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# ASSESSMENT OF THE POROSITY OF SOIL SAMPLES ACCORDING TO THE METHOD OF STEREOLOGICAL ANALYSIS*

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Abstract. The structure of porosity has a direct and an indirect effect on the other properties of soil. An attempt has been made at accomplishing a quantitative assessment of the volume of pores in soil samples, one of the most important parameters of the structure of soil porosity. The assessment of the parameter was based on the method of stereological analysis and performed using sections of loess soil samples. Preparation of soil sections was possible after hardening a liquid binder which was used to fill the pore spaces of soil samples. A method was developed for contrasting soil sections to facilitate the distinction between pores (filled with binder) and soil particles in the planes of the soil sections. Optimum parameters were selected for the operation METAPERICOLOR automatic image analyzer, to ensure correct identification of soil components. The results of automatic planar analysis were verified against the results of point analysis conducted directly by an observer. The results are presented statistically. The good level of agreement between the results obtained may constitute a basis for a wider application of the method of stereological analysis for quantitative assessments of the structure of soil porosity.

Keywords: porosity structure, stereological analysis, soil porosity

## INTRODUCTION

Mechanical tillage of soil is frequently defined as soil manipulation aimed at improving its physical properties and thus ensuring better crop yields. The application of tillage measures causes a number of interrelated processes affecting the soil environment. Volumetric strain results in changes in soil density and porosity, and therefore also in the air and water capacity of the soil and in the processes of air and water flow. These changes are determined by the level of stress applied and by the initial condition of the soil subjected to strain, and the main difficulty in quantitative description results primarily from the complexity of the material under study. Soil is a diminuted multiphase polymineral medium including also humous components. Under natural conditions soil occurs in various states of moisture content and temperature, changing within broad ranges of values [9,16,17]. In the modelling of physical processes taking place in soil one cannot assume the continuity and homogeneity of the medium under study.

In the course of soil strain its structure is the primary object of changes. In soil science there is a number of definitions of soil structure, but all of them define it as a spatial system of solid phase elements and soil pores [14].

Most frequently, total porosity is determined on the basis of the density of the solid

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phase of soil and the soil density at current moisture content. Also, equipment is used whose operation is based on the Boyle and Mariotte law. What is really determined is the air capacity at the current moisture content.

In soil science soil porosity is frequently determined using the capacity of a soil to retain water in, or filter water through a given soil sample. What is then determined is the amount of water seeping out of a capillary-saturated soil sample at various predetermined, gradually increasing levels of pressure.

Other methods, like, e.g. that of mercury porosimetry, make use of the behaviour of non-wetting liquids in capillaries, giving as a result the relationship of pressure required to force mercury into a capillary to the radius of the capillary.

Both these groups of methods assume that the pores are cylindrical in shape and that the values of surface tension of the liquid filling the pores and liquid-soil wetting angle (angle of contact) are correctly adopted for the assumed mean value of temperature [11].

Microscopic observations of soil structure, and especially of its changes under the effect of various tillage measures, indicate that external forces can cause changes in the size and shape of soil aggregates, their decay and crumbling, formation of whole high density blocks of aggregates composed of smaller aggregates, and that the pores filling the solid phase cannot be compared to capillaries or to other known geometrical shapes [7].

In the description of soil structure, a distinction is made between original aggregates, resulting from the soil structure (separated from one another by pore spaces), and aggregates formed as a result of tillage or the effect of frost and drought, especially on the soil surface [3].

Qualitative analysis of soil structure determines the form of aggregates (blocks, spheres, plates, prisms), the arrangement of aggregates with relation to one another, the types of pore space (within aggregates, between aggregates, within non-aggregate material), and the roughness of aggregate surfaces.

Classification of aggregates and pores leads to the identification of various classes of microstructure, e.g., block structure, prism structure, plate structure, etc. [15].

To relate, however, changes in soil structure with external forces causing the changes, e.g. in the course of mechanical tillage, requires quantitative determinations. The choice of the parameters measured and the method of measurement, from sampling to image analysis, becomes the main problem of such a task.

The study presented herein was aimed at demonstrating how the method of stereological analysis can be applied in studies on soil porosity, through methodological problems involved in the preparation of sections, selection of microscopic image parameters, and the stereological analysis itself.

It is a completely new approach to soil porosity and it is justified to state that it has considerable chances of finding application in describing the basic stress-strain relationship, and the developing micromorphological studies can utilize such a method as an expansion of their analytical capabilities [13].

## PREPARATION OF SOIL SECTIONS

For the study a soil was selected for which a complete agrophysical characterization had been worked out at the Institute of Agrophysics [6]. It was a loess soil (Orthic Luvisol) from a field after potato (Z) and maize (K) crop. Samples of the soil in natural state were taken into test tubes, 22 mm in diameter, from Kopecky's cylinders. Further in the study the samples are referred to as series Z (Z1, Z2) and series K (K3, K4, K5, K6). The porosity analysis was performed at the Strata Mechanics Research Institute.

