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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Specific water regime in technogenic soils: preferential water flow formation

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Abstract

Technogenic soil (technozem) was created on the surface of the former sludge pond of the iron-ore quarry in the course of land rehabilitation. The upper chernozemic layer in the technozem was underlain by sandy or loamy layers. The soil land reclamation constructions were created 20 years ago: the chernozemic 60-cm layer with classical granular fine and medium-size aggregates (1-5 mm) was sprinkled on the deep layer of sand. This construction was in agricultural use during the last 20 years. At present, the layers of prismatic coarse peds (>50mm) bounded by flat to rounded vertical faces and columnar, very thick, vertically oriented blocks (>100mm) have been formed at the depths 20-40 and 40-60 cm. The water regime of these soils differed from that of the background automorphic natural soils and was characterized by periods of water stagnation at the boundary between the two layers. In the course of 20 years, this type of water regime resulted in the development of a columnar structure in the lower part of the chernozemic layer. The coatings on the ped faces in this part of the profile had an increased content of Fe and Ca ions. There was no differentiation of the carbon of organic substances and carbonates in the soil profile. Field studies of water flows in this soil based on starch label and laboratory experiments on infiltration of salt solutions though the soil columns with determination of breakthrough curves demonstrated the existence of preferential water flows in technozem. Rapid infiltration of water through preferential water paths in chernozemic layer after abundant rainfalls and during the snowmelt season leads to the development of perched water above the textural boundary. This preferential water and matter flows are generated along the faces of the peds and form the perched water layer on the sand. Such kind of water phenomenon with preferential flows and perched water table formation transforms the granular aggregates into columnar blocks by the temporary gleyzation process.

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Keywords: technogenic soil, preferential flow, soil structure

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1. Introduction

The problem of water regime of disturbed under land reclamation soils is one of the pressing problems in the world. Especially, works on the ecological monitoring of reclaimed soils are rarely performed. At the same time, significant changes in the agrophysical properties of such soils may take place upon their exploitation and result in the development of soil degradation. The essence of the physical and hydrological processes leading to degradation of reclaimed soils upon their exploitation remains poorly known.

The aim of the work is to study the physical properties, hydrological processes and structure degradation in the artificially created layered technogenic soils (technozems).

2. Materials and methods

Technogenic soils formed within the reclaimed area of the former sludge pond, the sand-chalk mixture was covered with a thick layer of loesslike loam. After drying of the sand and loam, the material of the humus horizon of a typical chernozem was used as a fill. It was applied in the dry state. The thickness of the applied chernozemic layer was about 60 cm. In 1986, the artificial layered soil was created on the former sludge pond surface. After this, this area was involved in agricultural use.

Soil profile was excavated in the southwestern part of the former sludge pond. The technozem included the following layers.

Layer I, 0-22 cm. Dark fray heavy loamy plow horizon with a fine crumb structure and smooth lower boundary; numerous roots oriented in both vertical and horizontal directions.

Layer II, 20-26 cm. Dark gray heavy loam; crumb-granular structure; smooth boundary; some aggregates are up to 5 mm in diameter.

Layer III, 26-35 cm. Brownish dark gray heavy loam; angular blocky; the size of peds increases down the soil profile; abundant roots of predominantly vertical orientation.

Layer IV, 35-60 cm. Brownish dark gray heavy loam; coarse angular blocky structure with ped diameters of 20-40 mm; ped faces are covered with brown coatings. In the lower part, the columnar-prismatic structure is clearly seen; the roots stretch along the vertical faces; the columnar aggregates are relatively loose and can be mechanically destroyed into separate fragments.

Layer V, > 60 cm. Sand layer; in some places, fragments of a thin (1-2 cm) crust can be seen on the sand surface. This crust could form on the sand surface due to the uneven deposition of the sand pulp.

The soil bulk density, solid phase density, and aggregate-size distribution were analyzed by routine methods [1,2]. The coefficients of water infiltration for separate layers were obtained according to Horton's equation from the results of infiltration tests with the method of water tubes with variable head, which made it possible to estimate the coefficients of infiltration (unsaturated hydraulic conductivity) in the area close to the saturated hydraulic conductivity [3].

