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Determination of Flow Parameters in Layered Rockfill Media Using Tracer Technique

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Abstract

The present paper aims to develop improved models for predicting flow behavior, accounting for factors such as layer properties, grain size distributions, and transition zones between layers. Mathematical equations, including the Forchheimer equation and modified Darcy-Weisbach friction factor, are derived for characterizing non-Darcy flow in layered porous media. Empirical investigations employed using a laboratory flume with four layers of rockfill material arranged from coarse to fine, with particle diameters of 3.1, 1.8, 1.1, and 0.8 cm. Tracer injection techniques were used to study pore flow velocities, with electrical conductivity sensors capturing breakthrough curves. The effects of varying tracer mass and discharge rates on peak arrival times and flow profiles were analyzed. Key findings include the oscillatory behavior of flow depth, hydraulic gradient, head loss, and friction factor profiles at layer interfaces, particularly at higher discharge rates. These discontinuities highlight the influence of layer transitions and heterogeneities on flow dynamics. Additionally, higher discharge rates resulted in faster tracer transport, indicating less dispersion at higher velocities. The experimental data revealed linear relationships between hydraulic gradients and intrinsic velocities, with decreasing slopes for smaller particle sizes, reflecting reduced hydraulic conductivity. The study provides insights into modeling techniques that incorporate layer properties, grain size variations, and transition zones.

Keywords: Equivalent Hydraulic Conductivity, Flow Parameters, Layered Rockfill Media, Tracer Technique.

1. Introduction

Reducing the peak flow and improving downstream slope stability can be achieved by using rockfill embankments. They can be employed to design rockfill dams, where floods are controlled at their outlet. The construction’s most significant concern is the stability of the structure as it happens. However, there are still very high flows that may move in case of floods. For instance, there are different rockfill structures which include plain rock dumping, timber cribs, and gabions. There is always need to provide for an overflow structure while stepped overflow geometry helps in energy dissipation (Chabokpour and Amiri Tokaldany, 2017). In many civil engineering projects, layered rockfill structures are used to build embankments, dams, and other water-retaining or water-diverting structures. These structures consist of distinct layers of rock, gravel, or other materials of varying particle sizes and permeability. Typically, coarser materials are placed at the core of the structure, while finer materials are used as a protective cover on the surface (Chabokpour et al., 2020). Engineers and environmental scientists are frequently confronted with flow through porous media. Certainly, traditional theories, such as Darcy’s Law, offer valuable frameworks for grasping and anticipating fluid circulation in permeable mediums in some circumstances.

Nevertheless, deviations are commonly observed when actual situations adhere to Darcy’s theorem since they involve inertial effects, turbulence and intricate pore systems. The use of mathematical models for non-Darcy flow is necessary in order to correctly characterize and forecast fluid behavior in such situations. Models of Non-Darcy flows review, their applications and underlying principles (Gudarzi et al., 2020; Hansen et al., 2005; Salahi et al., 2015). There is also a case of fluid flowing through medial types like rockfill materials as it happens with other engineering and environmental occurrences. That comprises of groundwater flow, dam construction and geotechnical engineering.

This is critical for understanding and modelling the behavior of flows in such media. Usually in the occurrence of the flow in the form of Darcys Law in the rockfill media is deviated. Non-Darcy flow is everything else that lies beyond the Darcy flow regime (Chabokpour et al., 2020). For modeling Darcy’s behavior in porous media several mathematical models are developed. Such a model includes the Forchheimer equation to extend Darcy’s law with additional cubic terms that capture inertial effects and turbulence. Another commonly used model for non-Darcy flow, especially for engineering purposes, is the Ergun equation (Stephenson, 1979). It was initially intended for flow through porous bed of solids and can be modified for use in porous media (Sedghi-Asl and Ansari, 2016).

Al-Obaydi et al. (2019) presents a 3D finite element formulation for simulating flow around underground excavations in rock media. Sedghi-Asl and Rahimi (2011) proposed a new relation for flow in porous rockfill media by combining Manning's formula with Darcy-Weisbach's friction loss concept. Li et al. (1998) presented theoretical relationships between friction coefficient and Reynolds number, as well as hydraulic gradient and bulk seepage velocity in rockfill material. Herrera and Felton, (1991) focused on the hydraulics of flow through rockfill sections using sediment-free water, developing equations to relate design parameters to unknown values. McCorquodale et al. (1978) investigated the hydraulic conductivity of rockfill structures. Through permeameter tests with crushed dolomite and gravel, they identified particle size, shape, packing density, fines content, and saturation degree as key factors influencing rockfill's hydraulic conductivity. This study offers valuable insights for engineers working with hydraulic structures.

Li et al. (1998) has arranged an investigation that describes a synthesis of various studies on non-Darcy flow in rockfill material. The study presents theoretical relationships between friction coefficient and Reynolds number, and hydraulic gradient and bulk seepage velocity. Their study emphasizes the importance of using a reliable non-Darcy relationship in engineering design of flow-through and overflow rockfill structures, as the flow within a rockfill dam is usually turbulent and the seepage forces on the rock particles are quite different from those acting in materials where Darcy's law applies. Curtis and Lawson, (1967) presented a method for determining head discharge relations and pressure and flow distributions within rockfill banks, aiding in the overtopping of partially completed dams and reducing diversion costs during construction.

Zhou et al. (2013) reported on fluid flow through porous sandstone with overprinting and intersecting geological structures of various types. Their study found that the effect of deformation bands on permeability in the fault damage zone depends on band clustering, orientation, and the distribution of permeability anomalies. A numerical model was used to investigate the fluid-flow properties of different structure configurations, including compaction bands, shear bands, joints, and faults. They observed that the flow effects of a vertical compaction band set plus an inclined compaction band set could be significantly different from those of two vertical compaction band sets.

Hosseini and Joy (2007) presented an unsteady model to describe the development of a one-dimensional numerical model called ROCKFLOW that analyzes unsteady non-linear flow through coarse porous media. The model is particularly applicable to flow through valley fills and rock drains resulting from mining operations and takes factors such as the spatial variability of material properties and the variability of the cross-sectional geometry into account. The modified Saint-Venant equations together with the Forchheimer equation constitute the mathematical formulation of the flow system. The model employs a four-point finite difference method and a Newton-Raphson scheme to solve the resulting non-linear equations.

