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Time-dependent hydraulic resistance of the soil crust: Henry's law

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Abstract

In earlier experiments on steady infiltration into crust-topped soil columns an additional resistance was observed in the vicinity of the boundary between the crust and the soil below it. I have performed laboratory tests in order to check the following hypothesis: high hydraulic resistance of the crust results in steep drop of the water pressure between the top and bottom part of the crust if water flows through the crust-topped soil. The concentration of dissolved air in water depends upon the pressure acting on water according to linear Henry's law. I am assuming that air is released in small, microscopic air bubbles at the bottom part of the crust due to a substantial drop of the pressure. The microbubbles are then blocking a part of micropores of the crust. Consequently, hydraulic resistance of the crust increases. In laboratory experiments, the crust-topped soil was modeled by ceramic plate of high resistance placed on the top of the sand, or alternatively of loamy loess columns. Unsteady infiltration into crust-topped soil was repeatedly realized with Dirichlet's boundary condition and the plate resistance was measured at each selected time of infiltration. Flow in the whole system saturated by water was performed and resistance of the system was measured, too. Hydraulic resistance of the plate was rising with time during infiltration. The increase of hydraulic resistance was more expressed when water infiltrated into crust-topped initially dry sand than in experiments with sand of initially high water content. Resistance increasing with time was measured in nearly saturated systems, too. The hypothesis was therefore macroscopically proved.

Keywords: Infiltration; Soil crust; Layered soil; Hydraulic resistance; Henry's law

1. Introduction

An additional resistance was observed on the boundary between the crust and the soil below when experimental studies on steady and unsteady infiltration into crust-topped soils were performed (Srinilta et al., 1969; Kutílek, 1974; Zayani, 1987). The nature of this additional resistance was not properly explained. Zayani (1987) has found the increase of the crust hydraulic resistance by 23% at the end of infiltration with Dirichlet's boundary condition. Infiltration lasted about 1000 min. With Neuman's boundary condition the increase of R was 4% only with the same length of infiltration time. For the explanation of the observed phenomena let us first consider the change of hydraulic conductivity due to the presence of air bubbles in soil pores. Soils containing entrapped air have lower value of 'saturated' hydraulic conductivity compared to soils fully saturated with water without air entrapment. This statement follows from physical models of hydraulic conductivity (Kutílek and Nielsen, 1994). Ronen et al. (1989) have proved that gas microbubbles clog pores and reduce saturated conductivity even without significantly reducing the soil water content. According to Ronen et al., the origin

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of gas bubbles is either the entrapped air after wetting, or gas developed due bacterial metabolism. However, there was one basic law neglected and this was the Henry's law. The aim of the performed research was to formulate the theoretical basis and to check experimentally on macroscopic scale the hypothesis on the role of Henry's law during infiltration of water in a crust-topped soil.

2. Theory

According to Henry's law the amount of gas dissolved in water depends upon the partial pressure of gas acting upon water,

$$C_G = ap_G \qquad \text{at } T = \text{const.}, \tag{1}$$

where C_G is the concentration of the gas dissolved in water, a is a constant for the given gas and water, p_G is the partial pressure of gas. Air is the mixture of gases. The value of a differs for individual gases, e.g. $a(N_2)/a(O_2) = 14.5/8.1$ at 10 °C and at atmospheric pressure 1000 hPa. This difference influences the ratio of gases dissolved in water. For further treatment of the problem I am neglecting this difference taking a as a quasi-constant for air at the conditions of the experiments. If the pressure acting upon soil water is significantly decreasing, the gases are excluded from soil water and the excluded air forms microbubbles. If they cannot escape through the top of the porous material saturated with water, they are caught in pores in the form of the entrapped air and the conductivity decreases. Iwata et al. (1995) quote a paper of Kuroda (1965, in Japanese), where the release of air bubbles is described as a result of soil water pressure drop. However, the experimental proof is not interpreted by Iwata et al. and their simplified theory is not related to our problem.

