University of Birjand
Water Harvesting Research Vol. 6, No. 2, Autumn & Winter 2023, Original Paper p. 276-287
10.22077/JWHR.2024.6793.1107

Computation of Water Surface Profile through the Gravel Dams in Series

Jafar Chabokpour [a*]

[a]Associate Professor, Civil Engineering Department, University of Maragheh, Maragheh, Iran.

*Corresponding Author, E-mail address: J.chabokpour@maragheh.ac.ir
Received: 17 September 2023/ **Revised**: 30 March 2024/ **Accepted**: 12 April 2024

Abstract

This paper presents an in-depth study of water surface calculation of rockfill detention structures in series. Different flow characteristics in porous media were investigated, explaining the influence of velocity, hydraulic gradient and geometric media characteristics. Two mathematical models were presented based on the fundamental relationships in gradually varied flow theory in open channels and combining it with the pore velocity equations of Wilkins and Forchheimer. The analytical solutions were evaluated using laboratory data sets of three angular rockfill materials and four employed discharges. It was observed that presented analytical solutions can accurately predict the water surface profile. However, the Forchheimer equation needs the calibration of two coefficients in comparison to the Wilkins equation with one coefficient. Also, the results show a good association between the Froude number and Manning's coefficient in the power form trend. It was seen that power variation provides a suitable interpretation of the flow coefficient for all flow and rockfill geometric conditions.

Keywords: Analytical Model, Gravel dam, Reservoir, Water surface profile.

1. Introduction

Flow through rockfill media gives an inventive and efficient storm water management and wastewater treatment solution. This method effectively filters and stores water, reducing flooding risks and improving water quality. Its economical and environmentally friendly nature makes it ideal for urban areas seeking sustainable water management (Chabokpour and Amiri Tokaldany, 2017; Chabokpour et al., 2020). Modeling water flow and estimating the water surface profile through large porous media involves complicated mathematical equations and computer simulations. These models help investigators and engineers comprehend how water behaves through the media. Various numerical methods, such as finite difference, finite element, and finite volume methods, are used to discretize the porous media and solve these equations. A timely and proper interpretation of water flow dynamics confirms water resources' efficient and sustainable use. The water surface profile inside large porous media is complicated, with numerous elements affecting its behavior. Understanding the intricacies of water flow within these media enables us to make informed decisions regarding water management and resource conservation. Various factors such as hydraulic gradient, media properties, and obstacles affect the water surface profile inside large porous media. Its understanding is crucial for numerous applications, from managing groundwater resources to designing infrastructure projects. The Reynolds equation is a fundamental equation used to define fluid flow within porous media. It is derived from the general Navier-Stokes equations; the Reynolds equation simplifies the calculation process by making several assumptions. These contain the assumption of incompressible fluid flow, steady-state conditions, and Darcy's law, which remarks that the flow rate is directly proportional to the pressure gradient. High velocities or turbulence sometimes characterizes the flow through porous media. Forchheimer's equation is introduced to account for these influences, extending the fundamental Darcy's law by incorporating an additional quadratic term. Including this term enables a more precise indication of flow behavior, especially in cases involving fast or highly permeable media (Bear and Cheng, 2010; Freeze and Cherry, 1979; Todd and Mays, 2004).

Darcy presented the first fundamental equation for fluid motion in porous media based on the outcomes of studies on the flow through a sand column. Darcy considered the velocity of the flow passing through the porous media proportional to the hydraulic gradient on both sides of the media and presented Eq. 1 (Sedghi Asl et al., 2013).

$$V = -K\frac{\Delta h}{l} \quad (1)$$

where V is the flow velocity, l is the length of the flow path, Δh is the water level difference upstream and downstream, k is the coefficient of hydraulic conductivity, which depends on the characteristics of the fluid and the surrounding materials.

The value of K is also can be obtained from the Eq. 2.

$$K = \frac{\rho g k}{\mu} \quad (2)$$

where g is the acceleration of gravity, ρ is the density of water μ, is the dynamic viscosity of the fluid, and k is the Intrinsic Permeability of Porous Media

The flow can be divided into laminar, transitional, and turbulent in pipes with open sections. In the porous media, the voids between the rock materials can be assumed to be crooked pipes, which direct the flow from upstream to downstream. The flow regime of these pipes is a function of the effective height and the geometric shape of the void. Conventionally, the Reynolds number has been used as a criterion for the detection of the type of flow conditions in porous media. Comparing the flow of water in the fine-grained media with the coarse-grained media, the flow velocity of the body of a fine-grained porous media such as the clay core of an earthen dam is low and due to low permeability. The Reynolds number is a numerical representation of the linear flow inside the material. However, if the porous media comprises coarse-grained materials, the size of the pores allows the flow velocity to increase. Consequently, the Reynolds number becomes significant, and the flow can become turbulent. These conditions are created in the flow passing through the Gabion dam. Thus, looking for an equation other than Darcy's relations is necessary to model the flow and predict its behavior. These equations usually correspond to the relation between the pressure loss and the flow rate, and the mathematical basis of all of them is the Forchheimer and Wilkin equations, referred to in Eqs. 3-4 (Bear and Cheng, 2010; Mccorquodale et al., 1978; Wu and Huang, 2000).

$$i = av + bv^2 \quad (3)$$

$$i = mv^n \quad (4)$$

where, i is the pressure gradient, v is the flow rate, and a and b are the laboratory coefficients, m and n are the experimental coefficient and are related to the properties of the material and fluid, flow rate and viscosity of the fluid.

Forchheimer added a quadratic term to Darcy's relation, which includes turbulence effects. In this way, if a calm flow is present, the effect of the second term is insignificant, and if there is a turbulent flow, the first term can be ignored (Garga et al., 1991; Hansen et al., 1995).

According to the Forchheimer equation, total energy loss consists of two parts. Therefore, the value will be very low if the fluid velocity is low and consequently, the total energy loss will be due to the viscosity of the fluid moving in the porous media. Forchheimer equation comprises the first term, the effect of fluid viscosity in slow flows, and the second term, the inertial force index in turbulent flows (Herrera and Felton, 1991; Zeng and Grigg, 2006).

Generally, the equations relating flow velocity and hydraulic gradient in coarse-grained porous media are generally in quadratic and power forms. For the flow regimes between laminar and turbulent, the relationship of the quadratic form between the velocity and the hydraulic gradient was studied in the research conducted after Darcy, particularly the research of Forchheimer (1901). The second category of equations showing the relationship between velocity and the hydraulic gradient is the equation in power form. Wilkins (1955) presents one of this category's most widely used equations with the following general form (Bari and Hansen, 2002; Joy, 1991).

