads applied, the aggregates in the soil being investigated have not been destroyed. A certain difference in the distribution, corresponding to the '906' sample, can be seen when compared with these samples.

Table 1. Results of image analysis and stereological parameters

Number of images on one sample		17			
Total area of image		62.32 mm^2			
Characteristic		Samples			
		'4'	'118'	'906'	Units
Number of objects	N_A	1581	1749	1412	
Total area of objects	ΣA	32.12±2.85	37.33±2.38	37.36±1.69	mm^2
Total perimeter length	ΣL	196.97±18.96	215.68±14.53	218.26±10.73	mm
Relative volume	V_V	0.543±0.05	0.5989±0.04	0.5995±0.03	
Porosity	T	0.457±0.05	0.4011±0.04	0.4005±0.03	
Relative surface	S_V	4.24±0.41	4.41±0.3	4.46±0.22	1/mm
Average chord length	L_3	0.51±0.04	0.54±0.03	0.54±0.03	mm
Average aggregate distance	λ	0.44±0.09	0.37±0.05	0.36±0.03	mm

Table 2. Coefficient α_{ij} Eq. (9) for 10 bins histogram

Bins of circles	Spheres	1	2	3	4	5	6	7	8	9	10
	Diamteres (mm)	0.286	0.532	0.778	1.024	1.27	1.516	1.762	2.008	2.254	2.5
1	0.286	0.9902	0.154	0.0687	0.039	0.0252	0.0176	0.013	0.01	0.0079	0.0064
2	0.532	0	0.8432	0.2003	0.1058	0.0663	0.456	0.0334	0.0255	0.0202	0.0163
3	0.778	0	0	0.7297	0.2043	0.1176	0.0781	0.0561	0.0424	0.0332	0.0268
4	1.024	0	0	0	0.6502	0.1989	0.1209	0.0834	0.0617	0.0477	0.0381
5	1.27	0	0	0	0	0.5915	0.1913	0.1206	0.0856	0.0647	0.0509
6	1.516	0	0	0	0	0	0.5461	0.1835	0.1188	0.0861	0.0662
7	1.762	0	0	0	0	0	0	0.5096	0.1762	0.1164	0.0858
8	2.008	0	0	0	0	0	0	0	0.4796	0.1694	0.1137
9	2.554	0	0	0	0	0	0	0	0	0.4543	0.1631
10	2.5	0	0	0	0	0	0	0	0	0	0.4326

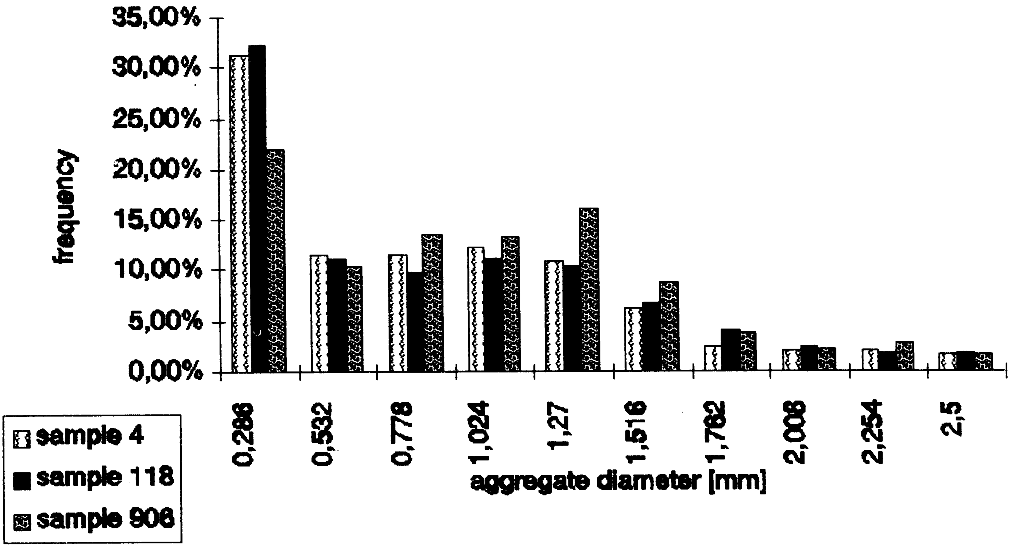

Fig. 4. Aggregates diameters histogram.

