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Effects of Land Slope and Flow Depth on Retarding Flow in Gravel-Bed Lands

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Abstract: Hydraulic calculations of the flow in channels and overbank areas of flood plains require an evaluation of roughness characteristics. The Manning roughness coefficient (*n*), Chesy coefficient (*C*) and Darsy-wesbach coefficient (*f*) are used to describe the flow resistance or flow retardation in canalized flow. In catchment areas, surface flow is shallow and non-canalized, thus velocity and roughness coefficients can't be determined. Flow depth and bed slope are the most effectual parameters of flow retardation in gravel-bed lands. In this study, a functional relationship between velocity of flow and bed slope is developed in order to covert velocity of flow to bed slope for estimation of roughness for non-canalized flow in gravel beds. Four rounded particles with different median sizes have been tested under different flow conditions in a 10 meter long flume. Coarse particles were placed in the middle of the flume. Water surface profile and flow velocity were measured. The results showed that the friction factor was considerably decreased, thus flow was less retarded with increase of bed slope as a result of increase in flow velocity. Also, friction factor decreased with increase of flow depth due to greater submergence of bed particles.

Key words: Flow retardation · Gravel-bed · Friction factor · Non-canalized

INTRODUCTION

Hydraulic resistance of open-channel and overland flows result from the viscous and pressure drag over the wetted perimeter. Hydraulic resistance of the watercourse determines the water level and flow distribution in the basin. Such resistance is commonly represented by parameters such as Manning's Roughness coefficient (*n*), Chezy's resistance factor (*C*), or the Darcy-Weisbach friction factor (*f*), among which Manning'*n* is most frequently used in the computation of open channel and over land flows. Reliable results of flood routing and undation simulation rely on an accurate estimation of the resistance coefficient [1]. The terms*C*, and *f* appear in the Manning, Chezy and Darcy-Weisbach equations for open-channel flow :

$$V = \frac{1}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad \text{(Manning Eg.)} \quad (1)$$

$$V = \sqrt{\frac{8g}{f}} \sqrt{RS_f} \quad \text{(Darcy-Weisbach Eq.)} \quad (2)$$

$$V = C\sqrt{RS_f} \quad \text{(Chezy Eq.)} \quad (3)$$

In which V = flow velocity, R = hydraulic radius, S_f = friction slope, g = acceleration of gravity and n = Manning's coefficient, f = Darcy-Weisbach's coefficient and C = Chezy's coefficient are related to each other by:

$$\sqrt{\frac{f}{8}} = \frac{n}{R^{1/6}} \frac{\sqrt{g}}{K_n} = \frac{\sqrt{g}}{C} = \frac{\sqrt{gRS_f}}{V} \quad (4)$$

Thus, knowing the value of one resistance coefficient, the corresponding values of the other resistance coefficients can be computed [2].

Many studies have been considered about effect of different factors on roughness coefficient. Strickler was the pioneer and presented the following general relation for predicting Manning's coefficient in coarse bed material canals [3]:

$$n = C_n K_s^{\frac{1}{6}} \quad (5)$$

Where:
C_n is a coefficient. Over the past decades many investigators have developed several relations similar to the Strickler's relationship.

Resistance to flow is intimately related to bed configurations: ripples, dunes, antidunes, chutes and pools. A relationship between stream power, diameter of bed material and bed configuration has been developed

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by Simons and Richardson [4]. There are several methods for determining the effects of trees and grass on main channel and floodplain resistance to flow. Thornton *et al.* [5] produced a predictive expression to permit the estimation of the apparent shear stress, average velocity and depth in both the main channel and floodplain. Several semi-analytical and purely empirical formulations for flow resistance in steep streams have been proposed. Of special interest are the formulations developed in [6-9]. Soto [10] proposed four empirical formulas based on data from Chilean rivers, for small and intermediate range of roughness ($1 \prec Y/D_{84} \prec 12.5$). Bathurst [6] has shown the flow resistance for channels with large-scale roughness to be a function of channel shape, roughness spacing and relative roughness. Thompson and Campbell [8] related resistance solely to relative roughness. Bathurst [7] considered resistance in mountain rivers. Twenty-seven carefully selected field datasets from seven literature sources are therefore analyzed empirically to show at-a-site variations in resistance, with the aim of improving the accuracy and applicability of mountain river flow resistance relationships. Considering only the bed grain roughness, the principal factors likely to determine flow resistance are identified as relative submergence Y/D_{84} (where Y is depth and D_{84} is the bed material 84 percentile size) and channel slope. The dependency of the resistance function $(8/f)^{1/2}$ (where f is the Darcy-Weisbach resistance coefficient) on Y/D_{84} is more accurately described by a power law than by a semi-logarithmic law, especially at large flow rates. However, as stated by Bathurst [6], the general resistance equation for different conditions in mountain rivers is yet to be developed. Shafai and Bahrami [3] considered effect of Manning's roughness of channels covered with different gravel shapes. In this study experimental tests were conducted to determine the Manning's roughness values for open channel covered with natural and broken rock particles. The results from this study show that the relative roughness, Froude number and friction slope are very important parameters which must be considered in predicting Manning's roughness.