Wilkins obtained the following relationship by conducting an experiment on a column of coarse-grained materials, using the results to determine the value of the above coefficients (Eq. 5).

$$V_V = Wm^{0.50} i^{0.54} \quad (5)$$

where *W* is Wilkins constant and its value is obtained according to the physical characteristics of porous media. The hydraulic conductivity of the porous media is often considered as $Wm^{0.5}$. Because in turbulent flows, the gradient is proportional to the power of 2 of the velocity, the power of 0.54 on the hydraulic gradient confirms that the flow is close to a completely turbulent state. Therefore, the Wilkins equation can be concluded to be applicable to turbulent flows (Bari and Hansen, 2002; Joy, 1991; Sedghi-Asl and Ansari, 2016).

Stephenson (1979) presented Eq. 6 for the hydraulic gradient of the flow in coarse-grained porous media using the concepts of flow in pipes and assuming the relationship between hydraulic gradient with $\frac{V^2}{gdn^2}$ and assuming the relationship between the average hydraulic radius and the particle size of the porous media.

$$i = \frac{K_{st} V^2}{gdn^2} \quad (6)$$

Where K_{st} is Stephenson factor, which calculated from Eq. 7.

$$K_{st} = \frac{800}{Re} + K_t \quad (7)$$

The value K_{st} is 1 for stones with a smooth surface, 2 for semi-smooth stones, and 4 for sharp and angular stones. It is also $K_{st} = K_t$ for completely turbulent flow and can be considered as the hydraulic resistance factor which is opposite of the hydraulic conductivity. Barry and Bajracharya (1995) presented a new algorithm combining the energy equation and the pore velocity equations of Wilkins and Stephenson to calculate the flow profile in long rock deposits. They also reported that the flow profiles in such rockfill media are more similar to those in open channels. Therefore, the formed profile depends on the physical characteristics of the rockfill materials forming the media, while in general, it follows Dupuy's assumptions. Bari and Hansen (2002) calculated the longitudinal profile using the Wilkins and Stephenson equations and concluded that both relationships can predict the water surface profiles and agree with the laboratory profiles (Li et al., 1998; Martins, 1990).

Samani et al. (2003) expanded the routing concept to calculate the water surface profile in the coarse-grained porous media by modifying the routing equations of the reservoir. Bazargan and Shoaei (2006) conducted further research on the method presented by Barry and Hansen (2002). Consequently, based on the simplification of the relations by Stephenson and Wilkins that were used to calculate the friction loss, the extracted relations show an increasing trend. They show the interaction between the pore flow velocity and the hydraulic gradient, while the laboratory data tend to have a constant value at the end of the flow profile.

Sedghi-Asl and Rahimi (2011) studied the formed flow profiles in coarse-grained porous media using a laboratory model. Their research used angular and broken materials, and the existing mathematical relationships were analyzed after recording the observational profiles. In horizontal and 4% slopes, it was concluded that the water surface profile of the flow passing through the drain follows the gradually varied flow theory, whereas in the 20% slope, the gradually varied flow theory is less accurate, and the flow depth is uniform (Salahi et al., 2015).

Sedghi Asl et al. (2013) using the fundamental relationships in the flow roughness in open channels and combining them with the previous relationships presented new equations for roughness estimation of the passing flow through coarse-grained materials. The relationships were in two categories: clear and sediment-containing flow conditions. (Sedghi-Asl et al., 2014) presented a one-dimensional analytical solution for the partial differential equation of fully turbulent flows in long rock deposits from zero to high slope. The analytical solution was evaluated by using two sets of laboratory data consisting of rounded and angular rockfill materials. One of the widely employed analytical models for water surface profile calculations is the Muskingum method. This method is founded on the principle of conservation of mass and provides a simplified representation of flow routing in rivers. Using the Muskingum method for each dam in the series, it is possible to determine the inflow and outflow discharges to create a water surface profile for the entire system. Another typically employed analytical model is the Saint-Venant equations, which deliver a more detailed picture of flow dynamics. These partial differential equations represent the conservation of momentum and help simulate the complex water flow behavior (Chabokpour and Azhdan, 2020).

Firstly, the literature shows that various aspects such as hydraulic gradients, rockfill geometry, and roughness coefficients influence water surface profiles in rockfill. Researchers have established empirical relationships through experimental and numerical studies and created mathematical models to predict the water surface profile under different conditions. This knowledge assists hydraulic engineers in designing and optimizing rockfill structures to ensure their stability and functionality. Additionally, comprehending how water flows within rockfill and the possibility for erosion can assist in identifying probable failure mechanisms and executing effective measures to mitigate risks. Therefore, the presented study was designed to precisely look at water surface calculation through the rockfill detention structures. The current study is crucial for the reliability of rockfill structures, which play a vital role in water resource management and flood protection. As is found by previous researchers, still there is any analytical equation to simulate water surface profile through the rockfill dams in series. Therefore the present study were arranged to develop a new analytical equation for water surface modeling.

2. Materials and methods

2.1. Laboratory equipment

The experiments were carried out in hydraulic laboratory of University of Maragheh using a laboratory flume with a length of 1300 cm, a width of 120 cm, and a height of 80 cm, and the physical model of gravel dams were created through it. After granulation using a sieve and shaker, the rock material was washed and poured into the gabions as a porous media. The slope of the flume floor was horizontal, and the considered flow rates were applied to the porous media. The variables used in this study include three rock materials with average diameters of 1.1, 2.3, and 3.6 cm and four flow discharges of 7.5, 9, 11, and 13.5 l/s. For the operation of experiments, firstly, the pump was turned on, and the desired flow rate was set using the valve. The current is allowed to pass through the flume for a period of time to establish stable flow conditions. The end sill adjusts the outflow at desired tail water conditions. Then, to measure the flow depth in different parts of the media at different flow rates, a marker was used. The schematic diagram of experimental apparatus and different parts of laboratory experiments was depicted in Fig. 1.

A certain amount of each rock material was filled into a container with a known volume of 5 liters, and then, the material was completely saturated to measure material porosity. The water fills the pores of the porous media, and the porosity can be calculated through Eq. 8. This test was performed five times for each rockfill material, and their average is considered as porosity. The obtained value for operated rockfill diameters of 1.1, 2.3, and 3.6 cm were 43, 44, and 45% respectively.

$$n = \frac{v_v}{v_t} \qquad (8)$$

where n is the porosity of the porous media, v_v is the volume of the porous media (the volume of water poured into the container) and v_t is the total volume of the rockfill sample.

