

The porosity determination of dispersion medium by the method of expansion of pore air into vacuum (on the example of the main soil types in the Chuvash republic)

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Abstract. Recently, for the study of the hydrophysical properties of finely dispersed systems, such as soils in Russia and abroad, tomographic studies are beginning to be widely used. The main lack of their use is a significant cost, the lack of the ability to conduct measurements directly in the field. Therefore, we have developed a fairly simple and accessible method for calculating the porosity, based on measuring the state of air both when the pore air expands into the region with a reduced pressure, and when air is pumped from the region of increased pressure. The method makes it possible to take into account the presence of pores covered by menisci and dead-end pores. Statistical processing of experimental results shows the identity of porosity values, with a confidence probability of more than 95 %. However, the relative measurement error is approximately half of that for the case of air injection. On the cultivated lands, after the passage of machine-tractor units, the appearance of a compacted soil layer often occurs. The study of the dynamics of deformations accumulation in the soil is conveniently investigated using maps with isolines of the soil porosity values. They can be used for economically justified planning of agricultural activities. The developed express method for determination of porosity, due to the speed and simplicity of measurements, makes it possible to obtain a large amount of the data in a short time.

1. Introduction

When designing technologies aimed at softening of ground, melioration, and cultivation of soils for a particular field, spatial variability is convenient to represent in the form of maps with isolines of soil porosity values. Many hydrophysical properties of soils are functions of its porosity changing when subjected to mechanical action on the soil. Since the operation of the units involves the use of different modes, it becomes possible to choose the most economically efficient mode. An important place is the assessment of the soil porosity dynamics and the overall structure of the pores around seeds and roots during vegetation. Recently, tomographic studies have begun to be widely used to study the hydrophysical properties of soils in Russia and abroad. Using modern tomographs (with a resolution of up to 16 μm), porosity, bulk density and soil moisture can be measured [1]. Analysis of 3D-images



makes it possible to determine the relationship between the sealing effect of the technique and the variation of the network of prevailing water-air canals in soils. The main disadvantage of using tomographs is a significant cost and, consequently, low prevalence in scientific laboratories. In addition, it is not possible to carry out measurements directly in the field. Therefore, we have to develop and use methods that are more accessible. One of these methods is the express method for determining porosity, which is based on taking into account pressures in the pore air before and after the rarefaction/injection. This method, thanks to the speed and simplicity of measurements, allows obtaining a lot of data in a short time, which is extremely important for obtaining isolines and mapping.

From a rather large number of methods for measuring the porosity and structure of the porous space of soils, a number of researchers can calculate the density of the solid phase; micromorphometric (measuring the pore size under the microscope); adiabatic expansion of soil air into vacuum; based on gas diffusion through a soil sample, etc.

One of the rapid methods for determining porosity is the method of adiabatic expansion of soil air into an area of low pressure. For an adiabatic process, the Poisson equation is valid, which has the form [2]

$$pV^\gamma = \text{const}, \quad (1)$$

where p is the pressure; V – volume and γ – adiabatic exponent.

Equation (1) makes it possible to calculate the porosity from the pressures before and after the expansion of soil air into the area of a known volume with a low pressure. The method makes it possible to measure the porosity of the same soil sample in multiple replicates (with a fivefold average relative error of less than 7–10 %). For different samples taken from the same depths (0.5 m apart), the average relative error does not exceed 10–12 %.

The most common method is the determination of the porosity in the close association with the porosity and the bulk mass, and density of the solid phase of the soil. The main difficulty of its use is that the solid phase of the soil is multicomponent and has both a mineral and organic components. Therefore, the measurement of the bulk mass of the solid phase is difficult [5, 6].

2. Materials and methods

Schematic diagram of the device for implementing the method of expanding the pore air to the area with low pressure (or injecting air from the area with high pressure) is shown in figure 1, the general view of the device and its use in field measurements – in figures 2 and 3.

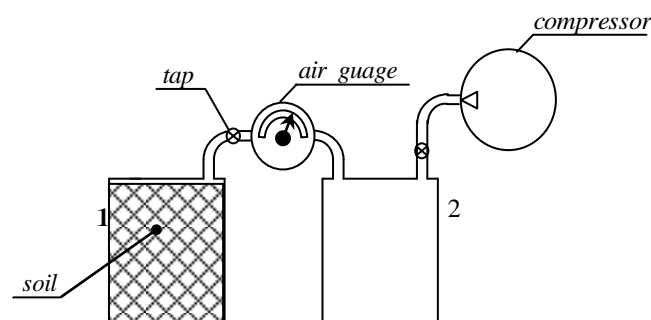


Figure 1. Scheme of the device for measuring soil porosity.

