Movement Properties of the Pipe Flow along Granite Slope of the Three Gorges Area on Yangtze River in China

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Abstract: It is well known that, in most cases, soil water doesn't move in the form of laminar flow as described by Darcy Law. Only when Reynolds number (*Re*) is no more than 10, does water movement follow Darcy law. A soil profile with 2.9m long and 2.13m—2.60m deep was excavated on a lower slope located in Zigui County, Hubei province, China. Field observation found that soil pipes were mainly distributed in a transient layer between horizon B with higher degree of granite weathering and horizon C with lower degree of granite weathering. At the foot of the slope, about 5—7 soil pipes per meter were observed along the vertical direction of the slope. The observed results, obtained from continuous observation of soil pipes and pipe flow processes at granite slope for many rainfall events, indicate that the relationship between velocity of pipe flow and hydraulic gradient along the pipe is parabolic rather than linear one. Based on the investigated data of soil, landform, and land use etc., combined with observed data of pipe flow derived from many rainfall events, a pipe flow model was developed. For velocity V_p, discharge Q_p of pipe flow and radius r of soil pipe, great similarity was found between simulated and observed values. Particularly, the simulated length of soil pipes reflects the great difference among soil pipes as a result of its different position in the soil profile. The length values of 4 soil pipes were estimated to be 98.1%, 27.6%, 11.0% and 3.0% of the longest distance of the catchment, respectively. As a special case of water movement, soil pipe flow follows Darcy-Weisbach law. Discharge of pipe flow is much greater than infiltration discharge in general sense. Only when the depth of groundwater is more than the diameter of soil pipe and water layer submerges soil pipes during rainfall, may pipe flow occur. Under these circumstances, discharge of pipe flow is directly proportional to the depth of groundwater.
Keywords: soil pipe, pipe flow, granite slope, the three gorges area of Yangtze River, pipe flow model

1 Introduction

Although many researchers had attempted to classify and define subsurface flow, there is little consensus on its definition owing to the different objectives of studies in different fields. Most of these classification systems have their own advantages. Japanese expert (Kitahara Hikaru, 1996) developed a classification system of soil water flow. The subsurface flow was divided into 2 types, one of which is uniform flow through micropores called matrix flow, the other is non-uniform pipe flow through macropores and super macropores called preferential flow.

2 The experimental and the soil profile

The experimental site was located in Zigui County, Hubei Province, China, 3km away from the under construction Three Gorges Dam on Yangtze River(111°57′20″N, 30°51′15″E). The bedrock of the experimental site is granite, covered by a weathering layer with a depth of more than 10 meters The 32.6 meters long study slope occupies a total area 328.4 square meters, with average slope of 33.3°, and elevation ranging between 250 meters and 271.41 meters.

Mean annual precipitation is approximately 1,150 mm, with more than 98 per cent falling as rain, occurring mainly from May to October. The climate is temperate with mean annual temperature of 17.4 degree centigrade, and mean January and July temperatures of 5.0 degree centigrade and 28.4 degree centigrade, respectively. There is a litter layer of 2cm—3cm depth on the surface of the ground. The soils consist of an organic layer, approximately 20cm thick, and the leached layer, 60cm—100cm, which is weathered product from granite (Zhang Hongjiang and Wang Lixian, 1997).

A soil profile, with 2.9m long, 2.23m—2.60m deep, was excavated vertically in the lower part of the experimental slope. In order to put together infiltration water from the soil profile and to measure discharge of water flow, a water-collecting trench was built near the lower part of the soil profile, with a length of approximating the soil profile. To prevent the soil profile from being destroyed by rainfall and to prevent raindrop from mixing with infiltration water from soil profile, a rain shed is built above the soil profile and the trench.

3 Calculation of hydraulic parameters of pipe flow

3.1 Hydraulic radius R

Hydraulic radius is defined as ratio of discharge cross-section area to wetted perimeter. Suppose the soil pipe cross-section is circular and the soil pipe is full of water, then:

$$R = D/4 \tag{1}$$

where D is diameter of soil pipe, and R is hydraulic radius.

3.2 Velocity of pipe flow V_p

Velocity of pipe flow refers to discharge of pipe flow in unit time through unit discharge section area, namely

$$V_p = Q_p/A \tag{2}$$

where V_p is velocity of pipe flow, Q_p is discharge of pipe flow in unit time, and A is discharge section area.

3.3 Reynolds number *Re*

According to principle of hydraulics, Reynolds number can be expressed as:

$$R_e = V_p D/v \tag{3}$$

where Re is Reynolds number, V_p is velocity of pipe flow, D is diameter of soil pipe, and v is kinetic water vicious coefficient.

