ISSN NO. 2320-5407

Journal homepage: http://www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH

RESEARCH ARTICLE

Resistance - Regime Relationship in Porous Media Flow with An Emphasis on Characteristic Length

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Manuscript Info

Manuscript History:

Received: 15 September 2015
Final Accepted: 22 October 2015
Published Online: November 2015

Key words:

Porous medium, Resistance coefficient, Reynolds number, Permeameter, Coarse gravel, Darcy equation

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Abstract

In recent days, flow through porous medium has become a subject of great significance. Two concepts of concern are *RESITANCE* and *REGIME* of flow, the former being expressed in terms of Resistance coefficient (λ) and the latter in terms of Reynolds number (Re). Both the variables are primarily dependent on characteristic length. In the case of pipe flow, 'diameter' is used as characteristic length to compute λ and Re. This is relatively an easier task. In porous media flow, pore size represents characteristic length. But, complex geometry of the pore system makes the task intricate to evaluate λ and Re. This paper presents the results of an experimental study on λ - Re relationship with an emphasis on characteristic length. A specially conceived permeameter with water as fluid medium and seven sizes of coarse gravel is used in the experimentation. Nineteen expressions for characteristic length are coined and a better one is proposed from the statistical analysis of experimental data. Findings are expected to add a little more to the subject of porous media flow.

INTRODUCTION

Investigation of subterranean part of the hydrological cycle – the dynamics of flow through porous media, is a fundamental part of the scientific background of water resources development of any country. Porous medium flow is an interdisciplinary subject and has wide applications in the design of water supply, irrigation and drainage systems, petroleum engineering, development of gas and oil wells, design of filter beds, extraction of water from artesian basins by deep wells, flow through around and beneath hydraulic structures, soil erosion, diffusion and flow of fluids through bricks and porous earthen ware.

Flow through porous medium at the first sight appears conceptually simple. Upon a detailed examination, exposes its complexity. Nature of flow is determined by the structure of pore channels, which is difficult to describe geometrically. Resistance of these continuous and tortuous channels has to be overcome by flowing water. Relationship established between resistance along the bed and corresponding flow rate is one of the solutions to interpret the nature of flow through porous medium.

Head loss, which is a measure of resistance, is expressed in terms of a Resistance coefficient (λ), and flow rate (velocity or regime) is expressed in terms of the Reynolds number (Re). Both Resistance coefficient and Reynolds number are primarily functions of characteristic length. That is, a proper insight into the subject of flow through porous medium requires the knowledge of characteristic length.

Aim of all the investigators on seepage flow is to relate flow resistance to its regime in terms of measurable properties of the fluid and the medium. Three methods of approach viz., i) Correlation based on pipe flow analogy, ii) Correlation based on flow characteristics of the medium and iii) Correlation based on drag on the individual particle, are in vogue. In pipe flow analogy, linear dimensions of the pipe are replaced with the corresponding hydraulic equivalents of the porous medium. However, absence of continuous acceleration and retardation and no transfer of flux from one pipe to another limit the application of pipe flow analogy. In the second approach, one or two flow parameters are determined from experiments and are used to predict flow pattern in all regimes of flow. For example, Darcy's law, which relates velocity of flow and hydraulic gradient as,

$$V = K\,i \qquad (1)$$

where, V = Velocity of flow, i = Hydraulic gradient, K = Coefficient of permeability, with the dimensions as that of velocity, is found to depend on both soil and fluid properties. It is given by,

$$K = k_0 \frac{\gamma}{\mu} \qquad (2)$$

where, k_0 = Intrinsic permeability, μ = Viscosity of fluid and γ = Specific weight of fluid. Intrinsic permeability (k_0) is dependent on size and shape of the particles, porosity and grain size distribution and is given by,

$$k_0 = Cd^2 \qquad (3)$$

where, C= constant. k_0 has dimension L^2. Third approach, based on principle of drag on an individual particle, defines two non - dimensional numbers to quantify resistance to flow and flow regime as Resistance coefficient (λ) and Reynolds number (Re) respectively. They are given by,

$$\boldsymbol{\lambda} = \frac{i * Lc * g}{V^2} \qquad (4)$$

and

$$\mathbf{Re} = \frac{V * Lc}{\nu} \qquad (5)$$

where, Lc = Characteristic length, g = Acceleration due to gravity, V = Bulk velocity and ν = Kinematic viscosity of fluid.

Based on different definitions of characteristic length, "λ" and "Re" can be defined in numerous ways.

Methodology

Characteristic length is one of the predominant parameters in defining the Resistance coefficient (λ) and Reynolds number (Re). In porous media flow, pore size is the characteristic length. Assuming that a pore channel forms an imaginary circular passage, size of the pore can be expressed as diameter of pore, which is practically very difficult, rather impossible, to measure. Even if, a theoretical model is developed, it would be of very limited use. Therefore, definition and determination of pore size is left to one's own approach.

It may be observed from Fig. 1, that as particle size increases, pore size also increases and vice versa. It is intuitive to assume a relation to exit between particle size and pore size. Therefore, as an initial attempt, particle size may be chosen as pore size. That is,

$$\mathbf{Lc_1 = d} \qquad (6)$$

where, Lc_1 = First trial definition of characteristic length and d = Particle size.

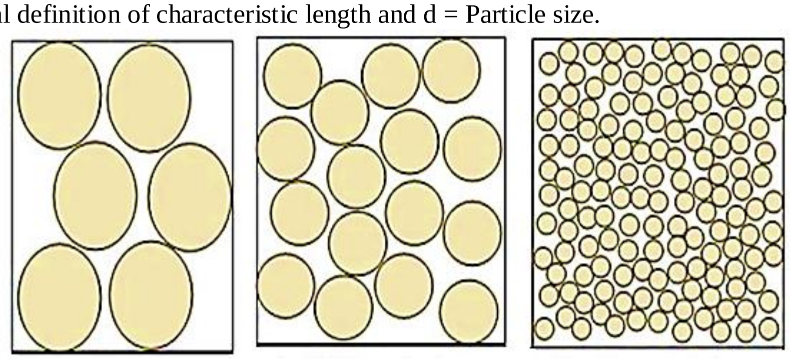


Fig. 1. Pore size Vs. Particle size

While 'diameter' is considered as particle size for regularly shaped particles like spheres, 'volume diameter' is considered as particle size for an irregularly shaped particles, like coarse gravel and river sand.

Another expression for characteristic length may be a combination of porosity function and particle size. That is,

$$\mathbf{Lc = d * f(n)} \tag{7}$$

where, f(n) = Function of porosity.

If f(n) = n then characteristic length is

$$\mathbf{Lc_2 = d * n} \tag{8}$$

where, Lc_2 = Second trial definition of characteristic length.