Soil samples sealed in a binder were prepared on a stand equipped with a vacuum chamber and an autoclave. All the samples were placed in the vacuum chamber on a carousel allowing for successive filling up the samples by liquid binder. After 24 hours in vacuum, the samples were flooded with methyl methacrylate monomer with hardener which has very good soil wetting characteristics. After filling the chamber with air the samples were placed in the autoclave where the binder was subjected to a 24-hour process of polymerization in nitrogen at a pressure of 7.5 MPa and a temperature of 338 K.

The preparation of soil sections involved the following operations: cutting the soil samples into slices about 6 mm in thickness, grinding and polishing one of the flat surfaces of each of the slices. Observation of the soil sections using an optical microscope showed that they were of good quality as concerns the smoothness of the polished surfaces. The pores were found to be well filled with binder, which additionally confirms that the system of pores in the soil represents the fully open type of structure. No chipping of soil particles was observed. However, the optical contrast between the binder and the soil particles was not sufficient for these section components to be distinguished with absolute accuracy.

Problems were encountered in developing a method for soil section contrasting. The best results were obtained through curing the soil particles in hydrofluoric acid vapour. Protracted washing and weathering of the soil sections was an important element of the procedure.

No method was developed for quantitative assessment of the optical contrast between the soil section components, i.e., the binder and the soil particles. The authors had to settle for a subjective, qualitative assessment. Agreement between stereological analysis of porosity performed by means of a METAPETRICOLOR automatic analyzer and point analysis performed by an observer with the help of a semiautomatic set of equipment was adopted as the ultimate criterion.

Microscopy of cured and non-cured soil sections leads to some conclusions. The binder, or to be more accurate - the soil pores filled with the binder, appears to be much brighter and whiter in cured sections. This is the result of optical contrast between the binder and the soil particles which are distinctly darker after curing as their reflectance has decreased. Vapour of hydrofluoric acid affects soil particles, leaving the binder intact. Magnification ratio of 10x10 was found to be optimal for the best distinction between the two section components. This magnification ensures good visibility of areas covered by the binder or by the soil particles, as well as the lines of contact between the two components. Using lenses of 20x or 50x power the quality of the image deteriorates with respect to contrast. For purposes of stereological analysis only the 10x lens was used. Figures 1 and 3 present photographs of the microscope field of view of section series Z and K. Figures 2 and 4 present printouts of the same fields after processing by the automatic image analyzer.

## ESTIMATION OF POROSITY

Let us consider a certain spatial region *R* of volume *V*, filled with a material made up of two components: a solid body (soil skeleton) of a volume $V_g$ and free spaces (pores) of a volume $V_p$. Let us assume that the areas of contact between the two components are regular enough for a finite surface area $F_g = F_p$ to exist. Porosity is a certain feature of the material; it is a substructure of its geometrical structure. The question arises immediately, whether a unique, and especially a quantitative characterization of porosity is at all possible. Generally, it is not. Geometry is not capable of unique characterizations of even single bodies. E.g., Hadwiger [8] quoted an example of a cylinder and a pyramid of the same volumes, surface areas, and the same total mean curvatures. Geometry provides unique characteristics of bodies within the same class of similarity. An analogous situation is encountered in the case of quantitative geometrical assessment of material structures. Unique characteristics of geometrical structures can be given only within the same class of similarity.

Porosity characteristics, $\varepsilon$, most frequently used is the volumetric content of pores in a material, i.e., using the symbols introduced above:

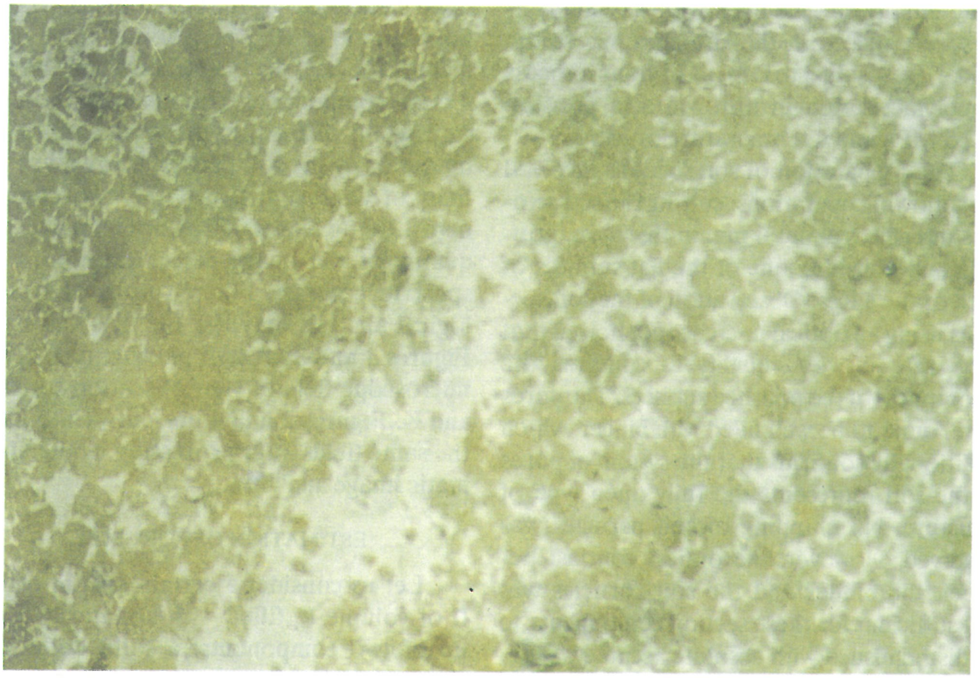

Fig. 1. Soil structure on section Z1.

$$\varepsilon = \frac{V_p}{V} \; . \tag{1}$$

Of course, the balance relationship occurs here:

$$\frac{V_g}{V} + \frac{V_p}{V} = 1 \; . \tag{2}$$

The volumetric content of pores is commonly known as the porosity of a material, which is a certain simplification as the volumetric content of pores is only one of the quantitative characteristics of the spatial porosity of a material [2]. Porosity, as defined by formula (1), is an integral concept characterizing the whole material of volume $V$. In probabilistic terms we could say that it is a mean porosity.

The essence of the methods of stereological analysis is the quantitative determination of spatial structure on the basis of information obtained from plane sections of a material, i.e. soil sections in our case (or thin polished sections). Stereological analysis uses three estimators for the assessment of unknown porosity (1).

If we project at random $N$ points on a section (statistically representative), out of which $n$ points ($n$ ) hit pores, the estimator of spatial porosity (1) is:

$$\varepsilon_{\mathrm{I}} = \frac{n}{N} \; . \tag{3}$$

If we project at random a certain number of straight lines on a section, whose fragments common with the section, i.e. intercepts, have a total intercept length $L$, while their fragments common with pores have a total length $l$, $l \leq L$, the estimator of spatial porosity is expressed by the formula:

$$\varepsilon_{\mathrm{II}} = \frac{l}{L} \; . \tag{4}$$

If, finally, we measure the surface area of the section and denominate it with the symbol $F$, and measure the total surface area of pore sections $f$, then the estimator of porosity (1) has the form:

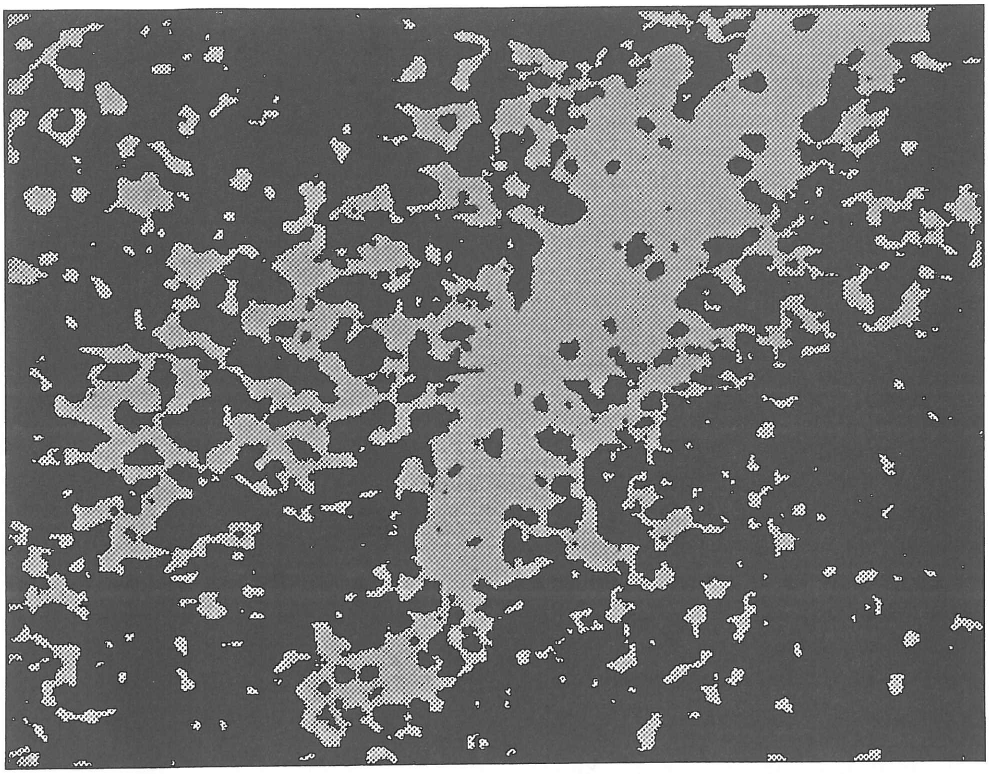

Fig. 2. Identification of soil structure on section Z1 performed by means of the METAPERICOLOR automatic image analyzer. Channel III.

$$\varepsilon_{\mathrm{III}} = \frac{f}{F} \ . \tag{5}$$

The application of one of the above estimators induces the use of a certain method of counting or measurement. They are called the point, linear or planar stereological analysis. To distinguish them from the spatial porosity, porosity determined by means of estimators (3,4,5) will be called point, linear or planar porosity, respectively.