If we transcribe Eq. (1) neglecting the difference in dissolution constant of individual gases, we get for C, concentration of air dissolved in water

$$C = \alpha h \tag{2}$$

where α is the coefficient of dissolution of air in water, dependent upon temperature T, h is the pressure head. Let us assume $T = \text{const.}$ and one-dimensional steady flow with flux density of water q in the direction of the vertical axis z. The concentration of the released air in unit volume of soil is A, analogous to soil water content, and for the rate of its release is

$$-q\frac{\partial C}{\partial z} = \frac{\partial A}{\partial t} \tag{3}$$

and with Eq. (2) we obtain

$$\frac{\partial A}{\partial t} = -q\alpha\frac{\partial h}{\partial z}. \tag{4}$$

I have neglected the diffusion of air through the liquid water as negligibly small in Eq. (3). The rate of the released air increases if q increases. For $q = 0$ we get $\partial A/\partial t = 0$ and the system is in equilibrium. Since $\partial A/\partial t = -\partial\theta/\partial t$ and hydraulic conductivity K [LT^{-1}] is at simple approximation $K(\theta^n)$ with empirical coefficient $n > 3$ (Kutílek and Nielsen, 1994), we obtain a decreasing value of K with time, $dK/dt < 0$. In hydraulics of layered soils, it is appropriate to work with hydraulic resistance $R = L/K$, where L[L] is the thickness of the layer and R[T]. Then we obtain an increasing value of hydraulic resistance R with time, $dR/dt > 0$. If we differentiate Eq. (4) with respect to t we can proceed to unsteady flow with generally still the same relationships of the rate of the release of air.

3. Materials and methods

The crust-topped soil was physically modeled in the traditional way by ceramic plate of a high hydraulic resistance placed on the top of homogeneous sand column. In one set of experiments the ground loamy loess was used, too. Thickness of the plate was $L = 0.74$ cm. When the oven dried plate was saturated under partial vacuum (−400 hPa), then its average hydraulic resistance $R_0 = 28.3 \pm 2.4$ h at the start of infiltration, $t = 0$. If the saturation of the plate was realized at atmospheric pressure, then R was in ranges between 58.3 and 83.6 h. This is in agreement with experimental data and with theoretical discussion on the effects of encapsulated air upon measurement of K_S in permeameters (Collis-George and Yates, 1985). In order to minimize the air entrapment at the start of experiments, the oven dried plate was saturated under partial vacuum in all instances of experimentation, if not mentioned otherswise. The length of the sand column was $L = 10.10$ cm and its hydraulic resistance $R = 0.33$ h if saturated under partial vacuum. Then the soil water content θ_S of the whole column was 0.379 $cm^3\ cm^{-3}$, very close to porosity, 0.388. Saturated hydraulic conductivity of loess $K_S = 0.92$ cm h^{-1} was determined separately on soil sample packed into a 100 cm^3 cylinder. Hydraulic resistance of the whole column of loess $R = 11.0$ h was obtained from this separately measured K_S and thus it is an estimate. Diameter of the plexiglas cylinder containing soil was 5.99 cm. Sand was uniformly packed into cylinder via the set of two sieves, one above the other. This arrangement enabled a relatively homogeneous distribution of sand particles. The uniformity of sand bulk density was checked by gamma ray attenuation. The results did not exceed ± 0.015 g/cm^3 for both, the bulk density along the z-axis and the bulk density in repetition of experiments. In column of loess slight layering was observed visually. The extent of in homogeneity was quantitatively not checked. Porosity of loess in the whole column was 0.457 in the first infiltration test and 0.478 in the second test. Constant head conditions were maintained by calibrated horizontal capillary for short time measurements and by Mariotte bottle for large time measurements, both installed at the inflow end. For saturated flow a constant hydraulic gradient was kept by inserting the bottom part of sand column in water of a constant water level. I have used following scenarios.