Another form of porosity function, f(n) = ($\frac{\mathbf{n}}{\mathbf{1-n}}$) can be used as,

$$\mathbf{Lc_3 = d * \frac{n}{1-n}} \tag{9}$$

where, Lc_3 = Third trial definition of characteristic length.

Reciprocal of specific surface (S_0), surface area per unit volume of a particle with dimension as L^{-1}, may also be assumed as pore size. That is,

$$\mathbf{Lc_4 = \frac{1}{S_0}} \tag{10}$$

where, Lc_4 = Fourth trial definition of characteristic length.

Another heuristic form, combining specific surface with void ratio (e), resulting in hydraulic radius, r, can be used as one more expression for pore size. That is,

$$\mathbf{Lc_5 = r = \frac{e}{S_0}} \tag{11}$$

where, Lc_5 = Fifth trial definition of characteristic length.

As already mentioned, intrinsic permeability (k_0) is given by $\mathbf{k_0 = C\, d^2}$ with dimensions of L^2. Square root of intrinsic permeability ($\sqrt{\mathbf{K_0}}$) may also be considered as characteristic length and is given as,

$$\mathbf{Lc_6 = \sqrt{k_0}} \tag{12}$$

where, Lc_6 = Sixth trial definition of characteristic length.

In addition, different combinations of $\sqrt{\mathbf{k_0}}$ and porosity function f (n) may be used as expressions for characteristic length for computing Re and λ. For example, Eq. (13) represents seventh trial definition of characteristic length. That is,

$$\mathbf{Lc_7} = \sqrt{\mathrm{n} * \mathbf{k_0}} \tag{13}$$

where, Lc_7 = Seventh trial definition of characteristic length.

Multiplication of square root of the product of intrinsic permeability and porosity with a random constant 5 (Kovacs (1981)), may also be used as characteristic length, as,

$$\mathbf{Lc_8 = 5\sqrt{n * k_0}} \tag{14}$$

where, Lc_8 = Eighth trial definition of characteristic length

Similarly, assuming f (n) = n^2, characteristic length is given by,

$$\mathbf{Lc_9} = \mathrm{Sqrt}\,(n^2 * k_0) = \mathbf{n * \sqrt{k_0}} \tag{15}$$

where, Lc_9 = Ninth trial definition of characteristic length.

Using volumetric porosity (n^3) as porosity function, then characteristic length is given as,

$$\mathbf{Lc_{10} = \sqrt{n^3 * k_0}} \tag{16}$$

where, Lc_{10} = Tenth trial definition of characteristic length.

Further, different combinations of porosity (n), intrinsic permeability (k_0) and specific surface (S_0) are used as definitions of characteristic length as,

$$\mathbf{Lc_{11} = \sqrt{\frac{\sqrt{k_0}}{S_0}}} \tag{17}$$

$$\mathbf{Lc_{12} = \sqrt{\frac{\sqrt{n * k_0}}{S_0}}} \tag{18}$$

$$\mathbf{Lc_{13} = \sqrt{\frac{n * \sqrt{n * k_0}}{S_0}}} \tag{19}$$

where, Lc_{11}, Lc_{12} and Lc_{13} = Eleventh, twelfth and thirteenth trial definitions of characteristic length.

Another combination involving hydraulic radius (r) and intrinsic permeability (k_0) is proposed as characteristic length. That is,

$$\mathbf{Lc_{14}} = \sqrt{\mathbf{r} * \sqrt{\mathbf{k_0}}} \quad (20)$$

where, Lc_{14} = Fourteenth trial definition of characteristic length.

Geometric mean of product of d, r and $\sqrt{\mathbf{k_0}}$ may also be used as,

$$\mathbf{Lc_{15}} = \sqrt[3]{\mathbf{d} * \mathbf{r} * \sqrt{\mathbf{k_0}}} \quad (21)$$

where, Lc_{15} = Fifteenth trial definition of characteristic length.

Further, combination of porosity (n), intrinsic permeability (k_0) and hydraulic radius (r) is considered as characteristic length as,

$$\mathbf{Lc_{16}} = \sqrt{\mathbf{r} * \sqrt{\mathbf{n^3} * \mathbf{k_0}}} \quad (22)$$

where, Lc_{16} = Sixteenth trial definition of characteristic length.

Another expression (Eq. 23) for characteristic length may also be used (Kovacs (1981)).

$$\mathbf{Lc_{17}} = \frac{\mathbf{4\,n}}{\mathbf{1-n}} * \frac{\mathbf{d}}{\propto} \quad (23)$$

where, Lc_{17} = Seventeenth trial definition of characteristic length and α = Shape factor

A combination of intrinsic permeability, porosity and shape factor (α) is considered as characteristic length and is given as,

$$\mathbf{Lc_{18}} = \frac{\sqrt{\mathbf{k_0}}}{\mathbf{2}} * \left(\mathbf{1} + \sqrt{\propto * \mathbf{n}}\right) \quad (24)$$

where, Lc_{18} = Eighteenth trial definition of characteristic length

Characteristic length, inclusive of shape effect, may be considered as,

$$\mathbf{Lc_{19}} = \sqrt{\propto * \mathbf{n} * \mathbf{k_0}} \quad (25)$$

where, Lc_{19} = Ninteenth trial definition of characteristic length and α = Shape factor.

Once different forms of characteristic length are known, the next step is to substitute them in the expressions for λ and Re, compare them through statistical and graphical analysis and propose a better definition for characteristic length and governing equation relating λ and Re. In order to achieve these objectives, an experimental program is planned, the details of which are as follows:

EXPERIMENTATION:

A specially designed permeameter made up of a circular G.I. Column of 6.20 m long (longest till now in the literature) and 0.15 m inner diameter, provided with three sets of piezometric tapping points for measuring head loss over three different lengths of travel (1.0 m, 3.0 m, 5.03 m) (till now unique in the literature) as shown in Fig. 2 is used. Water is supplied to the porous medium from a constant-head overhead tank. A perforated horizontal pipe is provided to avoid the water directly falling in the form of a jet. Media is retained in the permeameter using a perforated screen at the exit. Short copper tubings facilitate connection of polythene tubes to manometer board to measure heads. Two main valves and a bye pass valve regulate the discharge through permeameter. Entrapped air is removed before discharge is measured under steady state conditions. Three values of hydraulic gradient are obtained and are averaged to a single value in order to minimise the possible error due to non-uniformity in packing of media.