A soil sample of the volume V_{sample} with a pore volume of V_{por} is placed in a vessel 1, which is connected through a tap with a manometer, which in turn is connected to a vessel 2 of the volume $V_{\text{vessel}} = V_{\text{sample}}$. The vessel 2 is connected to a compressor or a Kamovski pump through a tap. Vessels are tight. If, with an empty vessel 2, raise the pressure to p_{ad} by the compressor and disconnect it with a tap from the compressor, connect it to vessel 1, then part of the air from vessel 2 will pass under pressure into vessel 1 and the total pressure for the system p_{est} will be established.



Figure 2. General view of the device.



Figure 3. Field measurements.

We will write down the Cliperon–Mendelev law for gas in the vessels before and after the tap opening:

for a vessel with soil,

$$p_{atm}V_{por} = \frac{m_0}{\mu} RT, \quad (2)$$

for an empty vessel,

$$p_{ad}V_{vessel} = \frac{m_1}{\mu} RT, \quad (3)$$

for the whole system,

$$p_{est}(V_{por} + V_{vessel}) = \frac{m_0 + m_1}{\mu} RT, \quad (4)$$

where m_0 is the mass of the pore gas in the vessel with the sample; m_1 is the gas mass in the vessel 2; p_{atm} is atmospheric pressure; p_{ad} is injected pressure / rarefaction pressure; p_{est} is the pressure established in the system after the junction of the vessels; R is the universal gas constant; T_1 , T_2 , T are temperatures in the first and second vessels and in the system as a whole; μ is the molar mass of air.

In respect that the temperature after the expansion is equalized to the original value, i.e.

$$T_1 = T_2 = T, \quad (5)$$

from equations (2–4), taking into account the conservation of the gas mass, we can write

$$p_{est} = (p_{atm}V_{por} + p_{ad}V_{vessel}) / (V_{por} + V_{vessel}). \quad (6)$$

The porosity $\Pi = V_{por} / V_{sample}$ is calculated by the equation (6):

$$\Pi = \frac{V_{por}}{V_{vessel}} = \frac{p_{ad} - p_{est}}{p_{est} - p_{atm}}, \quad (7)$$

To reduce measurement errors, one should take into account the volume of the connecting tubes and so on. For this, a preliminary experiment with a non-porous sample is performed.

With a parallel moisture measurement, the moisture content V_{water} contained in the pores can be calculated. Thus, the total porosity of the sample

$$\Pi = (V_{por} + V_{water}) / V_{vessel} . \quad (8)$$

The method is simple, but some nuances should be taken into account when implementing it. The pores in the soil are randomly distributed and therefore the presence of pores overlapped by menisci and dead-end pores is quite likely. The volume of air in such pores changes if the differences in the pressure Δp applied to them are greater than the pressures of the meniscus created by the curved surfaces Δp_m :

$$\Delta p > \Delta p_m. \quad (9)$$

To reduce the effects associated with the displacement of water cuffs, when the pressure changes step-by-step, the experiment is carried out at least five times.

In addition, the velocity of fluid movement in the pores is finite and depends on their radius in accordance with the Poiseuille law

$$v = (\Delta p / 4\eta l) R^2 , \quad (10)$$

where η is the viscosity of the liquid; l is the length of the pore filled with water; R is the radius of the pore. This circumstance in the experiment requires withstanding some time before recording the steady-state pressure. To ensure that the temperature in the system is sufficiently equalized with the ambient temperature, the vessels must have good thermal conductivity, therefore, metallic ones are more effective.

The active porosity is calculated from the values of the pressure, which is measured immediately after combining the vessels, and the pressure corresponding to the total porosity is measured after the pressure is stabilized, i.e. in 3–5 minutes.

3. Results and discussion

Field experiments and land surveys were conducted in accordance with known, most common methods. Samples of soil for carrying out measurements of hydrophysical parameters were selected with the help of a special drill, which minimally deforms the soil. The soil samples were taken in accordance with GOST 17.4.3.01-83, GOST 28168-89, GOST 17.4.4.02-84, OST 56 81-84. The pycnometric method (GOST 27395-87) was used to determine the density of the solid phase (skeleton) of the soil. To measure porosity, an improved device developed in the laboratory of “Hydrophysics and soil erosion” of the Chuvash State agricultural academy was used [3, 4]. In the absence of electricity, the device can also work with the Kamovsky pump.