Scenario No. 1. Ceramic plate was saturated with water under partial vacuum, its resistance was measured and then the plate was placed on the top of dry sand and infiltration was realized with the inflow pressure head $h_0 = 42$ cm (Dirichlet's boundary condition) for the first 3 min. Then the plate was removed and its hydraulic resistance R was measured. New column of dry sand was prepared, the plate was dried, saturated with water under partial vacuum, resistance of the plate was measured and infiltration ran again for a larger time of 5 min. After that time the plate was removed and its R was measured. Infiltration with a newly prepared sand column and plate was repeated again for 12 min and R of the plate was then measured. Results are plotted in Fig. 1, curve a. The same infiltration procedure was applied to loess and the crust resistance was determined after 12 min and after 480 min of infiltration. Reversibility of the plate resistance change was checked as follows: after 12 min infiltration and after plate resistance

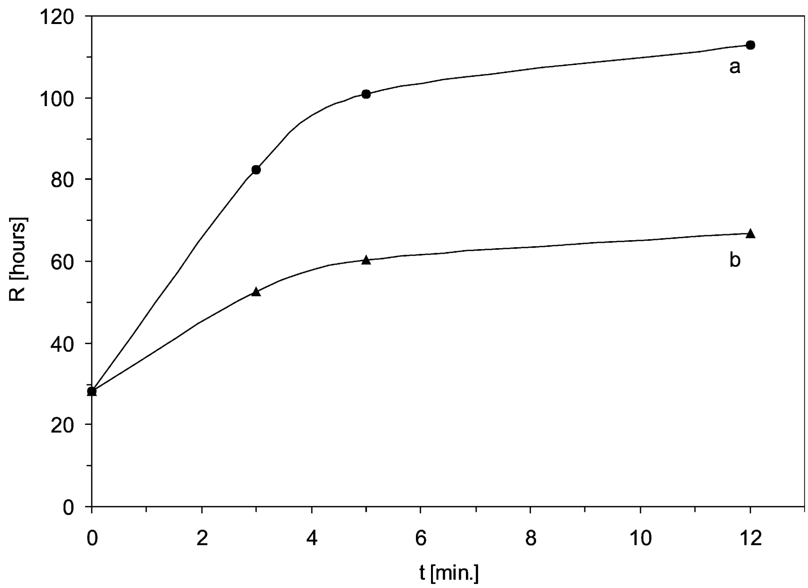

Fig. 1. Plate hydraulic resistance R measured after the end of infiltration tests at $t = 3$, 5, and 12 min, infiltration into (a) dry sand (circles), (b) wet sand (triangles), where $\theta_i = 0.245$. Pressure head on the surface of the plate $h_0 = 42$ cm.

measurement, the plate was inserted into the de-aired water and kept under partial vacuum of 400 hPa for 1 h and then its resistance was measured again.

Scenario No. 2. The method was identical with Scenario No. 1 with the exception that the sand was prewetted. Average soil water content $\theta = 0.245$ with drainage at $h = -50$ cm at the bottom end. Results are plotted in Fig. 1, curve b. After 12 min infiltration test, infiltration was repeated until the wetting front reached the bottom of the column. Scenario No. 3 started immediately.

Scenario No. 3. Hydraulic resistance $R(t)$ of the whole system plate + sand was measured after infiltration into wet sand has finished according to Scenario No. 2. Time t was taken as time elapsed from the start of infiltration. The test was performed at hydraulic pressure difference $\Delta h = 47.4$ cm between the inflow and outflow ends, hydraulic gradient $I = \Delta h/L = 4.37$. The amount of entrapped air was not measured. Results are plotted in Fig. 2. Reversibility of the plate resistance change was checked again, see Scenario No. 1.

Scenario No. 4. The whole system of dry plate + dry sand was saturated from bottom by de-aired water under partial vacuum −400 hPa. Hydraulic resistance $R(t)$ of the whole system was measured in time at hydraulic gradient $I = 4.37$. Results are plotted in Fig. 3.

Scenario No. 5. Continuation of the experiment of Scenario No. 4, hydraulic gradient I was increased 3.2 times to $I = 13.72$ at $t = 1025$ min. The relationship $R(t)$ is plotted in Fig. 4.

4. Results and discussion

I have obtained the time dependence of the crust hydraulic resistance $dR/dt > 0$ in all instances of infiltration into crust-topped profile. This increase was distinct for $t_E > t > 0$, while $R \rightarrow$ const. for $t \geq t_E$.

The results according to Scenarios 1 and 2 are plotted in Fig. 1. The increase of R with time was more expressed when water infiltrated into crust-topped dry sand, curve a, than in experiments with wet sand, curve b, Fig. 1.