Spurin et al. (2023) presented an investigation which describes an open-source image processing workflow written in Python using the sci-kit toolbox for segmenting multiple fluids and rock grains in porous media. The workflow is demonstrated on a Bentheimer sandstone and can be adapted to many applications. The investigation also discusses the need for accurate, consistent, and fast image processing in investigating multiphase flow through porous media and the challenges of segmentation. The article has not yet undergone peer review.

Almalki et al. (2010) analyzed steady flow of an incompressible viscous fluid through a porous channel composed of two layers with different permeability, porosities and thicknesses. Analytical expressions for velocity distribution in each layer are derived, incorporating interface matching conditions and no-slip walls. An expression for the interface velocity is obtained, dependent on Darcy numbers, porosities, viscosities and layer thicknesses. A four-step procedure to determine all parameters and the interface velocity is outlined. The properties of rockfill materials, such as grain size distribution, angularity, and compaction characteristics, significantly influence the flow behavior through layered rockfill. Various studies have investigated the impact of these properties on hydraulic conductivity and seepage flow patterns within rockfill layers (Zhang et al., 2013). Hasanavnd and Samani, (2019, 2021) developed a 2D computer model to investigate flow through two types of layered rockfill dams - horizontal and vertical. Experiments showed that in horizontal dams, having a finer lower layer reduced discharge, while in vertical dams, discharge was more sensitive to grain size of upstream/downstream layers. Sensitivity analysis quantified how grain size changes impacted discharge for each layer arrangement. Dou et al. (2021) investigated the influence of a grain size transition zone on fluid flow and solute transport in layered porous media. It highlights that the transition zone significantly affects solute concentration distribution and plume spreading. Different numerical models were used to fit simulation results, with the Mobile-Immobile Model showing better performance in capturing the transition zone's impact on solute transport. The study emphasizes the importance of considering transition zones in modeling solute transport through heterogeneous porous media. The research was supported by funding from Chinese research programs, and the authors declare no conflicts of interest. Heydari and Khodakaramian (2022) examined modifying the one-dimensional discharge-stage relationship for non-core rockfill dams through laboratory experiments using different rockfill sizes and dam cross-sections. Multivariate nonlinear regression was applied to fit modified one-dimensional equations to the experimental data. The results showed the modified two-dimensional equation provided high accuracy in estimating discharge compared to traditional one-dimensional equations. Developing simple yet accurate discharge rating curves is important for efficient operation and management of rockfill dams.

Unglehrt and Manhart (2023) studied a model for the volume-averaged dissipation rate in linear unsteady flow through porous media. The model blends asymptotic expressions from boundary layer theory and Darcy's law into a second-order Volterra functional of volume-averaged acceleration. Validation is done using analytical solutions and numerical simulations for transient and oscillatory flows in different porous geometries.

The literature review discusses the importance of rockfill dams and embankments in controlling flood flows and improving slope stability. It highlights the need to understand fluid flow through the porous, layered rockfill materials used in these structures. Previous research has investigated factors like grain size distribution, shape, compaction, and layering on hydraulic conductivity and seepage patterns in rockfill. Based on the introduction, the objectives of the current study appear to further investigate and model fluid flow behavior through layered rockfill materials, accounting for factors like layer properties (permeability, porosity, thickness) and grain size transitions, To develop improved analytical or numerical models that can more accurately predict discharge, velocity distributions, and other flow parameters in layered rockfill structures like dams and embankments, and to quantify the effects of varying layer configurations and grain size distributions on the flow characteristics through rockfill.

2. Materials and Methods

2.1. Mathematical relationships

Mathematical models for non-Darcy flow play a pivotal role in describing and predicting fluid behavior in porous media, where deviations from Darcy's law are prevalent. The Forchheimer equation, Ergun equation, and modified Forchheimer equations are valuable tools in various engineering and environmental applications. Accurate modeling of non-Darcy flow is essential for optimizing processes, managing resources, and protecting the environment. Further research and development of more versatile and accurate models will continue to enhance our understanding and prediction of non-Darcy flow in porous media.

2.2. Experimental apparatus

Understanding the flow characteristics of rockfill media is crucial in various engineering and environmental applications such as dam construction, geotechnical engineering, and groundwater reclamation. One technique used to investigate the velocity of the pore flow of these porous materials is the use of tracer injection. This technique is usually used to inject tracers, usually chemicals, into porous materials and monitor their movements. It allows researchers to visualize and quantify the movement of fluids through interconnected pores. The movements of the tracers in the rock filling medium indicate the velocity of the pore flow and are important parameters for assessing the material's hydraulic behavior. One of the key factors that affects the accuracy and reliability of measuring pore flow rate is the concentration of the injection tracer. Tracer concentration refers to the quantity or density of the substance in the injection solution. The concentration of the tracer is a basic parameter that can have a significant impact on the results of the experiment. This can make it difficult to accurately track the movement of the tracer and then calculate the velocity of the pores. The experimental data series of this study were extracted from an experimental box flow with a length, width and height (1.8, 0.2, 0.7) m, respectively. Layered rock materials, having mean diameters of the 3.1, 1.8, 1.1 and 0.8 cm also including the porosities of the (47, 44, 42 and 41) %, were placed inside the flume from coarse to fine respectively. A series of electrical conductivity sensors have been installed to capture the experimental concentration time profile, called the breakthrough curve (BTC). The thickness of each layer is 34.38 cm, and the EC sensor is located at 0.02, 17.18, 34.37, 51.56, 68.75, 86, 103.1 and 120.3 cm from the media entrance. After collecting EC data using a data logger and software system designed, the calibration relationship of the sensor presented by the manufacturer of the device is used to extract the experimental curve of the BTC. The EC sensor is calibrated by covering the special perimeter of the body and tested by a precise digital device from Genway in a chemistry laboratory. The maximum errors observed in the current study's EC sensor systems were reported at about 5%. Sodium chloride solution were selected as mass conservative tracer in the experiments and the tracer was injected suddenly at the upstream of rockfill media. Experimental variables are presented in Table 1. The schematic diagram of the flume and the location of the positioning of the EC sensors is presented in the Fig. 1. In addition, a real photo of the experimental apparatus is depicted in Fig. 2.