2.2. Derivation of analytical equation for profile estimation

2.2.1. Combined method of specific energy and Wilkins velocity Equation

In deriving this relationship, there is a possibility of operating the velocity relationship in power or fractional form, but using the power relationship form and especially the Wilkins velocity relationship makes the integration calculations easier. The specific energy equation for a cross-section can be written as Eq. 9 (Chanson, 2004; FRENCH, 1986)

$$E = y + \frac{V^2}{2g} = y + \frac{q^2}{2gn^2y^2} \quad (9)$$

where E is the specific energy, y is the flow depth, n is the porosity of the porous media, and q is the flow rate per unit width.

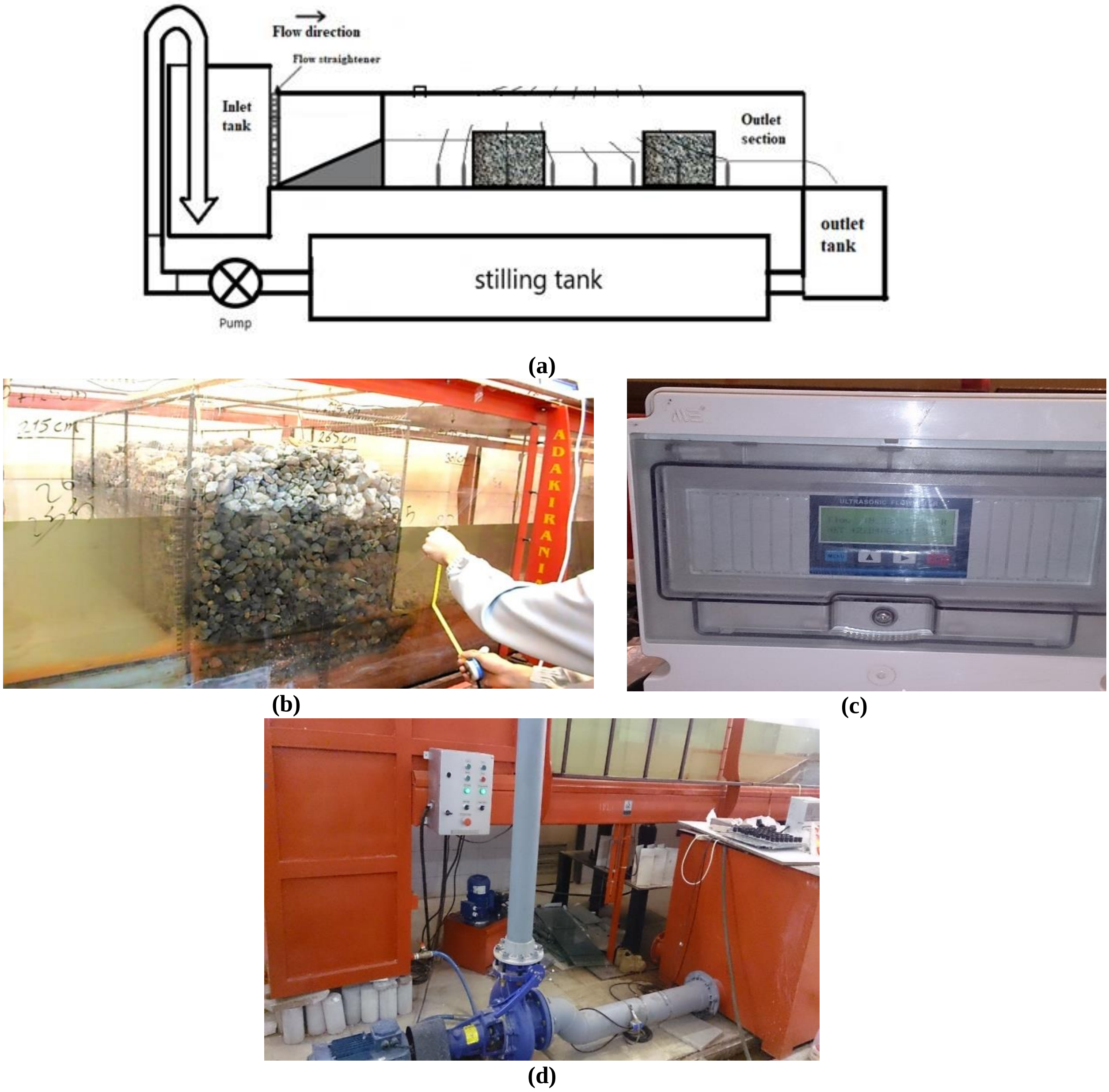


Fig. 1. Experimental data collection apparatus, a) Schematic of laboratory flume, b) operated gabion dams, c) Operated acoustic flow meter, d) pumping system of experimental flume

By differentiating the sides of Eq. 9, Eq. 10 can be achieved.

$$\frac{dE}{dx} = \frac{dy}{dx}\left(1 - \frac{q^2}{gn^2y^3}\right) \quad (10)$$

Eq. 10 can also be written as Eq. 11 by using the Wilkins relationship Eq. 12.

$$\frac{dE}{dx} = i \quad (11)$$

$$i = a(\frac{q}{ny})^b \quad (12)$$

where n is porosity of rockfill media. The power of the Wilkins relation is assumed equal to two by assuming the occurrence of turbulent flow in the gravel media. By replacing Eq. 11 in Eq. 10 and integrating Eq. 13 is obtained.

$$\int_{y1}^{y}\left(y^2 - \frac{q^2}{gn^2y^{3-b}}\right)dy = \int_{x1}^{x} a(\frac{q}{n})^2 dx \quad (13)$$

Ultimately, Eq. 14 can be obtained by replacing integration limits as final Equation.

$$\frac{y^3}{3} - \frac{q^2\ln(y)}{gn^2} - \frac{y1^3}{3} + \frac{q^2\ln(y1)}{gn^2} - \frac{aq^2(x-x1)}{n^2} = 0 \quad (14)$$

a coefficient is also should be calculated using experimental data series.

If a, n, q, and $y1$ are known through Eq. 14 and applying the downstream boundary conditions, which are the same as exit depth from the media, the water surface profile can be calculated and compared with the observed profile. The presented relationship can be converted into calculating distance in terms of depth or depth in terms of distance.

