INVESTIGATION OF GEOFILTRATION PROPERTIES OF CLAY SOILS

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Abstract. Filtration properties of clay (Kuksa mine, Lithuania) were investigated and analysis of the results was done. Investigations were carried out using a permeameter with a varying hydraulic head. A potential dependence of the clay hydraulic conductivity values on the filtration process duration as well as hydraulic gradient and compaction range were determined. The importance of the clay structural peculiarities, carrying out filtrations through clay paste, natural structure and compacted samples was evaluated. It was determined that the clay hydraulic conductivity values varied greatly only at the beginning of the filtration while, later on, when continuing the filtration for a few days, the change reduced. This shows that, during the filtration, there are structural clay-forming unit rearrangements that are taking place. The filtration investigation of the clay paste studies show that there exist clay structural links different changes the filtration capacity of clay. The determined varying behaviour of the clay and the clay paste in the course of filtration as well as under various loads must be evaluated in the design and reconstruction of roads with subgrade of the clayey soils.

Keywords: clay, clay paste, filtration, hydraulic conductivity value, hydraulic gradient, hydraulic head, laboratory investigations, permeameter.

1. Introduction

In order to reduce road building costs and time the local soils are used, i.e. clays of different plasticity, which according to their characteristics are almost unsuitable for building the subgrade. To ensure stability and consistency of subgrade, built of these soils, it is necessary to control a hydrothermal regime which is conditioned by the geofiltration properties of clayey soils. Also, the use of clayey soils, as of the impermeable rock, allows to qualitatively assessing the settlement of road bases and bridge piers due to the impact of filtration consolidation, while filtration parameters of clayey soils allow predicting their frost-sensitivity. The waterproofing properties of clay layers depend on various interrelated factors and parameters: hydraulic conductivity, porosity and micro-structural peculiarities of the pore space, moisture content, thickness of a natural or artificially-formed waterproofing layer, mineral composition of clay, chemical composition of filtrates, the future hydrodynamic loads, the possible frost impact and other factors. However, the main indices that are quantifiably regulated are hydraulic conductivity and layer thickness. Therefore, it is of utmost importance to determine a hydraulic conductivity of clay and its filtration properties meeting the current requirements.

The filtration properties of the Lithuania's clay are not widely investigated, because in the past, there was not much demand. Another reason is that from the scientific point of view experimental laboratory clay investigation is long-term due to the slow filtration and requires a lot of time to build a series of informative experimental data. The survey of the recent scientific publications shows a strong interest in clay geofiltration investigation in different regions. Filtration experiments were carried out with distilled water and several copper concentrations (10^{-3}–10^{-1} mol/l). The permeability variations with copper concentration using the syringe odometer, permeability is 1.1E-12 m/s with distilled water and 2.4E-12 m/s with the 0.1 mol/l copper solution (Julien *et al.* 2002). Compact Opalinus Clay core samples from a 200 m deep lying thickness were tested at the Mont Terri rock laboratory in Switzerland. It was

determinate, that permeability and porosity as a function of time at constant pressure (Jobmann *et al.* 2010). Similar functional dependencies in Lithuania Visaginas clays were determined (Klizas 2014). In Italy, tests with water vapour permeability of clay bricks showed that there exist links to get wide range of chemical and mineralogical compositions and particle size distributions. Links in sample between vapour permeability, open and closed porosity, bulk density, mean pore diameter, pore size selection and specific surface were determined (Dondi *et al.* 2003). Considerable attention is paid to the frozen soil filtration analysis, which is very important for those regions where the winter average temperature is negative, including Lithuania. This type of clay investigations were carried out in Lithuania for the first time (Klizas 2014). In France was studied permeability of various-texture frozen-bulk soil mixtures. The laboratory tests were carried out by means of a permeameter changing the negative temperatures and using various configurations of filtrate: water, various concentrations of NaCl solution, bentonite and traped decane (Enssle *et al.* 2011). In France, Callovo-Oxfordian clay formation consisting of muscovite mica (Comptoir de Mineraux et Matières premieres) essentially composed of SiO_2 is sodic montmorillonite, i.e., bentonite from Oene, France; the obtained results confirm that, in the course of filtration, the space structure changes. This power was analysed by Scattering Electron Microscopy (Nammar *et al.* 2001). The sand and clay mixture filtration investigation shows the importance of percentage of these soils, compression scope and clay mineralogical composition (Ebina *et al.* 2004; Schafiee 2007). The clay suspension investigation shows the importance of the structure of the clay filtration properties (Hamdi *et al.* 2008). Investigations were carried out in-situ and laboratory for the determination of anisotropic permeability of argillite thicknesses in Switzerland. Shao *et al.* (2011) evaluated importance of layering structure for filtration properties by horizontal and vertical directions.

