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Experimental Determination of the Relationship between Soil Structure Parameters and Indicators of Water Saturation and Filtration

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Abstract. Modern climatic changes, in particular, changes in the amount and intensity of soil moisture (precipitation regime), have a significant impact on the water-physical properties of mineral soils. The state of soil's solid phase and the mutual arrangement of its structural particles can be considered as the most significant factor for soil properties. Due to the structure of the soil, it is possible to influence the uniformity of the distribution of water in the soil sample not only in the vertical direction, but, partially, also in the horizontal direction, which will allow to resolve the issue of local flooding of individual areas and the bearing capacity of mineral soils. For the analysis of changes in the water-physical properties of the soil environment, the soil was considered as a homogeneous in density and continuous environment formed by a set of separate structural aggregates connected by cohesive forces. Based on the experimental results of the physical modelling, it was determined that the presence of structural soil macroaggregates with a size of 4 to 6 mm is the most appropriate for slowing down the vertical filtration of water saturating the lower soil layers, and the formation of structural soil macroaggregates of size larger than 6 to 10 mm for the predominant types of soils is necessary to increase the vertical filtration. Due to the size of the formed macroaggregates, it is possible to predict a change in the water-physical parameters of the soil, which then can be used for the assessment of the calculated characteristics of the soil environment.

Key words: ground water, soil structure, water saturation, filtration

1. Introduction

As is known, any soil is a complex three-phase medium, the physical and mechanical properties of which are largely determined by the quantitative ratio of these phases: liquid – water, solid – soil particles, and gaseous – air. All of them are interconnected, and the state of the solid phase of the soil and the mutual arrangement of its structural particles can be considered as the most significant for soil properties. The structural structure of the pores between the soil particles determines the prerequisites for filling the soil body with water or air.

Macroporosity of the soil is related to its index of strength and looseness, while no clear correlation with the characteristics of the pore geometry was found due to observed large variations in these properties. In addition, soil water strongly affects soil fragmentation and loosening (Munkholm 2002).

The temporary resistance to destruction of structureless samples at any moisture level is much higher than that of structural samples, which confirms the effect of the soil internal structure on its mechanical strength (Panov and Vetokhin 2008).

Due to changes in soil moisture, indicators of its physical and mechanical properties, according to various researchers, can vary within fairly wide limits, see plots in Fig. 1 to 4 (Babkov and Bezruk 1986, Zaika 2001, Revut 1964). In the above studies, the main characteristic of the solid phase is the soil density, which cannot be considered as an exhaustive initial criterion, as it does not take into account the macrostructure of soil particles, which can be different.

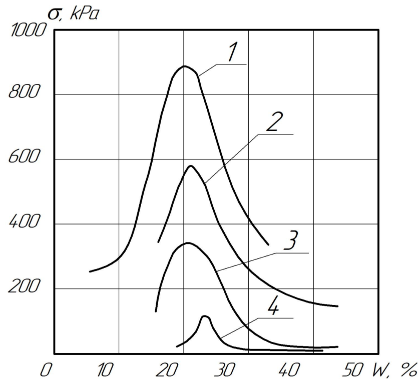

Fig. 1. Dependencies of the strength characteristics of clayey soil on humidity (according to A. Garcia): α – fracture stress, respectively, from 1 – compression; 2 – displacement; 3 – bending; 4 – stretching (Zaika 2001)

Obtaining a different soil structure through a set of microcracks and pores into which soil water or air will enter and be retained will result in a different moisture-accumulating capacity of the soil massif, which will directly affect its water saturation and filtration processes. Due to the structure of the soil, it is possible to influence the uniformity of the distribution of water in the soil massif not only in the vertical direction, but also partially in the horizontal direction, which will allow to solve the issue of local flooding of individual areas and the bearing capacity of the soil.

