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Critical Hydraulic Gradient for Sediment Transport Through Rockfill Structures

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Abstract: Rockfill structures are one of the most applicable structures in hydraulic engineering. Rockfill dams are always used to mitigate flood in the river to prevent damage in downstream of river basin. Since this type detention dams should carry large amount of sediment particles. Therefore a consideration should be taken to prevent from siltation of its pore system. To achieve this subject a minimum hydraulic gradient should be existed on the structure which is called critical hydraulic gradient for initiation of motion. Previously some semi theoretical researches were done on this aspect with different investigators but any general consideration was not accomplished to develop an equation which covers all available data series. In this research tried to collect all available data series for extraction a relationship with acceptable accuracy in the subject of sediment transport in porous media. An alteration was made on two basic existence relationships because of deflection from Darcy law. Then the coefficients of developed equation related to geometrical characteristics of rockfill media. Ultimately a favorable equation obtained with acceptable accuracy.

Key words: Rockfill structures; Sediment Transport; Critical hydraulic gradient; Non-Darcy flow

INTRODUCTION

Pervious rockfill dam is a type of detention dam which reduce the pick flow of the outflow hydrograph in the reservoir routing projects. This type of detention dam is a passing through flow structure capable to keep the dam and downstream river bed and bank more stable [1].

Sedimentation at upstream of the detention dam and scouring of the river bed and bank at downstream are two of the most important parameters which could affect the dam function and stability of high sediment concentration in the river. Especially during floods which results in sedimentation at the upstream of the dam and reduce dam storage capacity, it could be one of the restricting parameters in the detention dam function. In this regard, the design of rockfill dams should be done such that the available hydraulic gradient is kept greater than the critical hydraulic gradient [2].

Unfortunately most of previous investigators did not focus on sediment transport through large porous media. They mostly tried to introduce new relationships for water surface profile and flow characteristics in None Darcy flow condition for clear water. Just a few researches investigated on clogging process of pores in the porous media like Sakthivadivel [3], Joy [4], Wu [5], Schalchi [6], Wu and Huang [7], Indraratna and Radampola [8], Samani and Emadi [2], Mousavi *et al*. [9] and Nazemi *et al*. [1].

Based on an approach introduced by Duboys for open channel flow, Sakthivadivel developed a transport function for particulates. This approach envisaged the movement of the particulates as a series of sliding layers, each one grain thick. In the derivation of the transport function, the moving layers are driven by the excess shear stress applied by the fluid, i.e. that shears above some critical level. The moving layers themselves have a linear velocity distribution, the outer layer having a velocity equal to the seepage velocity and the innermost layer is

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stationary. The presence of the media was accounted for with an overall constant and a derived critical condition for the fines [4].

The critical hydraulic gradient is based on the stability of a single particle on a plane bed subjected to a shear stress parallel to the bed. No lift is considered. Using similar assumptions regarding the proportionality of shear, hydraulic gradient and seepage velocity, the critical condition is expressed as (equation 1):

$$i_c = k_c\left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right) \qquad (1)$$

In the above equations:

d_s = sediment particle size (m)
G_s = Specific gravity of sediment particles
φ = Angle of repose of sediments in the media
θ = Angle of bed to the horizontal
i_c = Critical hydraulic gradient for sediment transport (m/s)
k_c = Model constant

Conditions found in rockfills and embankments are such that the conditions assumed by Sakthivadivel are invalid. With these situations hydraulic gradients tend to be much higher and the pores somewhat larger. This in turn leads to the situation of non-linear (called none-Darcy) flow, i.e. the resulting seepage velocity is no longer proportional to the gradient with power of 1 and Darcy's law is invalid. Deviations from Darcy's law typically begin at a media Reynolds number ($R_m = \frac{V d_m}{n\vartheta}$; ϑ = fluid viscosity, n = media porosity, d_m = media size), of somewhere between 1 and 10 inclusion of the porosity in the expression for Reynolds number essentially converts the seepage velocity to the interstitial velocity (Bear, 1972).