The particle-size distribution analysis was performed by the method of laser diffractometry on an Analysette 22 NanoTec device after the pretreatment with 4% $Na_4P_2O_7$ and ultrasonic dispersion.

The results of soil analyses [4] demonstrated the alkaline reaction of the soil mass and the absence of clear differentiation of organic matter and carbonates in the soil profiles (Table 1).

In order to study preferential water flows in the soil, the method of starch label [5] was applied in the field experiment. Frames of 16 cm in diameter were installed on the soil surface and filled with a 2% starch solution. There were two variants of the experiment. In the first variant, the frames were initially filled with water (about 5 l/frame), after which the starch solution was applied. In the second variant, the starch solution was applied without preliminary filtration of water, which made it possible to trace the formation of water flows in the studied technozems at the initial stage. After the end of the starch solution infiltration the soil was cut down into 5 to 10-cm thick layers; on their horizontal surfaces (after cutting of the overlying layer), the pattern of water flows was fixed via staining the remaining starch with iodine water. The morphology of such sections was described, and the distribution of the starch label was recorded with a digital camera. For control, it was also plotted on polyethylene films. Then, the areas of starch-impregnated mottles were determined.

Table 1. Some physical and chemical properties of technozem

Layer, cm	Bulk density, g/cm^3	Soil particle density, g/cm^3	K_{inf}, cm/min	Sum of water-stable agr. >0.25 mm, %	Granulometric particles content (%)			pH_{H_2O}	C_{CaCO3}, %	C_{org}, %
					Sand (0.05 – 1 mm)	Silt (0.002 – 0.05 mm)	Clay (<0.002mm)			
0-10	1.04	2.62	0.72	60.4	4.37	75.26	20.37	8.73	0.69	2.99
10-20	1.22	2.65	0.63	61.4	3.91	76.22	19.87	8.74	0.73	2.87
20-30	1.28	2.67	0.44	71.4	3.03	76.78	20.19	8.75	0.77	2.98
30-40	1.22	2.68	0.93	77.2	2.53	76.88	20.60	8.71	0.78	2.83
40-50	1.35	2.68	1.80	84.8	2.44	76.61	20.95	8.57	0.63	2.84
50-60	1.37	2.66	2.60	80.2	1.41	77.86	20.73	8.52	0.76	2.84
60-70 (sand)	1.40	2.66	9.26	–	96.61	2.86	0.53	9.17	3.57	0.03

Note: K_{inf} is the coefficient of water infiltration; CCaCO3, Corg, content of mineral and organic carbon

3. Results and discussion

The structure of the filled chernozemic layer in the studied technozems differs considerably from the classical granular structure of chernozems, which was the basis for this material. In the course of 20 years, the classical chernozemic structure has degraded in the subplow horizons and, particularly, in the lower part of the chernozemic layer (40-60 cm). Field studies demonstrated that the growth of the size of angular blocky (and columnar-prismatic) peds is accompanied with an increase in the soil bulk density (Table 1). The study of water stability of the aggregates in the upper 10 cm showed that coarse aggregate fractions were completely destroyed upon slaking in water. In the lower part of the upper chernozemic layer, soil aggregates have an increased water stability against the background growth of the soil bulk density. A sharp change in the structural status of technogenic soils with an increase in the content of very coarse aggregates has already been noted in the literature [6,7]. Significant changes in the structural state of the soil and the development of interped fissures have resulted in the exceedingly high hydraulic conductivity within the upper (chernozemic) soil layer, particularly below 40 cm.

An analogous change in the structure of chernozems can be observed in natural soils upon the increasing duration of the temporary soil waterlogging. For instance, an increase in the size of aggregates and aggregate water stability down the soil profile has been noted for meadow-chernozemic soils of the Tambov Plain. The peds in these soils assume a prismatic shape [8]. The high content of humus and smectitic clay minerals in the chernozems contribute to the high sensitivity of these soils to the rise in the soil water supply [9].

