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Experimental analysis of preferential flow in dry snowpack

Takafumi Katsushima [a,*], Satoru Yamaguchi [c], Toshiro Kumakura [b], Atsushi Sato [c]

[a] Department of Maritime Technology, Toyama National College of Technology, Imizu, Toyama, 933-0293, Japan
[b] Department of civil and Environmental Engineering, Nagaoka University of Technology, Nagaoka, Niigata, 940-2188, Japan
[c] Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, Nagaoka, Niigata, 940-0821, Japan

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A B S T R A C T

Preferential flow in snowpack is an important phenomenon and influences snowpack modeling, avalanche forecasting and runoff forecasting for snow-covered basins. However, the theoretical foundation is not sufficient to develop a snowpack model that includes a water movement process including preferential flow. The water ponding process, which is caused by the water-entry value of capillary pressure, is a key process for capillary pressure overshoot, water saturation overshoot and the formation of preferential flow in other porous media like homogeneous dry sand. We attempted to apply theories of preferential flow in homogeneous dry soil to initially dry snow. Infiltration experiments into homogeneous dry snow and theoretical analysis were carried out to reveal the developing process of preferential flow during infiltration into a homogeneous dry snowpack and to obtain critical conditions for that process. The capillary pressure was measured just above the interface between the dry/wet snow layer by the tensiometer. Concurrently we conducted experiments with a dye-tracer in order to observe the flow patterns. The capillary pressure overshoot and the water-entry value were observed in experiments for samples of a large grain diameter (>0.25 mm). The capillary pressure overshoot was directly linked to the formation of preferential flow. The velocity criterion and the pressure head criterion which are used to predict preferential flow for dry sand were able to predict the preferential flow for three out of our four different samples. The velocity criterion failed, however, to predict the stable case (no occurrence of preferential flow) for the experiment with the smallest grain diameter and pore size. Good agreement experimental results and both criterions were obtained from the analysis. These results showed some similarities between the developing process of preferential flow in dry sand and in dry snowpack.

1. Introduction

The infiltration of rain and melt water into the snowpack is thought to be an important process for wet-snow avalanche (Baggi and Schweizer, 2009; Kattelmann, 1985). The type of water movement in a snowpack includes both, horizontally uniform flow and nonuniform flow that is called preferential flow or fingering flow. The preferential flow into dry snow layer produces a horizontal heterogeneousness of snowpack physical property by the wet metamorphism (Wakahama, 1968). Knowledge on the physical processes determining preferential flow is essential to realistically simulate the physical properties of snowpack (Gustafsson et al., 2004), but often complicated by the fact that dry snow is often maintained in the snowpack as the preferential flow paths develop (Marsh and Woo, 1984a; Wakahama, 1968). The water flux in the preferential flow paths is greater than the supplied surface water flux (Marsh and Woo, 1984a) which can lead to severe underestimation of arrival time and water flow at basal layers of the snowpack (Mitterer et al., 2011). However, most snowpack-simulating models such as SNTHERM (Jordan, 1991), CROCUS (Brun et al., 1992) or SNOWPACK (Lehning et al., 1999) do not consider the preferential flow process. The size and the number of preferential flow path per unit area is helpful to make a parameterization which decides the water flux and the water content in the preferential flow paths (Marsh and Woo, 1984b). To implement such a parameterization into the multiple snow layer model, it is necessary to be able to discriminate the snow layer to the preferential flow layer and the uniform flow layer because the preferential flow is not always formed. However, it is difficult because of the lack of theory of the preferential flow development in snowpack. Thus, at first, a critical condition for triggering preferential flow is needed in order to develop a water movement model that includes both water transport process which will improve results of common used snowpack-simulating models.

The occurrence of preferential flow in snowpack has been shown in with dye trace experiments (Gerdel, 1954; Marsh and Woo, 1984a). A water ponding layer on less permeable layer boundary is needed to form the preferential flow (Wakahama, 1963). The water on that layer boundary is laterally moved and concentrated in the preferential flow

* Corresponding author at: Department of Maritime Technology, Toyama National College of Technology, 1-2, EbieNeriya, Imizu, Toyama, 933-0293, Japan. Tel./fax: +81 766 86 5220.
E-mail address: katusima@nc-toyama.ac.jp (T. Katsushima).

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paths (Wakahama, 1963). The water ponding layer is usually observed in following three situations: (1) on a fine-textured overlaying a coarse-textured layer (capillary barrier); (2) on an impermeable ice layer under a snow layer. The ponding layer boundary (1) is formed due to a difference of the water-entry capillary pressure of the large pores in coarse lower snow layer compared to capillary pressure in the small pores in fine upper snow layer (Jordan, 1995; Wakahama, 1963). This effect is called the capillary barrier. The ponding (2) is explained by the low values of hydraulic conductivity for ice layers (Langham, 1974). The occurrence of these ponding layers were shown by the field and experimental observations, and the theories of ponding process were shown. Moreover, recent experimental observation under laboratory conditions showed that the preferential flow is formed from not only the fine over coarse textured layer boundary but also the wetting front into dry snow layer with the coarse textured snow (Waldner et al., 2004). However, the critical condition of the formation for these types of preferential flow has not been presented.

