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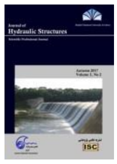

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An experimental study on hydraulic behavior of free-surface radial flow in coarse-grained porous media

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Abstract

In this paper, we have been used an experimental model to analyze the nonlinear free surface radial flows and to introduce an equation compliant with these flows. This is a semi cylindrical model including a type of coarse grained aggregate which leads the radial flow into the center of a well. Thereafter, the hydraulic gradient was measured on different points of the experimental model by three distinguished methods of difference of successive radii, keeping constant the minimum and maximum radii. An equation, describing the behavior of free surface radial flow, was then proposed by measured data (as regression data) from the laboratory and analysis of the results. Verification of the proposed equation by test data shows that the equation is valid on the established limits of the data.

Keywords: Hydraulic gradient, Hydraulic behavior, Forchheimer, Porous media, Radial flow.

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1. Introduction

The equations of fluids in porous media are very useful in engineering, especially, the rockfill dams, diversion dams, gabions, breakwaters, and ground water reserves (Bazargan and Zamanisabzi 2011). Flows in porous media are generally categorized into Darcy (linear) and non-Darcy (non-linear) ones. Several studies have been conducted in the field of flow in the porous media by researchers such as Ward)1964); Ahmed and Sunada (1969); Hansen et al.)1995), Li et al.)1998); Bazargan and Shoaei)2010) Bazargan and Zamznisabzi(2011); Wright(1958); Mc Corquodale)1970); Nasser(1970); Thiruvengadam and Kumar(1997); Reddy)2006); Reddy and Mohan)2006); Sadeghian et al.)2013). The Darcy equation, which is valid only in a limited interval of Reynolds numbers, provides a hydraulic description of Darcy

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flows (Mc Whorter and Sunada 1977). Turning a linear flow into a transitive and turbulent flow makes the Reynolds number violate its critical value, making the Darcy law null afterwards. Non-Darcy flow dominates these physical conditions (Das and Sobhan 2012; Hansen et al 1995; Bazargan and Bayat 2002; Wright, 1958). The analysis of the flow in porous media over the years, has been studied both analytically and empirically. Physicists, engineers, hydrologists have investigated the behavior of flow in porous media in the range of a variety of material in the laboratory and have also tried to formulate responses to the systems (Ahmed and Sunada 1969; Bazargan and Zamanisabzi 2011). Nonlinear flows in coarse-grained porous media may be classified into two categories. In the first category, i.e. parallel flow, the flow lines are relatively parallel and there is no curvature in the plan of flow lines. This type of flow is found in both pressurized (flows do not make contacts with the free surface) and free-surface (flows make contacts with the free surface) modes. The flows in the confined aquifers and earth dams are included in this category (Mc Corquodale 1970; Thiruvengadam and Kumar1997; Wright 1958). Venkataraman and Roma Mohan Rao (2000) and Reddy (2006) proposed the equations (1) and (2), respectively, as the governing equations of parallel flows.

$$I = a_c V + b_c V^2 \quad (1)$$

$$I = a_c V + b_c V \quad (2)$$

where *I* is the hydraulic gradient, *V is* the average velocity and a_c and b_c are constant values. In the second group of non-Darcy flow, the flow lines are contracted along the way and are known as radial (convergent) flows. These flows are, also, found under compressed or free-surface conditions. Flow through gravel filters used in water treatment plants is an example of pressurized converging flows (Sadeghian et al. 2013; Reddy 2006; Venkataraman and Roma Mohan Rao 2000). There can be seen a compression in the flow lines in radial, as opposed to parallel, flows. In the free surface radial flows, the compression of flow lines along the way, inflates the flow (Sadeghian, 2013). Sadeghian et al, 2013 provided the Equation (3) as their proposed model for description of radial flows:

$$i_{cf} = a_{cf} V_{ave} + b_{cf} V^2{}_{ave} \quad (3)$$

Where i_{cf} is the hydraulic gradient, V_{ave} is the average velocity, and a_{cf} and b_{cf} are constant coefficients. Ferdos and Dargahi 2016a addressed this issue through comprehensive numerical modelling. The novelty of the proposed approach lies in a combination of large-scale experiments and three-dimensional numerical simulations, leading to a fully calibrated and validated model that is applicable to flows through cobble-sized materials at high Reynolds numbers. Ferdos and Dargahi 2016b exerted a Lagrangian particle tracking model to estimate the lengths of the flow channels that developed in the porous media. Gamma distributions fitted to the normalized channel lengths, and the scale and shape parameters of the gamma distribution found to be Reynolds number dependent. Their proposed normalized length parameter can be used to evaluate permeability, energy dissipation, induced forces, and diffusion. They also found that shear forces exerted on the coarse particles depend on the inertial forces of the flow and can be estimated using the proposed equation for the developed turbulent flows in porous media. Sedghi-Asl et al. (2014) studied a fully developed turbulent regime considering as a specific case of non-Darcy flow, and developed an analytical approach to determine normal depth, water surface profile and seepage discharge of the flow through coarse porous medium in steady condition. Then the results of an experimental model compared with the analytical solution developed in their research. The results showed a good agreement between analytical and experimental data. The hydraulic behaviors of the parallel and radial flows are totally different.

Conspicuous among the differences, the flow's cross section in the parallel and radial flows are constant and variable, respectively. This is not a difference to be taken into account in the equations related to radial flows and the hydraulic behavior of the flow is still studied by modified linear relations inferred from Darcy equation. Due to the real world applications of radial flows, especially for pumping in oil and water wells in the course grained unconfined alluvial beds and also the necessity of modifying the computational methods provided as linear relations of adjusted from Darcy equation (Sadeghian et al. 2013) to be used in the investigation of nonlinear flows, it is necessary to develop equations that model the radial flows appropriately. In this paper, in order to describe the free surface radial flows in the coarse grained porous media, an experimental equation is provided by physical laboratory modeling that is used in especial cases of porous media.

2 Materials and methods

The cylindrical form was used in the present study due primarily to the adaptability and compliance of the cylinder coordinates with the physical conditions of radial flows problems. Semi cylindrical model allows the convergent (radial) flow towards the center of a well. The semi cylindrical physical model is of 6 and 3 meters in diameter and height, respectively. In 1 meter of the bottom is included a tank for required water supply during the experiments. The 2 meters above accommodates the porous media (aggregates) with a volume of about 28 m^3. Fig. 1 illustrates a schematic of the laboratory model. The aggregates used in the physical model are course-grained. The specifications of model have been provided in Table 1.

Figure 1. Schematic of the physical model used in the study

Table 1. Specification of the aggregates used in the physical model

Grains diameter (mm)	150-20
Grains shape	Rounded
Porosity (%)	43
Uniformity coefficient	2.13
Coefficient of curvature	1.016
Special weight (t/m^3)	1.68

According to Fig. 2, five metal meshes divide the semi cylinder to six equal sections. On every reticular section, 42 piezometers were installed in the apparatus to measure the piezometeric pressure of the flows.

A total of 210 piezometers show the pressure changes in the model. For a precise piezometeric pressure reading, a number of scaled dials were used with millimeter precision. Since the experiment was performed on various levels of the water surface, the model was filled up to the intended level for every experiment and the numbers on four meters (mechanical and digital) were read, showing the flow volume that crossed through the pumps (V_1). By looking at the water surface profile on the glass view of the physical model, piezometeric pressure was read on the piezometers panel. After a few minutes, the pumps and stopwatches were turned off simultaneously and the number on the four counters were noted again (V_2). The tank was filled up to a determined depth. The considered depths were 52, 70, 85, 95,110, 120, 140, 150, 160 cm. After every experiment, the data were noted for different depths and levels. Table 2 and 3 show a sample of the data for the depth of 85 cm.