The first Lithuanian low-permeable soil filtration laboratory investigations of the upper-middle Devonian clay, silt, clay marl, dolomite, and sandstone were carried out by means of the "Lita-5" permeameter designed by Klizas and Miksys (1984). Šaltiškės, Pašaminė and Stabatiškiai clays were studied. Odometer, field infiltration experiments with a double-ring permeameter and borehole filling were carried out under V. Nasberg methodology (Gadeikis *et al.* 2012). The latest Stabatiškiai body, i.e., Grūda deposit moraine clay filtration investigations showed that the clay properties are very variable when freezing it and then again after thawing. Such freeze-thaw cycles change the filtration properties of the clay (Klizas 2014).

2. Composition and structure of clayey soils

Structural features of clayey soil are determined by the properties of dispersed clay particles (micelles). What is typical of clay mineral micelles is a double electric layer, which forms at the boundary of solid and liquid, i.e., water present in clay. The structural clay mineral dispersion

heterogeneity and particle surface crystal-chemical specifics that manifest itself at the micro-structural level change the concept of the pore space of clay. The pore space is determined by the variable filtration process in comparison with other dispersed systems consisting of identical particles, among which there is no interaction, e.g., sand. The clay thickness micro-structural level has a higher heterogeneity and depends on the ratio of three main clay minerals: kaolin, mica and montmorillonite. The layer macro-structural heterogeneity is determined by large fragment spots, macro-pores, and lamination and cracking in strongly lithified columns. Macro-pores are specific for unsaturated zones in clay source thickness including artificially formed pre-filtration barriers. Pores and cracks mainly determine the filtration anisotropy of the clay layers. It is specific for these macro-porous that in the course of the long-term filtration they chock and as a result of the long term experiment clay-sample hydraulic conductivity values consistently decrease. During the filtration in clayey soils, pore dimensions vary from 3 Å (angstrom) to 20 Å, at the same time there is an on-going exchange of hydration-dehydration of clay minerals on the surface and inside as well as particles binding into larger aggregates. At the micro-aggregate level, when the pore dimensions are 1–10 μm, there are observed pore space and structural changes in a relatively homogeneous sample and layers, which results in the anisotropy of the clay water filtration properties (Oradovskaja 1983). Filtration occurs in clay particles while structural rearrangements are the larger the more diverse the original structure. It was determined that in the course filtration at higher hydraulic gradients, clay mineral particles re-orientate parallel to the water flow lines, and, with the hydraulic gradient dropping down, clay particles do not return to the initial position. This phenomenon is characterized by high humidity and porosity of clay.

3. Experiment (methods and materials studies)

The aim of investigations was to assess the potential change of the clay filtration properties in the course of the long-term and the short-term filtrations. The maximum filtration lasted almost 3 months. Kuksa mine clay (dark brown, greasy, varved limnoglacial (lgIIIgr), with bright light sandy inter-layers) mine was selected for a detailed investigation (Tables 1 and 2) (Petrikaitis 2007).

The results of the particle size distribution, Liquid Limit (W_L) and Plasticity Index (*PI*) investigation show that the clay mine thickness is very smooth up to the depth of 10.6 m. The clay from the depth of 1 m in the laboratory investigation of filtration was used. The filtration with undisturbed structure and compacted clay and clay paste at 0.5 kg/cm^2 and 1.0 kg/cm^2 loads were carried out. The clay paste was prepared by adding water and was softened with hands until homogenous mass, with which the filtration chamber ring was filled (Fig. 1).