Many investigations have been conducted to estimate flow resistance of submerged and non-submerged vegetation. Kouwen [11] and Fathi-Moghadam [12, 13], based on dimensional analysis and experimental results, developed a mathematical model for estimation of the friction factor for flow through submerged and non-submerged vegetation zones of waterways.

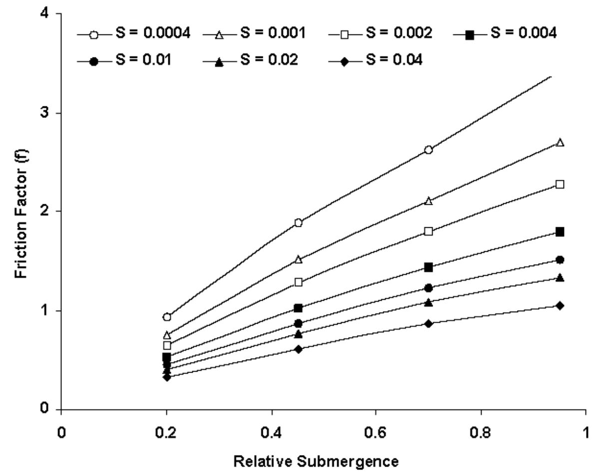

Fig. 1: Variation of friction factor (f) with flow depth and slope for non-submerged cedar tree models [14]

In accordance to the aforementioned literature, many empirical and quasi-empirical equations have been derived for the estimation of flow resistance in rivers and floodplains. However, resistance equations are primarily based on the channel velocity of flow which is not easily estimated for open lands. Non-canalized flow in open lands is normally expressed by slope rather than velocity.

Fathi-Moghadam [14] considered effects of bed slope and flow depth on retarding flow in Non-submerge vegetated beds. To evaluate effects of flow rate and flow depth on friction factor, tree models of pine and cedar were subjected to a series of flow rates at different flow depths. To include effects of bed slope on the analyses in this study, boundary shear approach (instead of direct drag force measurement) and dimensional similitude were used to develop a relation between flow velocity and bed slope. The results for variation of friction factor (f) with flow depth and bed slope are illustrated in Figures 1 and 2 for cedar and pine tree models. Results show that friction factor was considerably decreased, thus flow was less retarded with increase of bed slope as a result of increase in flow velocity and streamlining of the vegetation.

Recently, effect of roughness coefficient of rivers on synthetic unit hydrographs is evaluated [15]. The purpose of this study is to estimate effects of land slope and flow depths as the main parameters to balance run away and retardation of water for non-canalized flow in gravel beds. Advantages of the method over existing methods for estimating resistance factors is its ability to account for the interaction between bed particles and flow, taking into account velocity, depth of flow and the median size of

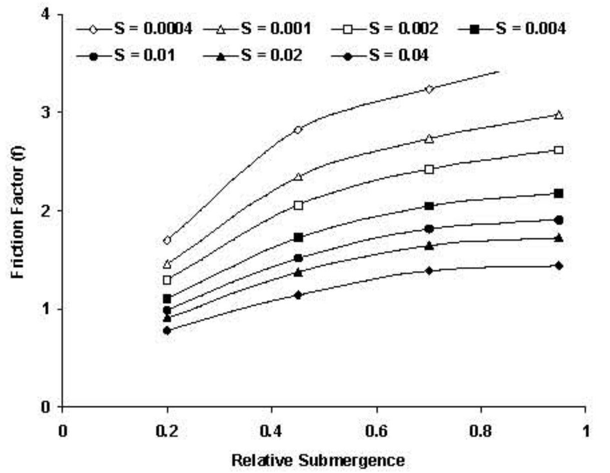

Fig. 2: Variation of friction factor (*f*) with flow depth and slope for non-submerged pine tree models [14]