The issue of modelling filtration processes was studied by many authors, owing to whom the main features of groundwater flow were established and described. The issue of filtration flows and the influence of the intensity and directionality of filtration processes on the condition of the soil were considered, taking into account weather

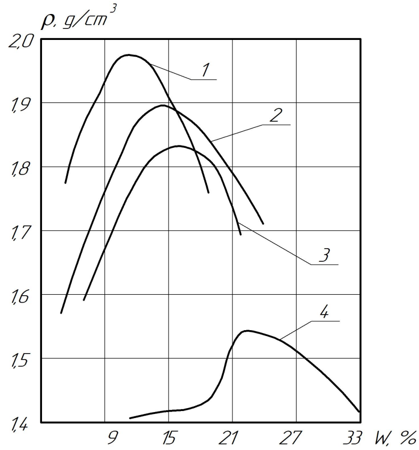

Fig. 2. Dependence of density on humidity during natural compaction: 1 – silty loam; 2 – dusty loamy loess; 3 – roofing dusty clay; 4 – clayey chernozem (humus layer) (Babkov 1986)

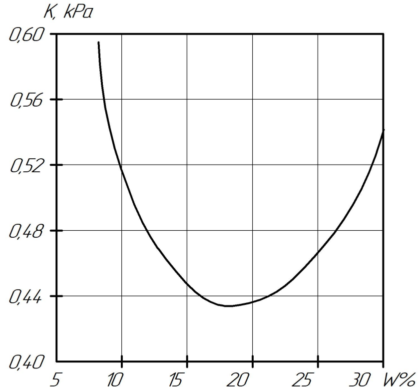

Fig. 3. Dependence of specific resistance to destruction of sod-podzolic soil on humidity (Revut 1964)

and climate studies of the increase in the unevenness of precipitation under conditions of climate change. The implementation of traditional water regulation technologies, with the intensification of excess water removal, are not sufficiently effective in practice (Indoria et al 2020, Auler et al 2014). In this regard, there is an objective need to adapt the soil environment by increasing the unevenness of water inflow into the soil to regulate filtration processes. Under such conditions, the development of modern technologies should be based on the introduction of progressive water regulation that takes into account the natural conditions of a specific object, which should ensure the saving of energy resources (Rokochinskiy et al 2020).

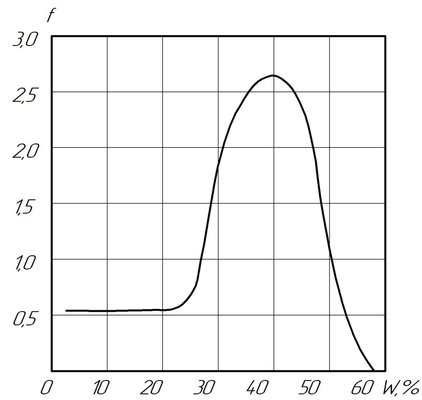

Fig. 4. Dependence of the soil friction coefficient on the absolute moisture content of the clay soil (according to A. Garcia) (Zaika 2001)

Groundwater regulation through mechanical impact on the soil is widely accepted as one of the appropriate ways to solve problems in agriculture. Results show that their effectiveness varies depending on the seasonal distribution of precipitation and its intensity (McHugh et al 2007, Miriti et al 2013, Haghnazari et al 2015, Haddad 2022).

Mechanical loosening of the soil to a depth of 30 cm or more loosens it well, and this allows for maximum absorption and retention of moisture in some soils (Unger et al 2010). Well loosened soil is able to absorb all the precipitation of a heavy downpour in 2 to 4 minutes and increase water penetration by 5.0 to 5.5 times compared to loosened soil (Odey et al 2014, Bertolino et al 2010, Soil water penetration 2018).

Intensive absorption of moisture formed after soil loosening occurs when soil aggregates provide conditions for maximum accumulation of gravitational moisture in the lower layers of the soil. In deeply loosened soil, water seeps depths of 24 to 32 cm within 45 minutes, increasing the moisture content of the lower layers by 1.5 to 1.6 times. Soil loosened to a depth of 31 cm is able to absorb 30 mm of rain within 5 to 10 minutes. Later, the intensity of absorption is levelled off when small soil aggregates (with a diameter of up to 10 mm) are formed in the loosened layers, which swell intensively and absorb moisture. The main factor affecting the intensity of moisture absorption is the depth of fluffing. In general, in the lower layers of plowed soil, more than two showers can be assimilated at the same time (Soil water penetration 2018).

Taking into account the necessary technological changes, it is important to model the theoretical structure of the loosened soil in order to conduct further research on the dependence of the water-physical properties of the loosened soil, accounting for the natural and technological prerequisites.