The condition of convergence of estimators (3,4,5) to the value of spatial porosity (1) is the so-called isotropic uniform randomness of plane (section) distribution within a sample, and of points and lines within the sections. We are not going to discuss this concept in detail here [14]. We will continue using the point and planar analysis.

It should be noted that the methods of stereological analysis impose the probabilistic approach to the concept of porosity. This is most distinct in the point analysis. Therefore porosity will be treated as a random variable $\varepsilon$. It is a variable of very specific characteristics: it can assume only one of two values:

$\varepsilon=1$, if the point hits a pore

$\varepsilon=0$, if the point misses a pore. (6)

To each of these mutually exclusive and complementary events to a certain event we can allocate specific probabilities of their occurrence:

$$Pr\ \{\varepsilon=1\} = p\ ;\ Pr\ \{\varepsilon=0\} = 1-p\ . \tag{7}$$

The random variable $\varepsilon$ has an expected value, variance, and resulting from it standard deviation:

$$E[\varepsilon]=p\ ;\ \sigma^2(\varepsilon) = E[\varepsilon-p]^2 = p(1-p)\ ;$$
$$\sigma(\varepsilon) = \sqrt{p(1-p)}\ . \tag{8}$$

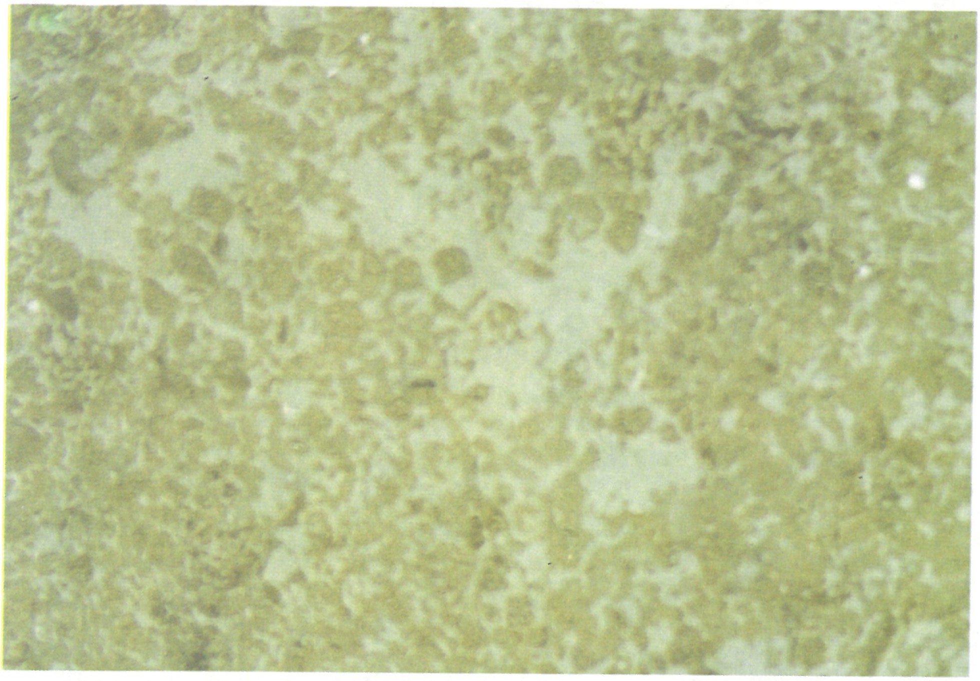

Fig. 3. Soil structure on section K4.

The expected value $E[\varepsilon]$ is not known. This value and the variance $\sigma^2(\varepsilon)$ should be assessed from a finite population of points projected on a section at random or in a regular manner. This is the essence of point stereological analysis. In the present study the authors adopted the following testing procedure.

On a section (or a series of sections) we distribute $k$ basic measurement fields of constant size and shape. Within each of the fields we place $N_i$ $(i=1,\ldots,k)$ points in a regular grid. Out of $N_i$ points $n_i \leq N_i$ hit pores. Basing on the results of counting we get, for a single basic field, the following assessment of the mean value and the variance of the random variable $\varepsilon$:

$$\bar{\varepsilon}_i = \frac{n_i}{N_i};\ \sigma^2(\bar{\varepsilon}_i) = \frac{\bar{\varepsilon}_i(1-\bar{\varepsilon}_i)}{N_i} \qquad (9)$$

Formula (9) is true with the assumption of random independence of point distribution on the section, i.e., when the assumptions of Bernoulli scheme are met [4] and the random variable has a binominal distribution tending towards normal distribution with increasing $N_i$. Regular distribution of points, and this is the type of scheme adopted, is, however, more effective statistically. For this scheme estimator (9) gives a poorer assessment. Its application is therefore acceptable [5], especially as the structure itself of the porosity of soil samples is random in character.

