THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

ISSN 1822-427X / eISSN 1822-4288
2015 Volume 10(4): 293–298

EVALUATION OF MORAINE LOAMS' FILTRATION PROPERTIES

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Abstract. In Lithuania, surface moraine loam, clay and other lithologic varieties with low permeability take around 60% of the territory. Roads, railway tracks, bridges, dumps intended for keeping waste of different level of danger and other overground structures are built in these areas. Moraine formations with low water permeability become the foundation for earth bank, roads, bridge supports, dumps and other engineering structures. Through these foundations water filtration, infiltration, movement of capillary water and evaporation to the atmosphere continue during the entire period of operation. In wintertime, the volumetric changes of water, contained and freezing in these soils, and water migration in soil towards the surface of freezing determine deformations of foundations or road surface and the occurrence of frost cracks. All the mentioned water migration processes in the layers take place in various directions and in different intensity. This determines the change in geomechanical and geofiltration properties of foundation soils. Foundation soil deformations are likely also due to the processes of drying, bloating and filtration of clayey soils. Thus, the goal of the present work is to evaluate the evolution of filtration features and evaporation intensity of moraine loam in time. The continuous duration of laboratory investigations was over 10 months. For filtration, the filtrometer was used containing the Proctor Standard moulds, water deaeration device and pressure measuring stand with three tubes of different diameter (piezometers). Water and air temperature and relative humidity of the laboratory were measured during each experiment.

Keywords: moraine loam, permeability, evaporation, hydraulic conductivity, relative air humidity, laboratory investigation.

1. Introduction

Filtration features of moraine loams in Lithuania, especially occurring at the surface, are subject to change. Geofiltration studies in situ were carried out in various regions of Lithuania (Dobkevičius *et al.* 1988; Klizas 1993). The majority of these studies were performed in the north of Lithuania – the karst regions in Biržai and Pasvalys Districts. In these areas, moraine loam at the surface covers the Devonian sulphate carbonate thickening, where at the moment intense karst processes and sinkhole formation of the surface are observed. Infiltration of precipitation through the covering moraine thickening is the main reason for development of underground karst which causes deformation of the ground surface. Filtration studies of solids with low permeability in this region were carried out with clays, loams, clayey marls, dolomites and chalk-stones of the Quaternary and Upper Devonian age, using the filtrometer LITA-5, designed by Klizas and Miksys (1985). For construction of the damp-proofing barrier of the radioactive waste repository for Ignalina Nuclear Power Plant, there have been laboratory investigations of loan deposits in Šaltiškės, Pašaminė and Stabatiškės (Klizas 2014) performed. Infiltration site tests of these clays were carried out with the two-ringed infiltrometer, using methods of Nasberg (Gadeikis *et al.* 2012). The abundance of scientific publications in the recent years, devoted to filtration studies of clayey solids of low permeability, show the scientific and practical relevance of such data. Studies of changes in filtration characteristics of clayey solids with low permeability are carried out in different directions.

The first direction – changes of sorption/desorption processes during filtration and chemical composition and concentration of the filtrate are studied. The mineral clay used for investigation is French expansive clay known as Fe-Ca, which is a natural French Ca-smectite coming from the Paris basin of Y Persian (Sparnacian) age. 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 distilled water and

doi:10.3846/bjrbe.2015.37

2.4E-12 m/s with the 0.1 mol/l copper solution (Jullien *et al.* 2002). Laboratory investigations of lime stabilized clays permeability show that calcium is the most important ingredient in the stabilization of clay. Lime provides calcium through the dissolution of calcium hydroxide in the presence of water (Yildiz, Sonğanci 2012).