Details of seven sizes of coarse gravel used in the present study are presented in Table 1. 'Size' means volume diameter, which is the diameter of an imaginary sphere having equal volume as that of the non-spherical particle. This is determined as follows:

After sieving the coarse material, sample of 400 to 500 particles is chosen at random from each size. Such a large sample will reduce the error in determining size of particle. Each particle is drowned in graduated cylinder containing predetermined volume of water. Difference in water levels before and after drowning indicates volume of the particle. Sometimes, a bunch of 10, 15 or 50 particles are drowned at the same time, care being taken to see that no water splashes. Volume of all the particles is noted from which volume of a single particle is deduced. All these steps are repeated for all sizes of the media. Using the Eq. (26), volume diameter is computed.

$$\text{Volume diameter (d)} = \sqrt[3]{\frac{\mathbf{6\ X\ Volume\ of\ bunch\ of\ particles}}{\mathbf{N}\,\Pi}} \quad (26)$$

where, N = Number of particles. Mean of above values is taken as 'size' of that sample. Water displacement method is used to determine porosity. Velocity of flow is calculated from known cross sectional area of the permeameter and measured discharge. Temperature of out flow is noted for every run, from which viscosity is determined.

ANALYSIS OF EXPERIMENTAL DATA:

Before proceeding with the analysis, it is necessary to have the values of porosity, velocity, hydraulic gradient, size, hydraulic radius, shape factor and intrinsic permeability involved in computation of λ and Re. Shape factor for different types of media are presented in Table 2. Except, intrinsic permeability, all the others are available in the beginning itself.

Figure 3 depicts variation of hydraulic gradient (i) with bulk velocity (Vb) for the chosen media, from which coefficient of permeability (K) is found through regression analysis. From these values of 'K', corresponding values of 'k_0' are calculated using the relation $K = \mathbf{k_0}\frac{g}{\nu}$. Values of coefficient of permeability for different sizes are given in Table 3.

With all the known values, using $Lc_1 = d$ as characteristic length, λ and Re are computed. Graph is plotted between Resistance coefficient (as ordinate) and Reynolds number (as abscissa) for seven sizes of coarse gravel. From Fig. 4.a, the resulting plot of the seven curves is analogous to Moody diagram used for pipe flow. The apparent difference is that there is a smooth transition from laminar to turbulent flow in the case of flow through porous medium, where as in pipe flow there is an abrupt variation. This characteristic of porous media flow may be due to shape and sizes of pore channel. As flow in some pore spaces attains turbulence, in others flow may still be laminar. The net effect is thus a gradual change from laminar to turbulent regime. Further, as Reynolds number increases, the values of resistance coefficient decreases indicating a inverse relationship between the variables. In the laminar regime, a steep slope of curves indicate a linear relation between the variables. As flow shifts to transition, a gradual variation between the variables λ and Re is observed. As flow changes to turbulent, at larger values of Reynolds number, it is observed that trend is almost horizontal indicating Resistance coefficient is independent of Reynolds number. It may also be noted that there is a systematic and regular orientation of curves corresponding to different sizes. While the λ - Re curve for smaller size of coarse gravel is found to lie at the bottom of set of curves, the curve corresponding to larger size of coarse gravel finds its place at the top. This infers that at particular value of Reynolds number, the value of Resistance coefficient for larger size of media is large and for smaller size of media it is small. This may be due to effect of drag. By method of least squares, relationship between Resistance coefficient and Reynolds number for the data is fitted with R^2 value of 0.69. A poor fit is obtained with larger dispersion from the mean curve. This is due to inappropriate definition of characteristic length Lc_1. Therefore, though a visually noticeable relationship exists between size of the particle and size of the pore, concept of considering size of the particle equal to size of pore appears to be inappropriate. As the pore size becomes equal to or greater than particle size in a porous medium, the system will collapse. Further, characteristic length Lc_1 in the present attempt is defined by considering mere volume diameter of the particle 'd'.

Next step is to use Lc_2 to Lc_{19} as characteristic length in λ and Re. Similar procedure is adopted with these definitions of characteristic length in computing λ and Re and plotting the variation of λ with Re. These curves are shown in from Figs. 4. b to 4.s. Similar trend is observed in all the figures, except for that pertaining to $Lc_{19,}$ the detailed discussion on which is presented in the succeeding section. Various expressions of characteristic length and corresponding R^2 values are listed in Table 4.

Results and Discussions:

Among all the proposed nineteen definitions of characteristic length, it is observed that a pretty good fit between Resistance coefficient and Reynolds number is found corresponding to the definition Lc_{19} supported by a strong negative correlation. The highest R^2 value among the nineteen definitions as 0.9137 is found. Further, Lc_{19} takes care of major influencing parameters of flow through porous medium viz., Intrinsic Permeability, Porosity and Shape Factor. From Fig. 4.s., scattering of the data corresponding to various sizes of coarse gravel is very minimum and λ - Re curves of seven sizes of coarse gravel seem to converge with each other resulting in a single curve. Using method of least squares, relation between Resistance coefficient and Reynolds number is found as,

$$\lambda = \frac{\mathbf{5.89}}{\mathbf{Re^{0.688}}} \tag{27}$$

and is proposed as governing equation relating resistance to flow and Reynolds number.

Conclusions:

Though porous media flow is simulated to flow through bundle of pipes, characterising the flow is not a simple task. The problem is further aggravated due to complex nature of flow and multiple definitions for characteristic length, resulting in multiple expressions for Reynolds number and Resistance coefficient. Hence, an attempt is made in refining the definition for characteristic length in terms of influencing properties of media and fluid. However, trend depicted in the plot between λ - Re is similar to that of earlier works, ascertaining the reliability of experimentation. From all the plots between λ - Re pertaining to present study, (Figs.4.a to 4.s) it is obvious that Lc_{19} yields a better correlation between Resistance coefficient and Reynolds number irrespective of size of media with higher R^2 value. Therefore, equation Lc_{19} is proposed as better definition for charateristic length in flow through porous media. Further, it is expected that findings of present study may provide a greater insight and clear probable uncertainities in defining characteristic length in flow through porous medium.

Acknowledgements:

The authors are thankful to the authorities of Sri Venkateswara University, Tirupati, Andhra Pradesh, India for funding to fabricate the permeameter, purchase of Coarse Gravel and to visit other institutions to gather related information.