the bed material (d_{50}). In contrast with the flow velocity, the bed slope is a geometric parameter that is more suitable and easy to measure for non-canalized flow in open lands. Hence effects of flow depth and bed slope on friction factor and flow retardation were estimated.

MATERIAL AND METHODS

To reach the goals of this study, extensive tests are conducted in the hydraulic laboratory of Shahid Chamran University, Ahwaz using a laboratory flume of 10 meter long, 25 cm wide and 50 cm depth. Figure 3 shows the cross sectional view of the experimental flume.

Flow depth (Y) was measured by a precision point gage with reading accuracy of 0.1 mm. A Nixon probe micro-propeller was used to measure flow velocity (V). A sharp V notch weir down stream of the flume was used to control the flow rate (Q) and check the micro-propeller readings. Ks' were measured as the size of gravel that was laid in the channel bed.

In this study four rounded particle with different median sizes (11, 16, 21 and 27 mm) was tested under different flow conditions. The procedure for each test was as follow:

- Slope of the flume fixed (0.0005).
- Bed material was glued on the test section.
- Pump was turn on and the flow allowed entering the flume at a desired discharge.
- Water surface profile along the flume and the flow velocity within the test section were measured.
- Flow discharge increased and the above steps were followed.
- New bed material was glued on the flume bed and the above procedures were repeated until all bed material was tested. It should be noted that in all tests the flow condition was hydraulically rough (with Reynolds numbers ranging between 10^5-10^6).

Formulations: To determine the Darcy Weisbach's coefficient from Eq. 2, the slope of energy grade line first was determined from the following equation:

$$S_g = \frac{(Y_1 + \frac{V_1^2}{2g}) - (Y_3 + \frac{V_3^2}{2g})}{\Delta X} \quad (6)$$

Where:

Y and V are flow depth and flow velocity respectively. The subscript 1 and 3 refers to the upstream and downstream section at the test section. ΔX is the distance between two sections which in this study is equal to 3 meters. Then the friction slope was determined from:

$$S_f = S_0 + S_g \quad (7)$$

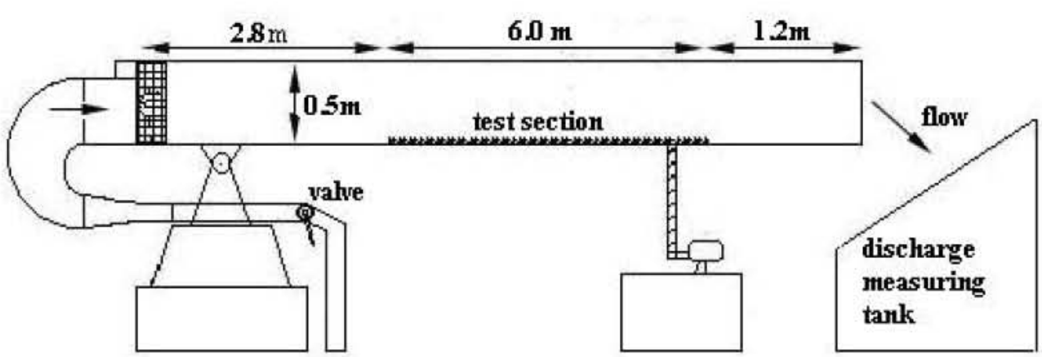

Fig. 3: Experimental flume

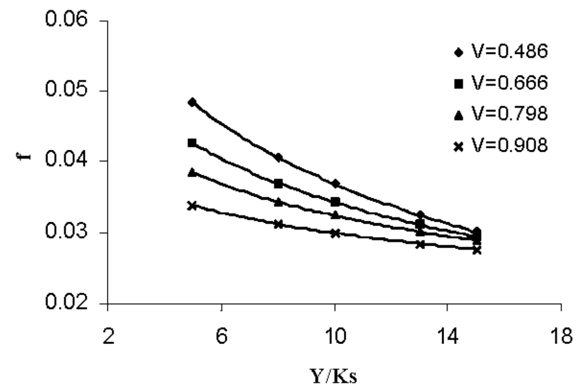

Fig. 4: Variation of friction factor (*f*) with flow depth and flow velocity

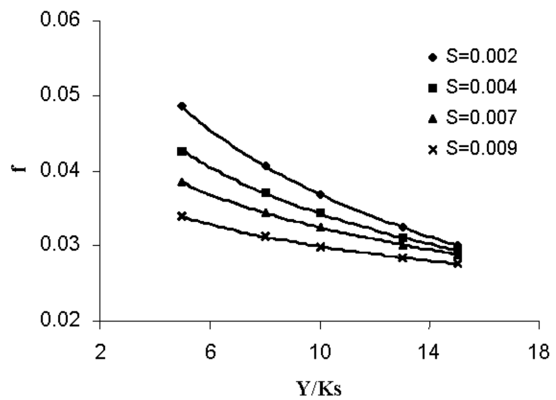

Fig. 5: Variation of friction factor (*f*) with flow depth and slope

RESULTS AND DISCUSSION

Variation of correlated friction factor (*f*, estimated from equation 2) for five relative depths of submergence (Y/K_s = 5, 8, 10, 13 and 15) and four flow velocities (V = 0.486, 0.666, 0.798 and 0.908 m/s) to are shown in Figure 4. To avoid complication, correlated friction factors were averaged and their velocity curves denoted by V in the Figure.

As it can be seen from this figure, friction factor (*f*) decreases as relative submergence (Y/K_s) increases as expected. Figure 4 shows inverse variation of friction factor with flow depth and flow velocity as was reported by kouwen [10]. This is due to the streamlining of flow through roughness elements and decrease of shear at outer layers of the boundary layer.

Fathi-Moghadam [14] used a dimensional similitude and relationship between boundary shear stress and friction factor to develop a functional relationship between velocity of flow and bed slope as:

$$\frac{S_1}{V_1^2} = \frac{S_2}{V_2{}^2} \tag{8}$$

Equation 8, can be used to covert the flow velocity data to the related bed slope data where a reference bed slope (S_1) and flow velocity (V_1) are available.

In a rational method, equation 8 can also be directly used to convert equal velocity curves in Figure 4 to equal slope curves for estimation of friction factor (*f*). In this study, reference average velocity (V_1) of 0.486, 0.666, 0.798 and 0.908 m/s respectively (recorded at reference slope S_1=0.0005 were used in equation 8 to calculate related slopes (S_2) for a range of velocities (V_2) from 0.5 m/s to near 1.3 m/s. The results for variation of friction factor (*f*) with flow depth and bed slope are illustrated in Figure 5. The figure shows that friction factor (*f*) decreases as the channel slope and velocity increase. The friction factor is also decrease as the relative flow depth increases.

CONCLUSIONS

A functional relationship was used to evaluate effects of flow depth and bed slope on friction factor as a parameter to measure flow retardation for non-canalized flow in open lands and watersheds. The following conclusions were obtained:

- The friction factor (*f*) or flow retardation is inversely proportional to the flow depth in gravel bed-rivers.
- The friction factor (*f*) or flow retardation decreases with increase of bed slope and flow velocity.
- Use of equation 8 allowed the flow velocity measurements to be replaced by bed slope as a geometric parameter that could be measured more easily in non-canalized gravel beds.
- Direct measurements of slopes less than 0.001 contribute large errors in short experimental flumes. Therefore, application of equation 8 has the advantage of excluding these errors when higher measured slope and flow velocity are used as reference to calculate lower ranges of slopes and flow velocities in practice.

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Notation: The following symbols are used in this paper:

C = Chezy's coefficient
d_{50} = Diameter of bed particles for which 50% are finer
D_{84} = Diameter of bed particles for which 84% are finer
f = Darcy-Weisbach's coefficient
g = Acceleration of gravity and
K_s = Equivalent gravel roughness
n = Manning's coefficient
R = Hydraulic radius
S_0 = Slope of channel bed
S_f = Friction slope
V = Flow velocity
Y = Flow depth
Y/K_s = Relative submergence
$\triangle X$ = Distance between two sections