Previous studies in the soil physics community summarized the following physical process and critical condition to be relevant for the formation of a preferential flow. The preferential flow in soil is formed in the cases in which the wetting front, the interface between the initial state zone and the newly wetted zone cannot maintain a horizontal flat front and becomes unstable (Hill and Parlange, 1972). The preferential flow is formed under certain infiltration conditions that the supplied water flux is less than the saturated conductivity (Hill and Parlange, 1972). The negative water pressure head gradient behind the wetting front in which the water pressure in pore is decreased upwards is a critical condition for the preferential flow during vertical water infiltration (Philip, 1975; Raats, 1973). Fig. 1 shows a conceptual schematic of preferential flow development into dry sand (Glass et al., 1989: Selker et al., 1992b; Jury et al., 2003). Capillary pressure P_c is a difference value of pressures in pore between air pressure P_a and water pressure P_w ($P_c = P_a - P_w$). If the air pressure in pore is equal to the atmospheric pressure, the air pressure is assumed that $P_a = 0$ and the capillary pressure has an opposite sign of the water pressure ($P_c = -P_w$). In snow community, capillary pressure P_c, capillary pressure head h_c, suction ψ are usually used to express energy state of capillary force. For unsaturated snow, capillary pressure (head) and suction are positive value and water pressure (head) are negative value. If the wetting front which has the negative water pressure gradient (positive capillary pressure gradient) advances partially at one location, the capillary pressure at the advanced position becomes higher than the capillary pressure at the adjacent position and a horizontal gradient of capillary pressure is created. As a result, a lateral flow toward the advanced position is created and the concentrated water advances the tip of preferential flow to a deeper position (Cho et al., 2005; Selker et al., 1992a). Thus, the negative water pressure gradient behind the wetting front affects the condition for preferential flow growth (Jury et al., 2003; Wang et al., 2004; Shiozawa and Fujimaki, 2004).

A threshold value of capillary pressure head that allows water to enter an initially dry pore exists at the wetting front into initially dry soil (Fig. 1). It has been defined as the water-entry value of capillary pressure head h_{we} (Hillel and Baker, 1988). The water ponding process caused by the water-entry value is a key process for the formation of the preferential flow in soil (Hillel and Baker, 1988) and the negative water pressure gradient behind both of the wetting front into the homogeneous dry sand (Cho et al., 2005; Geiger and Durnford, 2000) and the wetting front at the layer boundary between a fine-textured overlaying a coarse-textured layer act as capillary barrier (Baker and Hillel, 1990, 1988). When the capillary pressure at wetting front falls below the water-entry capillary pressure, the wetting front will advance into the dry layer. The high water content layer near the saturated water content is formed at the tip of the wetting front into dry sand which has a water-entry value (Glass et al., 1989; DiCarlo, 2004, 2007). The

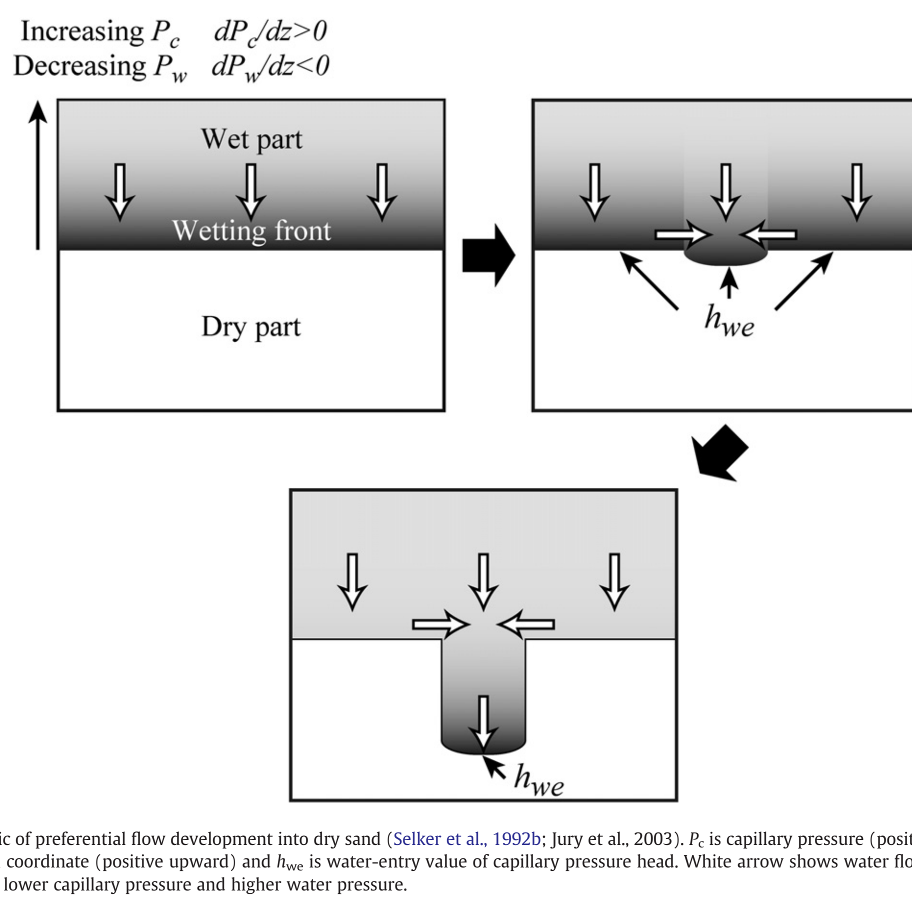

Fig. 1. A conceptual schematic of preferential flow development into dry sand (Selker et al., 1992b; Jury et al., 2003). P_c is capillary pressure (positive value), P_w is water pressure (negative value), z is vertical coordinate (positive upward) and h_{we} is water-entry value of capillary pressure head. White arrow shows water flow and darker gray colored part shows higher water content, lower capillary pressure and higher water pressure.