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EXTENDED ABSTRACT

Calculate the Output Flow Depth from a Coarse-Grained Porous Media with Radial Flow

Jalal Sadeghian[a,*], Hadi Norouzi[b], Jalal Bazargan[b]

[a] *Department of Civil Engineering, Bu Ali Sina University, Hamedan, Iran*
[b] *Department of Civil Engineering, University of Zanjan, Zanjan, Iran*

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1. Introduction

Coarse-grained gravel (rockfill material) has numerous applications in engineering including filtration, gabion construction, channel lining, stilling basins, ponds, and cobble stone dams as well as flood control. In the fine-grained media, there is a laminar flow with a linear relation between hydraulic gradient and flow velocity so that the flow follows Darcy law (Eq. 1) (McWhorter and Sunada, 1977). However, in the coarse-grained media, due to the presence of voids, flow velocity is high with a tendency to the turbulent flow formation (Hansen et al. 1995), and there is a nonlinear relation between hydraulic gradient and flow velocity and flow follows non-Darcy law. Hydraulic gradient equations in the non-Darcy media considering steady flow condition are classified into two groups of power and binomial equations, according to Eqs. 2 and 3 (Forchheimer, 1901; Leps, 1973; Stephenson, 1979).

$$i = \left(\frac{1}{k}\right)V \quad (1)$$

$$i = mV^n \quad (2)$$

$$i = aV + bV^2 \quad (3)$$

Where V is flow velocity (m/s), i is hydraulic gradient, m and n are values dependent on the properties of the porous media, fluid and flow, while a and b are coefficients dependent on the properties of the porous media as well as the fluid.

There are two general methods to analyze steady–non-Darcy flow through rockfill materials:

a) One-dimensional analysis of flow, using gradually-varied flow theory:

Application of this theory in simulation of flow through rockfill materials was investigated by (Bari and Hansen, 2002) and then by other researchers, such as (Bazargan and Shoaei, 2006). The results showed that at the end-points of the formed media, particularly at high discharges, there was a significant difference between the observational and computational depth results. Hence, in this method, computations of the longitudinal profile of water surface are not accurate enough because of the lack of output flow depth as downstream boundary condition.

b) Two-dimensional analysis of flow, using Parkin equation:

* Corresponding Author
E-mail addresses: j.sadeghian@basu.ac.ir (Jalal Sadeghian), hadinorouzi72@gmail.com (Hadi Norouzi), jbazargan@znu.ac.ir (Jalal Bazargan).

Parkin, 1969, combined the continuity equation with exponential function of velocity and hydraulic gradient for the first time and developed an equation as an alternative to Laplace equation. This equation could be solved by knowing the boundary conditions as well as porosity (Arbhabhirama and Dinoy, 1973). In other word, without knowing output flow depth as downstream boundary condition, and water surface profile as a boundary condition which depends on the output flow depth, the accurate solution of the Parkin equation is practically impossible. Stephenson (1979) considered the output flow depth through rockfill drainage equal to the critical depth in case of steady flow (Equation 4).

$$y_c = \sqrt[3]{\frac{q^2}{n^2 g}} \tag{4}$$

Where yc= critical depth, q= discharge in unit width of the rockfill, n= porosity of materials, and g= gravity acceleration.

However, experimental tests conducted by other researchers proved that Equation 4 is inaccurate. In this regard, (SedghiAsl et al. 2010) corrected the equation based on the experimental data by applying Γ coefficient (Equation 5).

$$y_e = \Gamma \sqrt[3]{\frac{q^2}{n^2 g}} \tag{5}$$

In the previous studies, values of Γ were calibrated by different researchers using experimental data. Using such data, (SedghiAsl et al. 2010) obtained the value of Γ coefficient for the angular and rounded materials as 2.3 and 2.4, respectively. There is no doubt that Γ value for open channels which lack rockfill materials is equal to 1. In other words, the difference between values of Γ is due to the fact that in the angular materials, porosity of media is more than the rounded ones and is closer to 1, which is the same as the porosity of open channels (SedghiAsl et al. 2010). In another study, (Chabokpour and Tokaldani, 2017) used their own experimental data and obtained the value of Γ coefficient for a length of 100 cm as 1.83 and 2.05 for aggregate diameters of 16 and 30 mm, respectively; and for a length of 193cm as 1.58 and 1.84, respectively considering the same aggregate diameters.