The desire to derive the macroscopic properties of the soil from the properties of its internal structure, composition and location of constituent parts in space has existed for a long time. The first model of the soil structure was proposed by the

English researcher B. Keen in 1933 (Michurin 1975). The issues of the internal soil structure modelling are relevant to the present time. One of the reasons for maintaining this relevance is the problem of modelling the soil moisture retention function – the main hydro-physical characteristic of interest.

All known soil structure models can generally be divided into two groups: the models using full similarity methods, and the models based on incomplete similarity which are self-affine. In the first case, in order to derive modelling results, the soil is treated as a more or less regular dense packing of the same (Romm 1985) or different-sized spheres (Michurin 1975). The number of hierarchical levels of such models is not mathematically limited, and is determined only by the presence of soil elements of various sizes. Depending on how densely packed the elements of the model are, hexagonal or cubic stacking is distinguished. The amount of integral and differential porosity of such a model, as well as the shape of soil pores, depends on the type of laying.

Among the structure models that are based on the principle of similarity ("ordered" models), capillary models are known. In a capillary model, the porosity of a continuous soil body is approximated by a system of pores and capillaries. The capillary system can have any complex structure, and the capillaries themselves can have a different shape; the shape of the capillaries depends on the value of the capillary forces of water retention of such a model. There are models that combine and complicate regular models of soil structure. Common to regular models is that the element of randomness, disorder, chaotic organization of soil macroelements, and their spatial arrangement, are completely excluded from considerations (Blunt et al 2013).

Relatively recently, fractal models of the internal soil structure have appeared. These models are based on the generalization of classical fractals – Serpinski's carpet or Menger's sponge. Fractal geometry is not interested in the shape of the elements of the structure involved, since it is only interested in the fractal dimension and the number of iterations which characterizes the number of hierarchical levels of the considered self-affine set. In reality, the soil structure occupies an intermediate position between these two poles.

The soil environment to be studied can be considered as a homogeneous in density and continuous medium formed by a set of individual structural aggregates interconnected by cohesive forces (Lukyanchuk 2019, Mazhayskiy et al 2021). According to the idealized scheme, the soil aggregates formed during loosening will have a regular rectangular shape. But it can be logically assumed that, in the future, the top surfaces of such soil aggregates will still be destroyed due to the interaction of soil aggregates with each other, so that they will become approximately similar to balls of different sizes (Corwin et al 2010). The water-physical properties of loosened soil, according to this scheme, will be determined by the volume of pores between structural units of different sizes in adjacent layers.

Similar studies, but without an emphasis on the structure of the soil environment, were conducted by C. Slichter. For the formation of a porous medium and determination of its filtration parameters, spherical particles packed in the entire volume in the same way by elements of eight spheres – Slichter cells (Romm 1985) – were taken.

Therefore, to analyse the ability of the loose soil structure to accumulate and filter soil runoff, it is necessary to develop a structural model with individual spherical particles up to 10 mm in size, forming a dense packing.

Based on the above, the following objectives for the experimental investigations on the laboratory scale were defined:

- the determination of the nature of the changes in water-physical characteristics (lowest moisture capacity, porosity coefficient, filtration time) depending on the size of the soil bulk structure of the particle array;
- the determination of the rational sizes of the particles of the idealized bulk structure according to the relative energy criterion.

2. Material and Method

The following materials and equipment were used in the laboratory during the experimental research: metal balls of diameters between 2 and 8 mm of SHH15 GOST 3722-81, two pieces of ferrite magnet of dimensions 85×65×17 mm (type $SrO \times 6Fe_2O_3$, $BaO \times 6Fe_2O_3$), electronic scales Pocket Scale MH-200 200g/0.01g, built-in electronic stopwatch Nokia 2730, measuring container for liquid with a mark of 1 dm^3, and through plastic tube with a cross-sectional area of 3.14 cm^2. These elements of the laboratory setup are illustrated in Fig. 5.

