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Behaviour of Water Flow Through Monosized Gravel Media

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Abstract: Gravel materials are widely used in hydraulic structures such as self-spillway dams. Darcy's law is used in engineering applications to represent flow through soil in this case the flow will be Laminar. When analyzing the flow through coarse porous materials such as gravel it leads to deviation in the results from Darcy's law because of high velocity of flow that causes a nonlinear relationship between hydraulic gradient and bulk flow velocity. The present study aimed to investigate the behaviour of flow through monosized gravel and to determine the effect of hydraulic gradient and gravel mean size in hydraulic conductivity under turbulent flow condition. The porous materials used in this study were seven monosized gravel samples with diameters ranging from -4.75+4 to -31.5+25 mm. A hydraulic conductivity test rig was constructed to measure the hydraulic conductivity of the gravel samples. Hydraulic gradient values used to conduct the experiments ranged between 0.01 and 0.237 while the discharge values ranged between 0.0149 and 0.255 L/sec. The results showed that the flow through monosized gravel didn't obey Darcy's law and a strong non-linear relationship was found between hydraulic gradient and bulk flow velocity with average R^2 equal to a 0.99. Results also demonstrated that a strong power formula was found between hydraulic conductivity for monosized gravel and Reynolds number with average R^2 equal to a 0.97. In addition, the results showed that friction factor has high values at low Reynolds number and for Reynolds number equal to or >200, friction factor decrease and it reaches an approximately constant magnitude.

Key words: Forchheimer equation, hydraulic conductivity, hydraulic structures, monosized gravel, non-linear flow, monosized gravel

INTRODUCTION

Non-Darcian flow through coarse porous materials is one of the important subjects that have been studied for its relationship with many fields such as weirs, water resources, environmental, petroleum and chemical engineering. Admittedly there is a difference in the theoretical bases of the Laminar and turbulent flow through porous media. Darcy's equation may be described the Laminar flow through porous media which is unable to explain turbulent flow which occurs at high velocity and Reynolds number. Non-Darcian flow takes place through hydraulic structures which to build from gravel or rockfill materials such as gabion weirs, gravel aquifers, rockfill dykes and gravel filters. Darcy's law has some limitations such as linear relation between flow velocity and hydraulic gradient. The flow with higher turbulence deflects from mentioned status, the flow regime transforms to the new condition which is called non-Darcy flow regime. When using gravel aggregates as a filter in drainage they can act as a porous media to transport a flow of water from one elevation to another in soil.

Generally, gravel and rockfill structures considered as an economical alternative compared with other types. Where gravel and rockfill materials are available in nature exuberantly which makes it economically and practically for use it in hydraulic engineering applications. In waste water treatment applications, several layers of gravel are used in stratified sand filters (Nichols *et al*., 1997). In ground water hydrology, gravel layers are commonly employed as aquifers and may also give rise to springs and hillside seepage (Selim and Kirkham, 1972). Many studies have been accomplished in the use of coarse porous media such as gravel and rockfill materials in various engineering applications (Maeno *et al*., 2002; Hosseini, 2002; Hansen *et al*., 2005; Heydari and Talaee, 2011; Morteza *et al*., 2014; Al-Mohammed and Mohammed, 2015). This study aims to study the hydraulic characteristics of flow through monosized gravel and to investigate the saturated hydraulic conductivity of the used materials as a result of a change in hydraulic gradient under turbulent flow condition.