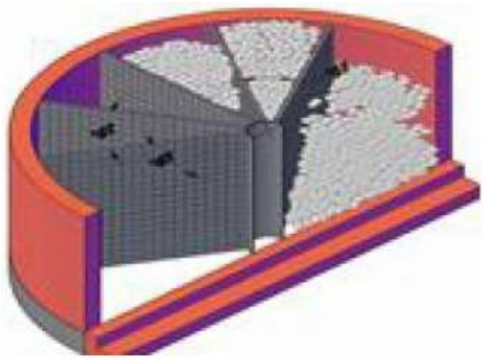
Norouzi et al. (2022) Using experimental data in different conditions and using particle swarm optimization (PSO) algorithm and dimensional analysis, a relationship to calculate the Γ coefficient based on the physical properties of aggregates and flow properties have been provided.

Calculating the output flow depth is of great importance in one-dimensional (the gradually varied flow theory) and two-dimensional (Perkin equation solution) steady-non-darcy flow analysis. In other words, the output flow depth is used in the one-dimensional analysis as the starting point for water surface profile calculations and in the two-dimensional analysis as the downstream boundary condition. In previous studies, the output flow depth from the parallel rockfill materials has been investigated. While in the present study, the output flow depth in the radial non-darcy mode has been investigated for the first time. In the present study, using experimental data (large-scale semi-cylindrical test device with dimensions of 6 m in diameter and 3 m in height) recorded for 10 different heights of water pumped upstream of the rockfill materials and dimensional analysis, a relation is provided to calculate the mentioned coefficient (Γ).

2. Material and Methods

2.1. Experimental Data

In the present study, due to the compatibility of cylindrical coordinates and its adaptation to the physics of problems related to radial flows, a device has been constructed in the laboratory of Bu Ali Sina University in the form of a semi-cylinder with a diameter of 6 meters and a height of 3 meters. The dimensions of this device are made on a large scale and the effects limitations have practically no effect on the testing process. To measure piezometric pressure, piezometric grids have been used. The device has a volume of 14,000 liters and a capacity of materials weighing approximately 40 tons. Four pumps are installed in parallel at the top of the device to generate the required flow. Coarse-grained river materials with a diameter between 2 to 10 cm, a porosity of 40%, a Cu of 2.13, and a Cc of 1.016 have been used. To perform the tests, the model is first filled to a certain height (53, 60, 70, 85, 95, 110, 120, 140, 150, and 160 cm) by pumping operations. The flow rate created in these experiments is in the range of 49.94 to 53.16 L/s.



(a)

(b)

(c)

Fig. 1. Different parts of the experimental device: a) Outline of experimental model, b) Front of experimental model, c) Placing parallel pumps on the model

3. Results and discussion

In general, the present study consists of the following stages:

1) According to Stephenson, 1979 (the output flow depth from the coarse-grained porous media is equal to the critical depth), the recorded output flow depth from the radial porous media was compared with the critical depth (Eq. 4).

2) Since the output flow depth from the coarse-grained porous media is very different from the critical depth, and according to Eq. 5 (the output flow depth from the coarse-grained porous media is as a coefficient of the critical depth) and studies performed, the coefficient is a function of the upstream depth (h) and distance from well center to upstream (R). For this reason, in the present study, using dimensional analysis and experimental data in different conditions, an equation was presented calculate the Γ coefficient with high accuracy.

According to the equation developed by (Stephenson, 1979), output flow depth from rockfill porous media in steady flow condition is equal to the critical depth (Equation 4). Fig. 2 shows changes in depth of the observational output flow and critical depth versus flow discharge for all experimental data.

As can be seen from Fig. 2, there is a significant difference between the observational output flow depth and critical depth.