The creation of an artificial layered technozem with abrupt boundaries between separate layers has changed the water regime in the upper chernozemic layer. Even a short-term overwetting of chernozems and alternation of wetting-drying stages lead to the structural rearrangement of the soil profile; often, vertic features appear in the soil. The degree of transformation of separate horizons of chernozemic soils (including filled chernozem in the technogenic soil) largely depends on the degree and duration of soil waterlogging with water stagnation in the profile. Water stagnation in chernozems leads to rapid substitution of anaerobic conditions for aerobic conditions. The heavy texture of the studied technozem (Table 1) and the presence of smectites in the clay fraction specify the high water retention capacity in the chernozemic layer. Differences in the texture of the upper chernozemic and underlying sandy or loamy layers may lead to the formation of a horizon with perched water above the litho-logical contact. The abrupt boundary between separate soil layers favors temporary water stagnation above this boundary and the horizon of perched water is formed above the boundary between the upper heavy loamy (chernozemic) and the underlying sandy layers. In turn, water stagnation and its spreading over the surface of the underlying layer contribute to the changes in the physicochemical and chemical properties of the soil and to differentiation of the peds into the surface and inner parts. These processes transform the structural state of the soil.

In order to confirm (or reject) the hypothesis about the transformation of the soil structure in the chernozemic fill under the impact of water stagnation at the boundary between separate soil layers, a field experiment in the study of preferential paths of water flows with the help of the starch label was conducted. The results of this experiment (the distribution of starch mottles in the soil mass within separate horizontal soil sections) are shown in Fig. 1.

In our field experiments the frames were installed on the soil surface and at a depth of 45 cm. The distribution of starch mottles shows that the transition from the upper layer with fine crumb structure to the underlying layer with coarse angular blocky structure is accompanied with the strong concentration of the water flow. This is especially well seen in the distribution of starch added with water at a depth of 45 cm. Within the lower part of the chernozemic layer, water infiltration proceeds mainly along the prisms and columns.

The irregular distribution of starch was more distinct in the experiments, when starch was added immediately, without the preliminary adding of pure water. In the case of the preliminary soil moistening with water, the infiltration of starch followed the steady-state pattern; the starch label quickly passed downwards through the soil profile along the fissures, so that no distinct coloring of the starch in the soil mass under the frame was seen. However, some bluish tint from the applied starch could be detected on digital photos processed.

Fig. 1 demonstrates that starch spread over the boundary with the underlying sandy layer and formed extensive zones of continuous coloring. It should be noted that the underlying sandy (sand-chalk) layer also exhibited a layered character, which could not be seen from the visual morphological description of the soil profile, but was evident from the distribution of the starch label. On the vertical wall of the pit, the layered character of the zones of most active starch coloring in the sandy material was distinct.

The investigations of organic matter in these soils displayed the absence of changes in composition of hydrophilic and hydrophobic components. The morphological study of the soil profile coupled with data on the elemental composition of the soil mass from the inner parts of the peds and the coatings on their faces in a layer of 50-60 cm (chernozem/sand) indicates that the brown coatings on ped faces are enriched in iron, which may attest to a periodical overwetting of this part of the technozem profile. The immobility of iron hydroxide in an alkaline medium (see Table 1) excludes the illuvial origin of these coatings. It is probable that their formation is related to microbiological processes causing some differentiation of the aggregates material. In any case, an increased content of iron ions with structural bonds of crystallization type facilitates the stability of the aggregates. In turn, this contributes to the enhanced interaggregate porosity and, hence, to the increased water infiltration through intraped fissure pores. "Breakthrough curves" of K and Cl ions concentrations were obtained in laboratory experiments. With an increase in the soil depth, the curves are shifted to the left, which points to the leveling of ion concentrations in the soil mass. In the deeper horizons, more considerable time is required for the leveling of ion concentrations, because the portion of macropores with preferential water flows increases, whereas the role of fine pores in the water migration decreases. The latter pores are slowly filled with migrating water. An increased velocity of the water movement through macropores leads to a less active sorption of potassium ions, which also results in the leftward shift of the curves down the soil profile; the inclination of the curves increases. Such changes in the filtration characteristics of the soil mass with the formation of a specific type of the soil water regime have already been described in the literature [10-12].