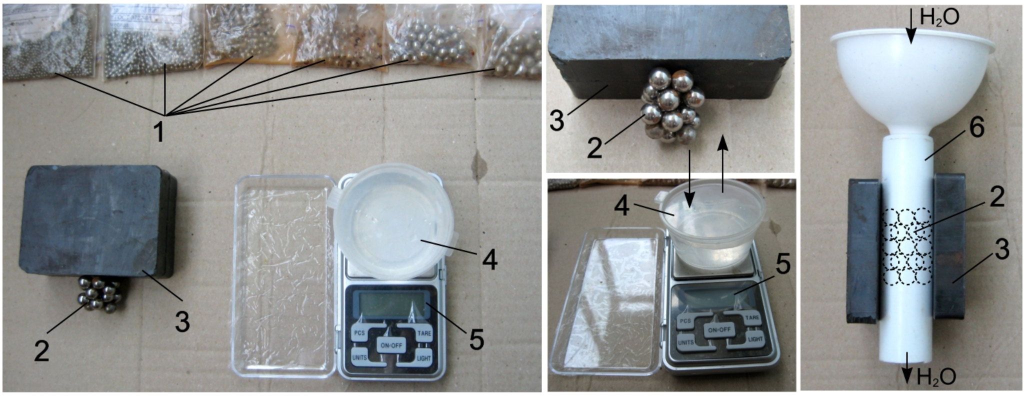

Fig. 5. Laboratory equipment and materials: 1 – a set of metal balls of different sizes; 2 – a set of balls kept together; 3 –retaining magnet; 4 – container with water; 5 – scales; 6 – through tube

To form a dense packing of the idealized bulk structure of the array of particles in order to maintain the exact size of the particles and to avoid the marginal effect of the container, metal balls were used, with their retention ensured by by a magnetic field.

To determine the nature of the change in water-physical characteristics, balls of different diameters were selected in the array so that their total volume was the unchanged. An array of balls of the same diameter was formed on the end of the magnets in the form of a dense lump. Then they were lowered into a pre-weighed container filled with water, until the array was completely submerged. After standing for a few seconds in this position, the sample was completely pulled out from the water, and after the water drained, the residual mass of the container with water was recorded. The bulk volume of the mass of balls was determined from the condition of their maximum dense stacking in a hexagonal cylinder, which most closely corresponds to the natural organization of soil macroaggregates with minimal influence of the side walls.

For determining the permeability of porous media, an array of balls of the same diameter was formed in a form of a dense lump in the middle of a through plastic tube, with two magnets being attached to the outer side surfaces of the tube in order to fix the position of the array of balls inside the tube. Water was poured into a tube filled with balls, and the time of the beginning and the end of filtration of a certain volume of water was recorded.

All measurements were performed with threefold repeatability and were processed by the methods applying statistics.

3. Results and Discussion

The results of experimental measurements are presented in the Table 1.

Table 1. Averaged results of experimental measurements

Parameters of the total volume of spheres, V_0 = 5630.0 mm^3			Mass of water in the container; m_v, g		Filtration time of 1 dm^3 of water, t_f, s
Ball diameter, d, mm	Number, n, pcs	The volume of the packed array of balls, V, mm^3	Before the immersion of the array of balls	After the immersion of the array of balls	
8	21	11323.5	155.21	154.88	20.66
7	31	10114.4	154.88	154.51	25.41
6	50	9554.2	154.51	154.09	27.17
5	86	9215.1	154.03	153.48	35.44
4	168	8492.6	153.46	152.69	39.28
3	398	8359.9	152.69	151.75	46.89
2	1344	8374.6	151.56	150.19	49.52

Based on the data obtained by direct measurements, the values of derived quantities have been determined, as shown in Table 2.

The porosity coefficient k_{por} was determined as the percentage ratio of the volume of pores to the entire packed volume of spheres V. The indicator of the lowest moisture content W_{HB} was determined by the percentage ratio of the volume of retained water

Table 2. Calculated water-physical characteristics

Ball diameter, d, mm	Porosity coefficient, k_{por}, %	The total surface area of the spheres, S_k, cm^2	The lowest moisture content, W_{HB}, %	Total moisture content, W_{pov}, %	Filtration coefficient, K_f, dm^3/h·cm^2
8	50.28	42.22	2.91	101.13	55.47
7	44.95	47.72	3.66	81.66	45.10
6	40,81	56,55	4.40	68.95	42.18
5	38.92	67.54	5.97	63.71	32.33
4	33.71	84.45	9.07	50.84	29.17
3	32.69	112.53	11.24	48.57	24.44
2	32.77	168.89	16.36	48.75	23.14

to the packed volume of spheres V. The indicator of total moisture content W_{pov} (water content) was determined as the percentage ratio of the volume of the formed pores to the packed volume of spheres V. The filtration coefficient K_f was determined by the time needed to filter 1 litre (1 dm^3) of water through a set of balls in a plastic tube with a cross-sectional area of 3.14 cm^2.