2.2.2. Combined method of specific energy and Forchheimer Equation

Another method presented to calculate the flow profile is to use the combination of forchheimer's relation (Eq. 3) with the specific energy relation (Eq. 9) and applying the assumption $\frac{dE}{dx} = i$, so Eq. 15 can be written as follows:

$$\frac{dy}{dx}\left(1 - \frac{q^2}{gn^2y^3}\right) = av + bv^2 \tag{15}$$

By algebraic extension of above equation for integration, Eq. 16 can be achieved.

$$\frac{dy}{dx}\left(1 - \frac{q^2}{gn^2y^3}\right) = a(\frac{q}{ny}) + b(\frac{q^2}{n^2y^2}) \tag{16}$$

Also by more extension, Eq. 17 can be obtained.

$$\frac{dy}{\frac{\left(1 - \frac{q^2}{gn^2y^3}\right)}{a(\frac{q}{ny}) + b(\frac{q^2}{n^2y^2})}} = dx \tag{17}$$

Integration from Eq. 17, should be done according to Eq. 18.

$$\int_{y1}^{y} \frac{\left(1 - \frac{q^2}{gn^2y^3}\right)dy}{a(\frac{q}{ny}) + b(\frac{q^2}{n^2y^2})} = \int_{x1}^{x} dx \tag{18}$$

Ultimately, the final equation after simplification is obtained according to Eq. 19.

$$\frac{y^2 n}{2qa} - \frac{by}{a^2} + \frac{1}{2a^3 qgbn}\Big((-2b^3gq^2 - 2a^3nq)\ln(any1 + bq) + (2b^3gq^2 + 2a^3nq)\ln(any + bq) - 2\Big(-\ln(y1)a^2q + \ln(y)a^2q + gb\Big(q(x - x1)a^2 + \frac{any1^2}{2} - bqy1\Big)\Big)an\Big) \tag{19}$$

Similar to Eq. 14, calibration of Eq. 19 is needed using experimental data series. However, it seems that Eq. 19 has two calibration coefficients, which causes difficulties in its operation.