3.4 Hydraulic gradient *I*

Considering that variation rate of kinetic energy $V_p^2/2g$ of pipe flow caused by velocity changes along the pipe is very small, angle of experimental slope I_s was used as appropriate value of hydraulic gradient I.

Assuming that soil pipe is full of water when discharge of pipe flow is the largest, hydraulic parameters of 4 soil pipes were computed for 5 rainfall events (Table 1).

For all the measured soil pipes, *Re* values ranging from 692 to 1,056, are much higher than the threshold of Reynolds number 10 defined by Darcy Law.

3.5 Roughness coefficient *n*

Since pipe flow follows Darcy-weisbach law, roughness coefficient can be derived from Manning Formula

$$n = R^{2/3} I^{1/2} V^{-1} \tag{4}$$

where n is roughness coefficient of soil pipe, R is hydraulic radius, I is hydraulic gradient, and V is velocity of water flow.

3.6 Saturated Conductivity *Ks*

Soil samples were collected from the experimental site, and the saturated conductivity Ks has been measured under constant water head by ST-70A osometer (Table 2).

Infiltration discharge through unit area of soil pipe walls is not only determined by the depth of groundwater but also by saturated conductivity of the soil pipe wall. Although saturated conductivity of soil pipe wall is different from that of soil surrounding soil pipes, saturated conductivity of surrounding soil is used to represent that of soil pipe wall due to the constraint of the measurement technique (Kitahara Hikaru, 1992).

4 Pipe flow model

Based on the data of the rainfall events and the corresponding pipe flow process in the experimental site, soil surface conditions such as soil, geology and land-use types are combined in this paper to develop the pipe model.

Modeling pipe flow in this paper is based on some assumptions as follows.(1) Branches, confluence and flexion of soil pipes in soil are not taken into consideration; (2) Soil pipe cross-section is circular and the roughness coefficient inside pipe is constant along a pipe; (3) Water within soil pipe just comes from soil water infiltration through soil pipe walls; (4) Underground water table is parallel to the impermeable layer in the slope, and the depth of groundwater along a specific pipe is constant; (5) All the soil pipes in the catchment converge in the outlet of the catchment, and (6) The flow-divided line on the slope is coincident with that under the ground.

Assuming that Q_p refers to discharge of a soil pipe (m-s series), r is radius of soil pipe, and V_p is velocity of soil pipe, then

$$Q_p = \pi r^2 V_p \tag{5}$$

Assuming again that Q_s is infiltration discharge through the pipe walls from surrounding soil, d is the depth of water table, K_p is saturated conductivity of the soil pipe walls, X is the oblique distance from beginning point of the soil pipe, and the shape of the soil pipe is approximately circular cone, thus

$$Q_s = \pi K_p d r (X^2 + r^2)^{1/2} \tag{6}$$

Radius of soil pipe is much smaller compared to pipe length. According to assumption (3), Q_s is approximately equal to Q_p. From equation (5) and equation (6), r can be calculated as

$$r = K_p d X V_p^{-1} \tag{7}$$

According to Manning Formula, velocity of pipe flow V_p is written as

$$V_p = n^{-1}(r/2)^{2/3} I^{1/2} \tag{8}$$

Where n is roughness coefficient; and I is hydraulic gradient.

Substituting equation (7) into equation (8), then

$$V_p = 0.758 K^{2/5} d^{2/5} n^{-3/5} I^{3/10} X^{2/5} \tag{9}$$

$$r = 2V_p^{3/2} n^{3/2} I^{-3/4} \tag{10}$$

and substituting equation (10) into equation (5), then

$$Q_p = 4.15 K^{8/5} n^{3/5} I^{-3/10} d^{8/5} X^{8/5} \tag{11}$$

5 Results analyses

Based on the equation (9), (10) and (11), velocity V_p, radius r and discharge Q_p of soil pipe G are calculated as in Tab.3.

Table 1 and Table 3 indicate that the largest observed velocity of pipe flow in soil pipe G is 17.68cm/s, while the largest simulated velocity of the soil pipe is 17.88cm/s, with absolute difference between them just 0.20cm/s. The largest observed discharge of the soil pipe is 3.33cm^3/s, while simulated value is 3.48 cm^3/s, with absolute difference of 0.15cm^3/s. The observed diameter of the soil pipe is 0.49cm, while simulated one is 0.50cm, with absolute difference of 0.01cm. Particularly, the simulated length of soil pipe G is 100cm and it is the shortest among the 4 experimental soil pipes. The length of pipe G coincides with its position in soil profile. Although soil pipe G is farther from soil surface, it is formed by slope deposit. Therefore the diameter is comparatively large, but its length can not be too long.