For the visual assessment of the nature of the change in water-physical characteristics (lowest moisture capacity, porosity coefficient, filtration time) depending on the particle size of the bulk structure, approximate relationships were derived (of approximation accuracy 0.93 of 0.99), see Fig. 6. The approximation formulae are defined by equations (1) and (2).

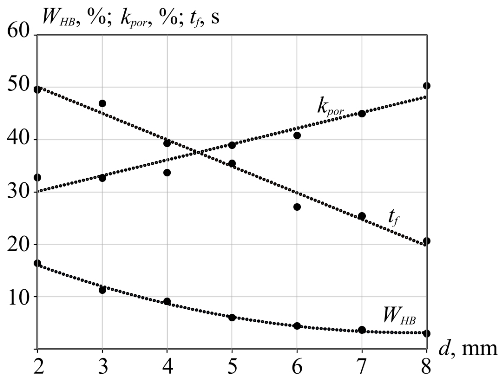

Fig. 6. The nature of the dependence of changes in water-physical characteristics on the particle size of the bulk structure: W_{HB} – the lowest moisture content; k_{por} – porosity coefficient; t_f – filtration time of 1 dm^3 of water

$$W_{HB} = 0.3822 \cdot d^2_{(mm)} - 5.9711 \cdot d_{(mm)} + 26.43, \quad (1)$$

$$k_{por(\%)} = 3.0052 \cdot d_{(mm)} + 24.135. \quad (2)$$

As seen in Fig. 6, the filtration time has an inversely proportional dependence on the particle size of the array, which is natural due to the corresponding increase in the size of the pores between the particles. The humidity indicator grows somewhat faster than the size of the array particles decreases according to an inverse parabolic dependence. The change in the porosity coefficient is directly proportional to the change in the size of the particles of the massif, it can be used when moving from the calculated parameters to the characteristics of the soil environment, see Fig. 7.

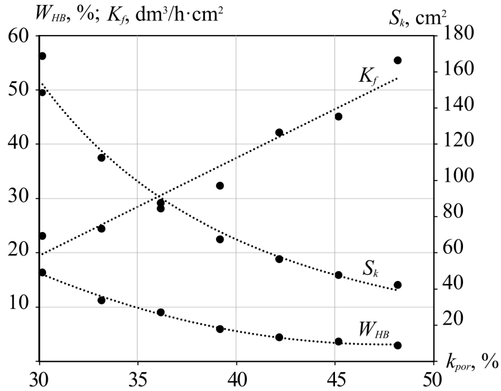

Fig. 7. The nature of the dependences of changes in water-physical characteristics on the porosity coefficient: W_{HB} – the lowest moisture content; K_f – filtering factor; S_k – the total surface area of the spheres

Grinding energy and moisture capacity depend on the formed contact area of soil macroaggregates. In our case, this is the surface area of the balls. As can be seen, the growth of the indicators of the surface area of the balls and the moisture content when the porosity coefficient decreases occurs at different ratios, see Fig. 7.

The energy efficiency for the value of moisture capacity E_w can be estimated as the ratio of its relative increase $\Delta W_{HB}/W_{HB}$ to the relative increase in the contact surface area $\Delta S_K/S_K$, which is proportional to the required grinding energy according to existing theories (Panchenko 1999). Hence, the capacity E_w is defined by

$$E_W = \frac{\Delta W_{HB}/W_{HB}}{\Delta S_K/S_K}, \ \%. \tag{3}$$

Having the approximation (1), the evaluation relation (3) and the predicted lowest moisture content for different types of soil (sandy – 5 to 10%, sandy loam – 10 to 20%, loamy – 20 to 30%, clayey – 30 to 45%), it is possible to proportionally model the dependences of $W_{HB} = f(d)$ for each type of soil and then to determine the rational particle sizes of the idealized bulk structure of spheres according to the relative energy criterion, see plots of E_w in Fig. 8.