Let us consider a combined population of counting results for $k$ basic fields. Then $N=\Sigma N_i$, $n=\Sigma n_i$. The estimators of the mean value and variance are calculated from the formulae:

$$\bar{\varepsilon} = \frac{n}{N} = \sum_i^k \frac{N_i}{N}\frac{n_i}{N_i} = \sum_i^k \frac{N_i}{N}\bar{\varepsilon}_i \qquad (10)$$

$$\sigma^2(\bar{\varepsilon}) = \frac{\bar{\varepsilon}(1-\bar{\varepsilon})}{N}. \qquad (11)$$

In a specific case, for $N_i = N/k = \text{const.}$:

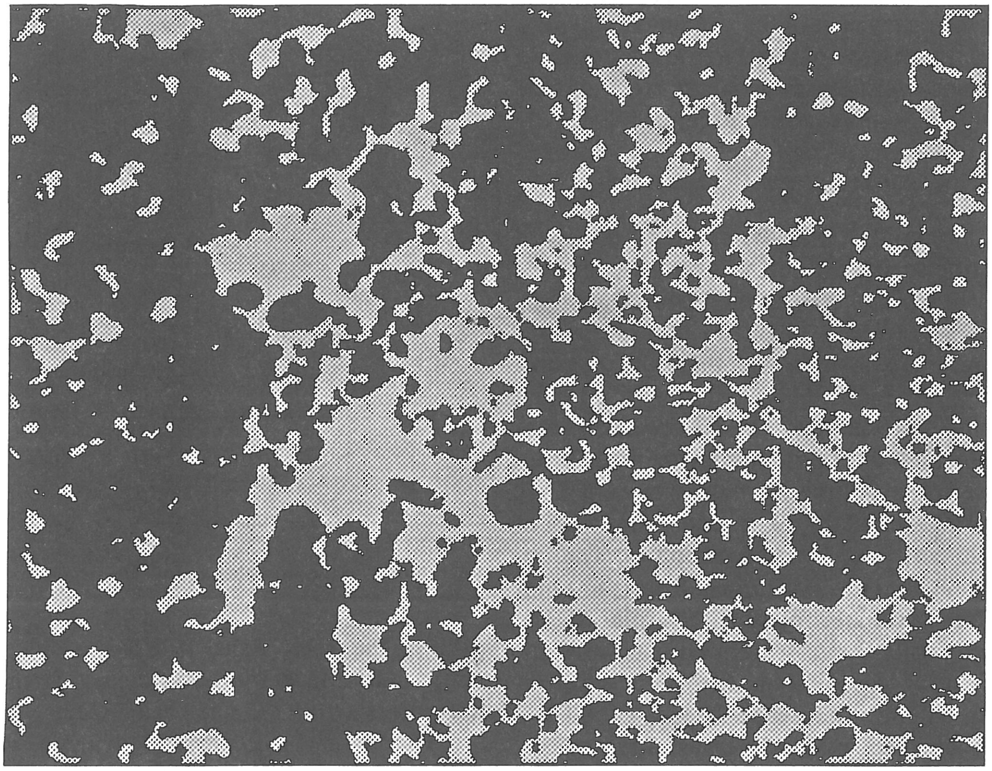

**Fig. 4.** Identification of soil structure on section K4 performed by means of the METAPERICOLOR automatic image analyzer. Channel III.

$$\sigma^2(\overline{\varepsilon}) = \frac{\sigma^2(\overline{\varepsilon}_i)}{k}. \tag{12}$$

Planar stereological analysis realized by means of the METAPETRICOLOR automatic image analyzer is essentially also point analysis. In the planar analysis an image of a basic field of the same shape and size as in point analysis is put on a monitor screen and analyzed in the system of 512x512 measurement lines, i.e., in 262 144 pixels, which gives a number of points 2 to 3 orders greater than the number of points in point analysis. The whole problem consists in proper identification of the soil components in the process of automatic analysis. It was assumed that each basic field is so densely sampled that the variance estimator (9) has the value of 0. As the basis of assessment of the unknown mean value of the distribution of porosity of the whole population of possible basic fields we adopt the arithmetic mean:

$$\overline{\overline{\varepsilon}} = \frac{1}{k}\sum_{1}^{k}\overline{\overline{\varepsilon}}_i \tag{13}$$

and as the estimator of variance of the distribution:

$$\sigma^2(\overline{\overline{\varepsilon}}) = \frac{1}{k-1}\sum_{1}^{k}(\overline{\overline{\varepsilon}}_i - \overline{\overline{\varepsilon}})^2. \tag{14}$$

Estimator (13) is an arithmetic mean of the porosity of *k* basic fields which is also a random variable. Estimator of variance of the arithmetic mean is determined by a formula analogous to (12):

$$\sigma^2(\overline{\overline{\varepsilon}})_k = \frac{\sigma^2(\overline{\overline{\varepsilon}})}{k}. \tag{15}$$

Formulae (9) through (15) provide a basis for the assessment of the porosity of soil samples. In the case of very large $k$, we can use a deeper statistical assessment based on the determination of confidents limits [4].