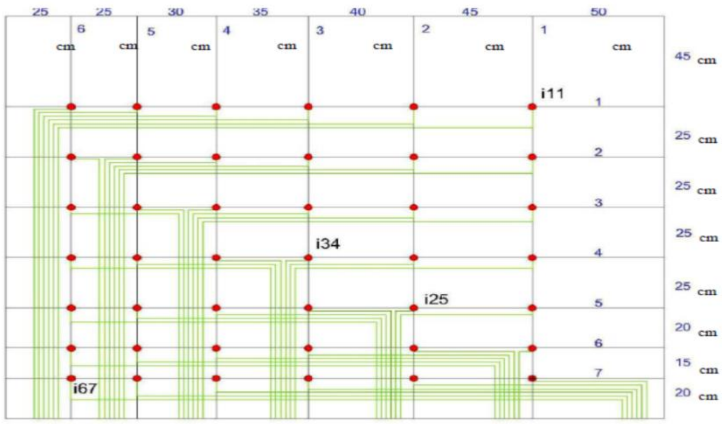

Figure 2. Position of piezometers on every section of the physical model

Table 2. Hydraulic specifications of the flow, measured for the depth of 85 cm

Radial (cm)	Section Number	Water Level (cm)	Flow Rate (cm/s)	Mean Flow Velocity (cm/s)
275	External Border	70.2	0.83	-
225	1	85.6	0.84	0.76
180	2	85.3	1.06	0.95
140	3	84.9	1.36	1.21
105	4	84.5	1.83	1.60
75	5	83.9	2.58	3.90
50	6	83.1	3.90	3.24
25	Internal Border	81.3	7.98	5.94

Table 3. Values of piezometeric pressure in different levels (z) for the depth of 85 cm

R*	z			
225	85.1	85.1	85.2	85.2
180	84.6	84.8	84.8	84.8
140	84.4	84.4	84.5	84.4
105	84	84.1	84.1	84.1
75	83.4	83.5	83.7	83.6
50	82.8	82.8	83	83

*R: Radial (cm); z: Water level (cm)

In the physical models of parallel flows, the cross section is constant. So, the hydraulic gradient is calculated for successive points, while the cross section in the radial flows is variable. Base on this, in this study, the hydraulic gradient was calculated by the three following methods; difference of successive radii (R_1-R_2), (Method I); keeping constant the minimum radius (R_1-R_{min}), (Method II), and keeping constant the maximum radius (R_1-R_{max}), (Method III). The hydraulic gradient sample values (i_{obs}) in the depth of 85 cm and level of 20 cm are shown in Tables 4, 5 to 6 for the three methods.

Table 4. i_{obs} values measured by the *Method I* in the depth of 85 cm and level of 20 cm

i_{obs} *	Δl	ΔH	H	R	r(cm)	v(m/s)
0.011	45	0.5	85.1	202.5	225	0.009
0.005	40	0.2	84.6	160	180	0.012
0.011	35	0.4	84.4	122.5	140	0.016
0.02	30	0.6	84	90	105	0.022
0.024	25	0.6	83.4	62.5	75	0.032

* The observed hydraulic gradient (i_{obs}) is obtained by the ratio of the difference between two successive points ($\Delta H = H_1 - H_2$) and the radial distance between them($\Delta l = R_1 - R_2$). Average radius was used in the calculations($R = (r_1 + r_2)/2$), H_1:The first point piezometeric pressure, H_2:The second point piezometeric pressure, R_1: The first average radius, R_2: The second average radius, H: Piezometeric pressure, R:radial, v: Velocity

Table 5. i_{obs} values measured by the *Method II* in the depth of 85 cm and level of 20 cm

i_{obs} *	Δl	ΔH	H	R	r(cm)	v(m/s)
0.013	175	2.3	85.1	137.5	225	0.023
0.013	130	1.8	84.6	115	180	0.024
0.017	90	1.6	84.4	95	140	0.026
0.021	55	1.2	84	77.5	105	0.028
0.024	25	0.6	83.4	62.5	75	0.032

* The observed hydraulic gradient (i_{obs}) is obtained by the ratio between the piezometeric pressure difference of a point and the minimum-radius point ($\Delta H = H - H_{min}$) and the radial distance between them ($\Delta l = R - R_{min}$) Average radius was used in the calculations($R = (r_1 + r_2)/2$); H_{min}:The minimum-radius point piezometeric pressure, R:Average radius, R_{min}: The minimum-radius point, H: Piezometeric pressure , r:Radial,v: Velocity

Table 6. i_{obs} values measured by the *Method III* in the depth of 85 cm and level of 20 cm

i_{obs} *	Δl	ΔH	H	R	r(cm)	v(m/s)
0.011	45	0.5	84.6	202.5	180	0.009
0.008	85	0.7	84.4	182.5	140	0.011
0.009	120	1.1	84	165	105	0.013
0.011	150	1.7	83.4	150	75	0.017
0.013	175	2.3	82.8	137.5	50	0.023