Literature review

Theoretical background: In this study, the most important relations in seepage flow through porous materials are presented. The fundamental equations governing the flow through porous materials depend on the case of flow as follows:

Linear flow: The differential equation in 3-dimensions that used to describe Darcy's law in saturated porous media at any point is as follows (Hillel, 1980):

$$q = -K\nabla H \tag{1}$$

Where:

- q = The water flux (LT^{-1})
- ∇H = The hydraulic gradient in 3 dimensional
- K = Saturated hydraulic conductivity of the porous media (LT^{-1})

Under 1-dimensional flow through isotropic homogenous saturated porous materials, low fluid velocities and low Reynolds number the hydraulic gradient various linearly with velocity, i.e:

$$Q = -KA\frac{dh}{dl} \tag{2}$$

Where:

- Q = The discharge of flow (L^3T^{-1})
- A = The cross-section area (L^2)
- h = The hydraulic head (L)
- l = The elevation head (L)

The quotient dh/dl represents the hydraulic gradient i (L/L). The specific discharge or Darcy Velocity V with dimension (LT^{-1}) may be expressed as Eq. 3:

$$V = \frac{Q}{A} \tag{3}$$

Then, Darcy's law becomes:

$$V = -Ki \tag{4}$$

The saturated hydraulic conductivity depends upon void ratio, fluid properties, particle size, particle shape and soil structure. The K values for sandy and compacted clay soil are 10^{-4} and 10^{-10} m/sec, respectively (Olson and Daniel, 1981; Youngs *et al*., 1995). Validity of Darcy's law requires that flow through porous media be Laminar. The Reynolds number Re serves as a criterion to distinguish between Laminar and turbulent flow, Re is defined as:

$$Re = \frac{\rho V d_m}{\mu} \tag{5}$$

Where:

- ρ = Mass density of fluid (mL^{-3})
- d_m = The gravel mean size (L)
- μ = The dynamic viscosity of fluid ($mL^{-1}T^{-1}$)

The previous studies showed that the relation given by Eq. 5 is valid only if Re values are ranging between 0.1 and 75 (Parkin, 1963). Actually, the flow velocity will be through the pore space only and it is depends on the media porosity n, so, it may be expressed average interstitial Velocity V_a by Eq. 6:

$$V_a = \frac{V}{n} \tag{6}$$

Non-linear flow: Generally, the relationship between hydraulic gradient and seepage velocity for flow through coarse porous media is non-linear. There are many equations commonly used to describe the relationship between velocity and the hydraulic gradient for non-linear flow. The first equation for non-linear flow was proposed by Forchheimer (Bear, 1972) this equation is given as:

$$i = AV_a + BV_a^2 \tag{7}$$

where, A and B are coefficients which depend on voids structures of the porous media and water kinematic viscosity. The second commonly used non-linear power equation outlined by Missbach (Scheidegger, 1974):

$$i = wV_a^r \tag{8}$$

where, the two coefficients w and r depends on the state of flow and the properties of porous media and fluid. Flow through porous media using an analogy with flow in conduits has been expressed as a relationship between a Reynolds number and a friction factor f (Stephenson, 1979). In analyzing flow through porous media, Re as in Eq. 5 and the friction factor is defined as:

$$f = \frac{id_m}{V^2/2g} \tag{9}$$

where, g is the gravitational acceleration. Hansen *et al*. (1995) mentioned that it is possible to describe the flow through porous media by Eq. 10:

$$i = pV^m \tag{10}$$

where, the coefficient p depends on the properties of porous media and fluid and m is an index refers to the level of flow turbulence. The value of m is ranging from 1-2. When the value of m = 1, the flow is Laminar and Eq. 10 reduces to Darcy's law Eq. 4. For the value of m = 2, the flow is fully turbulent. Equation 10 can be written as equation:

$$V = \left(\frac{i}{p}\right)^{\frac{1}{m}} \tag{11}$$

Equation 4 is used to create many mathematical models within the field of water resources engineering such as a groundwater finite difference model MODFLOW. To use such models in the applications of gravel aquifers, the deviation from Eq. 4 must be considered. This requires modifying (Eq. 4) in the model to be suitable for the case of non-Darcian (non-linear) flow through the gravel. In this case, the Eq. 4 becomes:

$$V = K_d i \tag{12}$$

where, K_d is an adjusted hydraulic conductivity (LT^{-1}) which means the hydraulic conductivity of porous media under turbulent flow condition. Substituting Eq. 11 into Eq. 12 yields the following equation:

$$K_d = \frac{i^{\frac{1}{m}-1}}{p^{\frac{1}{m}}} \tag{13}$$

For i = 1, the K_d will be equal to a denominator of Eq. 13 and is a constant. In this study, Eq. 5-12 were used in the analysis of data. The values of coefficient p and m index for Eq. 10 will be employed in this study to derive K_d equations from flow through monosized gravel tests.