The results confirm earlier reports on the existence of additional resistance in the crust (Srinilta et al., 1969; Kutílek, 1974; Zayani, 1987). In addition to it, I have experimentally proved, that the increase of the resistance is time-dependent. Since infiltration into crust-topped dry sand is realized at greater pressure drop than infiltration into wet sand, the exclusion of

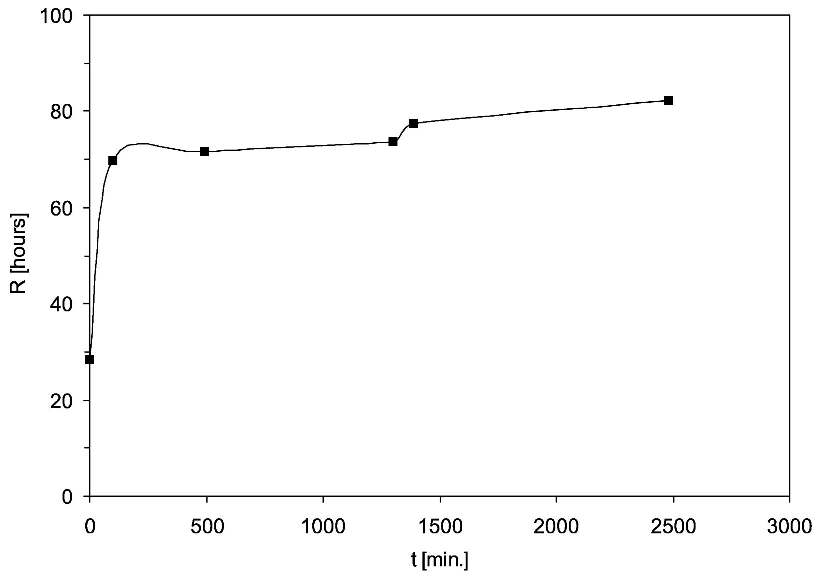

Fig. 2. Hydraulic resistance $R(t)$ of the ‘saturated’ whole system plate + sand after infiltration into wet sand (Fig. 1b), t is time elapsed from the start of infiltration. Pressure head difference between inflow and outflow $\Delta h = 47.4$ cm, hydraulic gradient $I = 4.37$.

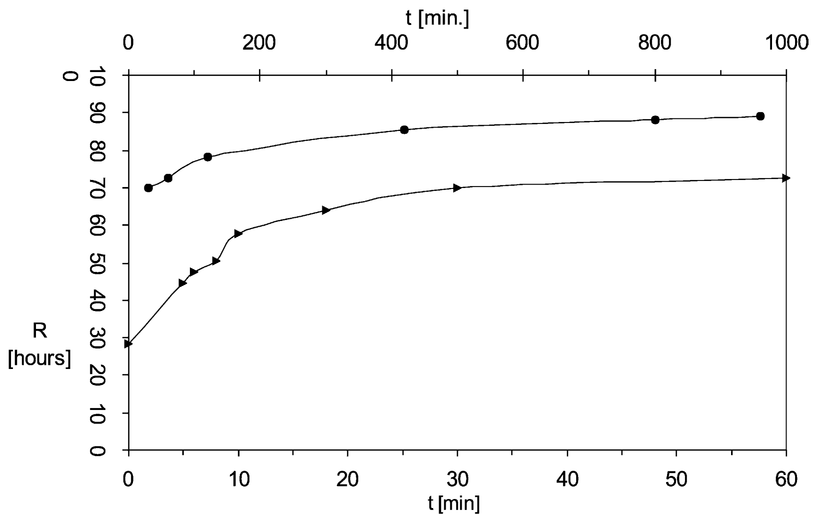

Fig. 3. The whole system dry plate + dry sand was saturated from bottom by de-aired water under partial vacuum. Hydraulic resistance $R(t)$ of the whole system. Triangles are related to short time scale (bottom axis), circles are related to large time scale (top axis). Pressure head difference between inflow and outflow $\Delta h = 47.4$ cm, hydraulic gradient $I = 4.37$.

air in accordance with Henry's law is more distinct in the initially dry sand. As a consequence there is a difference in R increase of the plate for infiltration into dry and wet soil, see Eq. (4) and compare curves a and b in Fig. 1. Since q decreases with time during infiltration, the rate of the air release is decreasing with time compared to time close to 0, and dR/dt is less steep with time.