* The observed hydraulic gradient (i_{obs}) is obtained by the ratio between the piezometeric pressure difference of a point and the minimum-radius point ($\Delta H = H_{max} - H$) and the radial distance between them ($\Delta l = R_{max} - R$)Average radius was used in the calculations($R = (r_1 + r_2)/2$), H_{max}: The maximum-radius point piezometeric pressure, R: Average radius, R_{max}: The maximum-radius point, H: Piezometeric pressure , R:radial, v:Velocity

3 Results and discussion

Using the hydraulic gradient and the average velocity obtained by the experimental data, *a* and *b* coefficients were calculated in the binomial Forchheimer equations for different levels and depths. Table 7 shows a sample of *a* and *b* values for the levels of 20 and 35 cm and the depth of 52 cm. The results show that in contradiction to the basic Forchheimer equation, the nonlinear coefficient of *b* (the slope of the hydraulic gradient-velocity curve (i-v), which is a positive) obtains negative values (Table 7 and Fig. 3).

Table 7. The calculated value of Forchheimer *a* and *b* constant coefficients for the levels of 20 and 35 cm and the depth of 52 cm

z	*a*	*B*
20	1.311	-7.310
35	1.409	-7.779

z: Water level (cm); a & b: The coefficients of Forchheimer equation

As seen previously, the hydraulic behaviors of parallel and radial flows are totally different. One of the differences is the constant and variable cross sections in parallel and radial flows. This declares the type of changes between hydraulic gradient and velocity of the flow along the way and the i-v curve form. On this basis, in the parallel flow, the flow’s cross section is constant along the way. So, the variations of hydraulic gradient are more pronounced than the velocity variations. However, in radial flow, the cross section of the flow is not constant along the way. So, the velocity variations are more than the pear hydraulic gradient variations. The i-v curve for the parallel flows (Forchheimer equation) is shown in the Fig. 3 which tends toward the orthogonal axis of the hydraulic gradient (i) and shows the higher variations of hydraulic gradient relative to the velocity in the parallel flows(v). However, in radial flows, the velocity variations are more significant than the hydraulic gradient variations and it is expected that the i-v curve tends towards the horizontal velocity axis (Fig. 3).

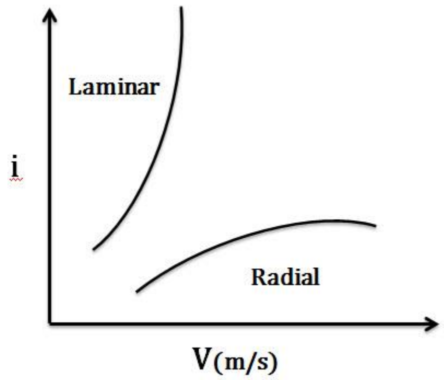

Figure 3. The schematic velocity – hydraulic gradient (i-v) curve of the parallel and radial flow

According to the Forchheimer equation, *a* and *b* parameters in the hydraulic gradient – average velocity curve (i-v) are the y-intercept and slope of the curve, respectively. Due to the positive *b*, the functional form of the equation shows an upward concavity and a positive slope for the curve. This is true in the curves related to the parallel flows (Fig. 3). Studying the radial flows has made clear the contradiction that in this kind of flow, the nonlinear *b* parameter has a negative value (Table 6). So, i-v curve shows a downward concavity, hence a negative slope. This is in contradiction to the Forchheimer principle. Therefore, this equation doesn’t allow the investigation of radial flows similar to the parallel ones. Thus, in this paper, we developed an alternative equation using an experimental model. The cross section of the flow is variable from point to point in the radial flows, as against the parallel flows. So, in order to obtain an equation for the analysis of the free-surface radial flows, unlike Forchheimer binomial, the radial independent variable (R) is also required in addition to the independent variable of velocity (v) and the dependent variable of hydraulic gradient (i). To provide the intended equation, some of the data related to the experimental readings for the depths of 52, 70, 85 and 95 cm and the levels of 20, 35, 55 and 80 cm were taken as regression data, and those related to the depths of 110, 120, 140, 150 and 160 cm and the levels of 20, 35, 55, 80, 105, 130 and 155 cm were taken as test or verification data. Therefore, the equations of (4), (5) and (6) were obtained for the methods I, II, III, respectively, in order to predict the hydraulic gradient i_{pre} by regression data (measured in various conditions in the laboratory, Tables 4, 5 and 6), including the hydraulic gradient(i), radius(R) and velocity (v) variables and using the common statistical software. The predicted hydraulic gradient, i_{pre}, was calculated as a sample using these equations for the depth of 85 and level of 20 cm, the values are provided in the Tables 8.