MATERIALS AND METHODS

Experimental work: In the following, the physical properties of different monosized gravel samples, materials classification the testing device used are briefly introduced. Moreover, the laboratory tests which were carried out to investigate the effectiveness of using different materials in K_d under different hydraulic gradient were summarized.

Gravel materials: The materials used in this study were seven monosized gravel samples with diameters (-4.75+4, -8+6.3, -9.5+8, -16+12.5, -19+16, -25+16 and -31.5+25 mm). The diameters of the used materials ranging between 4 and 31.5 mm. Materials were brought from the typical stone quarry of region of bahar annajaf in Al-Najaf Governorate, Iraq. Although, each sample was sorted and graded according to the American Society for Testing and Materials, ASTM it was washed in the laboratory to produce a suitable media for testing. Figure 1 shows photos for all the used gravel samples. The tap water was used in all laboratory tests. For each gravel sample, the gravel mean size which means an equivalent gravel diameter, particle density, porosity and shape factor were determined. To estimate the Shape Factor SF for the gravel samples 3 major axes were measured for the gravel particles using a vernier and the average axes lengths calculated for each sample. Shape factors were estimated using the following relationship (Hansen *et al*., 1995):

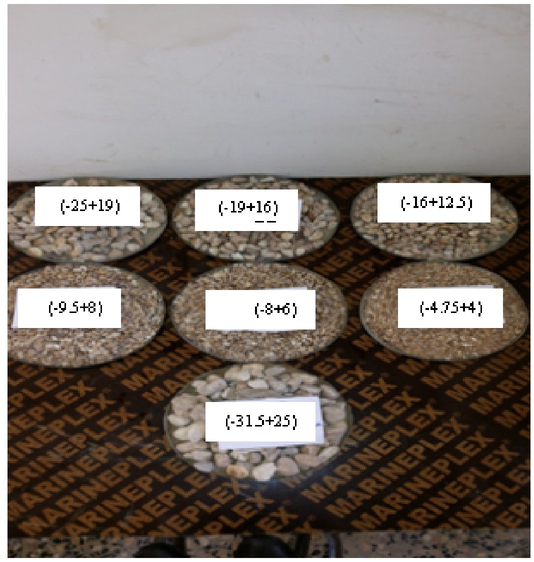

Fig. 1: Grading of monosized gravel samples in milimeters

Table 1: Properties of the monosized gravel samples

Monosized sample (mm)	Gravel mean size (mm)	Particle density (g/cm³)	Porosity (%)	Shape factor
(-4.75+4)	4.375	2.72	33.6	0.463
(-8+6)	7.00	2.75	35.6	0.497
(-9.5+8)	8.75	2.69	37.0	0.501
(-16+12.5)	14.25	2.71	41.3	0.497
(-19+16)	17.50	2.65	41.3	0.529
(-25+19)	22.00	2.69	42.3	0.512
(-31.5+25)	28.25	2.73	43.6	0.526

$$SF = \frac{c}{\sqrt{ab}} \tag{13}$$

Where:

a = Length in longest direction

b and c = The lengths measured in mutually perpendicular medium and short directions

(L) as shown in Fig. 2. Table 1 summarizes the properties of the three samples randomly drawn from each of the seven monosized gravel samples.