To increase the reliability of the data obtained under conditions of strong spatial variation of soil properties, the soil sample is used throughout the cycle of determining the hydrophysical characteristics. The soil moisture was measured by a modified weighing method in a drying cabinet and in a number of cases using a dielectric moisture meter (GOST 20915-75, GOST 28268-89). Data processing was carried out using mathematical statistics.

In the experiment, a sample taken by the drill is used. In our case, soil samples with a volume of about 500 cm³ were chosen, and the pressure was measured with an exemplary manometer with a fission value of 0.05 atm., which made it possible to measure porosity for the same sample at a fivefold replicate with an average relative error of about 2–6 %.

This method of measuring the porosity and density of the solid phase of the soil can be applied both in field and laboratory conditions.

The porosity of the sample is determined as follows:

1. Place the sample with the cassette in the vessel 2, seal, inject air and stand for 5 minutes, to partially eliminate the liquid “cuffs” that lock the air in the dead-end pores.
2. Transfer the sample to the vessel 1 and seal.
3. Inject air into the vessel 2. Allow to stand for about 2 minutes.
4. Connect with the taps vessels 1 and 2, noting the value of the pressure p_{ad} until the moment of connection and the pressure p_{est} after calming the oscillations of the manometer needle.
5. Calculate the pore volume.
6. Open chamber 1, replace the soil sample with a non-porous body and repeat steps 3, 4, and 5 to

determine the parasitic volume Π' .

According to the volumetric moisture determination w , the total porosity is calculated with the formula:

$$\Pi_0 = \Pi - \Pi' + w. \quad (11)$$

The porosities of the natural state characteristic of the most widespread soils in the Chuvash Republic are given in table 1.

Table 1. Soil porosity in the Chuvash Republic

Soil	Porosity Π_0 , m ³ /m ³		
	The adiabatic expansion method	Mass accounting method	Calculation of the density of the solid phase
Sod-podzolic light loam	$0,48 \pm 0,04$	$0,45 \pm 0,02$	$0,44 \pm 0,01$
Light gray forest	$0,38 \pm 0,03$	$0,36 \pm 0,01$	$0,38 \pm 0,01$
Dark gray forest	$0,47 \pm 0,04$	$0,47 \pm 0,02$	$0,49 \pm 0,01$
Leached chernozem	$0,55 \pm 0,04$	$0,57 \pm 0,02$	$0,58 \pm 0,01$

Statistical processing of experimental results shows that with a confidence probability of more than 95 %, none of the tested methods is predominant in terms of porosity estimation, but the method based on taking into account the air mass allows us to significantly reduce the relative measurement error.

Several methods for determining porosity using this device have been developed. These are methods based on the isothermal expansion of pore air to vacuum and on adiabatic expansion of pore air to vacuum. However, the air cools with expansion, and the adiabatic process can be considered only approximately. In addition, we have developed a method for calculating the porosity, based on the expansion of pore air to an area of low pressure and taking into account the conservation of the pore air mass. Therefore, the recently received wide distribution and availability of pressure superchargers (for example, an automobile compressor) led to the development of a method for calculating porosity in which soil air is brought into contact with air at higher pressure. Since the main effect depends on the absolute value of the pressure difference, the air injection approach we propose is preferable to the approach in which air expands. When the maximum pressure difference is discharged, the atmospheric pressure is the value, and when injected, this value depends on the compressor's performance characteristics and can exceed the atmospheric pressure several times. The relative error of the measurements decreases by approximately the same factor. The manometers of the compressors are equipped with a well-distinguishable and easy-to-use scale and have high accuracy and minimum error.

4. Conclusions

Anthropogenic compaction on fields allocated for agricultural crops, mostly appears after the passage of machine and tractor units. On the cultivated lands, the emergence of a compacted layer of soil often takes place, which has a significant effect on the growth and development of plants. The study of the dynamics of deformations accumulation in the soil is conveniently investigated using maps with isolines with the soil porosity values. They make it possible to obtain quantitative, easily observable information in general, which was used for economically justified planning of agricultural activities. Therefore, the developed and used express method for determining porosity is described in the paper. Due to the speed and simplicity of the measurements, a lot of data was obtained in a short time, which is extremely important for short-term agricultural field work.

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