There was a similar increase of the crust hydraulic resistance when infiltration was realized into plate

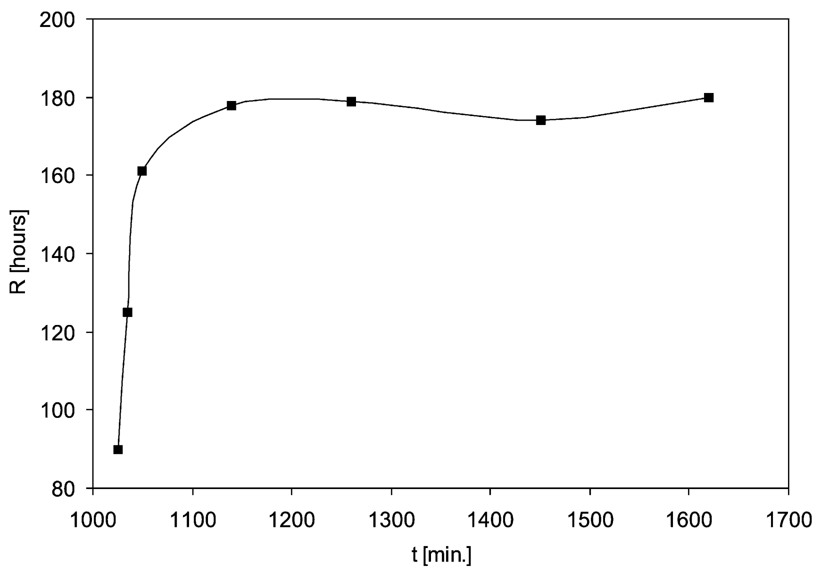

Fig. 4. Continuation of the experiment plotted in Fig. 3 when the pressure head difference was increased to $\Delta h = 148.7$ cm, $I = 13.72$ at time $t = 1025$ min. Time t is read from the start of experiment in Fig. 3.

topped loess. The ratio of R_0 ($t = 0$) and R_{12} (end of infiltration after $t = 12$ min) for initially dry sand was $R_{12}/R_0 = 4.0$ while for loess $R_{12}/R_0 = 3.1$. After 480 min of infiltration into loess was the ratio of resistances $R_{480}/R_0 = 4.7$. Neither quantitative nor qualitative conclusions can be formulated except that the time-dependent resistance of the crust exists when water infiltrates into crust-topped loamy soil.

The total hydraulic resistance of the system crust + sand column was time-dependent in a similar way if saturated flow was installed, Figs. 2 and 3. In experiments according to Scenario No. 3 (Fig. 2), the entrapped air existed from the start of measurement and therefore we denote the flow as saturated.

The small jump of $R(t)$ at $t = 1390$ min (Fig. 2) is probably due to switching of the inflow measuring device from Mariotte burette to the horizontal capillary. A slight pollution of the meniscus and of the walls of the horizontal capillary by air could exist at very slow flux for large time experiments. I have met a small fluctuation of flux when I have measured the resistance of the sole ceramic plate for a great extend of time. Similar type of 'inaccuracy' appears in some further tests, too. However, this type of small fluctuation of R does not effect the general run of the increase of plate hydraulic resistance with time within the infiltration into crust-topped soil.

In experiments according to Scenario No. 4 (Fig. 3) the amount of entrapped air was minimized by de-aeration at the start of measurement. The observed difference in R for those two instances is explainable by the theory of Collis-George and Yates (1985), who have found that the encapsulated air causes gradual increase of flux at the inflow end in permeameter experiments. Thus the systematically lower values of R in Fig. 2, compared to Fig. 3, are probably due to this counteracting effect against the action of Henry's law. The rate of increase of R with time is less steep in a system with a higher volume of entrapped air.