Samani and Emadi [2] improved the Sakthivadivel's formula to model the critical hydraulic gradient in turbulent flow. They introduced $(\cos\theta \tan\varphi - \sin\theta)$ in power form. They conducted 18 laboratory tests in which rock particle sized were between (1.45 and 2.1) cm and proposed following formula (equation 2):

$$i_c = 1.67\left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right)^{4.7} \qquad (2)$$

Mousavi *et al*. [9] followed the same approach and number of tests to improve the Sakthivadivel's formula for different rock particle sizes (3 and 4.5cm) and proposed following equation (equation 3):

$$i_c = 22.139\left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right)^{1.066} \qquad (3)$$

Nazemi *et al*. [1] arranged extensive experiments by conducting a series of larger scale and more equipped laboratory tests than previous studies to investigate critical hydraulic gradient in rockfill dam. Along with improvement of Sakthivadivel's equation including inertia effect and rocfill media characteristics. He introduced the constant coefficient of equation in terms of Reynolds number (R_e) and size ratio between media and sediment particles (λ) and calibrated it with his laboratory data (equations 4, 5, 6 and 7).

$$i_c = k_c\left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right) \qquad (4)$$

$$i_c = a\, R_e^b\, \lambda_1^c \left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right) \qquad (5)$$

$$\mathrm{R_e} = \frac{V\left(d - \delta\right)}{n\vartheta},\ \lambda_1 = \frac{\left(d - \delta\right)}{d_s} \qquad (6)$$

$$i_c = 600\ \mathrm{R_e}^{-0.748}\ \lambda_1^{0.094}\left(G_s - 1\right) g d_s \left(\cos\theta \tan\varphi - \sin\theta\right) \qquad (7)$$

Where: R_e Reynolds number, λ_1 = size ratio, d = media size, δ = standard deviation of media particles. The other parameters are introduced previously.

Indraratna and Radampola [8] tried to propose an explicit solution for the critical hydraulic gradient required to move a base particle within a pore channel. In their research the particle was assumed to displace when the applied hydrodynamic forces exceed the critical hydraulic gradient. They modified the limit equilibrium analysis of their previous research such that to include the effect of drag in the hydrodynamic force component. They also examined theoretical model in the laboratory using fine gravel filters and a cohesionless base soil consisting of very fine river sand.

They included Pressure and viscous drag forces due to flow, the gravity and uplift forces as well as the frictional resistance in their theoretical model. The movement of a particle maximum dimension less than the pore diameter can be described according to three possibilities which are outlined as below (Indraratna and Radampola [8]):

1 The particle will either propagate through a certain distance and then become stationary again, or
2 It will be completely washed out from the system, or
3 It will stop when it reaches a smaller pore or a pore comparable to its size. The above situations will be elaborated in the following section

Table 1: Experimental characteristics of data series

No.	Data index	Name of investigator and year of research	Number of Media diameter	d_{50} of Medium diameter (mm)	d_{50} of sediment diameter (mm)	Range of Media Reynolds number	Medium length, width and height (m)
1	SC-1	Samani and Emadi (2003)	2	14.5 and 21	0.256, 0.363 and 0.512	1100-4000	0.6, 0.3, 0.3
2	SC-2	Mousavi (2011)	2	30 and 45	0.15, 0.27 and 0.36	7000-13000	0.3, 0.6, 0.7
3	SC-3	Nazemi (2011)	2	50 and 120	0.425, 0.6 and 0.85	2000-20000	0.78, 0.6, 0.58

They have presented tow relationship for tow general mood of derivation i) free movement of particle inside of pore tube (equation 8) ii) plugged tube of pore system by sediment particle (equation 9).

$$i_c = \frac{2}{3\gamma w} \frac{d^2}{\left(d^2 + 0.375\, d_0^2\right)} (\gamma') \left[\cos\theta\,(f) + \sin\theta\right] \tag{8}$$

$$i_c = \frac{2(\gamma')}{3(\gamma w)} \left[\cos\theta\,(f) + \sin\theta\right] \tag{9}$$

Where: λ_w specific weight of water, λ' submerged weight of sediment particles, d = median size of media, d_0 minimum pore diameter

Most of above mentioned investigators have focused on basic relationship which was presented by Sakthivadivel and calibrated its coefficients with their experimental data for both liner and none-linear condition. But a general relationship which uses all of available data with better estimation is not presented yet.

Nevertheless the results of every investigator show some limitations such as rock particle sizes and ignorance of inertia of turbulent flow and ignorance of real field condition which should be generalized.

Laboratory and Experimental Conditions of Data Series: The data which were used in this research were collected from three different sources. All of them were operated in sediment contained flow through condition. The brief characteristics of experimental testes which were used in this research illustrated in the Table. 1. Total numbers of experiments were 90. All of experiments were accomplished in the None Darcy flow condition but as is mentioned with previous investigators, fully developed turbulent flow occurs in the Reynolds Number larger than 200, therefore all of experiments were also operated in the fully developed turbulent flow. It is also noteworthy to mention that all of these experiments were operated in the free water surface conditions and none of them were in the pressurized condition. In the all of data sets during the operation water profiles were measured using image processing from piezometers.