Notations:

C	=	Constant
C'	=	Constant
d	=	Diameter of particle
e	=	Void ratio
g	=	Acceleration due to gravity
i	=	Hydraulic gradient
K	=	Coefficient of Permeability
k_0	=	Intrinsic permeability
Lc	=	Characteristic Length
n	=	Porosity
r	=	Hydraulic radius
Re	=	Reynolds Number
S_0	=	Specific Surface
V	=	Velocity of flow
V_b	=	Bulk Velocity
μ	=	Dynamic viscosity of fluid
ν	=	Kinematic Viscosity of fluid
λ	=	Resistance coefficient

α	=	Shape factor
γ	=	Specific weight

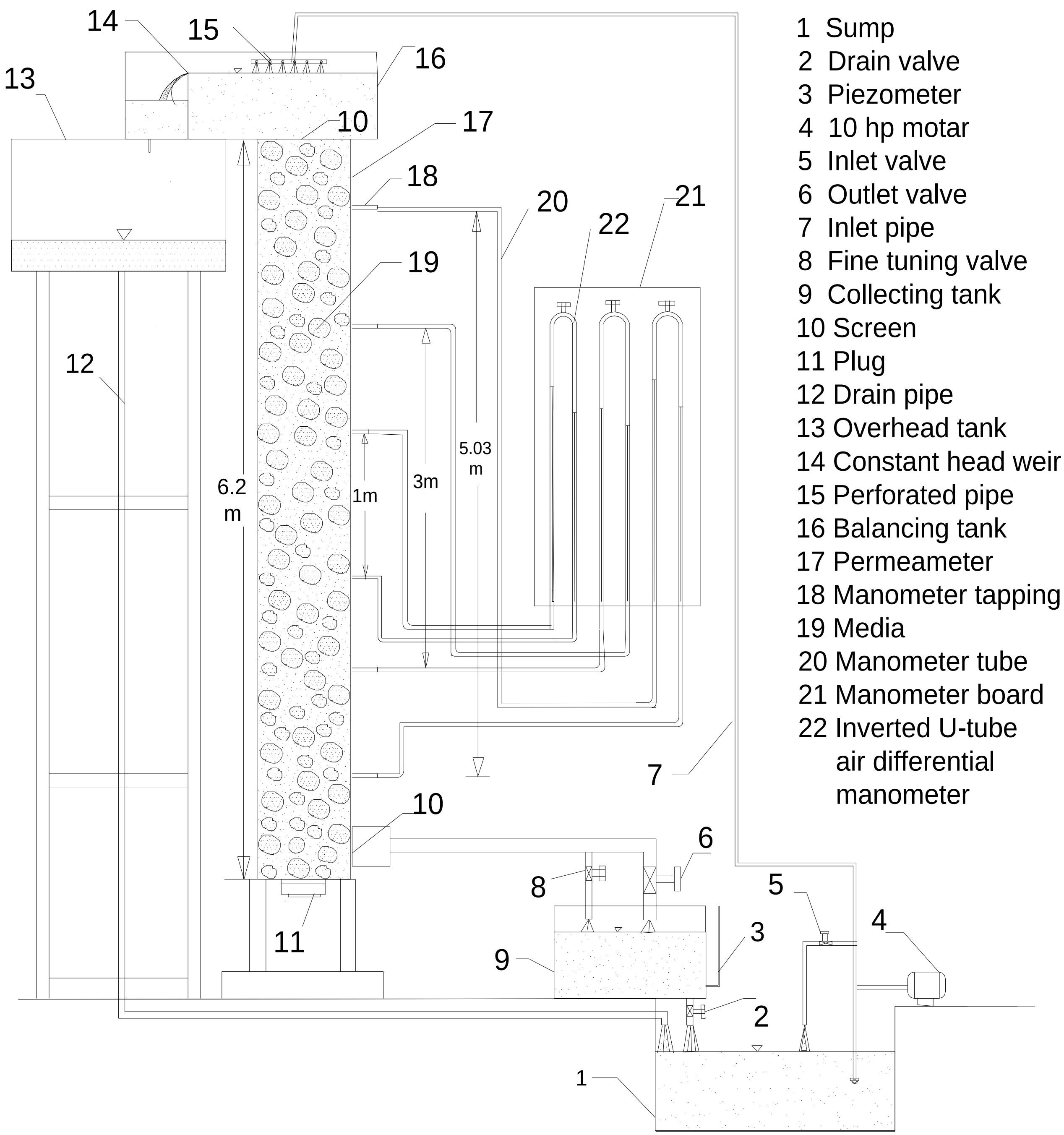


Fig. 2. Experimental setup – Permeameter

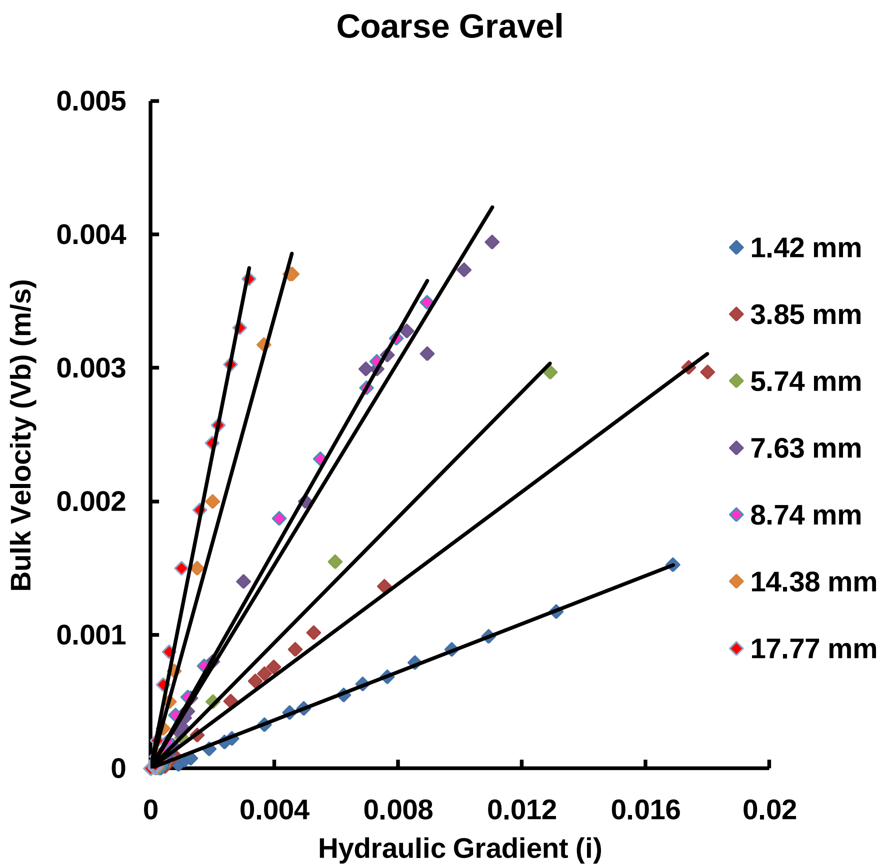


Fig. 3. Variation of Hydraulic Gradient with Bulk Velocity for Seven sizes of Coarse Gravel

