Return Flow Generating Point in Unsaturated Soils on a Layered Slope with Traffic Pan

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1. Introduction

Subsurface existence of densely-compacted traffic pan layer in Tsumagoi hillslope fields has prompted the research attention to investigate the effects of such pan on the downslope two-dimensional behavior of water flow in unsaturated soils. The purpose of this study is to observe the return flow generating point (RFGP), the length of slope surface saturation attributing to the return of infiltrated water in order to substantially contribute surface runoff, in a steady state unsaturated flow in layered slope with traffic pan. Results obtained from the experimental observations of two-dimensional unsaturated flow in the model slope under the artificial rainfall were used to validate RFGP approach.

2. Theoretical Considerations for RFGP

In a gradual progress of infiltration, percolation reaches the interface between top and pan layers and a saturated layer tends to back up above the interface. This layer of saturated subsurface flow, if exists, will also be receiving subsurface flow from upslope, and during a long wet period, the discharge in this layer will tend towards a steady state.

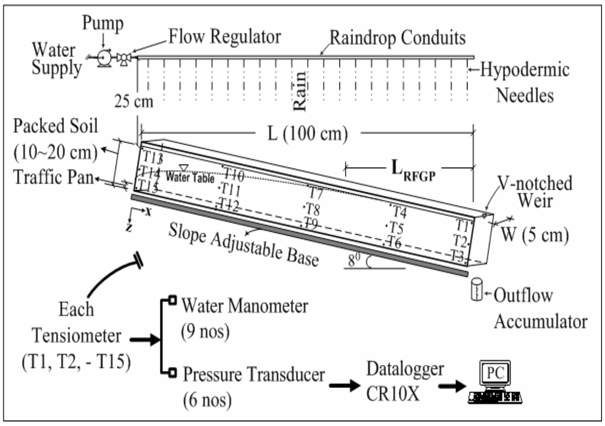

Fig. 1 Generalized schematic of laboratory setup and definition sketch of RFGP.

This increased flow may give rise in turn to an increasing depth of saturation downslope, acting effectively as perched water table within the soil. When this process continues for long enough, then water table may intersect surface of the slope or saturated layer may build up to the surface. Consequently, this intersected saturated layer causes overland seepage as subsurface return flow, and also prevents the entry of further rainfall, which therefore runs off directly. Under steady state conditions, mass balance for the flow domain of a long uniform model slope, as shown in Figure 1, is given by

$$r \cos \alpha \, L = qA \tag{1}$$

where, r is the rainfall flux, L is the length of the model slope, A is the area of flow domain, and q is the magnitude of fluxes per depth. Assuming that soil is isotropic, the flux q at any depth is decomposed into two components according to Darcy's law, which are, respectively, defined by

$$q_x = -K(\psi)\left(\partial\psi/\partial x - \sin\alpha\right) \tag{2}$$

$$q_z = -K(\psi)\left(\partial\psi/\partial z + \cos\alpha\right) \tag{3}$$

where, q_x and q_z are the components in the directions of the *x* axis and the *z* axis, respectively, ψ is the matric head, α is the slope inclination, and $K(\psi)$ is the unsaturated hydraulic conductivity. The magnitude and direction of all fluxes in the slope,

$$q = \sqrt{q_x^2 + q_z^2}\,;\ \gamma = \tan^{-1}\left(q_x/q_z\right) \tag{4}$$

where, γ is the angle between the *z* axis and flux q. If L_{RFGP} is the length of slope surface saturation where return flow possibly occurs, then RFGP in steady state conditions can be estimated from eq. (1) by substituting L_{RFGP},

$$L_{RFGP} = qA/r\cos\alpha \tag{5}$$

3. Model Slope Experiment

3.1 Materials

Volcanic ash soils collected from the hillslope field sites at Tsumagoi were used for the model slope. Soil physical properties determined for the top and pan layers are presented in Table 1. Soil water retention behaviors of the soils were also obtained.

Table 1. Soil properties used in the model slope

Soil Properties	Top Layer*	Traffic Pan Layer*
Bulk Density, gcm^{-3}	0.40	0.68
Saturated Hydraulic Conductivity, cm s^{-1}	0.014	0.00011

*Top layer indicates 0-10 and 0-15 cm depths for the experimental runs 1 and 2, respectively, and traffic pan layer indicates 15-20cm depth for experimental run 2

3.2 Laboratory Setup

Figure 1 shows the generalized schematic of laboratory setup. Natural field soils were packed within the rectangular boxes of 100cm×5cm×12cm

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(box no.1) and 100cm×5cm×22cm (box no.2), respectively, whose bottom was fixed at an inclination of 8º. Raindrop applicator was used to maintain constant rainfall of 12.5 cmh^{-1} and discharge was collected to record discharge rates during the short time intervals. Both boxes had 15 holes on one side, in which tensiometers were placed such that rectangular grids were formed to accomplish continuous observations of soil water suction, which were eventually used to estimate flux distributions using eqs. from (2) to (4) as well as soil water status in the model slope.