The permeameter adapted to carry out filtration tests under non-stationary filtration scheme. The maximum possible hydraulic head – 35 cm, the sample height – 4 cm, the cross-section area – 40 cm^2 and the maximum

Table 1. Particle size distribution of Kuksa mine clay

Depth, m	Particle size, mm				
	> 0.25	0.25−0.05	0.05−0.005	0.005−0.001	< 0.001
	Amount of particles, %				
1.5−6.0	0.03	0.09	8.56	30.12	61.20
6.0−9.8	0.33	0.78	14.65	20.08	64.16
0.2−6.0	0.06	0.62	21.08	22.32	55.92
6.0−9.0	0.25	1.53	19.94	23.04	55.20
2.5−6.0	0.16	0.25	12.33	27.48	59.88
6.0−10.6	0.10	0.54	17.12	22.40	59.84

Table 2. Liquid Limit and Plasticity Index of Kuksa mine clay

Depth, m	Liquid Limit, W_L, %	Plasticity Index, PI, unit	Plasticity group according *LST EN 1997-2:2007**
1.5−6.0	41.46	18.53	
6.0−9.8	41.92	19.66	
0.2−6.0	38.23	17.57	
6.0−9.0	38.81	18.96	Medium plasticity
2.5−6.0	41.22	19.43	
6.0−10.6	40.95	20.67	

Note: *LST EN 1997-2:2007 Eurocode 7 – Geotechnical Design – Part 2: Ground Investigation and Testing*

hydraulic gradient – 8.75. All filtration was carried out with water filtering from the bottom to the top.

The hydraulic conductivity is calculated:

$$K = \frac{2.3AL}{St \log \frac{H_1}{H_2}},$$

where K – hydraulic conductivity; A – cross-section area of the piezometer, cm^2; L – height of the sample, cm; S – cross-section area of the filtration ring, cm^2 ; t – the filtration time, s; H_1 and H_2 – hydraulic heads, the upper (H_1) and lower (H_2) water level in the standpipe measured using the same water head reference, m.

The aim of the geofiltration experiments was to find out the hydraulic conductivity values change in the course of long-term and short-term filtration. Suspending the filtration process and leaving samples in the permeameter in a saturated state for some time, to assess the time influence on the change of the hydraulic conductivity values. All filtrations were carried out under the non-stationary scheme. In the course of all experiments at the laboratory, water evaporation and air temperature measurements were taken in order to eliminate the impact of these factors on the hydraulic conductivity values. Therefore, it is very important to have the data on the evaporation intensity, especially for lengthy measurements at very low discharges of the filtrate under small hydraulic head gradients. The longest conducted filtration lasted 430 hours; the minimum hydraulic gradient was only the 10th part of the unit. Each filtration after a certain filtration stage shifted to the state when the

Fig. 1. Clay sample after filtration (top view)

filtration discharge was lower than the rate of evaporation of water in the laboratory, i.e. in the filtrate outlet there was no water dripping. For this reason, filtration discharges by the water drawdown in the piezometer were calculated. In the calculation formula, there are values: the piezometer cross-section area and water drawdown. Evaporation of water in the course of filtration took place not only through the filtrate outlet, but the water level in the open piezometer. The influence of the evaporation on the hydraulic conductivity values was determined experimentally in the laboratory. During the entire investigation period in parallel with filtration, evaporation intensity was measured in the second permeameter where no filtration took place and the water level in the piezometer was measured only due to evaporation. The data obtained through the evaporation intensity over the time were compared with an assumed filtration discharge and calculated to meet the hydraulic conductivity values (Fig. 2).

The obtained water evaporation data show that experiments in the laboratory are not affected by the hydraulic
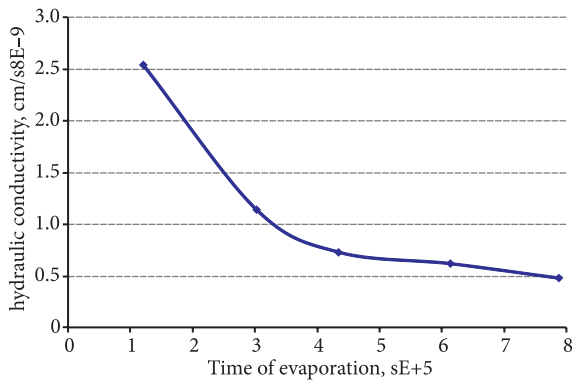
Fig. 2. Dependence of water evaporation time from water surface level of piezometer on hydraulic conductivity (assumed)
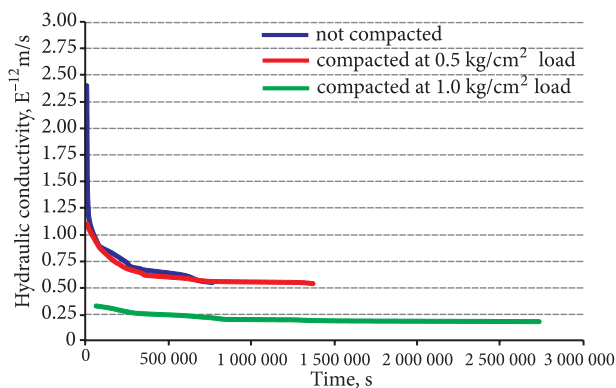