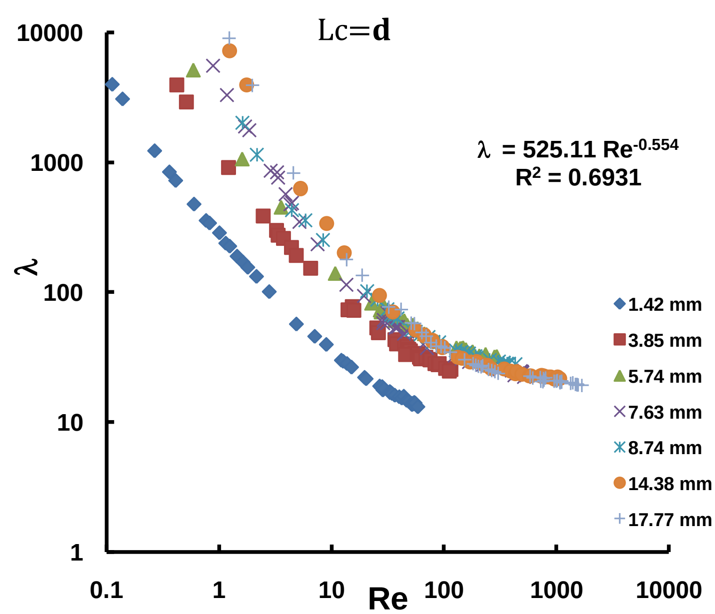


Fig. 4.a. Variation of Resistance Coefficient λ versus Reynolds Number Re with Lc = d

$$Lc = d * n$$

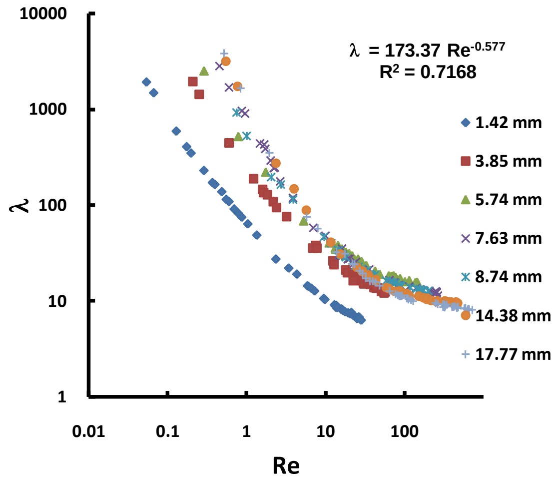


Fig. 4.b.

$$Lc = d\left(\frac{n}{1-n}\right)$$

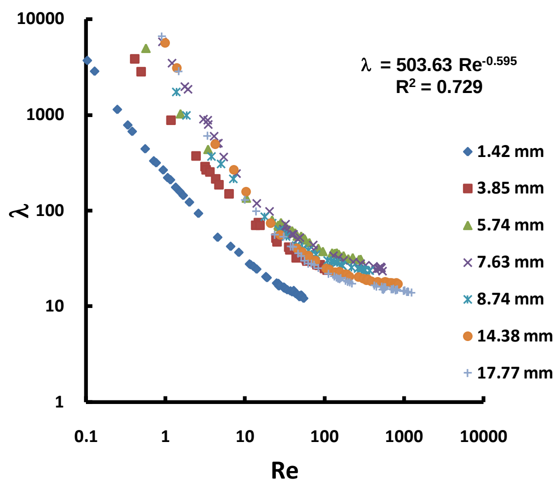


Fig. 4.c.

$$Lc = 1/S_0$$

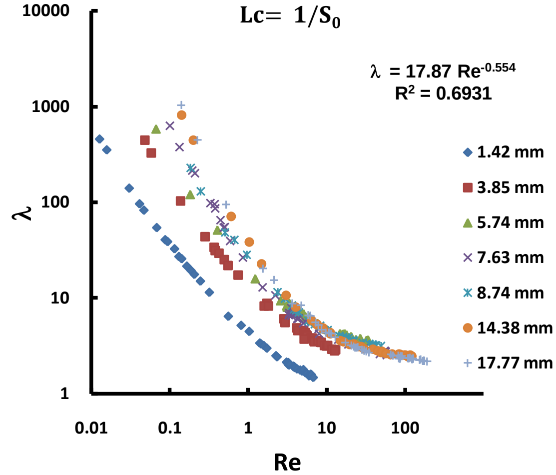


Fig. 4.d

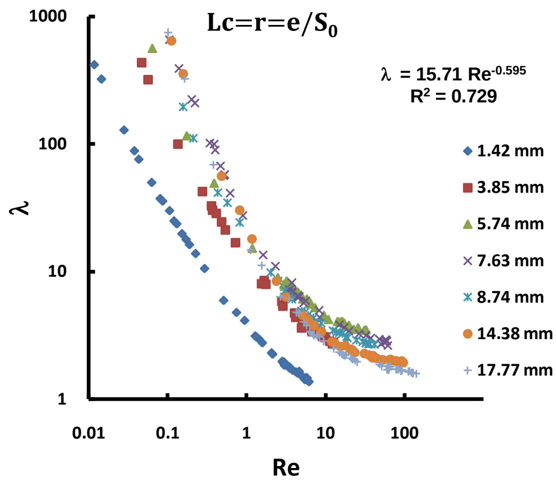


Fig. 4.e.

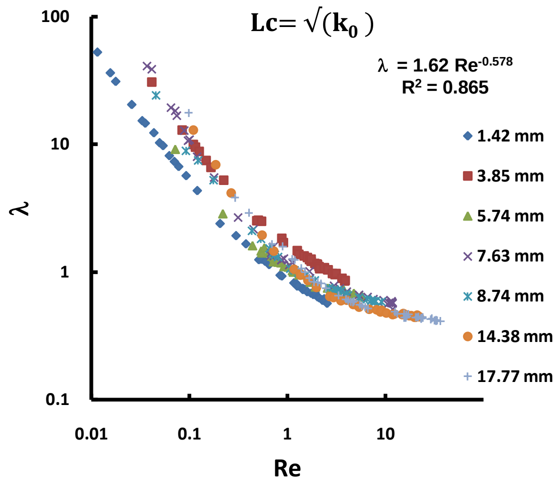


Fig. 4.f

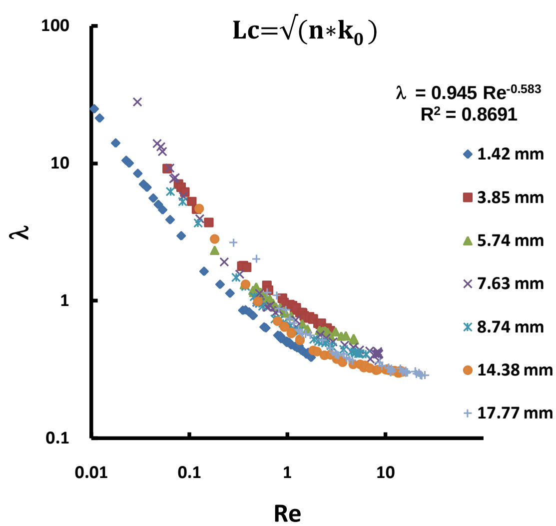


Fig. 4.g.

