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# RELATION BETWEEN BED FORMS AND FRICTION IN ALLUVIAL CHANNEL FLOW IN THE CONTEXT OF SEDIMENT TRANSPORT

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## ABSTRACT

*This paper reports development of a relationship between friction factor of bed with ripples and the size and other geometric properties of these bed forms. The objective of the present study is to establish a relationship of these bed forms to theory of resistance to flow in lower flow regime. Such a relationship has been established between the ripple friction factor and the parameter modified relative roughness. An empirical relationship has also been developed for computation of area average mean velocity of flow using experimental flume data.*

*Keywords : Alluvial Channel, Bed Forms, Friction Factor, Relative Roughness, Sediment Transport*

## 1.0 INTRODUCTION

The problem of resistance to flow over alluvial beds has received considerable attention during recent years. Almost all the tasks associated with alluvial channels namely preparation of stage-discharge curves, determination of sediment transport rates, design of stable channels, prediction of aggradations and degradation due to the presence of hydraulic structures, etc require an appropriate resistance law for their solution. In alluvial channels, the movement of the bed material is accompanied by the formation of undulations on the bed; the nature and size of these bed forms have been found to change appreciably with changes in flow condition. When the bed consists of medium or finer sand and when the velocity is only slightly greater than the critical tractive force offered by the bed, ripples form on the bed. If the mean velocity is increased beyond the value, which will just produce ripples, the sediment transport rate will increase and the bed form will tend to change such that the friction factor increases to a maximum and then decreases. A particular state of velocity and sediment discharge is finally reached where the ripples tend to be obliterated. This is the bed condition known as transition. Before transition occurs, the bed forms increase in length and height with a sharp crest.

## 2.0 LITERATURE STUDY

Relationships for resistance to flow in alluvial channels were proposed by Einstein and Barbarossa (1), Vanoni and Hwang (2), Lam (3) and several Japanese Engineers. Einstein and Barbarossa divided the bed resistance into two parts. The first part of the bed resistance was due to sand grain. Second part was the form resistance of the bed forms which was a function of sediment transport rate. Bed configurations for steady flow were observed by many investigators such as Garde and Ranga Raju (4) and Simons and Richardson (5). Garde and Ranga Raju concentrated on the study of the variation of the average ratio between the length and height of dunes. Simons and Richardson observed that sediment bed patterns also depend on the absolute width of flumes used. A study particularly in “Depth discharge relations in alluvial channels” was conducted by Simons and Richardson (6). The study remained concerned mainly with depth discharge relationship. It is not known whether in these studies systematic investigation about bed configuration and sediment transport has been made with different rate of change of discharge intensity with time. Relationships for flow resistance in alluvial channel were investigated by Yang

(7) and Kumar (8). Although many relationships for flow resistance have been put forward, they are applicable only to flows with dunes and other higher flow regimes corresponding to plane bed, standing wave and anti-dunes. A relationship that is applicable for ripples is not yet available and will form the subject of this research work.

## 3.0 WORKS DONE

The present investigation is concerned with developing a relationship between the friction factor of bed covered with ripples and the size and other geometric properties of these bed forms from the experimental flume data. An empirical relationship has been developed for computation of area average mean velocity of flow using flume data.

### 3.1 Experimentation

Experiments were conducted in a tilting flume 21.29 m long, 0.4562 m wide and 0.6082 m deep with glass walls and depth of sand bed 0.1521 m. Experiments were conducted for different hydrographs with different width to depth ratio of the channel. The widths to depth ratios were 2.5, 3, 3.5,4 and 4.5. For one set of hydrograph, duration of each stage was one hour during rise and one hour during recession. In the first phase, experiments were conducted with a particular bed material and bed slope. Then in subsequent phases, bed material and bed slope were varied. D50 of the bed material was 0.285 mm and bed slopes were adjusted to 0.0014, 0.002 and 0.0026. D50 of the bed material was chosen in a manner to avoid transition zone, from ripples to dunes and vice-versa. The study zone of 12.16 m in length in the flume was divided into four sections of observation. The data namely bed profile along the longitudinal section, water depth at pre-determined locations, velocity distribution along the vertical in a section of observation, plan view photographs of the bed forms were collected during each stage on both rise and recession period of the hydrographs. All observations during the above flume experiments were taken in ripple regime.