The second direction – impact of cold on geofiltration characteristics of clayey solids and occurrence of deformations at the ground surface is investigated. In France, permeability of various texture frozen bulk soil mixtures was studied. 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 sodium chloride (NaCl) solution, bentonite and trapped decane (Enssle *et al.* 2011). Vertical uplifting of boulders and stones is well known to take place in cold regions. Movements of stones in roads might lead to traffic danger, vehicle failures, and cause breakdown of the road surface with the need of expensive repair as a consequence. Freezing and having of frost susceptible soils may cause changes in their structure due to particle rearrangements, initiations of cracks, and consolidation (Viklander, Eigenbrod 2000). Investigations performed in Germany demonstrated the effects of freeze-thaw on microstructure of clayey soils and soil-bentonite mixtures in relation to changes of the permeability and the shear strength (Hohmann-Porebska 2002). Similar functional dependencies were determined in Lithuania, in Ignalina Nuclear Power Plant limnoglacial clays. The effect of clay freeze-thaw cycles on the hydraulic conductivity is not very high. During thawing of the test sample, the hydraulic conductivity ranges from 3.5E-6 cm/s to 5.0E-7 cm/s. The fully frozen clay sample is found to contain a newly formed vertical and horizontal crack system that raise the hydraulic conductivity in several times (Klizas 2014). The studied clay material originates from the clay between the motorway and railroad North East of the harbour in Rødbyhavn owned by Dansk Bentonit. According to the odometer test on cohesive soil, the determined compacted clay membrane showed the hydraulic conductivity – permeability of 5E-12 m/s to 1.5E-12 m/s decreasing with rising effective vertical stress (Foged, Baumann 1999).

The third direction – studies of structural peculiarities in clayey soils. Structural features of clayey soil are determined by the properties of dispersed clay particles called 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. Heterogeneity in structural arrangement of clay minerals and particle surface crystal-chemical specifics change the concept of the clay pore space. Filtration process in clay is determined by the pore space and is different compared to other dispersed systems consisting of identical particles, among which there is no interaction, e.g., sand. The clay column 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 clastic inclusions, macropores, lamination and cracking in strongly lithified beds. Macropores are specific for aeration zones in clay beds including artificially formed pre-filtration barriers. Pores and cracks mainly determine the filtration anisotropy of the clay layers. It is specific for macropores that in the course of long time filtration they can clog, therefore in the long time experiment values of hydraulic conductivity decrease. During the filtration in clayey soils, pore dimensions vary from 3 Å (Ångström is a unit of length equal to 0.1 nanometre (nm)) to 20 Å, at the same time there is an on-going action exchange, hydration-dehydration process at the surface and inside of clay minerals, as well as binding of particles into larger aggregates. At the micro-aggregate level, when the pore dimensions are 1–10 μm (micrometer), pore space and structural changes in a relatively homogeneous sample and layers are observed, which results in the anisotropy of the clay filtration properties (Oradovskaja 1983). During filtration the structural rearrangements of clay particles occur. These rearrangements are larger if the original structure is more diverse. It was determined that in the course of 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 effect is characteristic to clay and loam with high humidity and porosity.

Fig. 1. Sampling place

2. Experiment (methods and material studied)

The goal of studies performed was to evaluate the change of filtration coefficient of moraine loam under the conditions of filtration and water evaporation from the sample surface at the same time, i.e. to establish the ratio of filtration and evaporation processes in moraine loam and the impact on drying and bloating phenomena of this loam, causing deformations of the layer formed from such loam. Intensity of water evaporation was controlled by means of a screen or perforated plate. The maximum evaporation intensity was achieved leaving the upper loam layer completely unclosed. All long-term investigations were carried out in the laboratory. For detailed studies, moraine loam from the middle Pleistocene of quaternary of Medininkai (Lithuania) suite was taken from the excavation near the Vilnius Airport, where a road was being built.

Moraine loam was dark brown, with a little (up to 5%) admixture of sand particles. Structure unevenness and a small amount of rubbles of carbonate composition were observed. Natural humidity was determined in a thermal way and was subject to change from 27.24% to 29.33%. Natural density was 1.97 g/cm^3.

Laboratory investigations were carried out with the Falling Head Permeameter (Fig. 2).

This permeameter is adapted to carry out filtration under the non-stationary filtration scheme. Maximum possible head – 130 cm, sample height – 11.55 cm, cross sectional area – 81.67 cm^2, volume of sample – 943.3 cm^3 and the maximum hydraulic gradient – 11.26. The pressure measurement device consists of three tubes (piezometer), cross-sectional areas are as following: 0.4 cm^2, 0.6 cm^2, and 1 cm^2 (Fig. 1). Piezometers with a stand were attached to the wall in the laboratory in a way that the upper part of tubes is at 132 cm above the laboratory table surface. All tubes were interconnected with rubber hoses and a silicone transparent hose with the Proctor Standard mould base. Due to this reason, when filtration debit changes, a required number of piezometers are connected to have the same accuracy of debit and pressure measurements when debit and pressure reduces during the whole experiment. The silicone hose connection of piezometers with Proctor Standard mould enables adjustment of the height ratio of piezometers and Proctor Standard mould, when the latter is lifted above the table surface to a required height. During filtration and evaporation, this allows measuring negative pressures (pressure of unsaturated soil suction) that are formed when water level in the piezometer appears lower the base of Proctor Standard mould. Then, filtration stops in loam, and there only evaporation and water suction from down to up is carried out. The laboratory air and water temperature and relative humidity were measured during the entire experiment. The hydraulic conductivity was calculated by formula (1):