## STEREOLOGICAL ANALYSIS

Stereological analysis of the porosity of section series Z and K was performed using the point and planar methods of analysis. One section was taken for determinations from every sample, and therefore the sections were marked according to the marking of the soil samples. The point analysis was performed on a semi-automatic stand composed of an AXIOPLAN microscope, an XYZ coordinate meter of a minimum step of 0.625 $\mu$m, and an IBM computer. The coordinate meter, controlled from the computer keyboard, played the role of the microscope stage. It allowed for the realization of counting in the point grid required. The microscope image, in which a 10x lens was used, was transmitted onto a special monitor with cross hairs superimposed on the screen. In the point analysis the primary role was played by the element of personal decision by the observer watching the area surrounding the cross hairs. By pressing a suitable key on the computer keyboard the observer caused two effects: counting, in the computer memory, the number of points corresponding to pores or to the soil, and moving the microscope stage to a new position by a preset distance equivalent to the length of the side of the measurement grid eye. The selected set of points was used to realize a test of replicability of countings by particular observers. Optical contrast between the soil components was so clear that individual errors made by particular observers were considered negligible. The basic fields were 1 mm squares. The distribution of fields on the sections is presented in Fig. 5. Linear analysis was performed on some of the basic fields. Statistical analysis was performed for the selection of the grid eye size in the measurement point grid in the basic field. It was decided to adopt a grid of 40 mm eye side, which gave 676 points within a single basic field.

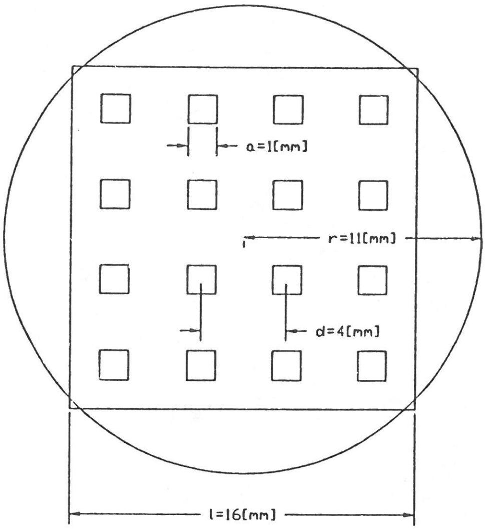

**Fig. 5.** Distribution scheme of basic fields in stereological analysis.

The planar stereological analysis was realized by means of the METAPERICOLOR automatic image analyzer as shown in the schema in Fig. 5. The main problem encountered in the planar analysis was such a selection of external conditions (illumination, magnification ratio of the microscope, possible use of filters) and steps of the automatic processing of images that the final effect, i.e. in our case identification of pores and determination of porosity, could be in statistical agreement with the result of the point analysis (Figs 2 and 4).

As a result of many tests which will not be described here the external conditions for the automatic processing of images were determined. In particular, it was decided to read colour images into computer memory. A colour image is coded by means of three images equivalent to shades of grey for the following colours: blue, green and red. Due to non-uniformity of illumination, each of the three component images (channels R,G,B) was corrected. The corrective image was separately recorded in the memory of the analyzer, an image of white field obtained under the same external conditions. It was decided that possible irregularities of illumination of the images will be the same for the white field and for each of the images of section surfaces read into the memory. Images processed in this way were binarized. Planar porosity was determined (automatic procedure of the analyzer) for each of the three component images (channels R,G,B) of a basic field. The arithmetic mean of the three results was determined also in an automatic procedure.

The stereological analysis was performed in two stages. The objective of the preliminary analysis was to determine such conditions of the analyzer operation that the results obtained conformed to the results of point analysis for the same measurement fields. The preliminary analysis was performed for 4 fields of section Z1. The results are presented in Table 1. The lowest line of Table 1 gives results for the combined population of the four fields. It was found that they provide a good basis for the application of the automatic analyzer for the determination of soil porosity.

The principal stereological analysis was performed for all six sections, according to the schema presented in Fig. 5. For control purposes, point analysis was performed for field No. 16 of each of the sections. A comparison of the results is presented in Table 2. The highest mean deviation was 0.0064, and the mean value was 0.0054, which should be considered as satisfactory. The main results of the planar analysis are presented in Table 3. Lines 17 through 21 present successively: the arithmetic mean of porosity for 16 basic fields calculated according to the formula (13), variance and standard deviation of porosity in the basic fields, calculated from the formula (14), variance and standard deviation calculated from the formula (15).