Fig. 3. Dependence on the hydraulic conductivity and the filtration time of natural structure clay
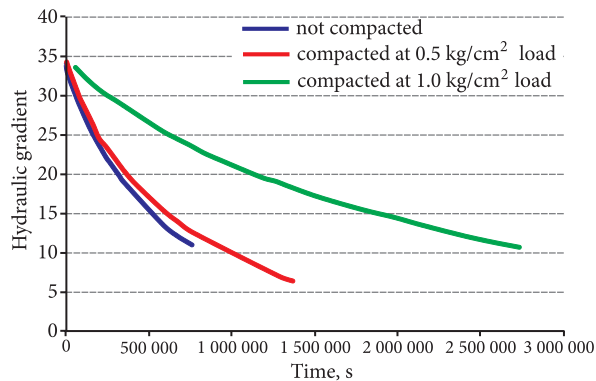

Fig. 4. Dependence on the hydraulic gradient and the filtration time of natural structure clay
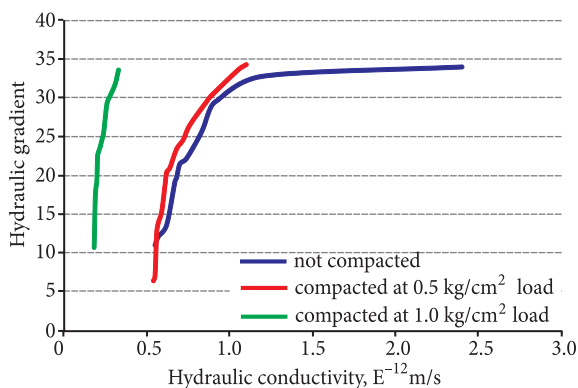

Fig. 5. Dependence on the hydraulic gradient and the hydraulic conductivity of natural structure clay

conductivity values, i.e., errors due to evaporation are much smaller than the estimation error. The actual evaporation error is relevant only in cases where the tested clay hydraulic conductivity values are 1000 times less and only at the beginning of the filtration in case the hydraulic head gradients are large.

4. Results and analysis

4.1. Clay

The first filtration experiments were carried out in the undisturbed structure sample. The dark brown clay with light and dark spots was placed in the filtration chamber. Taking the sample from the monolith and cutting with a knife, very fine grains were felt. It is light-coloured sand particles larger than 0.25 mm. The black spots were the roots of the plant remains of organic matter, because the sampling depth was of only 1 m. Before the first filtration the sample saturated with water (mass – 320 g, density – 2.0 g/cm^3). Mass increased to 326 g and density to 2.04 g/cm^3 after saturation. Dependences on the hydraulic conductivity, the hydraulic head gradient and the filtration time of clay are presented Figs 3–5.

The results of natural structure clay show that at the beginning of the filtration at high hydraulic gradient, hydraulic conductivity values are the highest (Figs 3–4). Since all experiments were carried out under the varying hydraulic head (non-stationary) filtration scheme over the time, during a longer filtration period, the hydraulic conductivity values decrease. A descending trend is linear and, after 14 days, the hydraulic conductivity values stabilize. In comparison the hydraulic conductivity and the hydraulic gradient change over time graphically, it seen that the filtration time influences the hydraulic gradient change rapidly. Hydraulic head gradient effects on the clay hydraulic conductivity values and explained as follows:

– the total clay in the water is bound to forming clay particles, because the clay sample has no gravity water filtration, which linearly depends on the hydraulic gradient;

– saturated clay pores are filled with capillary, weakly and strongly bound hygroscopic water.

These different types of water are maintained in the soil of different sizes of molecular attraction forces. The filtration process involves capillary water and a part of weakly bonded one depending on the flow energy, since this type of water is maintained in the soil of the weakest forces. Flow energy is determined by the size of the hydraulic gradient. With a greater hydraulic gradient, the filtration process involves more capillary bound water volume, but at the same time increases the filtration discharge and hydraulic conductivity. With flow energy decreasing, a part of the water stops moving resulting in decreasing filtration discharge and hydraulic conductivity values.