Table 1. Experimental variables of the study

Rockfill materials (cm)	Entrance discharges (l/s)	Tracer solution mass (gr)	Material porosities (%)
0.8, 1.1, 1.8, and 3.1	0.197, 0.26, 0.367	8, 15, 30, 60, and 100	41, 42, 44, and 47

2.3. Analytical solution for phreatic line based on Forchheimer equation (Basake's equation)

By operating Forchheimer equation for hydraulic gradient (Eq. 1), Eq. 2 can be written by more simplification.

$$i = aV + bV^2 \quad (1)$$

$$i = a\left(\frac{q}{y}\right) + b\left(\frac{q}{y}\right)^2 \quad (2)$$

where i is hydraulic gradient, V is bulk velocity, q is discharge per unit width of channel, y is flow depth, and a and b are coefficients. Under the Dupuit assumption, and for a rectangular channel, it can be rewritten as Eq. 3.

$$\frac{dy}{dx} = a\left(\frac{q}{y}\right) + b\left(\frac{q}{y}\right)^2 \quad (3)$$

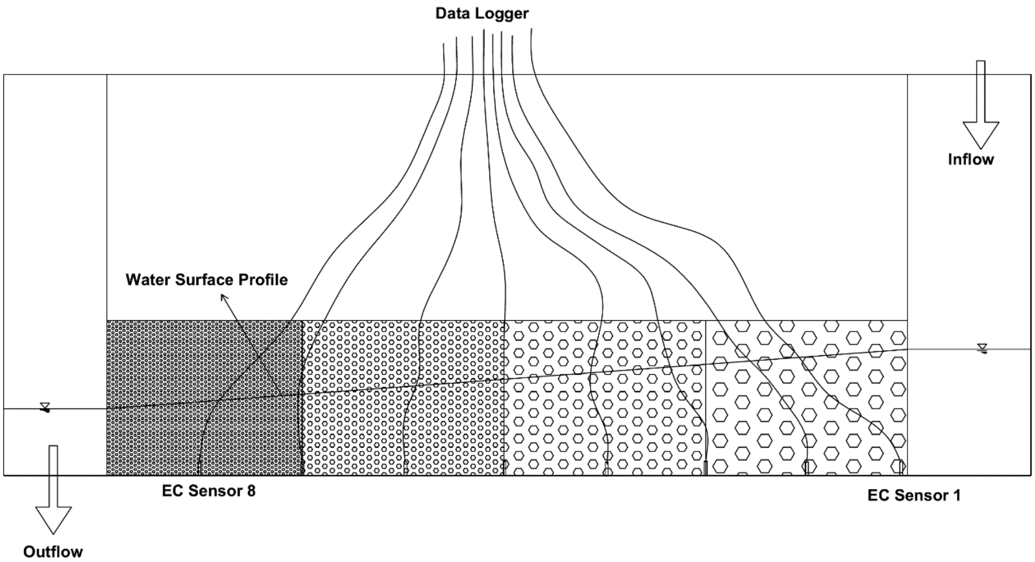
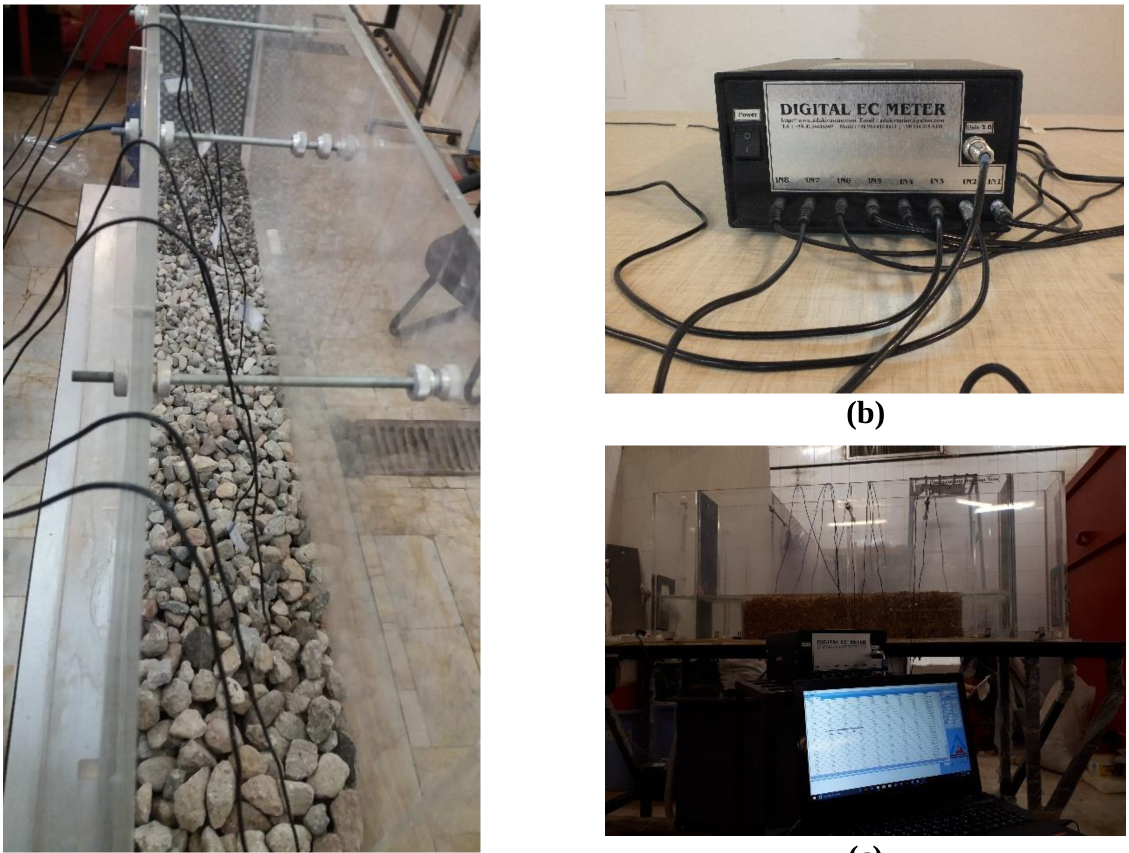