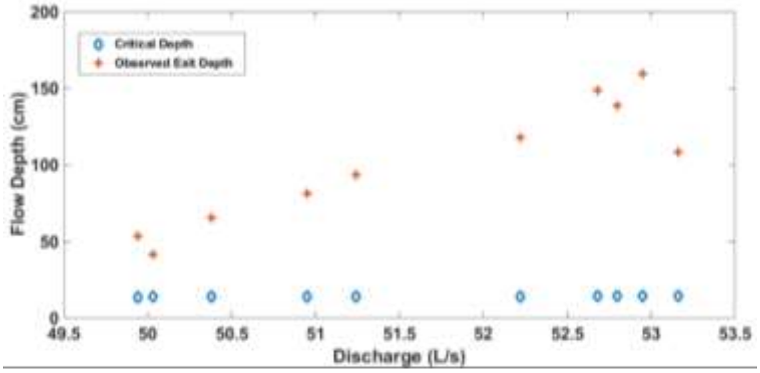


Fig. 2. Changes in experimental output flow depth and critical depth in terms of discharge

The output flow depth from the porous media according to Equation (5) is a coefficient of critical depth. The studies performed in the present study indicate that the coefficient is a function of upstream depth (h) and the distance from the center of the well (downstream) to upstream (length of the gravel) (R). In other words, using experimental data for different conditions of upstream water height, Equation (6) is presented to calculate the Γ coefficient.

$$\Gamma = J^*\left(\frac{h}{R}\right) \tag{6}$$

Using Excel software and linear regression, the value of J coefficient equal to 20.75 has been obtained. Fig. 3 shows changes in the observational output flow depth (observed in experiments) and computational output flow depth (using the proposed equation in the present study) versus flow discharge for different materials.

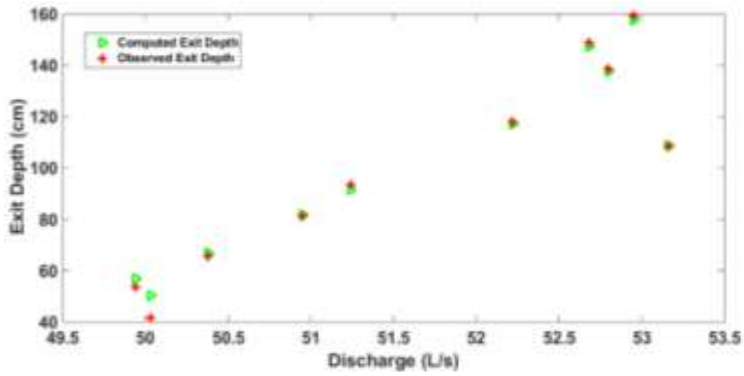


Fig. 3. Observational and computational output flow depth changes in terms of discharge

Also, the values of observational output flow depth, critical depth, computational output flow depth in the case of using the solution presented in the present study, and the mean relative error values of both cases are expressed in Table 1.

Table 1. Observational and computational output flow depth values and critical depth and mean relative error values

Height of pumped water (m)	Critical Depth (m)	Observed output flow depth (m)	Computed output flow depth (m)
0.53	0.1372	0.415	0.503
0.60	0.1371	0.535	0.569
0.70	0.1379	0.655	0.668
0.85	0.1389	0.813	0.817
0.95	0.1395	0.934	0.916
1.10	0.1429	1.085	1.087
1.20	0.1412	1.180	1.172
1.40	0.1423	1.386	1.378
1.50	0.1421	1.488	1.474
1.60	0.1425	1.593	1.577
Mean Relative Error %	83.43		3.53

4. Conclusions

If according to Stephenson's hypothesis, the output flow depth from the radial porous media is considered equal to the critical depth, the mean relative error is calculated as 83.43% and indicates that the output flow depth in the radial non-darcy state there is also a significant difference with the critical depth. If the relationship presented in the present study (a function of upstream depth (h) and the distance from the center of the well to the upstream (R)) is used to calculate the output flow depth in the radial state, the mean relative error is equal to It is obtained with 3.53%. In other words, the relation presented in the present study has high accuracy in calculating the output flow depth in the radial non-darcy state.

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