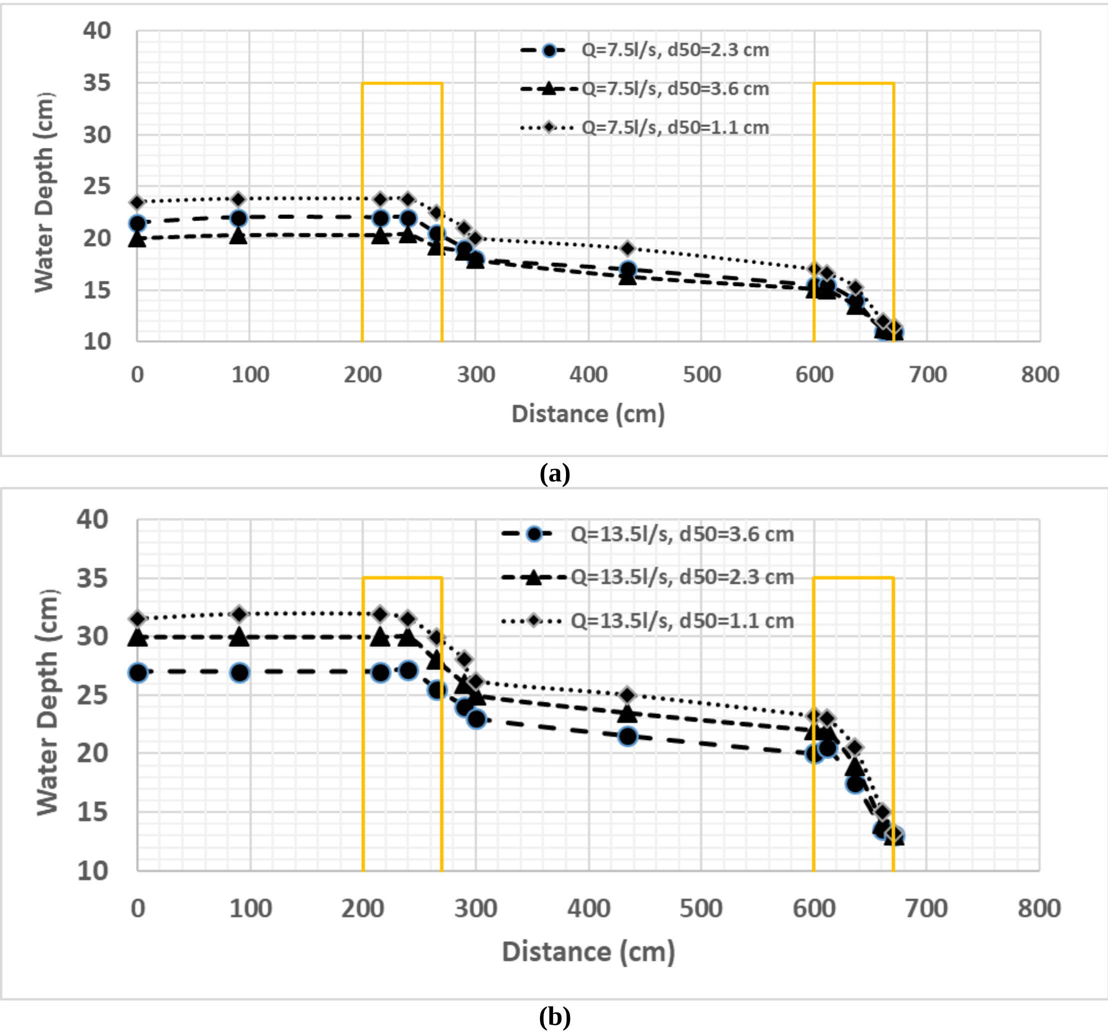
3. Results and Discussion

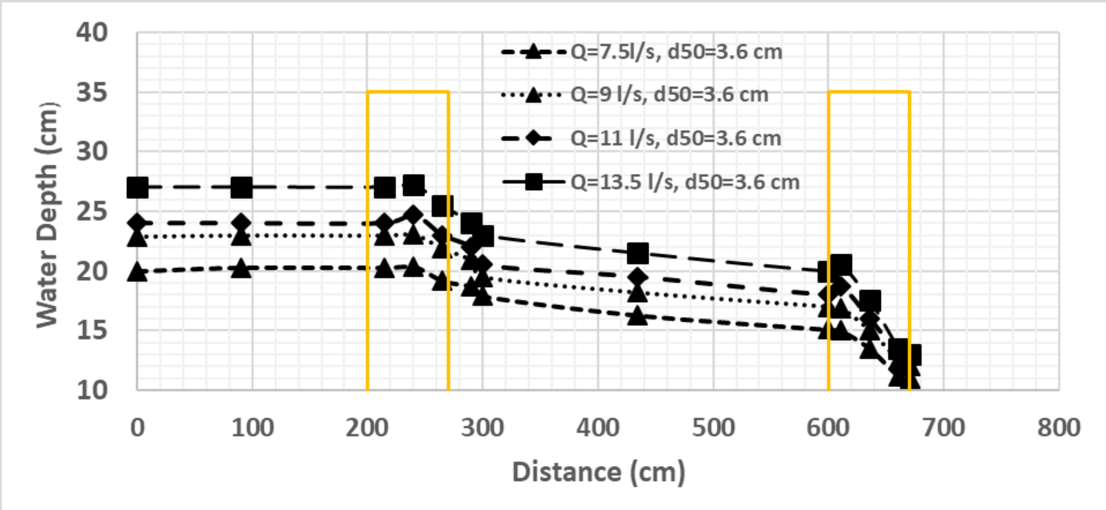
For the analytical modeling of water surface profiles in dams in series, several factors need to be considered, including the characteristics of each dam, the upstream inflow rates, and the downstream boundary conditions. Considering these, it was tried to estimate the water surface profile inside each dam and predict the system's behavior under different scenarios. The flow does not have a constant depth along the coarse-grained porous media. It overcomes the media roughness by energy consumption and moves towards the outlet with a constant hydraulic gradient. The flow depth behind the gravel structures generally depends on the diameter, length, and rock material roughness. Regardless of the passing flow condition, the upstream water level rises so much that the required specific energy for the flow passage is provided. Generally, the passage of flow through the porous media is the same as the subcritical flow passage over the bed-level step so that the step height of the rise is such that the obtained specific energy is less than the corresponding minimum specific energy on the particular energy curve. In this case, blockage occurs, and the upstream flow height is placed at a new level to provide the required minimum specific energy for flow passage. The state of the flow height before the gravel deposits is the same as the mentioned description, so with the change of the conditions of rock diameter, media length, and media roughness, the required energy to pass through the media changes and, consequently, the upstream flow level increases or decreases to supply the required energy. Formed flow profiles inside the porous media generally show a uniform trend (except at the outlet). Different relationships have been presented for the exit flow height by various researchers.

The flow output from inside the porous media has special conditions regarding hydraulics and material stability issues. Therefore, the outflow flow depth is a primary boundary condition for advanced numerical calculations inside the porous media. The profile calculations are started from that point, and the position of the water surface inside the coarse-grained porous media can be well calculated. Whereas for more straightforward purposes and issues related to the design of dams with coarse-grained porous media, the existence of simpler and more practical methods like those extracted in the previous part of the current study is also necessary to solve the requirements of hydraulic engineers in this regard.

After recalibrating and validating Eq. 14 and obtaining a value coefficient, it was observed that the extracted relationship, despite its simplicity, could predict the flow profile with acceptable accuracy. It was observed that a coefficient is only a function of the media diameter, and the media length or the different flow rates do not affect the value of this coefficient. The value of this coefficient was found to be 3.04, 2.63, and 2.09 for the rock diameter of 1.1 cm, 2.3 cm, and 3.6 cm respectively.

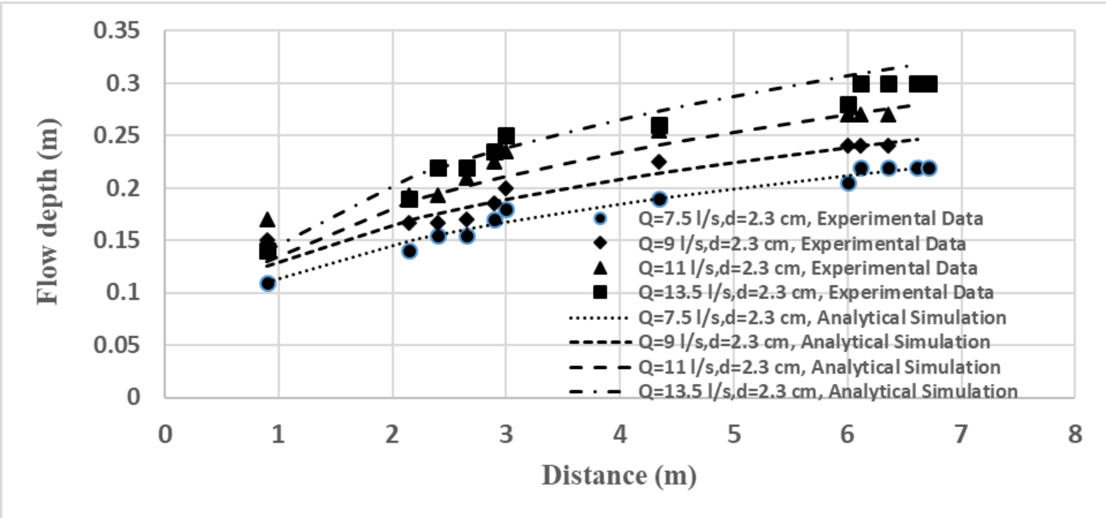
The calculation method was such that by assuming the observed exit flow depth as a boundary condition, the calculations were continued upstream, and the flow depth was calculated at distances of media where the observed depth was acquired. This was due to the subcriticality of the flow inside the media, demonstrated by the Froude number calculations. In Figs. 2-3, experimental and analytical results with different discharges and diameters of rockfill are shown. As can be seen, Eq. 14 is well capable of profile calculations inside the porous media. As can be seen from these figures, with the increase in the flow discharge at a constant media diameter, the height of the flow upstream of the porous media increases to an extent to supply the energy loss inside the porous media. This water surface drop equals 5 cm in the porous media with d_{50}=2.3 cm and flow rates of 7.5 and 11 l/s. This difference is due to the lower height of the profile compared to the previous state, which causes a lower level of rockfill media to be involved in front of the flow, and as a result, the value of energy loss is lower due to the reduction of friction between the flow and the rockfill material.