$$K = \frac{2.3AL}{St\log\frac{H_1}{H_2}}, \tag{1}$$

where A – cross-sectional area of the piezometer, cm^2; L – height of the sample, cm; S – filtration ring cross-sectional area, cm^2; t – the filtration time and H_1 and H_2 hydraulic heads. Hydraulic conductivity K_{10} was recalculated at the standard 10 °C temperature of underground waters *(LST CEN ISO/TS 17892-11:2005 Geotechnical Investigation and Testing – Laboratory Testing of Soil – Part 11: Determination of Permeability by Constant and Falling Head (ISO/TS 17892-11:2004))* using the formula (2):

$$K_{10} = \frac{K}{0.7+0.03T}, \tag{2}$$

where K – hydraulic conductivity, cm/s; T – water temperature, °C.

Laboratory investigations with this moraine loam were started from full (complete) saturation with water, since natural humidity was lower than saturation humidity. Loam bloating was not observed during the initial saturation. After saturation, there was filtration carried out without evaporation and hydraulic conductivity was determined and recalculated at 10 °C. The value at the maximum hydraulic gradient 9.3 was 7.74E-10 cm/s. The studies confirmed the results of investigations of clayey rocks by Klizas (2014) that when hydraulic gradient reduces, hydraulic conductivity value reduces as well.

All filtration experiments were carried out setting pressure through the lower plate water outlet, and filtrate was flowing through the upper plate water outlet. During filtration, the upper plate was taken off to evaluate the impact of evaporation. Other filtrations were performed with the upper loam part closed with a perforated plate or stainless steel gauze. During all filtration experiments, the laboratory air temperature and water (filtrate) temperature and relative humidity were measured in parallel, using Heat Stress Meter (model HT30 with main parameters – air temperature accuracy – 1 °C, resolution – 0.1 °C, relative humidity – 0–00%, accuracy – 3%), and the laboratory water temperature, coinciding with filtrate temperature, was measured with a usual mercury thermometer. The results of carried measurements are given in Fig. 3. The change trends of each of these parameters during filtration experiments were determined based on these results.

Long-term measurements of the laboratory air, water and relative humidity demonstrate a visually observed correlation between air and water temperature. The higher is the laboratory air temperature, the higher is the difference

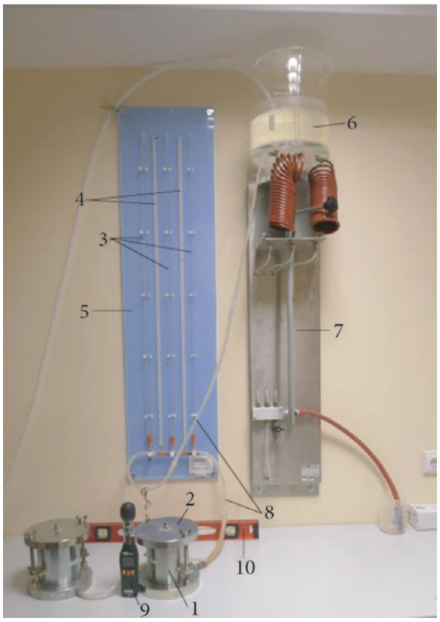

Fig. 2. Falling Head Permeameter scheme: 1 – compaction permeameter (Proctor Standard mould S191); 2 – Proctor Standard mould cover; 3 – manometer tube (piezometer) 4 – ruler of water table measurement; 5 – stand; 6 – reservoir of dearation of water; 7 – stand of dearation of water; 8 – silicon connecting bowels; 9 – Heat Stress WBGT Meter (WET Bulb GlobTemperature, Model HT30); 10 – level (picture by Klizas, P.)

between air and water (filtrate) temperature and it changes from 1.3 °C to 0.8 °C. Therefore, measurements of the laboratory air temperature cannot be used for recalculations of hydraulic conductivity. The correlation between relative humidity of air and air and water temperature is complicated, since relative humidity of air is dependent on a number of factors. Changes of relative humidity of air are caused not only by evaporation from the loam surface during the experiment but also by the air getting into the laboratory through the ventilation system or the hallway, when the door is opened and closed. During all the experiments, entering to the laboratory and window opening were minimal, and all measurements were performed early in the morning, once per day or even less frequently, depending on the experiment process. Some positive coincidences were highlighted when air temperature was increasing and relative humidity of air was deceasing. Good correlation was determined 8–9 days after the beginning of observations and on days 40–42. An attempt to reliably correlate the data of these measurements and filtration features of loam was not successful.