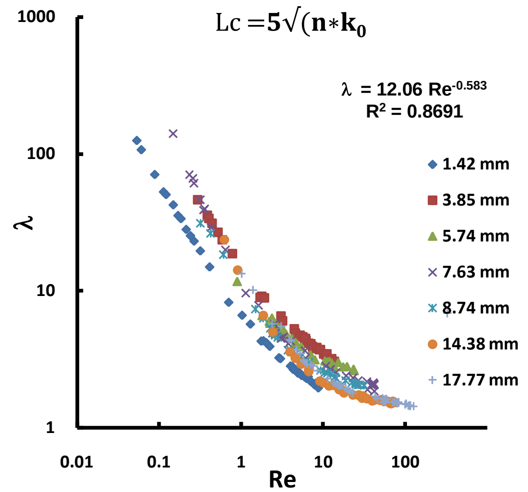


Fig. 4.h

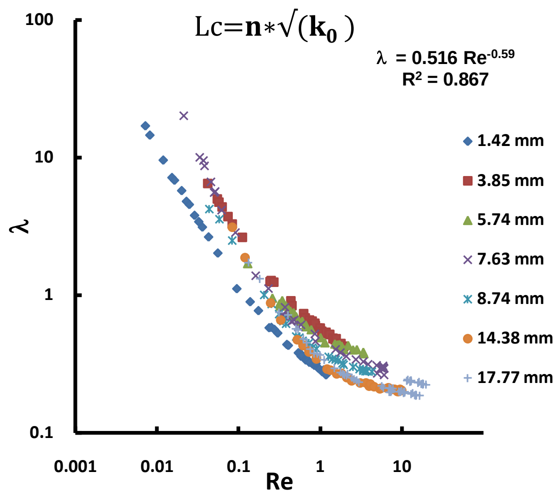


Fig. 4.i

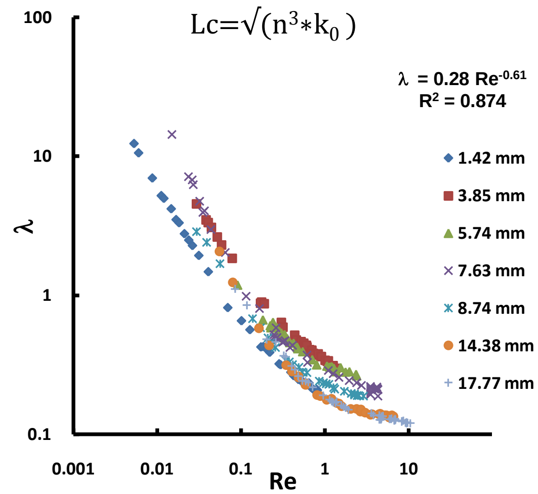


Fig. 4.j.

$$Lc = \sqrt{\frac{\sqrt{k_0}}{S_0}}$$

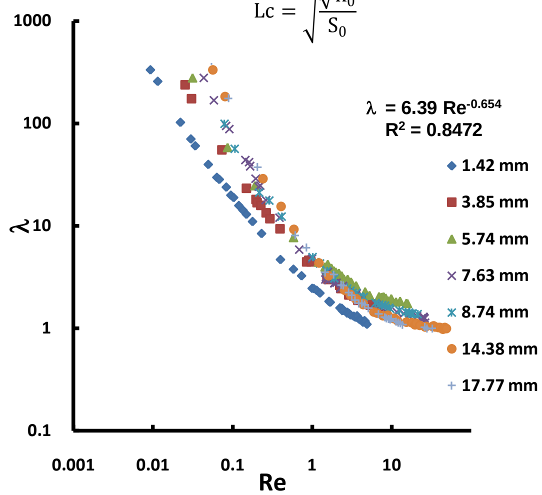


Fig. 4.k

$$Lc = \sqrt{\frac{\sqrt{n * k_0}}{S_0}}$$

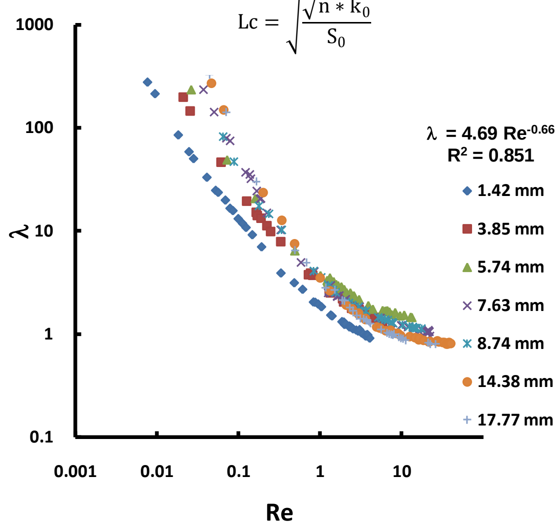


Fig. 4.l.

$$Lc = \sqrt{\frac{n\sqrt{n * k_0}}{S_0}}$$

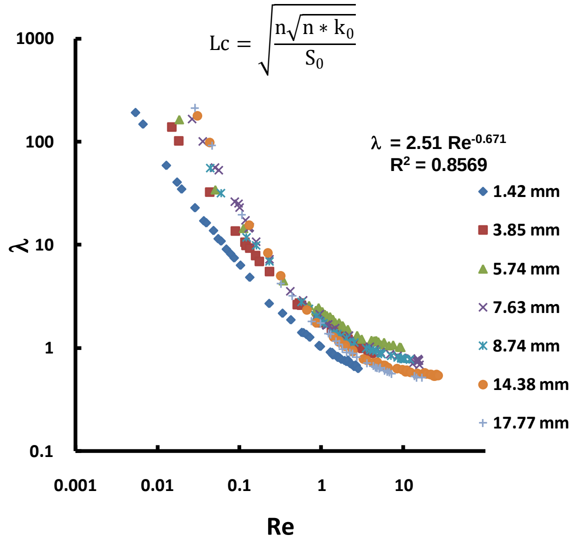


Fig. 4.m

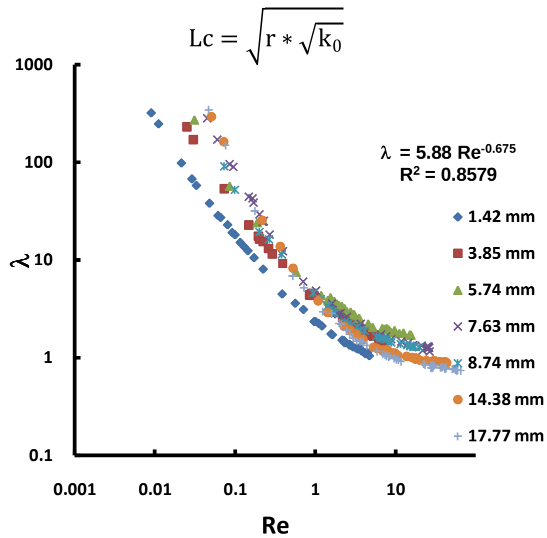


Fig.4.n.