## COMPARISON OF THE EMPIRICAL DISTRIBUTION OF POROSITY TO THE NORMAL DISTRIBUTION

Above the authors discuss the question of agreement of the empirical distribution of porosity with the normal distribution. Such an assumption for the point stereological analysis of the volumetric content of a given component was already adopted by Glagolev [5], and it is commonly used. We shall illustrate this problem on the example of section Z1, for which 40 analyses of basic fields were performed by means of the automatic image analyzer. The population, however, is not large enough for the application of the hypothesis of agreement between the empirical distribution and the normal distribution. Therefore the authors settled for a plain comparison of the normal to the empirical distribution. The principle of the adaptation consisted in assuming the values of the mean value and variance of the normal distribution as equal to the corresponding moments of the empirical distribution. The results of the comparison are presented in Table 4. Figure 6 presents the distribution functions of the distributions in the so-called probabilistic scale. In this scale the distribution function of the adopted normal

**Table 1.** Results of the preliminary point analysis and the planar (automatic) stereological analysis - section Z1.

| Field No. | Point analysis | | | | Planar analysis | | Mean deviation |
|---|---|---|---|---|---|---|---|
| | No. of points | | Porosity | Variance | Porosity | Variance | |
| | $n_i$ | $N_i$ | $\varepsilon_i$ | $\sigma^2(\bar{\bar{\varepsilon}}_i)$ | $\bar{\bar{\varepsilon}}_i$ | $\sigma^2(\bar{\bar{\varepsilon}}_i)$ | $\lvert \bar{\varepsilon}_i - \bar{\bar{\varepsilon}}_i \rvert$ |
| 1 | 201 | 676 | 0.2973 | 0.000309 | 0.3259 | 0 | 0.0286 |
| 2 | 196 | 677 | 0.2895 | 0.000304 | 0.3167 | 0 | 0.0272 |
| 3 | 204 | 676 | 0.3018 | 0.000312 | 0.3102 | 0 | 0.0084 |
| 4 | 210 | 678 | 0.3097 | 0.000315 | 0.3053 | 0 | 0.0044 |
| Total | 807 | 2707 | 0.2981 | 0.000077 | 0.3145 | 0.00008 | 0.0164 |

**Table 2.** Comparison of porosity determined in the point and the planar stereological analyses

| Section No. | Z1 | Z2 | K3 | K4 | K5 | K6 |
|---|---|---|---|---|---|---|
| Point analysis | 0.3166 | 0.3151 | 0.3132 | 0.3171 | 0.3580 | 0.4112 |
| Planar analysis | 0.3159 | 0.3162 | 0.3085 | 0.3107 | 0.3551 | 0.4286 |
| $\lvert \bar{\varepsilon} - \bar{\bar{\varepsilon}} \rvert$ | 0.0007 | 0.0011 | 0.0036 | 0.0064 | 0.0029 | 0.0174 |

**Table 3.** Porosity determined in the planar automatic stereological analysis

| Field No. | Z1 | Z2 | K3 | K4 | K5 | K6 |
|---|---|---|---|---|---|---|
| 1 | 0.2865 | 0.3223 | 0.2942 | 0.3361 | 0.5254 | 0.3432 |
| 2 | 0.2650 | 0.2992 | 0.3019 | 0.3210 | 0.3417 | 0.3791 |
| 3 | 0.2924 | 0.2903 | 0.2853 | 0.2856 | 0.3491 | 0.3327 |
| 4 | 0.3094 | 0.2987 | 0.3209 | 0.3066 | 0.3532 | 0.3400 |
| 5 | 0.3236 | 0.2861 | 0.3451 | 0.3065 | 0.3468 | 0.3369 |
| 6 | 0.3081 | 0.3821 | 0.3281 | 0.3273 | 0.3248 | 0.3507 |
| 7 | 0.2799 | 0.2945 | 0.3015 | 0.2697 | 0.3405 | 0.3425 |
| 8 | 0.2967 | 0.3331 | 0.3009 | 0.2874 | 0.3505 | 0.3414 |
| 9 | 0.2899 | 0.2988 | 0.3059 | 0.3232 | 0.3398 | 0.4246 |
| 10 | 0.3353 | 0.2371 | 0.3349 | 0.2839 | 0.3612 | 0.3022 |
| 11 | 0.2726 | 0.2708 | 0.3337 | 0.2579 | 0.3429 | 0.3573 |
| 12 | 0.2950 | 0.2740 | 0.3130 | 0.2832 | 0.3443 | 0.3377 |
| 13 | 0.3189 | 0.2961 | 0.3302 | 0.2942 | 0.2861 | 0.3609 |
| 14 | 0.3259 | 0.2631 | 0.3126 | 0.2791 | 0.2889 | 0.3140 |
| 15 | 0.3065 | 0.2759 | 0.3052 | 0.3014 | 0.3018 | 0.3268 |
| 16 | 0.3159 | 0.3162 | 0.3085 | 0.3107 | 0.3551 | 0.4286 |
| $\bar{\bar{\varepsilon}}$ | 0.3014 | 0.2961 | 0.3139 | 0.2984 | 0.3470 | 0.3512 |
| $\sigma^2(\bar{\bar{\varepsilon}})$ | 0.00040 | 0.00107 | 0.00028 | 0.00048 | 0.00279 | 0.0012 |
| $\sigma(\bar{\bar{\varepsilon}})$ | 0.0200 | 0.0328 | 0.0167 | 0.0220 | 0.0529 | 0.0344 |
| $\sigma^2(\bar{\bar{\varepsilon}}16)$ | 0.00003 | 0.00007 | 0.00002 | 0.00003 | 0.0002 | 0.0001 |
| $\sigma(\bar{\bar{\varepsilon}}16)$ | 0.005 | 0.0082 | 0.0042 | 0.0055 | 0.0132 | 0.0090 |