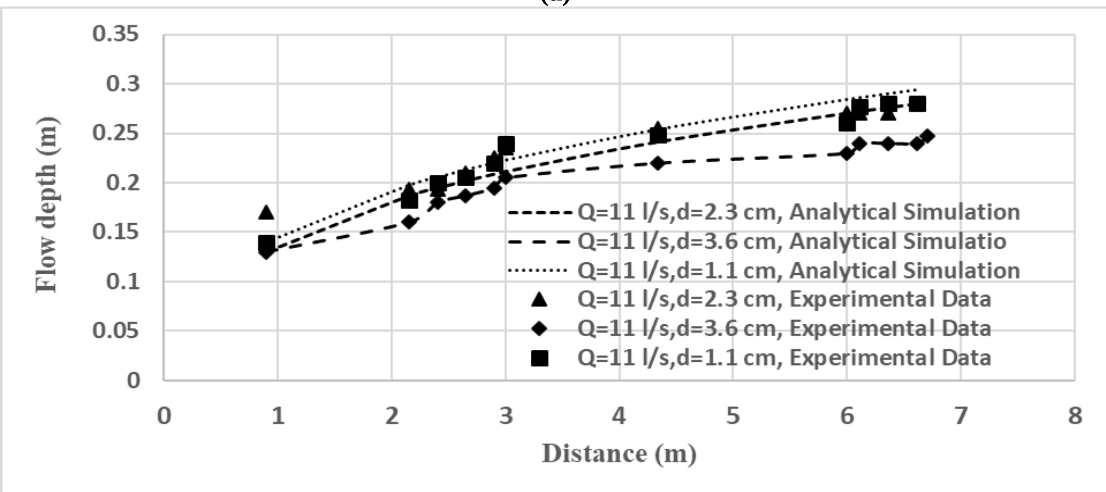


(c)

Fig. 2. Experimental and analytical water surface profile, a) water surface profiles for Q=7.5 l/s and different media diameter, b) water surface profiles for Q=13.5 l/s and different media diameter, c) water surface profiles for d=3.6 cm and different flow discharges



(a)



(b)

Fig. 3. Experimental and analytical water surface profile, a) water surface profiles for d=2.3 cm and different discharges, b) Water Surface Profile for Q=11 l/s and different media diameter

The rock's diameter in a rockfill dam can significantly affect its permeability. Typically, smaller-diameter rocks have a greater surface area than larger ones, presenting more corresponding void spaces. This increased surface area and interconnectedness of void spaces raise the resistance factor, resulting in lower permeability. On the other hand, larger-diameter rocks have fewer surface irregularities and void spaces, which decreases the overall resistance to the flow of the dam. A lower permeability can limit the dam's ability to drain water effectively, increasing pressure on the dam structure. This increased pressure can compromise the dam's stability and increase the risk of failure. Secondly, lower permeability can also affect the dam's ability to discharge water safely during high-flow occasions. It is worth noting that while larger-diameter rocks deliver higher permeability, they also tend to have lower shear strength compared to smaller ones. Shear strength refers to a material's ability to resist deformation under applied loads. In the context of rockfill dams, shear strength is crucial to ensure the dam's stability and control any possible sliding or failure. Thus, striking the right balance between permeability and shear strength is essential in designing and building rockfill dams. In high-flow conditions, large-diameter rocks may be more suitable to make a more substantial barrier that can resist the force of the water. Conversely, in low-flow situations or zones prone to sediment build-up, smaller diameter rocks can facilitate water passage and prevent clogging. For testing simulation accuracy of proposed analytical equation, RMSE (root mean square error) R^2 (coefficient of determination) statistical parameters were calculated, consequently, average value of 1.23 cm and 0.87 were calculated for them, respectively.

One of the crucial issues in the field of flow inside coarse-grained porous media is the relationship between the flow friction coefficient and the flow characteristics, which various researchers have investigated in the past. In open channels, the channel roughness is known as a characteristic that reduces the flow velocity. In the hydraulics of open channels, three coefficients usually express the resistance value to the flow. a) Darcy Weissbach roughness coefficient, b) Manning roughness coefficient, and c) Chezy roughness coefficient. Usually, different researchers divide the resistance value against the flow into several parts, including bed resistance, channel shape resistance, vegetation resistance, and sediment particle resistance. Still, in general, a single coefficient is used to express the total flow resistance, representing an overall evaluation of All the above factors. The relationships related to the roughness coefficients are connected through different uniform flow equations and are expressed in the form of Eq. 20.

$$\frac{V_n}{u_*} = \frac{V_n}{(gRs_f)^{0.5}} = \frac{C}{\sqrt{g}} = \sqrt{\frac{8g}{f}} = \frac{R^{1/6}}{n_m\sqrt{g}} \quad (20)$$

where V_n is the average flow velocity, u_* is the shear velocity, g is the acceleration of gravity, C is the shear coefficient, f is the Darcy-Wiesbach coefficient, R is the hydraulic radius, $n_m$is the Manning roughness coefficient, g is the acceleration of gravity, and s_f is the slope of the energy line.

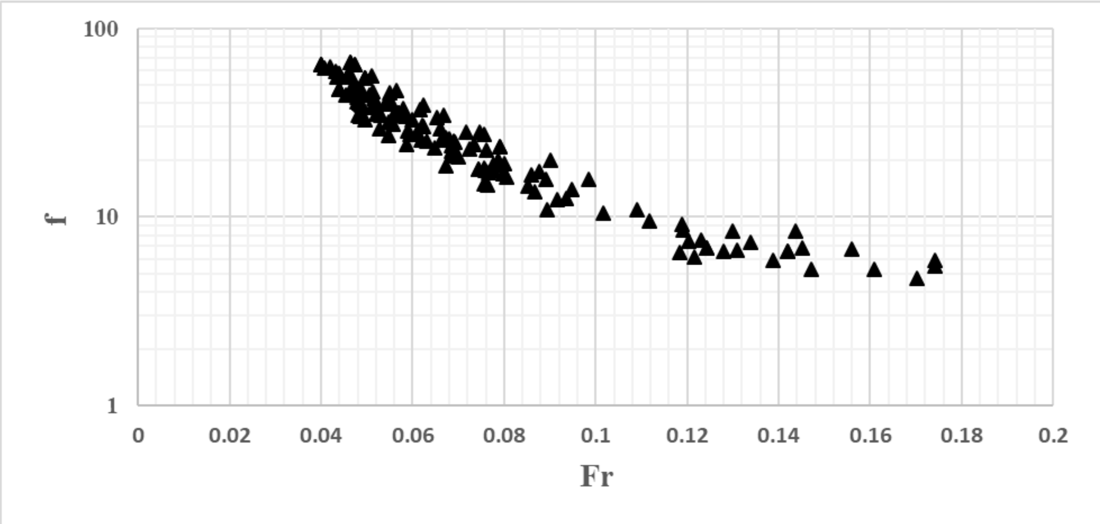
Considering that the created flow profile inside the porous media consists of different flow depths along the profile, it is clear that the applied roughness by the rockfill would be different. Therefore, one of the objectives of this research is to test the relationship between the roughness coefficient and the dimensionless flow parameters of the porous media along a profile to clarify whether, like what previous researchers have pointed out, the roughness coefficient has a high functional correlation with Reynolds number or not.