3.3 Experimental Procedure

Two experimental runs were performed: (1) uniformly 100cm×5cm×10cm soil packed in box no.1 assuming the bottom of box as traffic pan, and (2) 100cm×5cm×20cm including 5cm traffic pan layer packed in box no.2. Each experimental run was carried out until steady state conditions prevailed. Bulk densities at different locations in the model slope were gravimetrically determined after each experimental run was completed.

4. Results and Discussion

4.1 Matric potentials

Matric potentials at different observation nodes (T1, T2, etc. in Figures 1 and 3) during the two experimental runs are observed at 30 minutes intervals and matric potential profiles in the direction of the *z* axis on 25 cm intervals of the *x* axis is demonstratively presented in Figure 2 for the run 2. Steady state flow was attained at 540 minutes and 600 minutes for the runs 1 and 2, respectively, and nearly the entire flow region became saturated excluding a small upper end of the upslope. Negative pressure profiles within the traffic pan layer at steady state suggest that experimental run 2 might have been prolonged to achieve complete steady state conditions.

4.2 Water Table and Flux

Corresponding to Figure 2, Figure 3 illustrates water table advancement and flux distributions at different times, indicating that perched water table above traffic pan rises in turn to an increasing depth of saturation downslope and eventually intersects the surface of the midslope to cause return flow. Observations of a small infiltration zone at the upper end of the upslope suggest that infiltration capacity of the upslope portion is not generally exceeded at steady state and slightly high fluxes occurring at this unsaturated portion are attributed to the relatively higher saturated hydraulic conductivity of top soil.

4.3 RFGP in Steady State Conditions

RFGP was experimentally observed at 42.5 and 49.5 cm from the downslope end for the two runs, respectively, suggesting the agreement with the estimations (42.78cm and 49.79 for the two runs, respectively) of the analytical approach expressed in eq. (5). Figure 3 illustrates the observed RFGP in steady conditions, the length of slope surface saturation that acts as seepage face and returns the infiltrated water to the slope surface.

5. Concluding Remarks

RFGP in steady state unsaturated flow in a sloping rectangular region layered with densely-compacted traffic pan is proposed. Results observed from the two experimental runs of volcanic ash model slope show agreement with the analytical approach in estimating RFGP. Such RFGP may extend ideas to a number of phenomena of the hillslope field erosion concerning the presences of subsurface traffic pan.

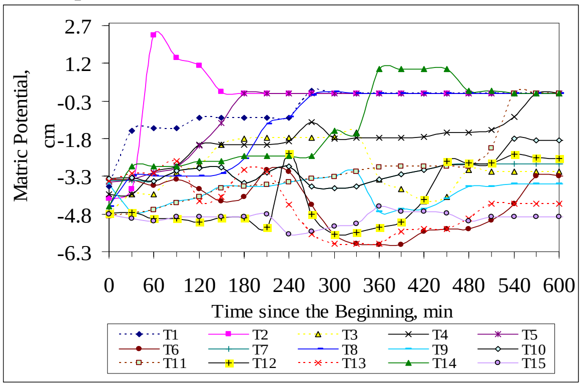

Fig. 2 Matric potentials in the model slope for the experimental run 2. Here, observation nodes T1, T2, etc. are shown in Figures 1 and 3.

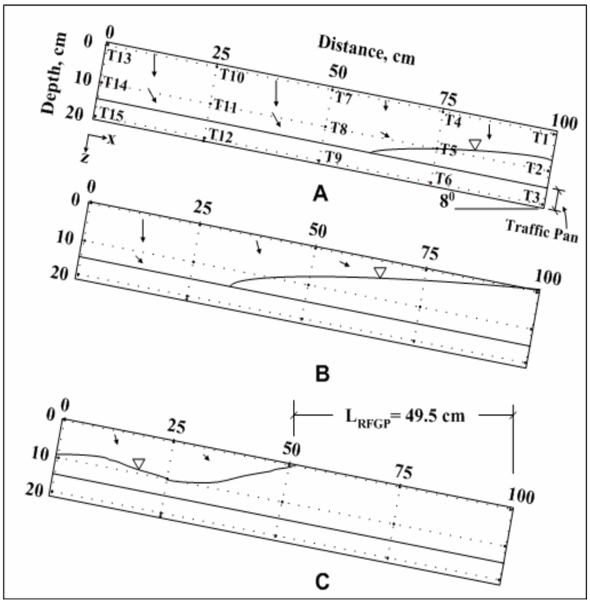

Fig. 3 Illustration of water table position and flux distributions at different times of the experimental run 2: (A) at elapsed time t = 180 min, maximum flux velocity is 0.192 cmh^{-1}; (B) at t = 360 min, maximum flux velocity is 0.15 cmh^{-1}; and (C) at t = 600 min, steady state is attained, maximum flux velocity is 0.07 cmh^{-1}, RFGP is observed at 49.5 cm from the downslope end, which is considered to be at the midslope.