Upon completion of the first filtration, the sample of clay was compacted to full stabilization at 0.5 kg/cm^2 load. Compaction results for deformation and mass measurements showed that the sample pore volume decreased by 3 cm^3.

The results show that the initial hydraulic conductivity values decreased from 2.4E-7 cm/s to 1.1E-7 cm/s

with the same hydraulic gradient compared with the undisturbed structure. The filtration process and dependence trends did not change. After the 16 days of the filtration, hydraulic conductivity values were on par with the undisturbed structure clay obtained values at the end of filtration. This indicates that 0.5 kg/cm^2 compaction load is too small for a substantial reduction of clay hydraulic conductivity values.

The third filtration was held after the sample compaction to 1 kg/cm^2 load. Compaction reduced pore volume by 1 cm^3. The results show that in this case the initial hydraulic conductivity values decreased to 0.34E-7 cm/s, compared to 2.4E-7 cm/s or non-compacted clay compared with 1.1E-7 cm/s after compaction at 0.5 kg/cm^2 load. The filtration at the end was 0.18E-7 cm/s (3 times less). After the second compaction pore volume decreased by only 1 cm^3 (after the first compaction – 3 cm^3), but it changed more the hydraulic conductivity values. This indicates that in clay there remained significantly less weakly bound water which filled the larger pores.

4.2. Clay paste

The last series of the filtration were carried out with the clay paste to assess structural links of clay particles and the importance for the filtration process and consolidation possibilities of the clay paste. The clay paste was prepared by kneading with hands the undisturbed structure clay sample, pouring water till a plastic state. The parameters of clay paste made-up for the filtration were the following: moisture content – 34.29%, density – 1.92 g/cm^2. Dependences on the hydraulic conductivity, the hydraulic head gradient and the filtration time of clay paste are presented Figs 6–8.

The first filtration carried out with the clay paste was also saturated after placing in the filtration ring, as the initial moisture content was less than the saturation humidity. The filtration process did not differ from the previous experiments. The initial hydraulic conductivity value was 1.2E-7 cm/s and at the end of the filtration – 0.52 E-7 cm/s, which was very close to minimal value after the 0.5 kg/cm^2 compaction. The filtration results of the clay paste compacted to 1.0 kg/cm^2 load are presented in Figs 6–8 too. The compaction of clay paste highly reduced the hydraulic conductivity values: at the beginning of maximum filtration was minimal – only 0.28E-7 cm/s and the minimum value of 0.09E-7 cm/s was also the lowest, compare with all the previously obtained results. The decrease of the hydraulic conductivity values from time to time becomes almost linear.

5. Discussion

Having analysed the results of the carried out filtration investigation, it was identified some regularities. The behaviour of the investigated Kuksa mine clay filtration was the same during the experiments. In particular, the hydraulic conductivity values of the undisturbed and thickened structure clay, and prepared clay paste for the filtration were always decreasing over the time. Descending trend in each case was different. It was determined that

the clay hydraulic conductivity values are influenced by the hydraulic gradient, e.i., with the hydraulic head gradient decrease hydraulic conductivity values also reduce. Comparison of investigation results of the clay paste and of the undisturbed and thickened structure samples showed that the compaction load up to 0.5 kg/cm^2 is not effective, because the hydraulic conductivity values of the undisturbed and thickened structure clay almost coincided with the results of the clay paste. The difference of the hydraulic conductivity values of the undisturbed structure clay and clay paste indicate that structural links between clay particles in the natural structure clay increase the hydraulic conductivity values. During clay paste preparation the clay structure was destroyed, pore space reduces, thus reduced
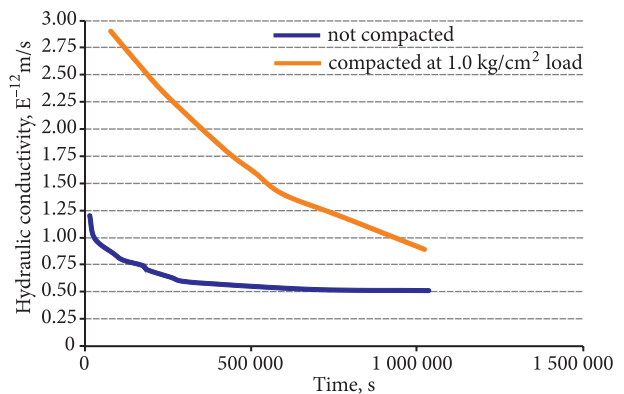