Experiments with saturated flow indicated that R was approaching a constant value for large time. The condition $R = \text{const.}$ at t_E, looks as probable for infiltration, too. The value of t_E is smaller for infiltration into initially wet soil than for dry soil. The existence of t_E is explainable by three assumptions: (1) the equilibrium between the rate of exclusion of air and diffusion flux of air through liquid water from the microbubbles is reached; (2) the increase of air pressure inside the air microbubbles reaches such values due to the local non-equilibrium; further exclusion of air is prevented; (3) at large time extend of experiments when a constant pressure head is kept, the value of flux density q decreases as R of the crust increases. The rate of air release $\partial A/\partial t$ is then lower, compared to short time values just due to the decrease of q. Neither of the assumptions was tested by the performed experiments.

The reversibility of the plate resistance increase was only partial. After the infiltration into dry sand, the plate was de-aired in water under partial vacuum without drying it, and the resistance was $R = 56$ h. The same procedure of de-aeration of the plate was realized after infiltration into wet sand and subsequent resistance was $R = 49$ h. Ronen et al. (1989) quote Gardescu (1930) that a very high pressure is required to force entrapped bubbles through a pore space and to overcome the resistance to flow offered by detached gas bubbles. The difference in R of the two tests after simple de-aeration of the plate is probably due to the difference of the volume of entrapped air bubbles, but there is not a direct proof on it.

The potential argument against the hypothesis on release of air due the pressure drop states, that there was entrapped air just from the start of measurement. Encapsulated air could exist in plate, or in sand, when the plate–soil system was saturated with water without de-aeration and at atmospheric pressure. If there was just entrapped air without the Henry's effect, the rate of flow would rise at the inflow end, leading to apparent decrease of R (Collis-George and Yates, 1985). The observed general trend was in all instances opposite. The values of R at a certain time were lower for soils where the air entrapment is probably higher, i.e. when the soil was saturated at atmospheric conditions, compared to soil saturated under vacuum, Figs. 2 and 3. If the air entrapment is high, the final effect can be divided into Henry's effect and the phenomenon observed by Collis-George and Yates. The rate of increase of R with time is then less steep.

For saturated flow, the increase of R was greater if hydraulic gradient was increased, see Fig. 4. The steeper drop of pressure head with z results in greater release of air. The increase of flux density q contributes to the rate of air release, too. Due to more intensive blocking of micropores by air microbubbles, hydraulic conductivity is more reduced and R increases to a greater extent, compared to experiments with a lower hydraulic gradient.

Observed effects on the time-dependent change of hydraulic resistance of soil crusts and seals due to the action of Henry's law have to be considered in theoretical treatment on soil crusting. The discussed phenomena should not be neglected. Soil hydraulic methods based upon infiltration through a less permeable membrane are probably influenced by Henry's law effect, too.

5. Conclusions

Infiltration and flow in crust-topped soil was physically modeled by infiltration into system of ceramic plate placed on the top of the column of homogeneous sand and alternatively of loamy loess. Dirichlet's boundary condition was installed on the top boundary in infiltration tests. Initial hydraulic resistance of the plate was approximately by two orders of magnitude greater than resistance of sand. The results support the validity of hypothesis on Henry's law effect. High hydraulic resistance of the crust results in steep drop of the water pressure between the top and bottom part of the crust if water flows through the crust-topped soil. The concentration of dissolved air in water depends upon the pressure acting on water according to linear Henry's law. Since water dissolves a certain volume of air in the top part of the crust while in the bottom part this capacity is decreased, air is released at the bottom part of the plate. All results support the hypothesis that the released air exists in small, microscopic bubbles, which are blocking the micropores of the bottom part of the crust, provided that there are no macropores free of water. A certain amount of microbubbles may remain on the interface between crust and soil. Consequently, hydraulic resistance increases with time up to time of quasi-equilibrium when hydraulic resistance remains quasi-constant with time. Observed effects play a role in change of hydraulic resistance of soil crusts and seals in time and should not be neglected. Field methods of unsaturated conductivity estimation based upon infiltration through a less permeable membrane are probably influenced by Henry's law effect, too.

6. A note

I am admitting that the indirect proofs on Henry's law effect have to be completed by direct measurement as, e.g. by CT, or NMR, or by another adequate microtechnique. I have planned to continue on the theme but after my retirement I had no opportunity to finish the research up to the expected extend. Thus, the hypothesis even if theoretically based cannot be considered as finally and completely proved.

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