Using Eq.20 for each cross-section and at different flow rates, the value of Manning's coefficient was calculated, and then an attempt was made to provide relationships between this coefficient and dimensionless flow or the media numbers to determine which of these numbers correlates well with Manning's coefficient. The tested dimensionless numbers include $(\frac{h}{d_{50}})$, (Re), (Fr) and $\frac{V_n}{(ghs_f)^{0.5}} = \frac{V_n}{u_*}$. These parameters have already been introduced in Eq. 20.

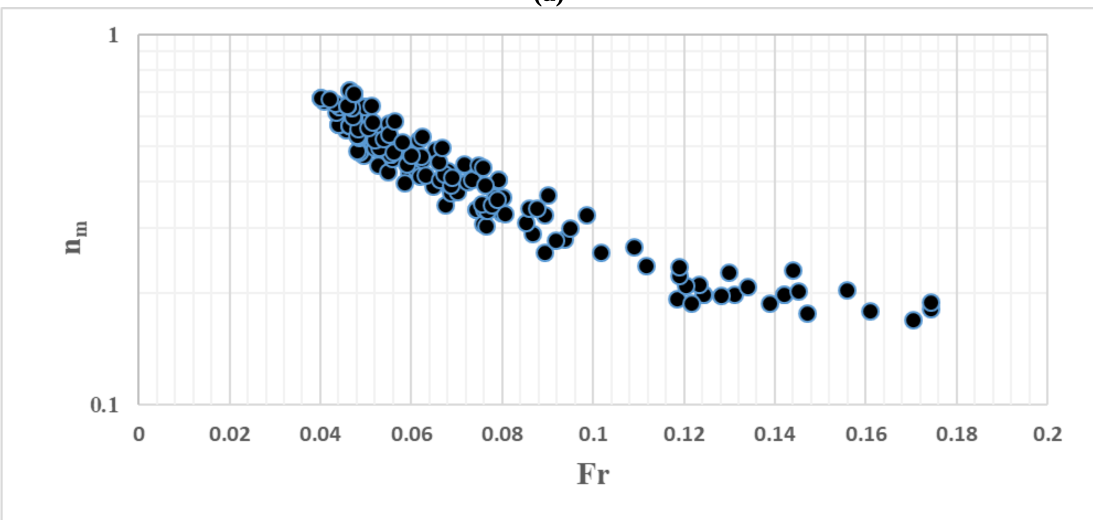
However, the fundamental point for calculating the roughness coefficient in coarse-grained porous media is to have a method to calculate the water surface profile accurately. It should be mentioned that the calculation of the water surface profile and the roughness coefficient are dependent on each other, which requires trial and error.

In Fig. 4, Manning's roughness coefficient and Darcy-Weisbach friction factors are depicted versus the calculated Froude number along the profile. It shows that there is a good relationship between the Froude number and both roughness coefficients in the power form. The data are presented for different flow discharges, grain diameter, and porosity. It can be almost claimed that power variation provides a suitable interpretation of the roughness coefficient for all flow and rockfill geometric conditions.

In Fig. 5, the mentioned hydraulic parameters are plotted versus the ratio of flow depth to the porous medium's diameter. It can be seen that the mentioned power variation trend here is also present. It can be said that with the increase in the flow depth, which leads to a decrease in the pore velocity, the roughness coefficient also increases. On the other hand, it can be seen that with the increase in the flow depth, the shear velocity and the Fr number also decrease.



(a)



(b)

Fig. 4. a) Darcy Welsbach friction factor versus Fr number, b) Manning friction coefficient versus Fr number

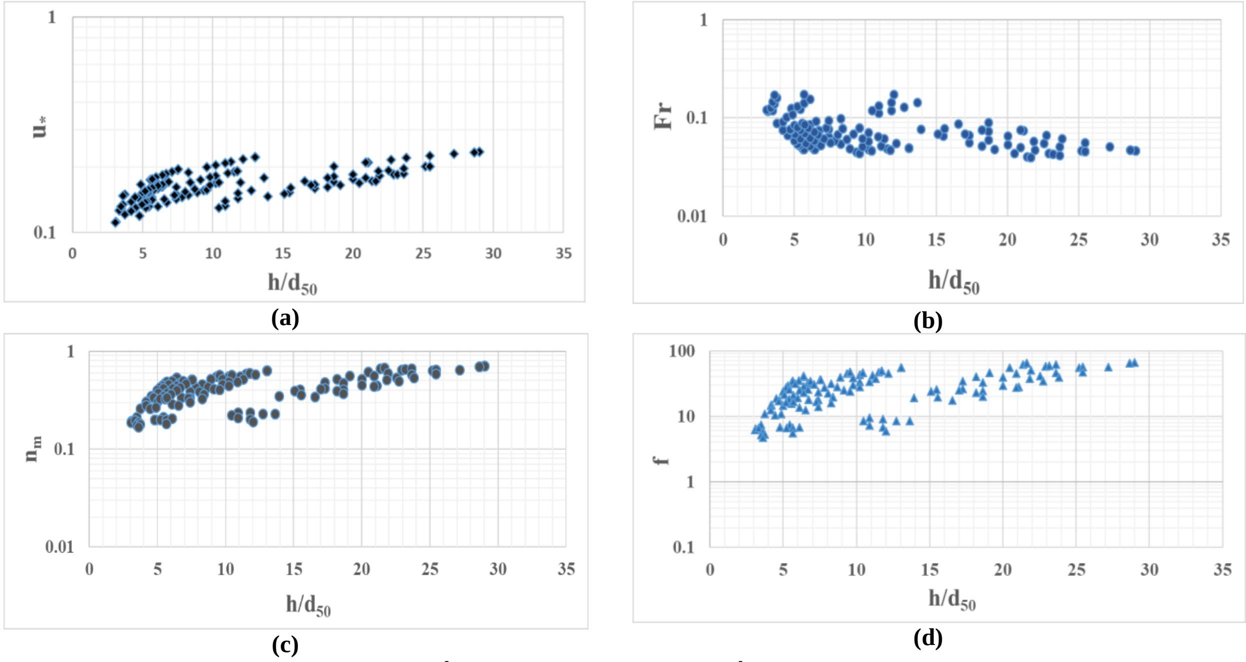


Fig. 5. a) Shear velocity (u_*) versus $\frac{h}{d_{50}}$, b) Fr number versus $\frac{h}{d_{50}}$, c) Manning friction coefficient versus $\frac{h}{d_{50}}$, and Darcy Welsbach friction factor versus $\frac{h}{d_{50}}$