$$i_{pre} = {}^{v}/_{-a + bR} \tag{4}$$

$$i_{pre} = aR^{-b/v} \tag{5}$$

$$i_{pre} = V \,/\, (a - bR^2\,) \tag{6}$$

where i_{pre} is the predicted hydraulic gradient, *R* is the average radius, *V* is the average velocity, and *a* and *b* are the constant coefficients.

Table 8. The values of i_{pre} predicted by the *Method I*, II, III in the depth of 85 and level of 20 cm

	i_{pre}	i_{obs}	R	r	v
Method I	0.006	0.011	202.5	225	0.009
	0.008	0.005	160	180	0.012
	0.012	0.011	122.5	140	0.016
	0.017	0.02	90	105	0.022
	0.028	0.024	62.5	75	0.032
Method II	0.013	0.013	137.5	225	0.023
	0.014	0.013	115	180	0.024
	0.017	0.017	95	140	0.026
	0.020	0.021	77.5	105	0.028
	0.024	0.024	62.5	75	0.032
Method III	0.010	0.011	202.5	180	0.009
	0.009	0.008	182.5	140	0.011
	0.009	0.009	165	105	0.013
	0.010	0.011	150	75	0.017
	0.013	0.013	137.5	50	0.023

i_{pre}:Predicted hydraulic gradient, i_{obs}:Observed hydraulic gradient, R:Mean radius(cm), r: Radial(cm); v: Velocity(m/sec)

In this study, using the three parameters of the variations percentage of equations' empirical coefficients, the Nash coefficient (E) and the root mean square error (RMSE), the effectiveness of the three Methods have been analyzed. The variations percentage of *a* and *b* coefficients used in the calculation of gradient (relations 4, 5 and 6) is shown in the Table 9 in terms of the three methods I, II and III. According to these values, using the equations (4), (5), related to the Methods I and II (difference of successive radii, and keeping constant the minimum radius) is not appropriate due to high variations of the experimental coefficients. Considering the Table 9, the variations of *a* and *b* coefficients in the Method III are 0.128% and 0.301%, respectively. Considering these values, the equation (6) is more appropriate than others in the calculation of hydraulic gradient by keeping the maximum radius constant.

Table 9. Variation percentage of a and b coefficients in the three methods

Variation percentage	*a*	*b*
Method I	0.671	0.236
Method II	0.294	0.173
Method III	0.128	0.301

In this study, Nash coefficient (E) and Root Mean Square (RMS) are used to measure the hydrological prediction ability as the equations (7) & (8).

$$E = 1 - \frac{\sum_{i=1}^{n}(N_{i(0)} - N_{i(p)})^2}{\sum_{i=1}^{n}(N_{i(0)} - N_m)^2} \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(N_{i(0)} - N_{i(p)})^2}{n}} \tag{8}$$

In these equations, $N_{i(0)}$, $N_{i(p)}$ and N_m are the observed, predicted and mean values, respectively, and n is the number of the data. The closer the E and RMSE to 1 and 0, respectively, the more suitable the behavior of the model or equation. Table 10 shows the values of E and RMSE to evaluate the three methods related to different depths and levels. According to the Table 10, the values of E and RMSE related to the Method III are closer to 1 and 0, respectively.