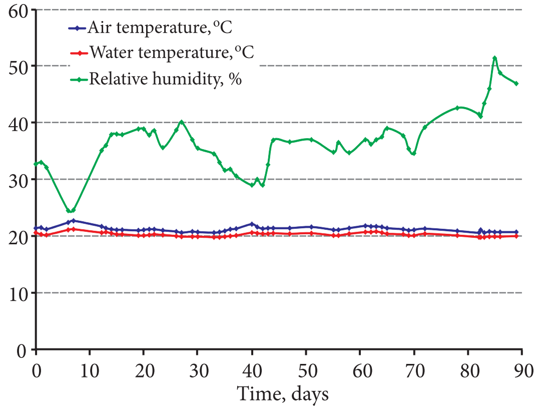

Fig. 3. Water, air and relative humidity dependence on time

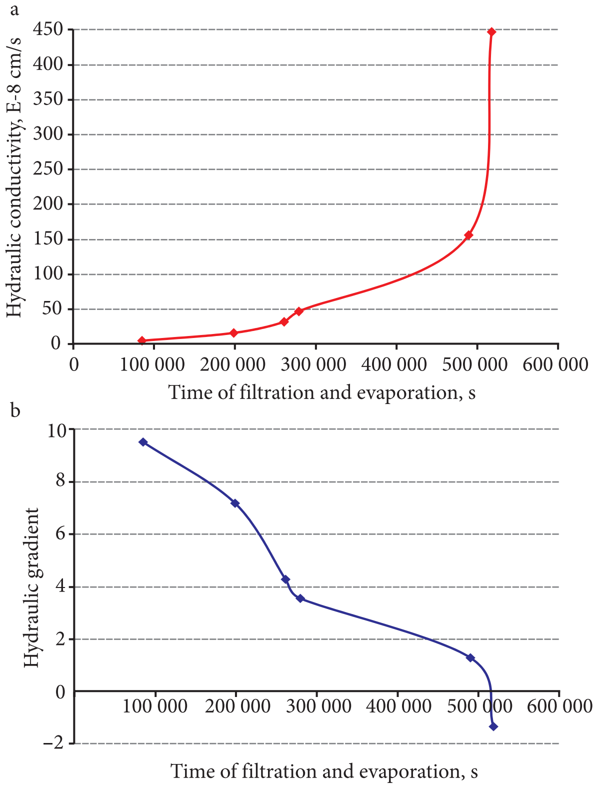

Fig. 4. Results of simultaneous filtration and evaporation experiment (the sample surface covered with the perforated plate and steel screen): a – hydraulic conductivity dependence on time; b – hydraulic gradient dependence on time

Filtration experiments were performed under the following hydrodynamic conditions:

- without evaporation from the sample surface;
- with evaporation through the perforated plate and screen holes;
- with open evaporation from the whole sample surface that had a more significant impact on changes of filtration features to compare with changes of the relative air humidity.

3. Results and analysis

The essence of the performed experiments is that two processes – filtration from below and water evaporation from the surface – proceeded in loam simultaneously; only during the first experiment, the sample surface was covered with the perforated plate and steel gauze, and during the second one sample surface was uncovered.

The first experiment was performed according to the following scheme:

1) hydraulic conductivity of saturated loam was determined at the maximum hydraulic gradient 9.3;

2) the upper plate of Proctor Standard mould was taken off but the upper perforated plate and stainless steel screen remained to ensure direct evaporation from the loam surface;

3) during evaporation, the maximum pressure came from below and filtration started; pressure change in time was measured.

The experiment results are given in Fig. 4.