Fig. 1. Schematic layout of the layered material and the locations of the sensors



(a) (b) (c)

Fig. 2. A real photo from different parts of the experimental apparatus

By more simplification, Eq. 4 can be achieved.

$$\frac{dy}{dx} = \frac{aqy^2 + bqy}{y^3} \quad (4)$$

By separating variables for integration of Eq. 4:

$$dx = \frac{y^3}{aqy^2 + bqy}dy \quad (5)$$

By integration and simplification of Eq. 5, Eq. 6 can be concluded.

$$x = \frac{y^2}{2aq} - \frac{by}{qa^2} + \frac{b^2 \ln(ay+b)}{a^3 q} + C \quad (6)$$

For estimation of C value, it is needed to use boundary condition. Exit depth from rockfill media can be operated as boundary condition. Such that for exit depth of y_c, longitudinal distance is equal to zero (x=0). Therefore, by more algebraic operations Eq. 7 can be achieved.

$$x = \frac{y^2}{2aq} - \frac{\left((ay_c - 2b)a - a^2 y_c\right)y}{2a^3 q} + \frac{-2b^2 \ln(ay_c + b) + 2b^2 \ln(ay+b)}{2a^3 q} - \frac{(ay_c - 2b)ay_c}{2a^3 q} \quad (7)$$

where x is distance of upstream of y_c (positive direction).

Deriving an equation for hydraulic conductivity in layered rockfill media for non-Darcy flow involves considering the flow through porous media that does not follow Darcy's law. The non-Darcy flow occurs when the flow velocity is high, and inertial forces become significant. For computation of equivalent hydraulic conductivity of vertical rockfill layers, bellow mathematical methods can be done. Firstly, using Wilkins hydraulic gradient formula, Eq. 8 can be written.

$$i = \frac{V_v^2}{k^2 ged} \quad (8)$$

where V_v is void flow velocity, k is empirical coefficient, g is gravitational acceleration, d is media diameter, $e = \frac{n}{1-n}$ void ratio, and n is porosity. According to findings of Wilkins, hydraulic conductivity is equal to $K = \sqrt{k^2 ged}$.

Because the arrangement of layers in the rockfill media experiments of current study is vertical, therefore, sum of head loss in each layer should be equal to the equivalent layer. It is clear that $= \frac{h_f}{L}$, h_f is head loss of layer, and L is layer length. Consequently, for layered system Eqs. 9 and 10 can be written.

$$h_f = \sum_{j=1}^{j=m} h_{fj} \quad (9)$$

$$\frac{V_v^2 L}{{k_{eq}}^2 g e_{eq} d_{eq}} = \sum_{j=1}^{j=m} \frac{V_v^2 L_j}{{k_j}^2 g e_j d_j} \quad (10)$$

By replacing $V_v = \frac{V}{n}$ in Eq. 10:

$$K = \sqrt{\frac{L}{n_{eq}^2 \sum_{j=1}^{j=m} \frac{L_j}{K_j n_j^2}}} \quad (11)$$

$$n_{eq} = \frac{\sum_{j=1}^{j=m} n_j}{m} \quad (12)$$

where, equivalent porosity (n_{eq}) can be calculated by arithmetic mean formula (Eq. 12).

Additionally, for extracting a new relationship for Darcy-Weisbach friction factor, basic Eq. 9 can be used. Such that by using Darcy-Weisbach equation, Eq. 13 can be achieved.

$$h_f = \sum_{j=1}^{j=m} h_{fj} \xrightarrow{replacing} \frac{f_{eq} L V^2}{2g d_{eq} n_{eq}^2} = \sum_{j=1}^{j=m} \frac{f_j L_j V^2}{2g d_j n_j^2} \quad (13)$$

where f_{eq} is equivalent friction factor, L is total length of porous media, d_{eq} is average diameter of porous media layers, n_{eq} is the average value of layers porosity, f_j is the friction factor for layer j, L_j is the length of layer j, n_j is the porosity of layer j, d_j is the average value if rock material diameter for layer j, and g is the acceleration of gravity. By more simplification, Eq. 14 for equivalent Darcy Weisbach friction factor (f_{eq}) can be achieved.

$$f_{eq} = \frac{\sum_{j=1}^{j=m} \frac{f_j L_j}{d_j n_j^2}}{\frac{L}{d_{eq} n_{eq}^2}} \quad (14)$$

Also equivalent diameter (d_{eq}) can be calculated by arithmetic mean formula Eq. 15.

$$d_{eq} = \frac{\sum_{j=1}^{j=m} d_j}{m} \tag{15}$$

where m is number of layers.

3. Results and Discussion

The depth profile of the observed flow of M2 is characterized by the parabolic flow patterns of the rock filling material. It represents the specific distribution of flows in which the highest flow rate occurs near the center of the flow path, and as the flow path moves away from the center towards the boundary, the speed gradually decreases. This phenomenon is common in porous materials, including rock filling materials, caused by the interaction of liquids and flowing materials. The main cause of M2 profile formation is the interaction between liquid flow and porous rock filling medium. When liquid moves through media, it experiences different levels of friction resistance. This resistance is the lowest in the center of the flow channel, where the flow rate is the highest, and increases with the increase in interaction with solid particles and moves to the boundary. Furthermore, the pore structure of the rock filling materials plays an important role in the formation of the M2 profile. Interconnected pores create a path for liquid movement, and the distribution of these paths affects flow patterns. The central regions usually contain larger and more interconnected pores, which promote higher flow rates. In addition, hydraulic gradients, i.e. pressure differences that drive the flow, also affect the M2 profile. The higher water gradient may produce a more prominent M2 profile, as it exerts more force on the liquid and pushes it into the center of the flow channel. The flow in the rock filling material is not uniform, which means that different layers and regions of the medium experience different flows.