Table 10. The values of E and RMSE in the three Methods (*I, I* and *III*)

Depth	z	RMSE			E		
		(I)	*(II)*	*(III)*	*(I)*	*(II)*	*(III)*
52	20	0.0118	0.0007	0.0007	0.4762	0.7143	0.9989
52	35	0.0123	0.0013	0.0007	0.5760	0.4140	0.9993
70	20	0.0082	0.0009	0.0005	0.3759	0.5138	0.9989
70	35	0.0093	0.0007	0.001	0.5759	0.2139	0.9971
70	55	0.0071	0.0004	0.0219	0.3762	0.3144	0.9452
85	20	0.0949	0.0008	0.00061	0.4763	0.7145	0.9991
85	35	0.0057	0.0005	0.0005	0.7760	0.6141	0.95125
85	55	0.0041	0.0007	0.00028	0.8758	0.7137	0.9300
85	80	0.0053	0.0004	0.00057	0.3762	0.7144	0.9776
95	20	0.0044	0.0002	0.0003	0.8761	0.5142	0.8943
95	35	0.8354	0.0003	0.0005	0.9762	0.3143	0.9416
95	55	0.8372	0.0002	0.0005	0.5760	0.6141	0.9971
95	80	0.0043	0.0003	0.000629	0.0763	0.7145	0.9743

D: Depth (cm); z: Water level (cm); RMSE: Root Mean Square; E: Nash Coefficient

For example, the data in Table 6 for the Method III (Equation 6) is provided in Fig. 4 as a relationship between i_{pre} and i_{obs} values and the average velocity. The values of RMSE and E obtained by Table 10 are, respectively, 0.0006 and 0.9991, showing the closeness of i_{pre} values to i_{obs} values using the equation (6). Then this equation would be an appropriate equation for the description of free-surface radial flow behavior.

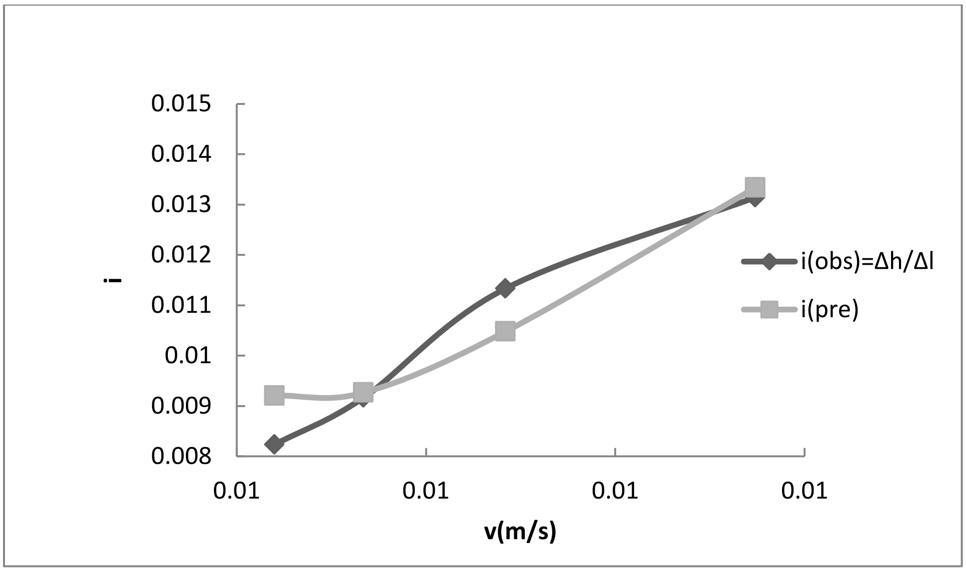

Figure 4. i-v curve for the depth of 85 cm and levels of 20 cm

In order to assess the consistency of the values obtained by the experimental results (observed values) with the values predicted by the equation (6), verification was performed by test data. For verification of the equation (6), the values of *a* and *b* coefficients should be determined for studied aggregates. Table 11 shows *a* and *b* coefficients and their average for the test data.

Table 11. *a* and *b* coefficients used in calculation of the gradient based on the equation (6) for the aggregates tested in this study

	*a**	*b*	z	D
	2.542	4.05×10^{-5}	20	85
	2.521	3.58×10^{-5}	55	85
	2.458	3.53×10^{-5}	80	85
	2.394	2.84×10^{-5}	20	95
	2.409	2.96×10^{-5}	35	95
	2.724	4.07×10^{-5}	55	95
	2.748	3.82×10^{-5}	80	95
Average	2.542	3.546×10^{-5}	-	-

* a & b: the coefficients of Forchheimer equation; z: water level(cm); D: depth (cm)

By averaging the experimental coefficients of *a* and *b* and their substitution in the equation (6), a basic equation is obtained for the verification of the proposed equation for tested aggregates as follows:

$$i = V \,/\, (2.542 - 3.546 \times 10^{-5} R^2) \tag{7}$$

In this equation, *i* is the hydraulic gradient, *R* is the average radius, and *V* is the average velocity.