Hydraulic conductivity test rig: A new hydraulic conductivity test rig was constructed at the hydraulic laboratory at the Technical Institute of Karbala (TIK) to measure K_d for the selected gravel samples. TIK is located in the central zone of Iraq 32° 34' 35" North 44° 10' 24" East with an altitude of 28.5 m. The rig consists of a smooth walled PVC pipe (test pipe) that was 1.5 m long and 100 mm bore as shown in Fig. 3. This pipe was placed horizontally on a metal base and connected to cylindrical constant head tank with a 60 cm diameter. Besides, the rig consists of a 2 m^3 main tank and 800 l collector tanks supported by a metal frame. Two valves are used to control direction of flow. A range of hydraulic gradients was achieved by adjusting the elevation of water in the vertical PVC pipe that was 80 cm long and 103 mm bore using 6 taps installed on it. A piezometers board was fixed with dimensions 80×35 cm. This board contains two piezometers, the first measures the water level in the constant head tank while the second piezometer measures the water level in the vertical pipe. The rig was provided with a recirculation system with a capacity of 15 L/sec to divert water from collector to the main tank. Figure 4 shows a schematic diagram of the rig.

Tests procedure: This study describes the procedure that followed in carrying out laboratory tests. The experiments were conducted for various ranges of hydraulic gradient and flow discharge. Hydraulic gradient values used to conduct the experiments ranged between 0.01 and 0.237 while the discharge values ranged between 0.0149 and 0.255 L/sec. The total number of experiments that have been conducted is 250. The laboratory research included the calculation of K_d for all gravel samples used in this study. The K_d tests for each gravel sample were carried out with the following steps:

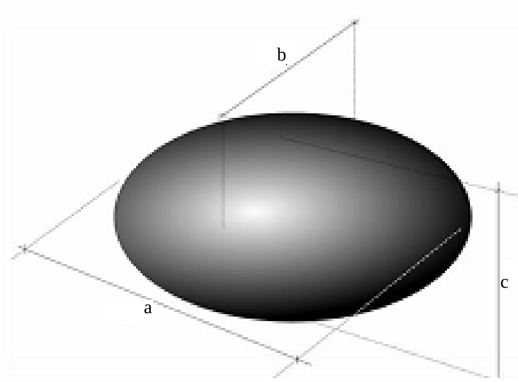

Fig. 2: Gravel particle principal axes

Fig. 3: General view of the hydraulic conductivity test rig

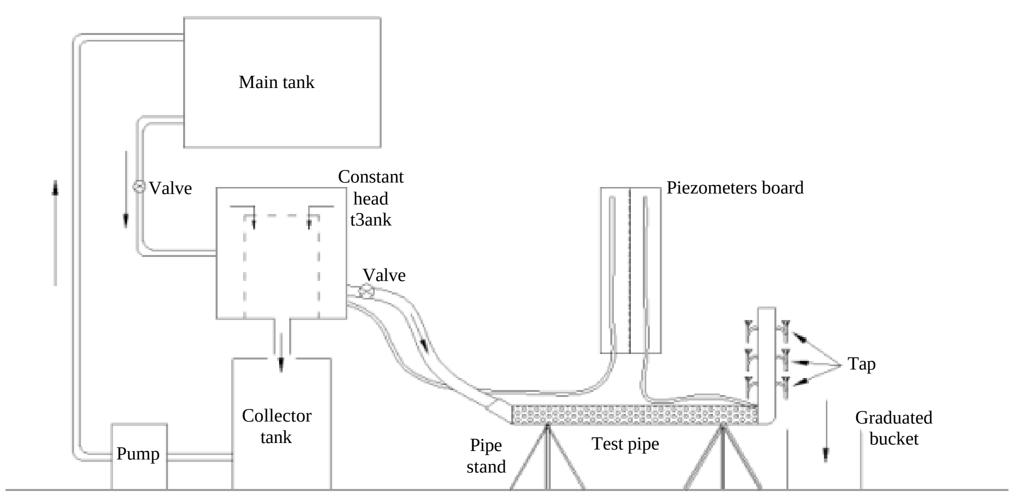

Fig. 4: Schematic diagram of the test rig

- Packing a particular gravel sample in a test pipe in 0.8 kg aliquots the sample were retained by mesh screens at both ends of the pipe
- Connecting the test pipe to the constant head tank
- Opening the supply valve for feeding the test pipe with water
- Adjusting a water elevation in the vertical pipe by controlling the discharge of the taps that installed on it
- Waiting 30 min, so that, water elevation equilibrium in the vertical pipe is established
- Recording a water level difference in piezometric board
- Recording water discharge of flow through the taps by using volumetric method
- Repeating step 75 times
- Measuring the water temperature during the test
- Calculating the hydraulic gradient, average discharge and bulk velocity defined as the result of the average discharge to the cross section area of the test pipe
- Calculating the adjusted hydraulic conductivity by using Eq. 12
- Changing the level difference in piezometric board (hydraulic gradient) several times by controlling the discharge of the taps and repeating steps from 4-11

RESULTS AND DISCUSSION

Variation of bulk velocity with hydraulic gradient: Figure 5 shows the relation between bulk velocity and hydraulic gradient for different monosized gravel sizes. Bulk velocity is directly proportional with hydraulic gradient. It is seen from Fig. 5 that bulk velocity increases as hydraulic gradient is increased for all gravel samples and for same hydraulic gradient the velocity increases as the gravel mean size increases. This result goes with what was indicated by Morii (2002). The gravel sample with d_m of (-31.5+25 mm) has the highest value of bulk velocity than that of other gravel samples. Experimental coefficients values of all the specified monosized gravel according to Eq. 10 are summarized in Table 2. Results of Table 2 showed that the m- index value increases by increasing the d_m. This result goes with what was indicated by Siddiqua *et al.* (2011). Figure 6 shows the variation of the m- index with d_m.

Variation of adjusted hydraulic conductivity with hydraulic gradient: Figure 7 shows the variation of adjusted hydraulic conductivity with hydraulic gradient for different gravel mean sizes. It is seen that the K_d decreases with increasing hydraulic gradient and that for same hydraulic gradient the K_d increases as the gravel mean size increases. Mulqueen (2005) obtained same result. The K_d for any gravel mean size can be estimated by the following power equation:

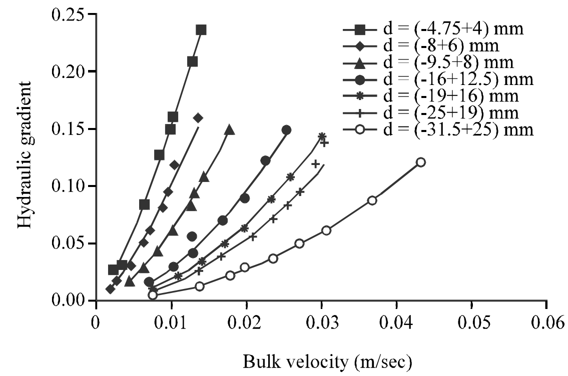

Fig. 5: Hydraulic gradient in relation to bulk velocity of flow through gravel

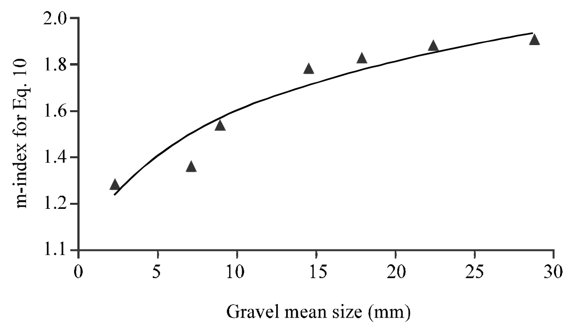

Fig. 6: Variation of the m-index with gravel mean size

Table 2: Experimental coefficients values according to Eq. 10

Gravel diameter (mm)	d_m (mm)	p (m/sec)	m	R^2
(-4.75+4)	2.1875	56.393	1.283	0.981
(-8+6)	7.0000	53.954	1.364	0.994
(-9.5+8)	8.7500	74.028	1.539	0.998
(-16+12.5)	14.2500	102.830	1.781	0.983
(-19+16)	17.5000	84.455	1.822	0.999
(-25+19)	22.0000	84.783	1.882	0.989
(-31.5+25)	28.2500	48.104	1.905	0.999

$$K_d = di^j \tag{15}$$

Where:

d = The coefficient of the adjusted hydraulic conductivity equation

(L/T) and j = The exponent of the adjusted hydraulic conductivity equation (dimensionless)

The K_d values for the seven d_m were obtained based on the Eq. 15 and are presented in Table 3. Results of Table 3 showed that the d value increases by increasing the gravel mean size (Fig. 6 and 7)(Table 2 and 3).

Table 3: Equations for estimating K_d of the gravel mean size

Gravel diameter (mm)	d_m (mm)	K_d equation	R^2
(-4.75+4)	2.1875	$K_d = 2940.2i^{-0.347}$	0.969
(-8+6)	7.0000	$K_d = 4581.5i^{-0.476}$	0.959
(-9.5+8)	8.7500	$K_d = 5248.7i^{-0.352}$	0.993
(-16+12.5)	14.2500	$K_d = 6328.7i^{-0.45}$	0.998
(-19+16)	17.5000	$K_d = 7560.5i^{-0.452}$	0.999
(-25+19)	22.0000	$K_d = 8024.6i^{-0.474}$	0.987
(-31.5+25)	28.2500	$K_d = 11295i^{-0.476}$	0.999

Table 4: Equations for estimating K_d of the gravel mean sizes

Gravel diameter mm	d_m (mm)	K_d equation	R^2
(-4.75+4)	2.1875	$K_d = 31101E07Re^{-0.448}$	0.964
(-8+6)	7.0000	$K_d = 40069Re^{-0.364}$	0.923
(-9.5+8)	8.7500	$K_d = 155122Re^{-0.539}$	0.982
(-16+12.5)	14.2500	$K_d = 2E06Re^{-0.801}$	0.981
(-19+16)	17.5000	$K_d = 3E06Re^{-0.822}$	0.995
(-25+19)	22.0000	$K_d = 7E06Re^{-0.882}$	0.953
(-31.5+25)	28.2500	$K_d = 2E07Re^{-0.905}$	0.996

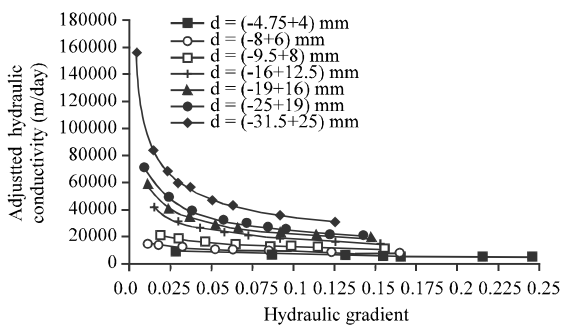

Fig. 7: Adjusted hydraulic conductivity of samples versus hydraulic gradient

Variation of adjusted hydraulic conductivity with reynolds number: Figure 8 plots K_d as a function of Re for various d_m. Figure 8 shows that at the same Reynolds number, the values of K_d increase by increasing the gravel mean size. In addition, for specific gravel sample the values of K_d decrease by increasing the Reynolds number. K_d values of the gravel samples depend on d_m and Reynolds number. Regression analysis with a power function was used to obtain an equation to estimate K_d values as a function of Re. Table 4 shows the equations for estimating K_d of gravel mean size in which K_d in m/day (Fig. 8).