The greatest accumulation of moisture in the soil will occur in the structure with the formation of macroaggregates 4 to 6 mm in size and smaller, which will contribute

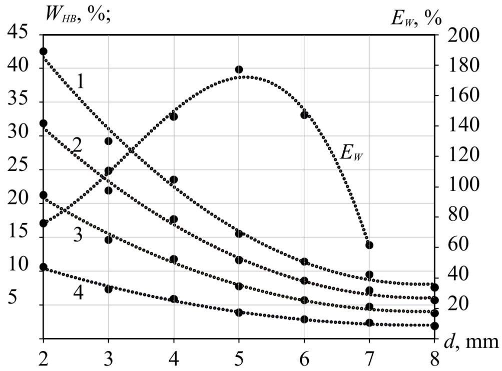

Fig. 8. Rational particle sizes of the idealized bulk structure: W_{HB} – the lowest moisture content; E_w – the relative energy efficiency of the increase in the amount of moisture capacity due to the grinding of the structure; 1 – clay soils; 2 – loamy soils; 3 – sandy loamy soils; 4 – sandy soils

to slowing down the vertical filtration of water. But in the case of macroaggregates smaller than 4 to 6 mm, there is a high probability of waterlogging of such an area, with a possible loss of the soil bearing capacity, which is undesirable. Taking this into account, in order to increase the vertical filtration, it is necessary to have a soil structure with the size of macroaggregates of diameters larger than 6 mm, and for a temporary slowdown – of diameters 4 to 6 mm.

The experimentally measured values for particles with a diameter of 7 to 8 mm can be considered of having only a theoretical potential, since smaller particles, with a diameter of 1 and 2 mm, respectively, can be placed in the gaps between such larger particles, which will be decisive, and which is what happens in reality.

The curves $E_w = f(d)$ shown in Fig. 8 will be common for all selected types of soils, which also means that mechanical loosening of the soil can be used equally effectively for different types of soils, guided by the specific costs of the required energy.

4. Conclusions

Based on the results of the physical modelling, it was found that the formation of structural soil macroaggregates with a size of 4 to 6 mm is the most appropriate for slowing down the vertical filtration of water, with the water saturating the lower soil layers. On the other hand, for strengthening the vertical filtration, the formation of structural soil macroaggregates larger than 6 to 10 mm in size is necessary for the predominant types of soils.

Due to the size of the formed macroaggregates and the indicator of the soil porosity coefficient, it is possible to determine the energy required for grinding, and to predict the change in water-physical parameters of the soil. These, in turn, can be used for the assessment of the calculated characteristics of the soil environment.

References

Auler A. C. et al (2014) Soil physical and hydraulic properties resulting from the management in integrated production systems, *Rev. Ciênc. Agron.*, **45** (5) (Especial), 976–989.

Babkov V. F., Bezruk V. M. (1986) *Fundamentals of soil science and soil mechanics* (in Russian), M.: Higher. school, 239 p.

Bertolino A. VFA, Fernandes N. F., Miranda J. PL, Souza A. P. et al (2010) Effects of plow pan development on surface hydrology and on soil physical properties in Southeastern Brazilian plateau, *Journal of Hydrology*, **393**, 94–104, https://doi:10.1016/j.jhydrol.2010.07.038.

Blunt M. J., Bijelijic V., Dong H., Gharbi O., Iglauer S. et al (2013) Pore-scale imaging and modeling, *Advances in Water Resources*, **51**, 197–216.

Corwin E. I., Clusel M., Siemens O. N. et al (2010) Model for ransom packing of polydisperse frictionless, *Soft Matter.*, **6**, 2945–2959.

Haddad A. (2022) Extreme Rainfall-Runoff Events Modeling Using HEC-HMS Model for Oued El Hachem Watershed, Northern Algeria, *Archives of Hydro-Engineering and Environmental Mechanics*, **69** (1), 45–57, https://doi.org/10.2478/heem-2022-0004.