### 3.2 Instrumentation

The photograph of the experimental flume is shown in Fig. 1. A motorized carriage with all sensors mounted on it traverses the study zone of the flume (shown in Fig 2) from upstream direction to downstream direction. The speed of the motorized carriage was adjusted to 3 cm / sec and the motorized carriage usually takes seven minutes for traversing the study zone. Two nos. of Electronic Profile Indicators (PV-09 System, imported from Delft Hydraulics Netherlands), were mounted on the carriage to record the bed profile along the longitudinal sections of the flume. These Electronic Profile Indicators (PV-09 System) are capable of sensing bed level variation of the order of 0.2 mm. Velocities at 0.2 D, 0.4 D, 0.6 D and 0.8 D were measured in a section of observation. A personal computer based Data Acquisition and Control Room was constructed where all the sensors were connected to the PC based Data Acquisition and Control System (PCDACS) through remote-sensor interface electronics. A software system G-Lab was installed in the PCDACS to suit our experimental requirements. View of the experimental Set up is shown in Fig. 3.

**Fig 1** : View of the experimental flume

**Fig 2** : Photograph of the Bed Profile Indicator (PV-09 System) mounted on the motorized carriage

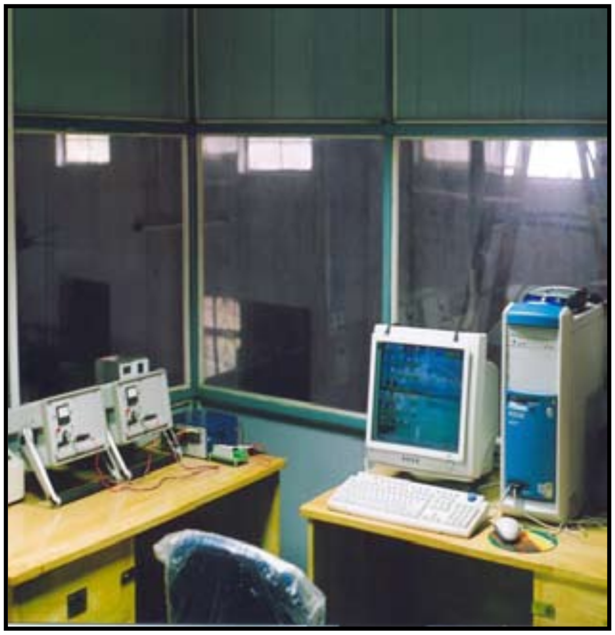


**Fig 3** : View of the PCDACS set-up

## 4.0 ANALYTICAL CONSIDERATION

The mean velocity U can be expressed in terms of Darcy Weisbach friction factor, f,

by the relation (Vanoni and Hwang 1967)

$$U = \sqrt{8/f}\,\sqrt{g\,r\,s} \qquad ...(1)$$

Where g is the acceleration of gravity, r is the hydraulic radius of the water cross-section and s is the channel slope. The quantity $\sqrt{g\,r\,s}$ is called the shear velocity and $\gamma rs$ is the mean shear at the boundaries of the channel, in which $\gamma$ is the specific weight of the flowing water. The quantity $\sqrt{8g/f}$ is known as Chezy's coefficient.

In alluvial channels with beds covered with ripples, the roughness of the sides is usually different from that of the bed so that the mean shear stress on the channel boundaries is not a good estimate of the shear stress on the bed. This estimate may be improved by using the side-wall correction procedure. This gives a value, $\gamma$ rb s, for the bed shear stress, in which rb is the bed hydraulic radius. Then according to the side-wall correction procedure,

$$U = \sqrt{8/f_b}\,\sqrt{g\,r_b\,s} \qquad ...(2)$$

in which fb is the bed friction factor and can be determined from the above equation after calculating the value of rb.

The bed shear stress ($\tau_b = \gamma\, r_b\, s$) has two parts. One part ($\tau_b$') resulting from the sand grain roughness and the other part ($\tau$b") caused by the form drag of the ripples. The slope, s, is also partitioned into s' and s" so that $\tau_b' = \gamma\, r_b\, s'$ and $\tau b'' = \gamma\, rb\, s''$ and friction factors $f_b'$ and $f_b''$ corresponding to $\tau_b'$ and $\tau_b''$ are defined by the relations,

$$U = \sqrt{8/f_b'}\,\sqrt{g\,r_b\,s'} \qquad ...(3)$$

$$U = \sqrt{8/f_b''}\,\sqrt{g\,r_b\,s''} \qquad ...(4)$$

Once $f_b'$ is determined from Manning Strickler equation, s' can be calculated from (3). s" is obtained as the difference between s and s'. The friction factor $f_b''$ then follows from (4).