The effect of water evaporation on filtration speed was noticed almost immediately. During filtration, pressure measurements were taken once per day or less frequently, depending on the hydraulic gradient. When pressure was reduced, measurement intervals were prolonged. On the second day from the beginning of the experiment, pressure difference was 13.3 cm, whereas during filtration without evaporation it was only 1.5 cm at the same initial pressure. Hydraulic conductivity values increased from 7.74E-10 cm/s to 4.46E-8 cm/s. With continued filtration and evaporation, hydraulic conductivity values tended to increase and hydraulic gradient – decreased. As filtration still proceeded, evaporation impact on hydraulic conductivity values grew constantly (Fig. 4a). Within three days, pressure obtained negative values (Fig. 4b). Values of hydraulic conductivity increased to 4.67E-7 cm/s. During next three days, when evaporation still continued, negative values of pressure increased to −20 cm, i.e. after five days from the beginning of the experiment only suction pressure was active in loam. Processes observed in loam were not filtration but moisture transport, and the value of moisture transport coefficient increased to 1.56E-5 cm/s. The experiment was terminated when at intense drying of loam the sample shrinkage, i.e. vertical deformation, was 3 mm, and horizontal one – 2 mm, after 9 days.

When starting a new filtration, the sample was saturated. During saturation, the sample bloated and vertical deformation was restored, i.e. height of the sample increased to 5 mm and rose 2 mm above the top of Proctor Standard mould. Saturating the sample for the first time, when the sample had its natural density and was taken from the layer, bloating was not observed. Bloating appeared when saturating loam for the second time, after filtration and evaporation.

The new filtration was performed following the same scheme as in the first case, only the upper perforated plate and stainless steel screen were taken off the loam surface. The results are given in Fig. 5.

The results show that values of hydraulic conductivity increased from 1.68E-7 cm/s to 2.1E-6 cm/s, i.e. more than ten times (Fig. 5a). Evaporation impact occurred quicker, after three days, and its change tend was higher. Decrease of hydraulic gradient was almost linear (Fig. 5b).

The process of the next experiment was as following: after the sample saturation and placing it into the permeameter, the perforated plate and stainless steel screen were taken off; but the upper cover of permeameter was put on (Fig. 2(2)). In such case, a closed air space formed above the sample, but not pressure. The following situation was modelled: filtrated water evaporates in this closed air volume only, without getting into the laboratory area. When air is saturated with water vapour, it gets into the laboratory area through the connecting hole above. In this case, relative humidity of the air above the sample remains stable and close to the saturation degree. The present experiment models filtration through clay and evaporation to underground cavities that are isolated with clayey rocks. The results are given in Fig. 6.

On the first day, when filtration started, values of hydraulic conductivity decreased instantly (Fig. 6a). Afterwards, filtration got stable. Water layer formed on the sample surface and above this water layer there was air. The chamber was later filled with water, and air was pushed out of it; values of hydraulic conductivity and hydraulic gradient decreased. Decrease of hydraulic gradient trend was almost linear (Fig. 6b), even though values of hydraulic conductivity fluctuated insignificantly and periodically. The beginning of the experiment process reminded filtration without evaporation, and the end is, most probably, an intermediate version between evaporation and filtration with a very limited evaporation possibility.

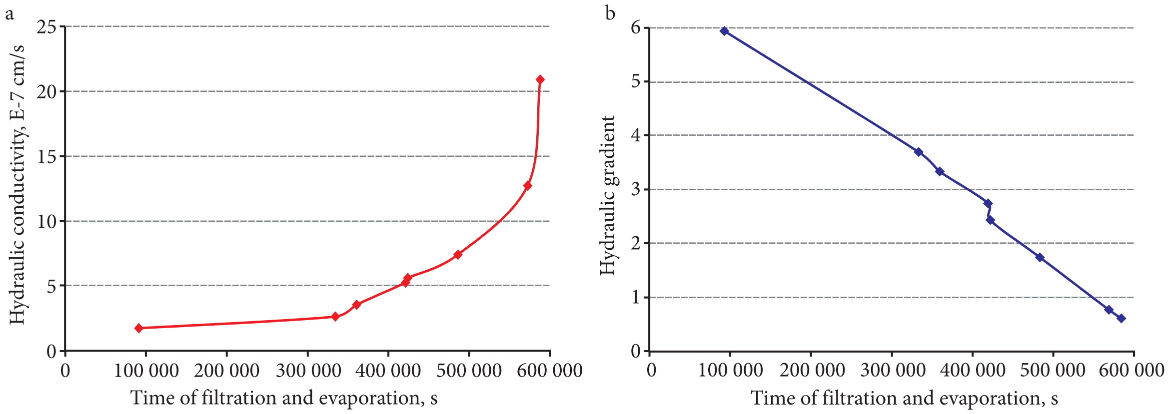

Fig. 5. Results of simultaneous filtration and evaporation experiment (the sample surface uncovered): a – hydraulic conductivity dependence on time; b – hydraulic gradient dependence on time