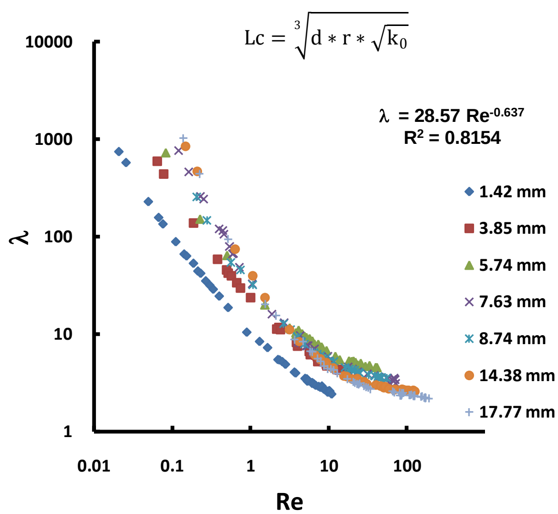


Fig.4.o

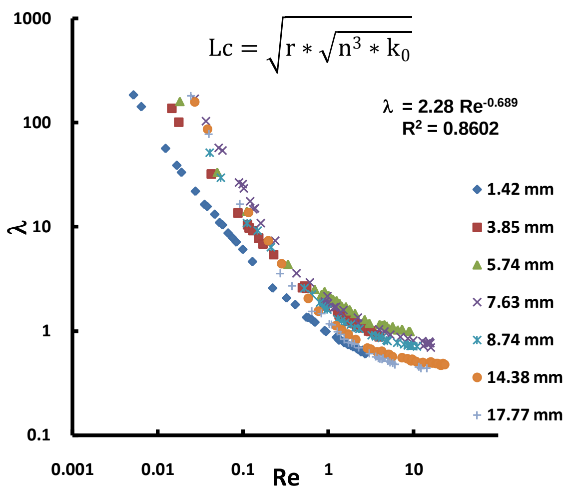
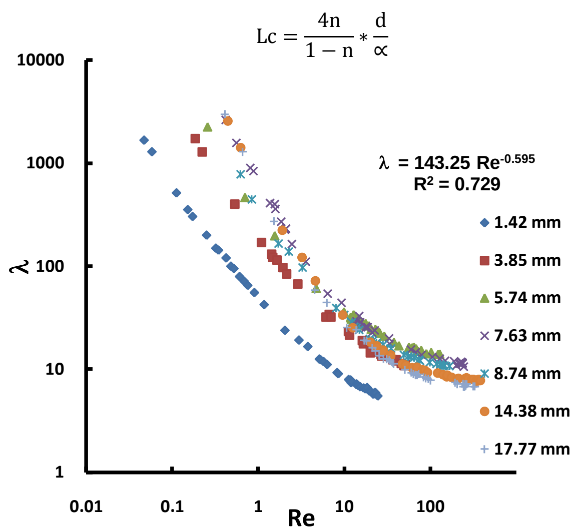
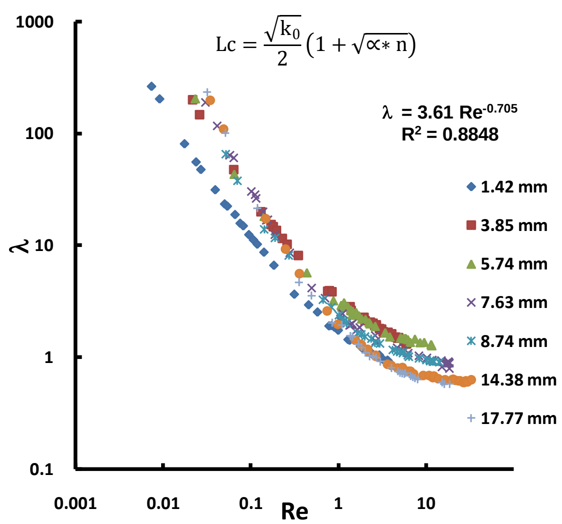


Fig. 4.p.



$Lc = \frac{4n}{1-n} * \frac{d}{\propto}$
λ = 143.25 Re-0.595
R2 = 0.729
1.42 mm
3.85 mm
5.74 mm
7.63 mm
8.74 mm
14.38 mm
17.77 mm
λ
10000
1000
100
10
1
0.01
0.1
1
10
100
Re

Fig. 4.q.



$Lc = \frac{\sqrt{k_0}}{2}\left(1 + \sqrt{\propto * n}\right)$
λ = 3.61 Re-0.705
R2 = 0.8848
1.42 mm
3.85 mm
5.74 mm
7.63 mm
8.74 mm
14.38 mm
17.77 mm
λ
1000
100
10
1
0.1
0.001
0.01
0.1
1
10
Re

Fig. 4.r.