RESULTS AND DISCUSSION

The available sediment transport discharge of mentioned data series is depicted versus pore media velocity (Fig. 1). As is illustrated in Fig, by increase in pore velocity inside of the media, the sediment transport discharge increases. By intersecting of regression line with horizontal axis which shows a zero sediment rate, it was observed that a minimum pore velocity (representative of an especial magnitude of Reynolds number) is necessary to initiate sediment transport through the media. This fact is showing necessity of existence of critical hydraulic gradient for initiation of motion of sediment particles.

As is illustrated in Fig. 2, by increase in size ratio the requirement critical gradient decreases. The illustrated trend is in such a way that with increase from especial magnitude in the size ratio, the requirement gradient for initiation of motion of sediment particles through the media limits to the minimum value. Otherwise by decreasing of size ratio, the requirement critical gradient suddenly increases in asymptote condition to vertical axis.

It is essential to conclude a favorable equation from previously presented literature such that could estimate critical hydraulic gradient with acceptable accuracy. To achieve this purpose some modifications were done to Sakthivadivel's basic equation and Indraratna's one to change them to nonlinear condition and Then all of previously calibrated equations compared with them.

By equalizing of d with d_0 in the equation of (8) and changing it to the power form equation (Because of deflection from Darcy law) (equation 10), it was found that calibrated equation (equation 11) has a weak estimation capability with average error of 130%. It is also noteworthy to mention that because of some another factors which is not considered, in the sediment transport cases there is some uncertainty. Therefore an equation would be reliable which could estimate the subject with accuracy of ± 40 %.

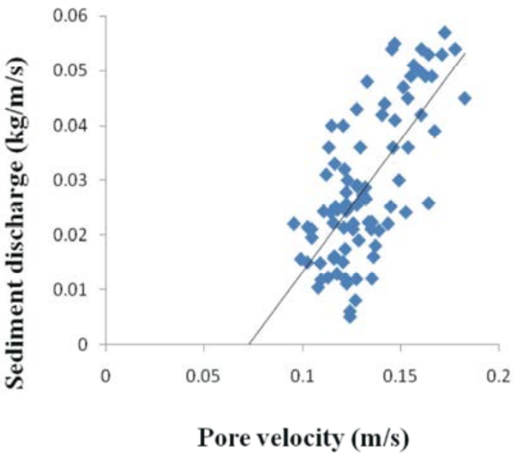

Fig. 1: Sediment discharge versus media pore velocity

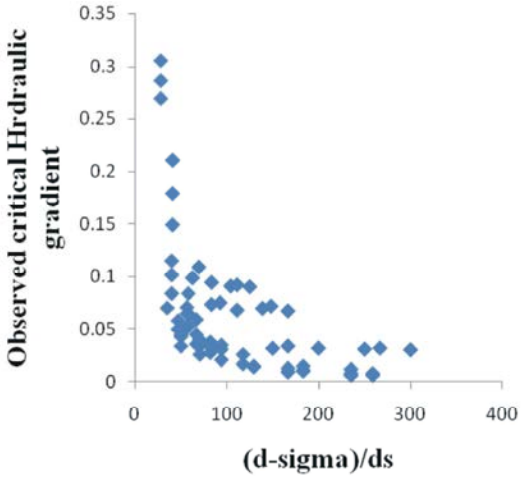

Fig. 2: Observed critical gradient versus size ratio

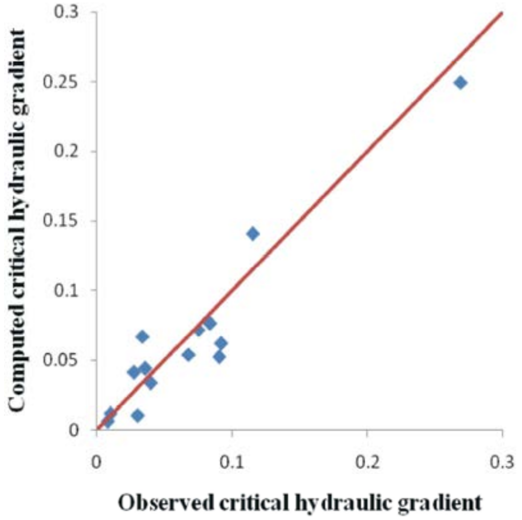

Fig. 3: Observed critical gradient versus computed gradient

$$i_c = a\left[\cos\theta\,(f) + \sin\theta\right]^b \tag{10}$$

$$i_c = 0.089\left[\cos\theta\,(f) + \sin\theta\right]^{1.338} \tag{11}$$

The most famous relationship for estimation of critical hydraulic gradient through the rockfill media is Sakthivadivel's relationship. Previously Samani and Emadi [2] and Nazemi *et al*. [1] have done some corrections to develop a new relationship for None Darcy flow through rockfill by changing equation form to power form and relating its constant to variables of flow and media characteristics. But unfortunately they did not generalize their research to other investigators data. Therefore there is not any general relationship to cover all available data with acceptable accuracy of estimation.