Using the hydraulic gradient values obtained by the Method III and the average radius (R), the velocity of the flow (v_{pre}) was acquired according to the equation (7). Fig. 5 shows the relationship between the hydraulic gradient and the observed and predicted velocities and shows the acceptable consistency of the graphs. According to the Fig. 5, there is a small difference between the values of v_{obs} (average velocity between every point and the most distant point from the center of the well) and v_{pre} (obtained by the equation 7). So, the equation (6) is an appropriate functional form for the analysis of the hydraulic behavior of the free surface radial flows.

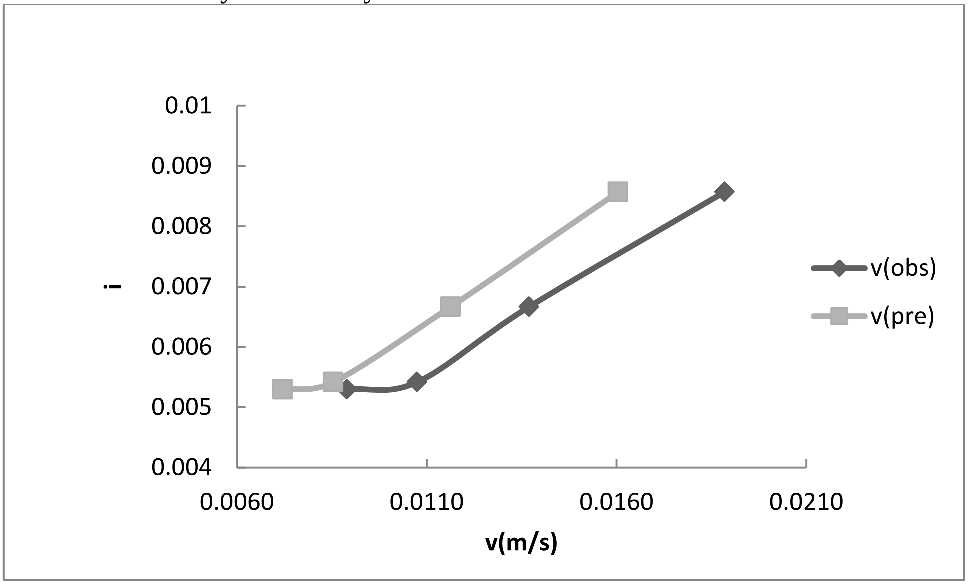

Figure 5. i-v curve for the depth of 110 cm and the levels of 20 cm

4 Conclusions

Equations of fluids in porous media are very useful in designing the rockfill dams, diversion dams, gabions, breakwaters, and ground water reserves. The behaviors of the parallel and radial flows are totally different. Of importance among the differences is the constant and variable cross section of the flow in parallel and radial flows, respectively. This determines the type of variations between the flow velocity and hydraulic gradient along the way, and also variations in the profile of velocity-hydraulic gradient (i-v) curve. A new equation has to be developed which is applicable for the course grained porous media due to the negative coefficient of the nonlinear binomial Forchheimer equation in practical applications of the radial flows on the one hand, and the invalidity of the mentioned equation for the description of the free surface radial flows in the course grained porous media, on the other. Accordingly, in the present paper, a radial flow to the center of a well was modeled by developing a semi cylindrical physical model. Thereafter, different flow parameters were measured, including flow rate, hydraulic gradient, velocity, radial distance from the center of the model and various levels. Then, choosing a series of data as regression data, different equations were obtained for the prediction of hydraulic gradient by the three methods of difference of successive radii, keeping constant the minimum radius and keeping constant the maximum radius. The comparison of the attained the equations and verification of results obtained by them was shown that the functional form of the equation $i = V / (a - bR^2)$ is appropriate for the analysis of the hydraulic behavior of free surface radial flows. This study was performed on a bed with a predetermined grain size and flow rate and in the laboratory conditions. This phenomena is slightly different in nature than what has been observed in the study. This study can be carried out in a porous medium with different granulation, different flow rates and hydraulic gradients and compared to the results of this study. Also, changing the dimensions of the physical model and therefore the boundary conditions, can yield different results.

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