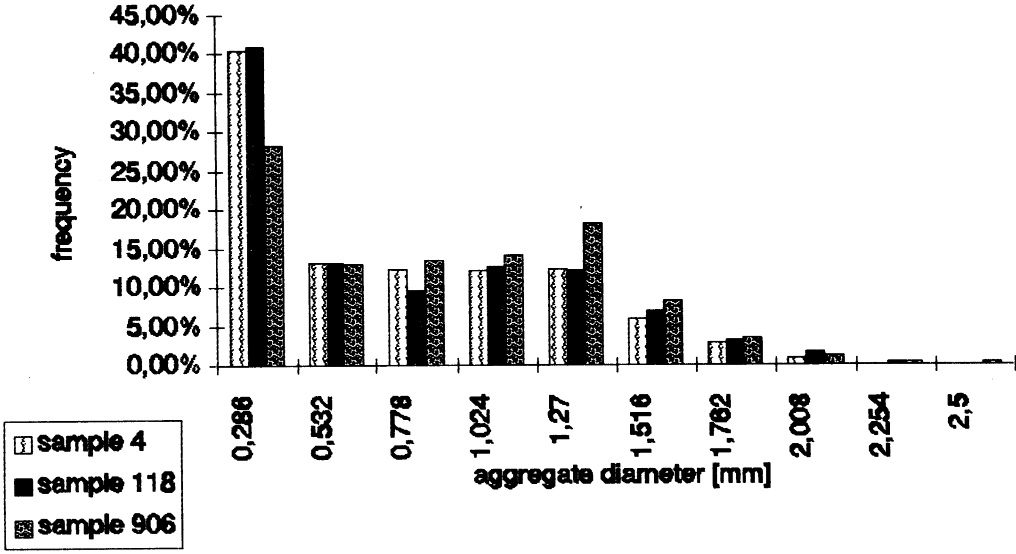

Fig. 5. Aggregates areas histogram.

In the case of the '906' sample a pronounced increase in the number of particles within 1.024-1.27 mm range can be noticed, which indicates that big particles had been crushed. Besides, the number of small particles (<0.286 mm) gets reduced as they are pressed into the edges of bigger particles. Besides, there are some differences among grain size distributions determined by areas and diameters, especially within thick fractions. This may result from inaccurate segmentation of soil aggregates. It brings bigger errors in diameter than