Otherwise, it is better for any relationship in estimation of critical gradient to relate geometrical characteristics of media with critical gradient for some practical aspects. Indeed an engineer should be able to estimate requirement characteristics of rock material for design of structure. This is an important subject which Nazemi [1] did not consider it.

In the present study another tow geometrical none dimensional parameters (λ_1 and λ_2) were developed instead of constant coefficient of relationship (equation 12). For another consideration for better estimation of gradient relationship, two other types of exponent were imposed to the relationship (equations 13, 14).

$$\lambda_1 = \frac{(d_m - \delta)}{l},\ \lambda_2 = \frac{(d_m - \delta)}{d_s} \tag{12}$$

$$i_c = a\,\lambda_1^{a}\,\lambda_2^{\beta}\left[(G_s - 1)\,gd_s\left(\cos\theta\,\tan\varphi - \sin\theta\right)\right]^{\gamma} \tag{13}$$

$$i_c = a\,\lambda_1^{a}\,\lambda_2^{\beta}\,(G_s - 1)\,gd_s\left(\cos\theta\,\tan\varphi - \sin\theta\right)^{\gamma} \tag{14}$$

It was found that form of (12) has better estimation rather than (13) for all of data series with average error of 30% which in the sediment transport subjects is acceptable. The coefficients and constants of the proposed relationship then calibrated and illustrated in equation (15). The observed critical gradient versus

$$i_c = 10335\,\lambda_1^{1.33}\,\lambda_2^{-2.97}\Big[\big(\boxed{G}_s - 1\big)\,gd_s \\ \left(\cos\theta\,\tan\varphi - \sin\theta\right)\Big]^{-0.86} \tag{15}$$

Predicted magnitudes are depicted in Fig. 3 for data series that did not participate in equation development. As is shown, the data points are about line of agreement.

CONCLUSION

In this research an improved form of Sakthivadivel's equation was introduced for design consideration of rockfill detention structures for aspect of sediment contained flow through. The advantage of presented equation is calibration with all available data from three different sources. It is important for an engineer to estimate required hydraulic gradient with geometrical characteristics of rock material. Therefore in developing new relationship tried to focus on rock characteristics rather than flow characteristics. Validation of presented formula is also done with another series of data which did not participated in calibration of presented formula. And it was found that the predicted magnitudes of hydraulic gradient are about line of agreement with observed magnitudes.

REFERENCES

1. Nazemi, A., 2011. "Flow hydraulics and sediment transport through pervious rockfill detention dams", Ph.D Thesis, University of Putra, Putra, Malaysia.
2. Samani, J. and A. Emadi, 2003. "Introducing the relationship of critical hydraulic gradient to noncohesive sediment transport in rockfill dams" Paper presented at the 4th Iranian Hydraulic Conference, Oct. pp: 21-23. Shiraz, Iran.
3. Sakthivadivel, R., 1972. "Sediment Transport through a Porous Column", In Shen, H W, Ed, Sedimentation.
4. Joy, D.M., W.C. Lennox and N. Kouwen, 1991. "Particulate Transport in Porous Media under Non-linear Flow Condition", Journal of Hydraulic Research, 29(3): 373-385.
5. Wu, F.C., 1993. "Stochastic Modeling of Sediment intrusion in to Gravel bed", Ph.D Thesis, University of California, Berkeley, California.
6. Schalchli, U., 1995. "Basic Equation for Siltation of Riverbed", Journal of Hydraulic Engineering, 121(3): 274-287.
7. Wu, F.C. and H.T. Huang, 2000. "Hydraulic resistance induced by deposition of sedimentation in porous media.", Journal of Hydraulic Engineering, 126 (7): 547-551.
8. Indraratna, B. and S. Radampola, 2002. "Analysis of Critical Hydraulic Gradient for Particle Movement in Filtration.", Journal of Geotechnical and Geoenvironmental Engineering, 128(4): 347-350.
9. Mousavi, S.A., E. Amiri-Tokaldany and M.H. Davoudi, 2010. "A relationships to determine the critical hydraulic gradient and non-cohesive sediment transport discharge in rockfill dams" Research journal of Environmental sciences.