Haghnazari F., Shahgholi H., Feizi M. (2015) Factors affecting the infiltration of agricultural soils: review, *International Journal of Agronomy and Agricultural Research (IJAAR)*, **6** (5), 21–35, ISSN: 2223-7054 (Print) 2225–3610 (Online).

Indoria A. K., Sharma K. L., Reddy K. S. (2020) Hydraulic properties of soil under warming climate, *Climate Change and Soil Interactions*, Chapter 18, 473–508, https://doi.org/10.1016/B978-0-12-818032-7.00018-7.

Lukyanchuk O. P. (2019) Modeling of the structure of loosened soil after the action of the curvilinear working element of the tiered deep loosener, *Bulletin of the NUVHP. Technical sciences. Collection of scientific papers*, Rivne: NUVHP, Issue 2(86), 225–238, https://doi.org/10.31713/vt2201919.

Mazhayskiy Y., Rokochynskiy A., Lukianchuk O. et al (2021) Research of energy capacity of structural comminution in deep loosing of sandy and loamy soil, *Engineering for Rural Development*, **20**, 57–62.

McHugh O. V., Steenhuis T. S., Abebe B., Fernandes E. C. M. (2007) Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands, *Soil & Tillage Research*, **97**, 19–36. https://doi:10.1016/j.still.2007.08.002.

Michurin B. N. (1975) *Energy of soil moisture*, L.: Gidrometeoizdat, 140.

Miriti J. M., Kironchi G., Esilaba A. O., Gachene C. K. K., Heng L. K., Mwangi D. M. (2013) The effects of tillage systems on soil physical properties and water conservation in a sandy loam soil in Eastern Kenya, *Journal of Soil Science and Environmental Management*, **4** (7), 146–154, November, 2013, https://doi:10.5897/JSSEM2013.0395.

Munkholm L. J. (2002) *Soil Fragmentation and Friability. Effects of Soil Water and Soil Management*, PhD thesis, Danish Institute of Agricultural Sciences, Department of Crop Physiology and Soil Science. Danish Institute of Agricultural Sciences, 50 p.

Odey S. O., Manuwa S. I., Ademosun O. C. (2014) Effect of Tractor Traffic and Moisture Content on Cone Index in a Crop-cultivated Land, *Proceedings of the International Soil Tillage Research Organization (ISTRO) Nigeria Symposium*, Akure 2014, November 3–6, Akure, Nigeria, 134–142.

Panchenko A. N. (1999) *The theory of soil grinding by tillage tools* (in Russian),. Dnepropetrovsk: DGAU. 140 p.

Panov I. M., Vetokhin V. I. (2008) *Physical foundations of soil mechanics* (in Russian), Monograph. K.: Phoenix, 266 p.: ISBN 978-966-651-621-6.

Revut I. B. (1964) *Soil physics* (in Russian), L., Kolos, 320 p.

Rokochinskiy A., Volk P., Koptyuk R., Prykhodko N. (2020) Formation of water demand of drained lands in relation to changing climatic and agromelioration conditions. (Formation of water demand of drained lands in relation to changing climatic and agromelioration conditions), *Reclamation and Water Management*, **1**, 76–85, https://doi.org/10.31073/mivg202001-231.

Romm E. S. (1985) *Structural models of porous space of rocks*, M.: Nedra, 241.

Soil water penetration. Chisel-deep loosener CHG-40 (2018) Protocol No. 01-18-2018 (01-18-2018) of July 24, 2018. Functional tests (focus test) of the Center for the Development of UkrNDIPVT named after L. Pogorily. Research, http://www.ndipvt.com.ua/focus_tests/Chizel_ChG-40_waterpen.pdf, http://www.ndipvt.com.ua/focus_tests/Chizel_ChG-40-02_waterpen.pdf.

Unger P. W, Kirkham M. B., Nielsen D. C. (2010) Water Conservation for Agriculture, [In:] *Soil and Water Conservation Advances in the United States*, Chapter 1, 1–45, Soil Science Society of America. February 2010, https://doi:10.2136/sssaspecpub60.c1.

Zaika P. M. (2001) *Theory of Agricultural Machinery* (in Russian), Vol. 1 (part 1): *Machines and tools for soil cultivation*, Kharkiv, Oko. 444 p.