Variation of friction coefficient with Reynolds number: Figure 9 represents the relationship between reynolds number and friction factor using the similarity concept between the flow through porous media and flow through pipes according to Eq. 5 and 9, respectively. As illustrated, increase of Re leads to decrease friction factor. It also shows that friction factor has high values at low Reynolds number. This result goes with what was indicated by Reddy (2006). After Reynolds values equal

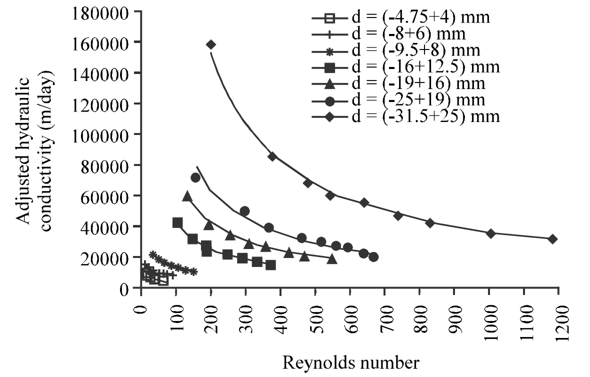

Fig. 8: Adjusted hydraulic conductivity of samples versus Reynolds number

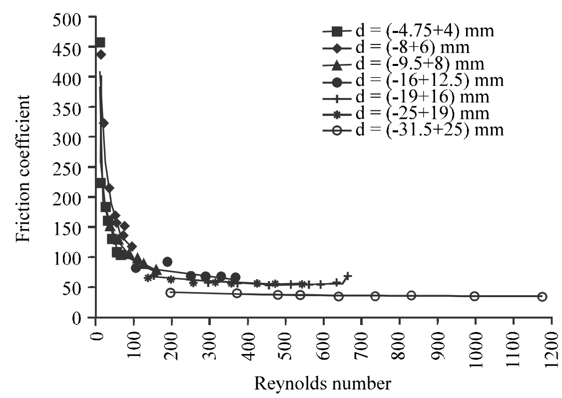

Fig. 9: Friction factor versus Reynolds number of gravel mean size

to or >200, friction factor decrease and it reaches an approximately constant magnitude. The increase in flow velocity through monosized gravel leads to increase the flow turbulence. Therefore, the kinetic forces will overcome the viscous forces and the coefficient of friction decreases similarly to the case in moody diagram.

CONCLUSION

In this study a series of laboratory experiments were conducted to investigate the flow through monosized gravel materials. According to the results of the laboratory experiments, the following conclusions were found. Bulk velocity through monosized gravel is directly proportional with hydraulic gradient. A strong non-linear relationship was found between hydraulic gradient and bulk velocity for all seven gravel mean sizes with average R^2 equal to a 0.99. Bulk velocity increases as hydraulic gradient is increased and for same hydraulic gradient the bulk velocity increases as the gravel mean size decreases. Adjusted hydraulic conductivity for monosized gravel decreases with increasing hydraulic gradient and that for same hydraulic gradient the adjusted hydraulic conductivity increases as the gravel mean size increases. A strong power formula was found between adjusted hydraulic conductivity for monosized gravel and hydraulic gradient for all seven gravel mean sizes with average R^2 equal to a 0.99. At the same Reynolds number, adjusted hydraulic conductivity for monosized gravel values increase with increasing values of the equivalent diameter of the gravel sample. Adjusted hydraulic conductivity for monosized gravel decrease by increasing the Reynolds number. A strong power formula was found between adjusted hydraulic conductivity for monosized gravel and Reynolds number for all 7 gravel mean sizes with average R^2 equal to a 0.97. Increase of Reynolds number leads to decrease friction factor for all gravel samples. Friction factor has high values at low Reynolds number. For Reynolds number equal to or >200, friction factor values decrease and it reaches an approximately constant magnitude.

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