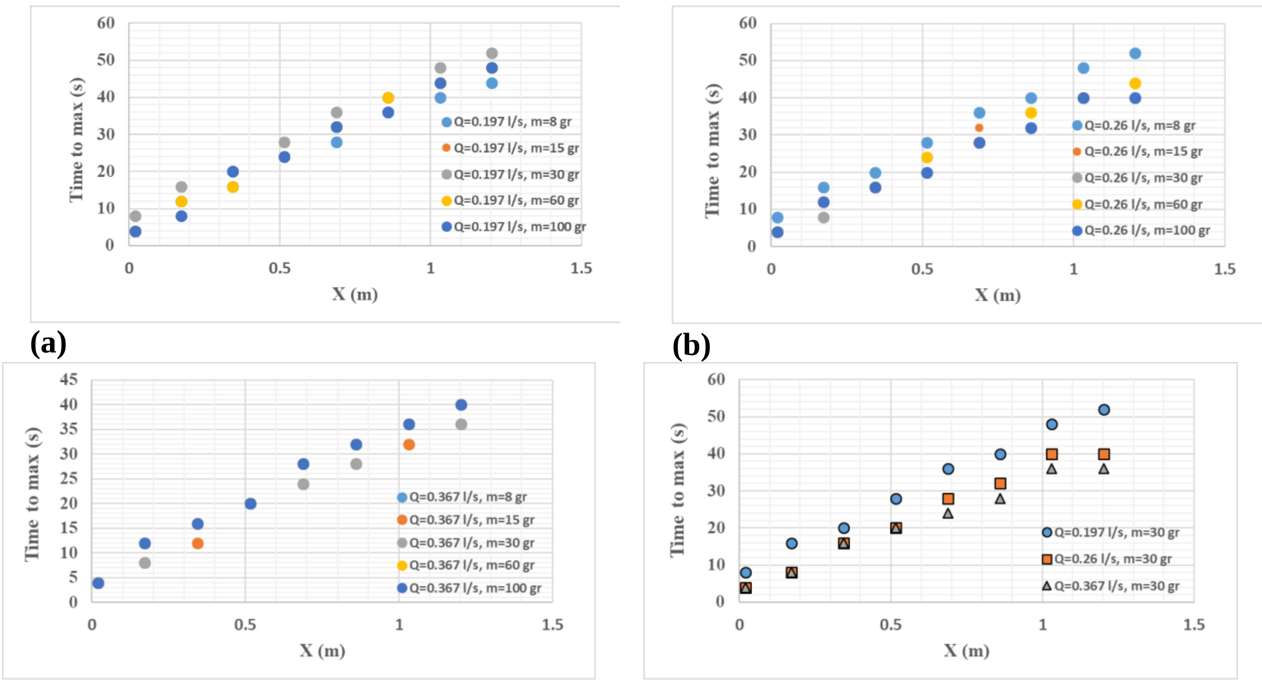


Fig. 3. Effect of variation of experimental parameters in flow maximum concentration parameter, a, b, and c) tracer mass variation during different flow discharges, d) flow discharge

Fig. 3 consists of four graphs analyzing the effects of experimental parameters on the time required to reach the maximum concentration (or peak delivery time) of a tracer through a four-layer rock-fill porous medium arranged from coarse to fine grains. Three different discharge rates (0.197 l/s, 0.26 l/s, 0.367 l/s) and five different trace mass (80, 15, 30, 60, 100) gr are considered. Fig. 3 (a) shows the peak arrival time of different tracer masses with a discharge rate of 0.197 l/s. It is clear that the increase in the tracer mass also increases the time required to reach the maximum concentration. This trend is consistent across all discharge rates, as shown in Fig. 3 (b) and Fig. 3 (c). Figure 3 (d) directly compares the maximum arrival times for three discharge rates using 30 gr tracer mass. It is clear that higher discharge rates lead to shorter peak arrival times, which indicates faster tracer transport through porous media with higher flow rates. In addition, oscillations or fluctuations in the peak arrival time profiles of each graph indicate the influence of layer interfaces and the different hydraulic properties between layers on tracer transport dynamics. It was found that increasing the mass of the tracer leads to longer peak arrival times, possibly due to increased dispersion and retardation effects in porous media. Higher discharge rates result in shorter peak arrival times, implying faster tracer transport and less dispersion at higher flow velocities. Also, the oscillations or discontinuities in the peak arrival time profiles at layer interfaces highlight the impact of layer transitions and heterogeneities on the tracer transport behavior. Moreover, the magnitude of oscillations appears to be more significant at higher discharge rates, suggesting that the influence of layer contrasts becomes more pronounced when inertial forces are stronger.