$$Lc = \sqrt{\propto * n * k_0}$$

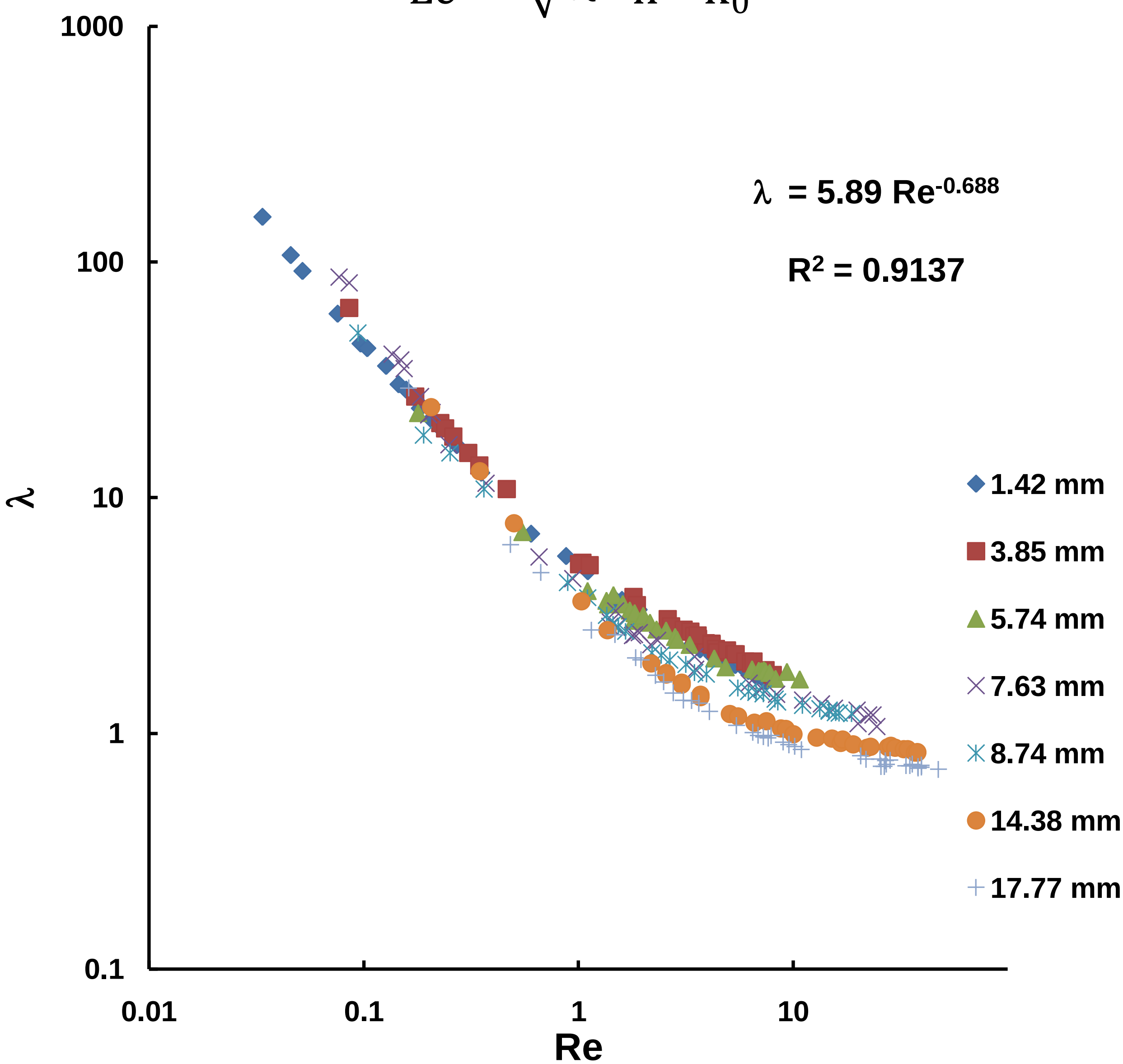


Fig. 4.s

Table 1 Characteristics of Media used in the Present Study

Sl. No.	Type of Media	Volume Diameter (mm)	Porosity (%)
1	**Coarse gravel**	**1.42**	**48.0**
2	**Coarse gravel**	**3.85**	**49.2**
3	**Coarse gravel**	**5.74**	**49.0**
4	**Coarse gravel**	**7.63**	**51.0**
5	**Coarse gravel**	**8.74**	**46.0**
6	**Coarse gravel**	**14.38**	**44.0**
7	**Coarse gravel**	**17.77**	**42.0**

Table 2 Shape Factor (α) for Different Shapes and Classes of Media

Sl. No.	Type/shape of Media	Shape Factor (α)	
1	**Gravel**	**8.8**	**(Pradeep Kumar (1995))**
2	**River sand**	**7**	**(Kovacs (1981))**
3	**Glass Sphere**	**6**	**(Kovacs (1981))**
4	**Cube**	**10.4**	**(Kovacs (1981))**
5	**Octahedron**	**10.4**	**(Kovacs (1981))**
6	**Tetrahedron**	**18**	**(Kovacs (1981))**

Table 3 Variation of 'i' with 'Vb' for the data in the present study

Type of Media	Size (mm)	$V_b = ki$
Coarse Gravel	**1.42**	$V_b = 0.095\ i$
	3.85	$V_b = 0.196\ i$
	5.74	$V_b = 0.272\ i$
	7.63	$V_b = 0.388\ i$
	8.74	$V_b = 0.432\ i$
	14.38	$V_b = 0.865\ i$
	17.77	$V_b = 1.203\ i$

Table 4 Various Definitions for Characteristic Length Adopted in the Present Study along with corresponding R^2 values

Sl.No.	Characteristic Length	R^2 Value	Sl.No.	Characteristic Length	R^2 Value
1	$Lc_1 = d$	**0.6931**	**11**	$Lc_{11} = \sqrt{\frac{\sqrt{k_0}}{S_0}}$	**0.8472**
2	$Lc_2 = d * n$	**0.7168**	**12**	$Lc_{12} = \sqrt{\frac{\sqrt{n * k_0}}{S_0}}$	**0.8511**
3	$Lc_3 = d * \frac{n}{1 - n}$	**0.7290**	**13**	$Lc_{13} = \sqrt{\frac{n * \sqrt{n * k_0}}{S_0}}$	**0.8569**

4	$Lc_4 = \frac{1}{S_0}$	**0.6931**	**14**	$Lc_{14} = \sqrt{r * \sqrt{k_0}}$	**0.8579**
5	$Lc_5 = r = \frac{e}{S_0}$	**0.7290**	**15**	$Lc_{15} = \sqrt[3]{d * r * \sqrt{k_0}}$	**0.8154**
6	$Lc_6 = \sqrt{k_0}$	**0.8650**	**16**	$Lc_{16} = \sqrt{r * \sqrt{n^3 * k_0}}$	**0.8602**
7	$Lc_7 = \sqrt{n * k_0}$	**0.8691**	**17**	$Lc_{17} = 4 * \frac{n}{1-n} * \frac{d}{\propto}$	**0.7290**
8	$Lc_8 = 5\sqrt{n * k_0}$	**0.8691**	**18**	$Lc_{18} = \frac{\sqrt{k_0}}{2} * \left(1 + \sqrt{\propto * n}\right)$	**0.8848**
9	$Lc_9 = n * \sqrt{k_0}$	**0.8673**	**19**	$Lc_{19} = \sqrt{\propto * n * k_0}$	**0.9137**
10	$Lc_{10} = \sqrt{n^3 * k_0}$	**0.8749**			

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