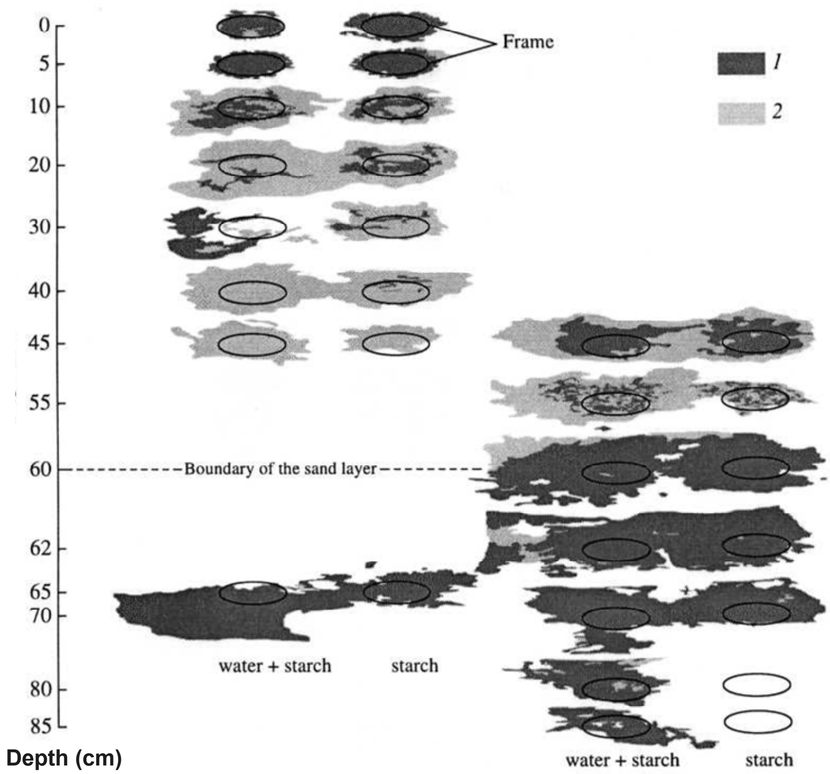

Fig. 1. Major paths of water filtration as judged from coloring of the applied starch in pit (chernozem/sand): (1) distinct coloring of the label and (2) indistinct coloring in the zones of capillary sorption of starch

Thus, the inner parts of the peds in this soil layer formed upon the structural transformation of the initial chernozemic material are subjected to relatively long periods with anaerobic conditions. As a result, the zones with the high water content in the central parts of the peds are preserved for a long time even in the case of the general drying of the soil mass. We assume that such kind of air–water mesoregime of the soil peds may be influenced by the distribution and functioning of soil biota. We guess that the group of Fe-reduction bacteria and other microorganisms with Fe-reduction abilities are developed in the centre part of the peds. So, the processes of the Fe^{3+} to Fe^{2+} reduction in the period of the inner part saturation, movement of Fe^{2+} to surface are carried out by the bacterium-anaerobes consortium. And F^{2+} to Fe^{3+} oxidation on the surface ped are carried out by soil biota.

4. Conclusions

In the period of 20 years of functioning of the artificially created technogenic soil composed of the upper 60-cm thick chernozemic fill underlain by sand or loam, considerable changes in the soil properties took place. From a depth of 35-40 cm, the granular structure of chernozem is transformed into the coarse blocky structure with the high water stability. In the lowermost part of the fill layer, such blocks compose prisms and columns. The indications of temporary water stagnation in this zone are clearly expressed in the form of iron-rich coatings on ped faces, rusty mottles above the contact zone, and vertic features. These features are developed under the impact of a specific water regime in the technogenic soil with the formation of preferential water flows. Under these conditions, the participation of intraped pores in the water migration is negligibly small. Preferential water flows are concentrated along fissures separating prismatic aggregates, which has been confirmed in the experiments with the starch label. The study of the spatial pattern of soil water flows made it possible to detect the horizontal spreading of water above the contact with the underlying sandy layer. As a result, the stagnation of water and the development of anaerobic conditions take place. Gleyzation is developed, particularly in the inner zone of peds. Iron compounds are concentrated on ped faces. In the concluding, emphasize the fact that in such situations the use of irrigation becomes crucial in order to replace the benefits that are missed due to the deep drainage.

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