The values of velocity V_p, radius r, and discharge Q_p for pipe A, pipe B and pipe C are also simulated.

Due to the different positions and the hydraulic properties within soil profile for each soil pipe, the change processes and trend of velocity V_p, discharge Q_p and radius r of soil pipe following the changing length of soil pipes X are significantly different.

6 Conclusions and discussion

Pipe flow, as a special type of water movement in soil, follows Darcy-weisbach law, whose discharge is much greater than general infiltration discharge.

Characteristics of rainfall directly influence the occurrence of pipe flow. Meanwhile, rainfall intensity, rainfall duration, antecedent soil water content and the position of soil pipe all closely correlate to velocity and discharge of pipe flow. When the depth of groundwater is more than diameter of soil pipe and groundwater level submerges soil pipes during rainfall, discharge of pipe flow is positively related to the depth of groundwater d.

This tentative model is developed under many assumptions. The simulated properties of pipe flow, however, are very similar to the observed ones, which indicates that the methodology of model development is basically right.

The study on pipe flow challenges the traditional knowledge that water movement just follows Darcy law. Except that a small part of pipe flow moves in form of groundwater, most of pipe flow transforms soil water into surface runoff by means of fast penetration out of the soil profile. Hence, such problems such as the distribution of soil pipe, proportion of pipe flow to the total discharge of infiltration, contribution of pipe flow to runoff processes etc. need to be studied further.

Acknowledgements

We would like to thank Dr. Fan Houbao (Fujian Forestry College, China) for his reviewing English of the manuscript. The research was funded by National Natural Science Foundation of China under the contract 40171014.

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Table 1 The largest discharge and hydraulic parameters of 4 soil pipes

Item		Pipe A	Pipe B	Pipe C	Pipe G
The largest discharge of soil pipe for individual rainfall event Q_p (ml/h)	Jul., 28	2,460	780	1,080	6,860
	Aug., 5	2,200	6,900	3,200	2,800
	Aug., 8	1,360	7,000	2,560	1,640
	Aug., 18	18,000	13,360	7,600	12,000
	Aug., 27	12,000	8,560	20,000	10,000
The largest discharge among 5 rainfall events Q_p (ml/h)		18,000	13,360	20,000	12,000
The largest discharge among 5 rainfall events Q_p (cm^3/s)		5.00	3.71	5.56	3.33
Diameter of soil pipes D (cm)		0.92	0.52	0.67	0.49
Cross-section area of soil pipes S (cm^2)		0.665	0.212	0.353	0.189
Hydraulic radius R (cm)		0.230	0.130	0.168	0.123
Velocity of pipe flow V_p (cm/s)		7.52	17.48	15.76	17.68
Reynolds number Re		692	909	1056	866
Hydraulic gradient I		0.657	0.657	0.657	0.657

Table 2 Saturated conductivity *Ks*

Experiment No.	Duration (min)	Infiltration discharge (ml)	Saturated conductivity *Ks*		
			(ml/(cm^2 • s))	(cm/s)	(m/s)
1	10.0	46.0	0.0011	0.0011	1.1e-5
2	15.0	65.0	0.0010	0.0010	1.0e-5
3	15.5	66.5	0.0011	0.0011	1.1e-5
4	15.0	67.5	0.0010	0.0010	1.0e-5
5	15.0	62.5	0.0010	0.0010	1.0e-5
6	15.0	63.0	0.0010	0.0010	1.0e-5
7	17.0	70.0	0.0010	0.0010	1.0e-5
Average	—	—	0.0010	0.0010	1.0e-5

Table 3 Simulated values for hydraulic properties of the soil pipe *G*

Parameter	Distance from the soil profile *X* (cm)					
	0	100*	500	1000	1500	2000
Velocity of pipe flow V_p (cm/s)	0.00	17.88	34.04	44.92	52.82	59.27
Roughness coefficient *n*	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113
Hydraulic gradient *I*	0.657	0.657	0.657	0.657	0.657	0.657
Radius of the soil pipe *r* (cm)	0.00	0.25	0.65	0.99	1.26	1.50
Saturated conductivity K_p (cm/s)	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
The depth of groundwater *d* (cm)	43.5	43.5	43.5	43.5	43.5	43.5
Discharge of the soil pipe Q_p (cm^3/s)	0.00	3.48	45.75	138.68	265.31	420.39

*Simulated value corresponds to observed value.