**Table 4.** Adaptation of the normal distribution to the empirical distribution of porosity determined in the planar stereological analysis-section Z1.

| Item | Class of porosity | Empirical distribtuion | | | Normal distribution | |
|---|---|---|---|---|---|---|
| | $\varepsilon$ | frequency $n_i$ | probability $p_i$ | distribution function $\sum p_i$ | probability $f(\varepsilon)\Delta\varepsilon$ | distribution function $F(\varepsilon)$ |
| 1 | 0.241 - 0.250 | 0 | | | | 0.0051 |
| 2 | 0.251 - 0.260 | 1 | 0.025 | 0.025 | 0.0172 | 0.0223 |
| 3 | 0.261 - 0.270 | 2 | 0.050 | 0.075 | 0.0517 | 0.0740 |
| 4 | 0.271 - 0.280 | 4 | 0.100 | 0.175 | 0.1142 | 0.1822 |
| 5 | 0.281 - 0.290 | 8 | 0.200 | 0.375 | 0.1852 | 0.3734 |
| 6 | 0.297 - 0.300 | 10 | 0.250 | 0.625 | 0.2209 | 0.5943 |
| 7 | 0.301 - 0.310 | 6 | 0.150 | 0.775 | 0.1940 | 0.7883 |
| 8 | 0.311 - 0.320 | 5 | 0.125 | 0.900 | 0.1251 | 0.9134 |
| 9 | 0.321 - 0.330 | 3 | 0.075 | 0.975 | 0.0594 | 0.9728 |
| 10 | 0.331 - 0.340 | 1 | 0.025 | 1.000 | 0.0207 | 0.9935 |
| 11 | 0.341 - 0.350 | 0 | | | 0.0052 | 0.9987 |

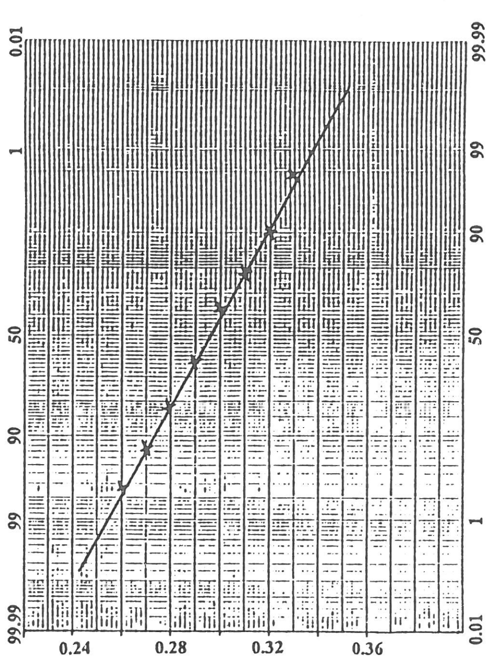

**Fig. 6.** The empirical distribution of soil porosity in the 'probabilistic' function scale, the integral of Gaussian function. The results of planar stereological analysis on section Z1.

distribution has a linear course. Points of the distribution function of the empirical distribution are plotted in the graph.

## CONCLUSIONS

1. An original element of the study presented herein is the method developed by the authors for making soil samples sealed in a binder, and especially their method of contrasting soil sections. It seems worthwhile to test the possibility of applying the method for section contrasting with relation to other soil types. It would also be worthwhile to further develop the method to allow for microscope lenses of higher power, e.g., 20x, 50x, etc., to be used.

2. The results of the point (semi-automatic) stereological analysis constituted a basis for the evaluation of the results of the planar (automatic) analysis of the porosity of soil samples. The good level of agreement between the results of the point and the planar analyses permits the conclusion that the automatic analysis of porosity can be used on a larger scale. Fragmentary point analyses are, however, necessary.

3. Porosity understood as the volumetric content of pores in soil samples is one of the parameters characterizing the quantitative structure of porosity. Examples of other parameters can be the specific surface area of pores, mean distances of visibility from any point within a pore, and covariance.

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