Fig. 6. Dependence on the hydraulic conductivity and the filtration time of clay paste
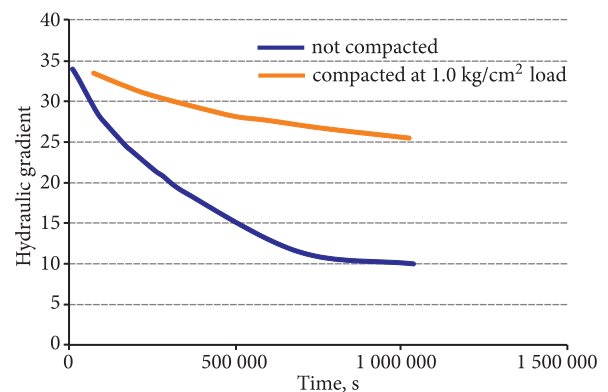

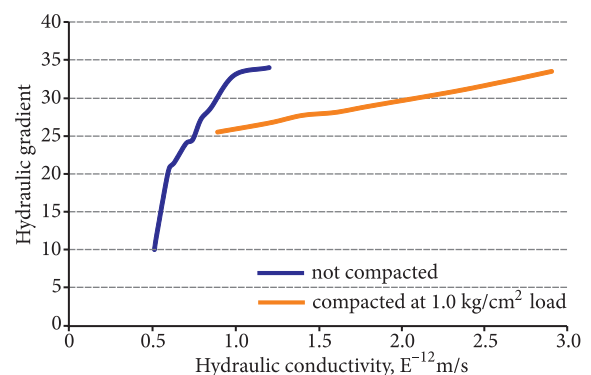**Fig. 7.** Dependence on the hydraulic gradient and the filtration time of clay paste

Fig. 8. Dependence on the hydraulic gradient and the hydraulic conductivity of clay paste

the hydraulic conductivity values from 2.4E-7 cm/s to 1.21E-7 cm/s. Clay structural links are eliminated by the load of 0.5 kg/cm^2, as the initial hydraulic conductivity value 1.21 m/s is close to the original clay paste. Further filtration process of the undisturbed and thickened structure clay is the same as the clay paste after compaction load of 0.5 kg/cm^2.

Conclusions

1. Particle size distribution and Plasticity Index data of the investigated clay thickness show that up to 10 m depth it is uniform. Therefore, it can be stated that the filtration properties are slow-changing.

2. The determined regularities of the time-dependent hydraulic conductivity values of undisturbed structure clay, compacted at 0.5 kg/cm^2 and 1 kg/cm^2 load, and the clay paste prepared from it show that under the short-term filtration investigation data it was obtained an increased clay hydraulic conductivity values. In the first hours of the filtration process a non-linear decrease of the hydraulic conductivity values takes place.

3. The experimental filtration investigation showed that in order to determine the hydraulic conductivity values, which are able to apply in the long-term prognostic calculations, the filtration duration vary from a few to a several dozens of days.

4. The comparison of the clay paste investigation results with undisturbed and thickened structure samples indicates that compaction with loads up to 0.5 kg/cm^2 is not effective, because the hydraulic conductivity values of the undisturbed and thickened structure clay almost coincided with the results of the clay paste.

5. In the investigated clay, there are structural links between the clay forming units, which affect the filtration properties of the clay. These structural links are not strong, because they are decomposed at relatively low compaction loads. It was a load of 0.5 kg/cm^2, which almost two-fold, reduced the initial hydraulic conductivity values. At the end of the filtration, they remained at the same level with the non-compacted clay. Compacting at 1.0 kg/cm^2 load reduced the initial hydraulic conductivity values about 8 times, and at the end of the filtration, there remained a three-fold difference. This suggests that in the course of long-term filtration compacting effect decreases, i.e., the clay some swells and its porosity increases.

6. The filtration results of the clay paste compacted up to 1.0 kg/cm^2 load show that the clay paste is easier to compact and to achieve a maximum clay insulating effect.

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