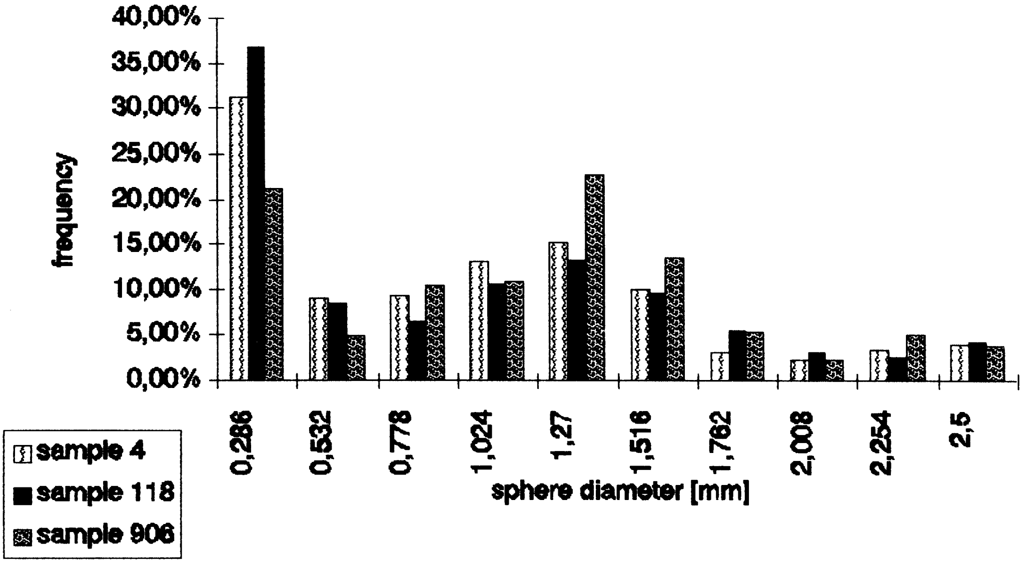

Fig. 6. Grain size distribution evaluated form aggregate diameters histogram.

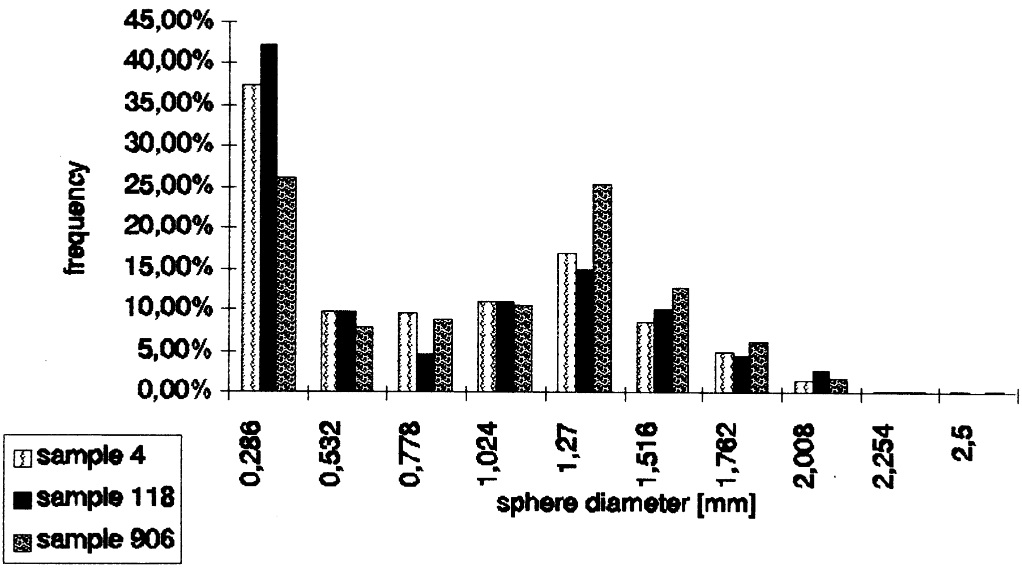

Fig. 7. Grain size distribution evaluated from aggregate areas histogram.

the area determination, especially if the aggregates are connected with one another next to their long axes. Moreover, the average diameter values of particles were additionally determined by grain size distributions (Table 3).

CONCLUSIONS

The results presented above imply that by means of structure stereological parameters one can attempt to estimate structure changes under the influence of stress. The possibility of

Table 3. Mean value of aggregate diameter evaluated from different grain size distribution

Grain size distribution evaluated from histogram of	Sample (mm)		
	'4'	'118'	'906'
Diameter	0.9580	0.9395	1.1198
Area	0.8174	0.8008	0.9647

determining grain size distribution of samples is very desirable. However, the obtained results indicate the necessity of further testing of this method to choose one determining variant: area, diameter or perimeter histograms. The last one was not carried out in the present work. Substitution of spheres by ellipsoids in the model of space soil structure is the next way of increasing quality and precision of grain size distribution.

Methodology of aggregate crushing degree determination by soil stress from the changes of grain size distribution requires further examination. But despite all these failings, it seems that the attempt at soil analysis by stereological methods is quite promising.

REFERENCES

1. **Rush J.C.**: Practical Stereology, Plenum Press, New York, 1986.
2. **Kok L.P.**: 100 Problems of my Wife and their Solution in Theoretical Stereology, Coulomb Press Leyden, Leyden, 1990.