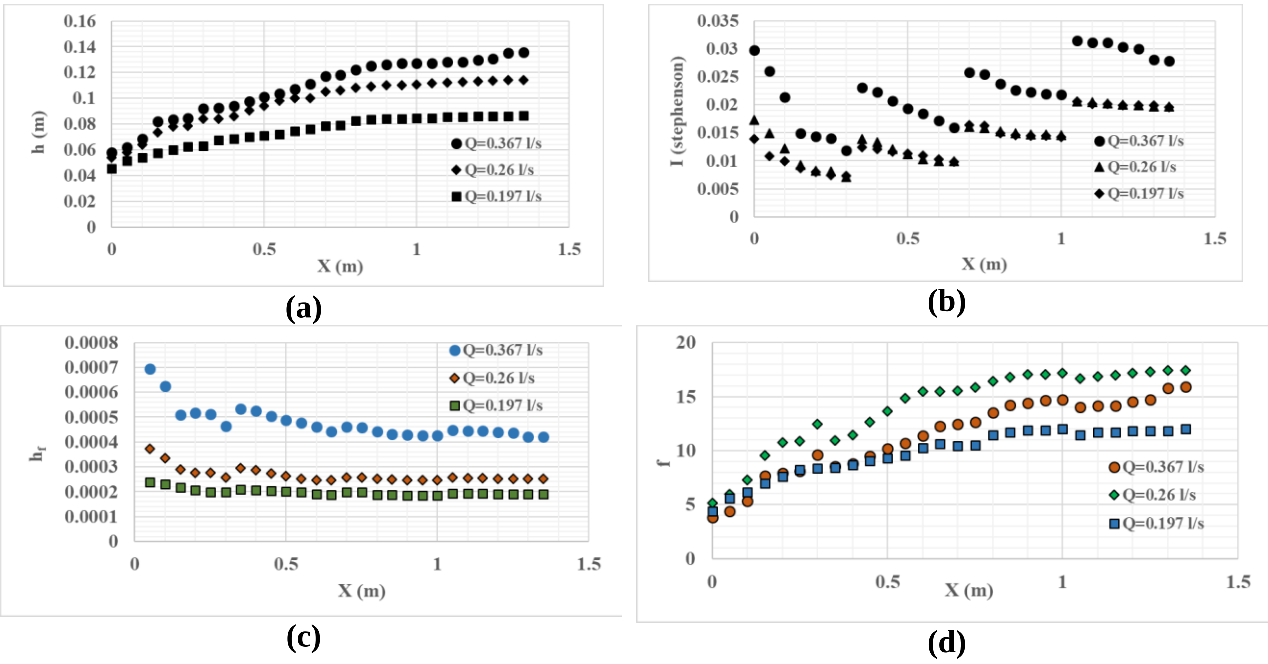


Fig. 4. a: Experimental water surface profile along layered rockfill material by discharge variation, b: Stephenson hydraulic gradient parameter along layered rockfill material by discharge variation, c: head loss along layered rockfill material by discharge variation, d: Darcy Weisbach friction factor parameter along layered rockfill material by discharge variation.

A remarkable observation in Fig .4 (a) is the oscillation or discontinuity of the flow depth profile at the interface of the layers, which indicates changes in hydraulic properties between layers. These oscillations are more pronounced at higher discharge rates, suggesting that layer transitions increase the influence on flow behavior when the inertial forces are greater. At the highest discharge rate, 0.367 l/s (black circle), the flow depth exhibits a significant jump or drop as it moves between layers, resulting in changes in the flow configuration and energy diffusion mechanism. Although these depth variations are less significant, the discharge rate is lower at 0.26 l/s (diamond) and 0.197 l/s (square). The layers of the rockfill medium introduce heterogeneity that affects flow dynamics, resulting in deviations from a smooth and gradually varied flow profile. The oscillations in the flow depth of layer interfaces highlight the importance of considering transition zones and differences in the characteristics between layers when modeling and analyzing flows in such heterogeneous porous media. Also, a notable observation in Fig .4 (b) is the abrupt changes or oscillations in the hydraulic gradient profiles at the layer interfaces, indicating contrasting hydraulic properties between adjacent layers. These oscillations are more pronounced at higher discharge rates, suggesting a stronger influence of layer transitions on the hydraulic behavior when inertial forces are more significant. At the highest discharge rate of 0.367 l/s (black circles), the hydraulic gradient exhibits distinct jumps or drops as it transitions between layers, implying changes in the flow regime and energy dissipation mechanisms. These variations in hydraulic gradient are less prominent but still noticeable at the lower discharge rates of 0.26 l/s (triangles) and 0.197 l/s (diamonds). Furthermore, the magnitude of the hydraulic gradient generally increases with increasing discharge rate, indicating a higher energy loss per unit length at higher flow rates, likely due to increased turbulence and inertial effects within the porous medium.

Head loss is the reduction of the total hydraulic head when flowing through layers of rock filling materials. Head losses are mainly caused by resistance to water flows in the rock foundation layer, which plays a decisive role in evaluating the performance and efficiency of hydraulic structures. Head loss can be divided into two major parts. First, large losses, which are energy losses caused by friction and resistance as water flows through the layers of rock filling. It depends on factors such as friction coefficients, flow rates, and layer properties. Small head losses occur at points along the flow path, such as layer transitions, direction changes or obstacles. These local losses contribute to the overall loss of heads. As mentioned above, each rock layer's friction coefficient plays an important role in determining the degree of head loss. Higher friction coefficients lead to more head loss. The speed of the flow through the layers is another important factor. Due to increased friction resistance, high flow rates increase head losses. The characteristics of each layer, including particle size, compaction, and permeability, affect head loss. The rougher and compacter layers will have a lower head loss than the finer and less permeable layers. The calculation of the head loss in the layer of rock construction includes evaluating the main components and the minor components. In general, the loss of the flow head is highest at the interface between different permeability layers. This is because the liquids have to move from one system of flow to another, which causes turbulence and increases friction. If the rock fill layer is arranged so that liquid flows first through the most permeable layer, the overall loss of head will be lower. Moreover, a notable finding in Fig .4 (c) is the stepped or discontinuous nature of the head loss profiles, particularly at higher discharge rates. These discontinuities or abrupt changes in head loss occur at the interfaces between layers, suggesting variations in hydraulic properties and flow behavior across the layer transitions. At the highest discharge rate of 0.367 l/s (blue circles), the head loss profile exhibits distinct steps or jumps as it transitions between layers, indicating changes in the flow regime and energy dissipation mechanisms. These abrupt changes in head loss are less pronounced but still noticeable at the lower discharge rates of 0.26 l/s (red diamonds) and 0.197 l/s (green squares). Moreover, the overall magnitude of head loss increases with increasing discharge rate, indicating higher energy dissipation at higher flow rates, likely due to increased turbulence and inertial effects within the porous medium.