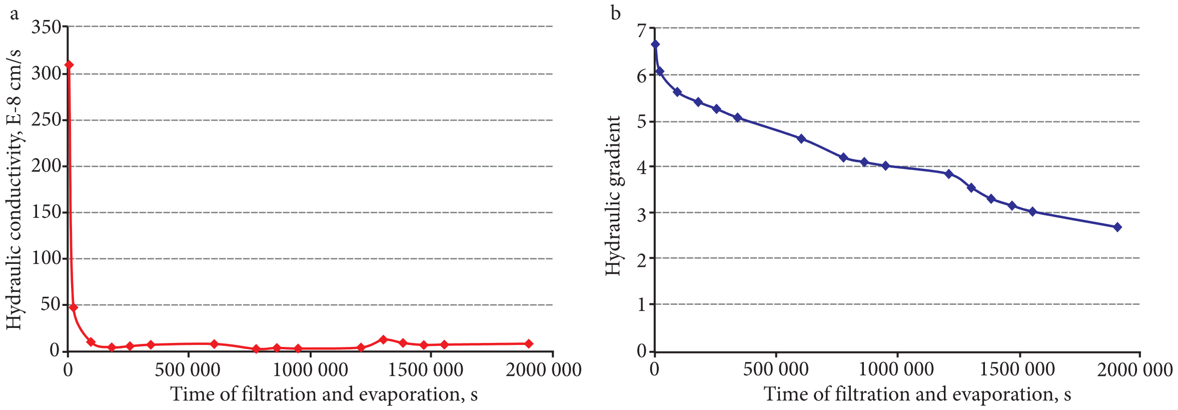

Fig. 6. Results of simultaneous filtration and evaporation experiment (the constant volume air chamber is formed above the sample surface): a – hydraulic conductivity dependence on time; b – hydraulic gradient dependence on time

4. Conclusions

For investigation, moraine loam from the middle Pleistocene of quaternary of Medininkai (Lithuania) suite was taken from the excavation near the Vilnius Airport, where a road was being built. Loam filtration features were determined together with their change in time, the impact of water evaporation from the sample surface on filtration features, also vertical and horizontal deformations of bloating and drying were evaluated during filtration and evaporation, and the following conclusions were made.

1. During the simultaneous water filtration from below and evaporation from the loam surface, volume of water, filtrated through loam, and water movement speed increases. This is demonstrated by increased values of hydraulic conductivity. Comparing the results when filtration and evaporation proceeded from the surface covered with perforated plate and stainless steel screen with standard filtration data, it is seen that immediately after evaporation starts, filtration features of loam increase, i.e. the value of hydraulic conductivity increase from 7.74E-10 cm/s to 4.46E-8 cm/s. The trend of this growth remains nonlinear, and the value of hydraulic conductivity at the end is 4.5E-6 cm/s.

2. Evaporation, when the loam surface is fully open, speeded up the filtration process, and at the same time it increased the filtrate debit and value of hydraulic conductivity to 1.7E-7 cm/s, comparing with the previous one of 4.46E-8 cm/s. Functional dependence of hydraulic gradient change on time became almost linear.

3. The results of experimental series when filtration proceeds with the close air chamber above the sample, limiting evaporation intensity, demonstrated that the values of hydraulic conductivity decrease very quickly at the beginning of the experiment. Decrease trend of hydraulic gradient was close to linear, except for the beginning of filtration.

4. During simultaneous evaporation from the sample surface and filtration from below, after eleven days, piezometers showed negative pressure of 20 cm (this is the suction pressure). The sample surface lowed by 3 mm, i.e. the relative coefficient of vertical deformation was 2.7%. The size of horizontal deformation was 2 mm. A crack of 2 mm formed around the entire sample perimeter, in the upper part of the sample. When evaporation was terminated and the sample was repeatedly saturated, the sample bloated and vertical deformation was 5 mm, i.e. the loam sample rose by 2 mm above the surface of Proctor Standard mould. At the same time, porosity of the sample, comparing with the initial natural loam, increased, and this caused the increase of hydraulic conductivity when the new filtration was started.

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Received 5 May 2015; accepted 7 September 2015