4. Conclusion

An insufficient understanding of the water surface profile in series system of rockfill dams can significantly raise the risk of flooding during heavy rainfall or sudden surge flows. A significant aspect of this paper is its development on the Forschheimer and Wilkins relations, which are mathematical models detailing the relationship between flow velocity and pressure gradient in porous media. Also, The roughness coefficient as a key parameter for estimating the water surface profile in coarse-grained porous media was investigated. It was concluded that obtained mathematical models could properly simulate the water surface profile through a double set of rockfill detention dams. Moreover, it was found that presented mathematical equation with combination of Forschheimer equation has two model coefficients which needs to be calibrated using experimental data in comparison with extracted model with aid of Wilkins equation. Additionally, Manning and Darcy Welsbach friction coefficients were also computed along the surface profiles. It was found that by variation in flow depth, the amount of involved rock material varies and consequently, the friction factor magnitude is also changed. This reveals the effect of $\frac{h}{d_{50}}$ parameter in friction factor estimation. It was found that gradually varied flow theory is completely applicable for flow through rockfill dams. It was seen that the media diameter and employed discharges are two more effective parameters in surface profile creation.

5. Disclosure statement

No potential conflict of interest was reported by the authors

6. References

Bari, R., & Hansen, D. (2002). Application of gradually-varied flow algorithms to simulate buried streams. *Journal of Hydraulic Research*, *40*(6), 673-683.

Barry, D., & Bajracharya, K. (1995). On the Muskingum-Cunge flood routing method. *Environment International*, *21*(5), 485-490.

Bazargan, J., & Shoaei, S. M. (2006). Application of gradually varied flow algorithms to simulate buried streams.

Bear, J., & Cheng, A. H.-D. (2010). *Modeling groundwater flow and contaminant transport* (Vol. 23). Springer.

Chabokpour, J., & Amiri Tokaldany, E. (2017). Experimental-numerical simulation of longitudinal water surface profile through large porous media. *Iranian Water Researches Journal*, *11*(3), 81-90.

Chabokpour, j., & Azhdan, Y. (2020). Extraction of an analytical solution for flood routing in the river reaches (case study of Simineh River). *Journal of Hydraulics*, *15*(2), 113-130. https://doi.org/10.30482/jhyd.2020.229739.1456

Chabokpour, J., Chaplot, B., Dasineh, M., Ghaderi, A., & Azamathulla, H. M. (2020). Functioning of the multilinear lag-cascade flood routing model as a means of transporting pollutants in the river. *Water Supply*, *20*(7), 2845-2857.

Chanson, H. (2004). *Environmental hydraulics for open channel flows*. Elsevier.

Freeze, R. A., & Cherry, J. A. (1979). Groundwater Prentice-Hall Inc. *Eaglewood Cliffs, NJ*.

FRENCH, R. H. (1986). *Open channel hydraulics*.

Garga, V., Townsend, R., & Hansen, D. (1991). A method for determining the surface area of quarried rocks. *Geotechnical Testing Journal*, *14*(1), 35-45.

Hansen, D., Garga, V. K., & Townsend, D. R. (1995). Selection and application of a one-dimensional non-Darcy flow equation for two-dimensional flow through rockfill embankments. *Canadian Geotechnical Journal*, *32*(2), 223-232.

Herrera, N., & Felton, G. (1991). Hydraulics of flow through a rockhll dam using sediment-free water. *Transactions of the ASAE*, *34*(3), 871-0875.

Joy, D. (1991). Nonlinear porous media flow: determination of parameters for a coarse granular media. 13th Canadian Congress on Applied Mechanics, Winnipeg, Canada,

Li, B., Garga, V. K., & Davies, M. H. (1998). Relationships for non-Darcy flow in rockfill. *Journal of Hydraulic Engineering*, *124*(2), 206-212.

Martins, R. (1990). Turbulent seepage flow through rockfill structures. *Water power & dam construction*, *90*, 41-45.

Mccorquodale, J. A., Hannoura, A.-A. A., & Sam Nasser, M. (1978). Hydraulic conductivity of rockfill. *Journal of Hydraulic Research*, *16*(2), 123-137.

Salahi, M.-B., Sedghi-Asl, M., & Parvizi, M. (2015). Nonlinear flow through a packed-column experiment. *Journal of Hydrologic Engineering*, *20*(9), 04015003.

Samani, H. M., Samani, J. M., & Shaiannejad, M. (2003). Reservoir routing using steady and unsteady flow through rockfill dams. *Journal of Hydraulic Engineering*, *129*(6), 448-454.

Sedghi-Asl, M., & Ansari, I. (2016). Adoption of extended Dupuit–Forchheimer assumptions to non-Darcy flow problems. *Transport in Porous Media*, *113*(3), 457-469.

Sedghi-Asl, M., & Rahimi, H. (2011). Adoption of Manning's equation to 1D non-Darcy flow problems. *Journal of Hydraulic Research*, *49*(6), 814-817.

Sedghi-Asl, M., Rahimi, H., Farhoudi, J., Hoorfar, A., & Hartmann, S. (2014). One-dimensional fully developed turbulent flow through coarse porous medium. *Journal of Hydrologic Engineering*, *19*(7), 1491-1496.

Sedghi Asl, M., Amiri Tokaldany, E., & Chapokpour, J. (2013). Estimation of friction coefficient in sediment contained flow through rockfill. *International Journal of Engineering*, *26*(2), 187-196.

Stephenson, D. (1979). *Rockfill in hydraulic engineering*. Elsevier.

Todd, D. K., & Mays, L. W. (2004). *Groundwater hydrology*. John Wiley & Sons.

Wilkins, J. (1955). Flow of water through rock fill and its application to the design of dams. *New Zealand Engineering*, *10*(11), 382-387.

Wu, F.-C., & Huang, H.-T. (2000). Hydraulic resistance induced by deposition of sediment in porous medium. *Journal of Hydraulic Engineering*, *126*(7), 547-551.

Zeng, Z., & Grigg, R. (2006). A criterion for non-Darcy flow in porous media. *Transport in Porous Media*, *63*(1), 57-69.