The friction coefficients often represented by the Darcy–Weisbach friction factor play a crucial role in determining flow resistance and flow speed distribution in porous materials such as rocks. The f friction coefficient is the ratio of the loss of the friction head to the head of movement in liquids passing through a porous medium. It quantifies the flow resistance caused by friction between liquids and porous materials. Different permeability layers have different flow resistances. The thickness of a large diameter layer is smaller because the pores are larger, and the thickness of a fine layer is larger. The thickness of the layers varies and affects the friction coefficient. Thin layers tend to have higher friction coefficients as the flow extends further through the media. The variation of the friction coefficient can occur in the layers of rock filling materials, both vertically and horizontally. Because each layer has different properties, the flow direction can be influenced by horizontal and vertical gradients. Variations in friction coefficients directly affect the flow behavior and speed distribution of layered rock filling materials. The areas with high friction coefficients exhibit greater flow resistance and lower flow rate. On the contrary, regions with low friction coefficients enable greater flow and velocities. Variations in the friction coefficient contribute to uniform flow patterns in the rockfill structure. The flow can be preferred by seeking the least resistance path and causing an uneven flow distribution. The oscillations of friction factor profiles at the interface between layers also suggest changes in the flow resistance and energy dissipation mechanisms during the layer transition. These vibrations are more pronounced with higher discharge speeds, indicating that when the inertial force becomes more powerful, the layer contrast has a stronger influence on the flow behavior. In addition, the total magnitude of the friction factor decreases generally along the flow path, indicating a reduction in flow resistance as the flow moves through the porous medium. This behavior may be due to changes in the geometry of the pores, particle arrangements, or flow patterns along the rock filling medium length, as shown in Fig. 4 (d).

Each layer of rockfill structure has different permeability properties due to changes in particle size, compression and thickness. When water flows over the surface, it tends to enter layers and the permeable gradient causes different flows through these layers. In rock formations layers, hydraulic conductivity may vary depending on the properties of the layers. The vertical variation of hydraulic conductivity is influenced by the symmetry of the layer and the presence of the transition zone. For example, when water moves from the fine layer to the coarse layer, the flow slows down and extends to the surface. The surface of the rock filling structure is not completely smooth, and the presence of rocks and unevenness affects the flow profile. The surface profile of the flow can be influenced by the roughness of the surface, with water following the least resistance paths. Transition areas occur between different layers of permeability and can lead to vertical leakage paths. These regions may have high or low hydraulic conductivity depending on the characteristics of adjacent layers. The change in hydraulic conductivity of the rock coating material can have a significant impact on drainage and flow patterns. Water usually follows the least resistant route and flows more easily through layers with high water conductivity. This leads to preferred flow paths within the structure. The gradient of the rock filling structure also affects the flow surface profile. Steering slopes can accelerate the flow and change the flow and depth of the surface. The shape of the flow profile depends on several factors such as layer structure, hydraulic gradient, and flow conditions.

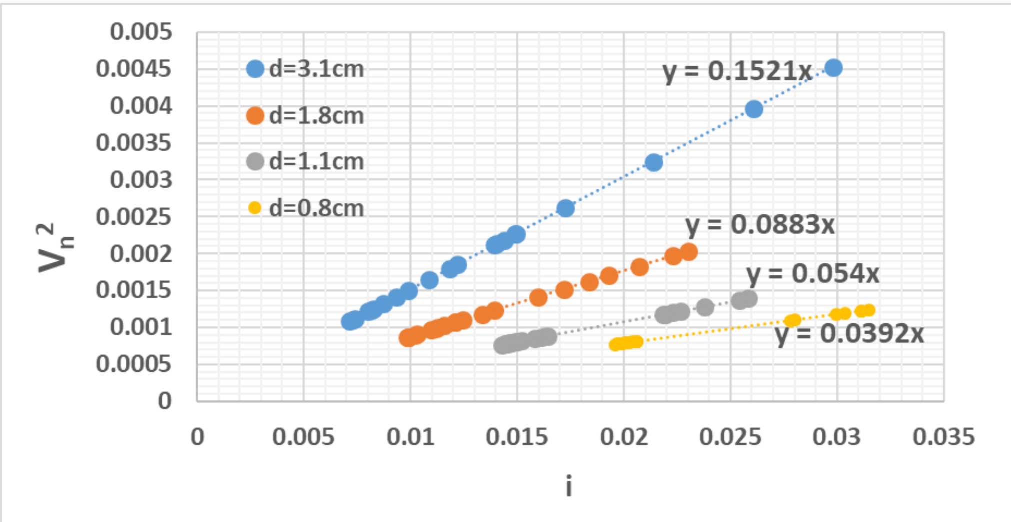


Fig. 5. Variation of (V_n^2) versus hydraulic gradient for four rockfill layers with different diameters

Fig. 5 presents experimental data that show the relationship between the hydraulic gradient on the x-axis and the square intrinsic velocity (V_n^2) on the y-axis to flow in a multi-layer, rough porous medium. The four different layers consisted of sphere particles d = 3.1 cm, 1.8 cm, 1.1 cm and 0.8 cm diameter and were determined by decreasing the size of the particles. Data points for each layer follow a linear trend, and the corresponding slope of the trend line represents the hydraulic conductivity of the layer. With particle size reduction, the hydraulic conductivity of the porous medium layer decreases, leading to lower slope. The trend lines at d = 1.8 cm (orange, y = 0.083x), d = 1.1 cm (gray, y = 0.054x), d = 0.8 cm (y = 0.0392x) show a decreasing hydraulic conductivity. The observed trend corresponds to the expected behavior of the porous media flow, where the smaller particle size increases the tortuosity and reduces the connectivity of the pores, thereby obstructing the flow of liquids and reducing hydraulic conductivity.

The friction factor is influenced by both inertial and viscous forces in the Ergun relationship for non-Darcy flow in granular media. It incorporates non-Darcy effects into the original Ergun equation (Ergun and Orning, 1949) for laminar flow. Equation 16 represents the modified Ergun equation for non-Darcy flow.

$$f = \left(150 \times (1 - \varepsilon)^2 \times {d_m}^2\right) \times (\varepsilon^3 \times V^2) / (\rho\ g\ L) + (a / Re^n) \qquad (16)$$

where: f is the Darcy-Weisbach friction factor, ε is the porosity of the granular media, d_m is the mean particle size of the granular media, V is the superficial velocity (velocity based on the entire cross-sectional area), ρ is the fluid density, g is the acceleration due to gravity (9.81 m/s²), L is the length of the granular media bed, a and n are empirical constants related to the non-Darcy behavior.

The head loss (h_f) for non-Darcy flow in a granular media bed can be calculated using Eq. 17.

$$h_f = (f \times L) \times (\rho \times V\text{^}2) / (2\ g\ d_h) \qquad (17)$$

where: $h_f$is the head loss (m), d_h is the hydraulic diameter of the granular media bed

Another empirical method that takes into account the impact of both viscous and inertial forces on the friction factor is the Stephenson relationship (Stephenson, 1979) for non-Darcy flow in granular media. It connects the Reynolds number, Forchheimer number, and a dimensionless parameter (Kt) that describes the granular media to the friction factor. Eq.18 is one way to express the Stephenson equation.

$$f = (8 \times \gamma^2) / (Re) + (Kt / Re^n) \qquad (18)$$

where: f is the Darcy-Weisbach friction factor, γ is the non-Darcy parameter, related to the Forchheimer number (Fo), Re is the Reynolds number, Kt and n are empirical constants related to the granular media. The head loss (h_f) for non-Darcy flow in a granular media bed can be calculated using the same equation as in the Ergun relationship.

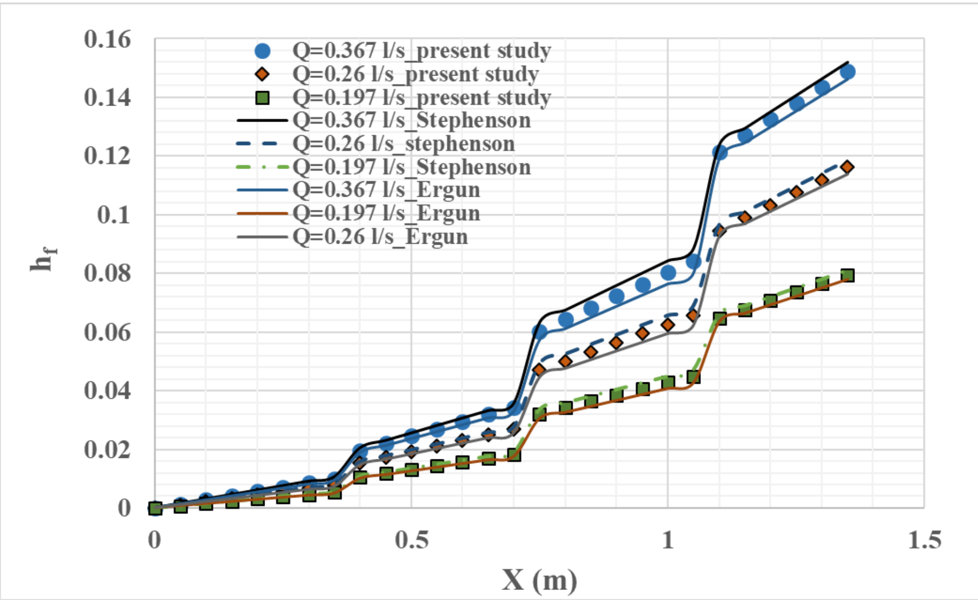


Fig. 6. Comparison of head loss (h_f) versus rockfill distance using three different methods (present study (Eq.13), Stephenson method, and Ergun method

Fig. 6 presents a comparative analysis of head loss (h_f) calculations using three different methods: the present study's approach, Stephenson's method, and Ergun's equation. The analysis is conducted for three flow rates: 0.367, 0.26, and 0.197 L/s. The results demonstrate a strong correlation between all three methods across the entire length of the rockfill medium (X ranging from 0 to 1.5 m). Notably, the head loss profiles exhibit distinct step-like patterns, corresponding to the transitions between the four layers. This indicates that each layer contributes differently to the overall head loss, likely due to variations in porosity or particle size distribution. The magnitude of head loss increases with flow rate, as expected in porous media flow. The close agreement between the present study's results and established methods validates its accuracy and applicability. Furthermore, the non-linear relationship between head loss and distance, particularly evident at higher flow rates, suggests the presence of non-Darcy flow regimes within the coarse-grained medium. This comprehensive comparison not only corroborates the reliability of the proposed method but also provides valuable insights into the complex hydraulic behavior of vertical flow through layered, coarse-grained porous media.

4. Conclusion

Non-Darcy flow behavior in rockfill media is a complex phenomenon influenced by factors such as porosity, particle size distribution, flow velocity, and fluid viscosity. Mathematical models like the Forchheimer equation provide a framework for describing non-Darcy behavior and incorporating it into flow simulations. The current study investigates fluid flow through layered rockfill media, relevant for hydraulic structures like dams and embankments. The M2 profile, characterized by parabolic flow patterns with highest velocities near the center, is observed in rockfill materials due to pore structure and hydraulic gradients. Experimental analysis using a four-layer rockfill media in the experimental flume with decreasing particle sizes (3.1 - 0.8 cm) and varying tracer mass and discharge rates revealed oscillatory behavior in flow depth, hydraulic gradient, head loss, and friction factor profiles at layer interfaces, particularly pronounced at higher discharge rates. Increasing tracer mass prolonged peak arrival times, attributed to dispersion and retardation effects, while higher discharge rates facilitated faster tracer transport due to reduced dispersion at elevated velocities. Layer transitions and heterogeneities significantly impacted tracer transport dynamics. Head losses exhibited abrupt changes across layers, indicating variations in hydraulic properties and flow regimes. Friction factors oscillated at interfaces, suggesting altered flow resistance and energy dissipation mechanisms during layer transitions, with greater influence at higher discharge rates. Vertical variations in hydraulic conductivity arose from layer symmetry and transition zones, while surface roughness affected flow profiles by creating preferential paths. Data revealed linear relationships between hydraulic gradients and squared intrinsic velocities, with decreasing slopes for smaller particles due to increased tortuosity and reduced pore connectivity, obstructing flow.

5. Disclosure statement

No potential conflict of interest was reported by the authors

6. References

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