The object of the present investigation is to express $f_b''$ in terms of hydraulic quantities and bed geometry described in terms of a characteristic length, h, of the bed forms and a quantity, $A_s / A$, expressing the aerial concentration of the bed forms. The assumption here is that the ripples are sufficiently far apart so that their wakes do not interfere and each roughness element acts more or less independently. This condition is known as isolated roughness flow. The characteristic hydraulic length of the system is the bed hydraulic radius $r_b$. The friction factor, $f_b$", may also be expressed as

$$f_b" = f\,(r_b / h\,,\, As / A\,) \qquad ...(5)$$

where h is the height of the roughness elements. By introducing an equivalent sand roughness size, Ks , for a ripple bed, (5) can be simplified as

$$f_b" = f\,(r_b / K_s) \qquad ...(6)$$

where Ks is a function of h and As / A. For low aerial concentration of roughness elements, Ks is proportional to the roughness height, h , times the concentration. Introducing this relationship, (6) takes the form

$$f_b" = f\,[\,r_b / (h.A_s / A)\,] \qquad ...(7)$$

In the present study, the dimension h for a ripple was taken as the mean height, H, of the ripples. The area As was taken as the horizontal projection of the lee faces of the ripples and A was taken as the total bed area over which As was measured. Because the lee faces stand approximately at the angle of repose of the bed sediment and because the angles of repose vary little, As may be assumed proportional to the vertical projection of these faces. Therefore, As was actually a measure of the projection of the bed forms into the flow, that is, to their exposure to the flow. The ratio As / A is called the exposure parameter and is denoted by 'e'. The last (7) can be written as

$$f_b" = f\,(rb / e\,H\,) \qquad ...(8)$$

where $r_b$ / (e H) is the modified relative roughness and eH is the characteristic roughness length of the ripples.

From our experimental data, we have observed that the exposure parameter 'e' is proportional to H / L or steepness of the ripple (shown in Fig. 4). The above (8) can be written as

$$f_b" = f\,(r_b\,L / H^2) \qquad ...(9)$$

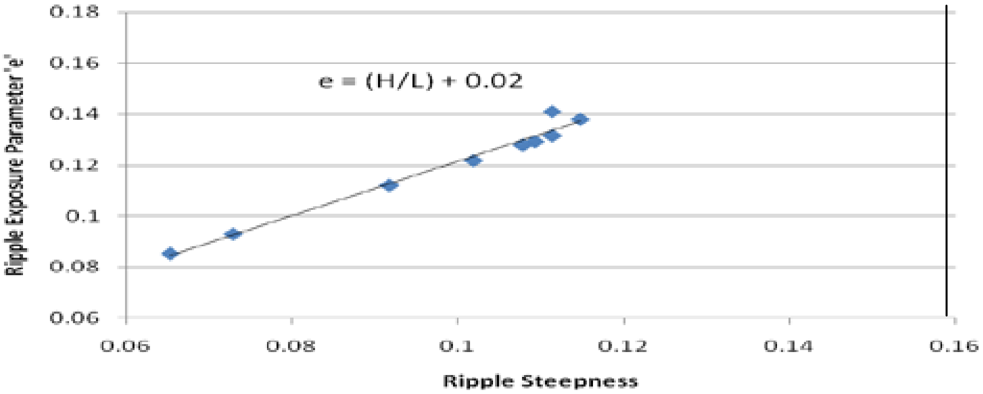


**Fig 4** : Ripple exposure parameter versus ripple steepness

## 5.0 ANALYSIS AND PRESENTATION OF DATA

The data obtained from the flume experiments are presented in Table-1 for one set of hydrograph (shown in Fig. 5). Plan view photograph of the bed forms has been presented in Fig. 6. The bed profile along the longitudinal section of the flume, obtained from the Electronic Profile Indicator (PV-09 System), has been presented in Fig 7.. From the bed profile graphs (Fig. 7), the ripple height and length are computed. All the data obtained from the present experiments are plotted (as shown in Fig. 8 & Fig. 9 ). The following relationship is established between the ripple friction factor (fb") and the parameter modified relative roughness (rb L / H2 ) .

$$1 / \sqrt{f_b"} = 34.33\;\;(r_b\,L / H^2)^{\,-0.6309}\text{, which can also be expressed as,} \qquad ...(10)$$

$$\log 1 / \sqrt{f_b"} = 1.536 - 0.6309 \log\,(r_b\,L / H^2) \qquad ...(11)$$

Velocities at 0.2 D, 0.4 D, 0.6 D and 0.8 D are measured in a section of observation. The collected data have been analyzed. It has been observed that maximum velocity near the bed occurs near the crests of the ripples and is caused by the contraction of the flow over them. In the wakes in the lee of the crests, the velocity goes to zero and near the bed, the velocity is actually in the upstream direction.

The following empirical relationship is established for computation of mean velocity,

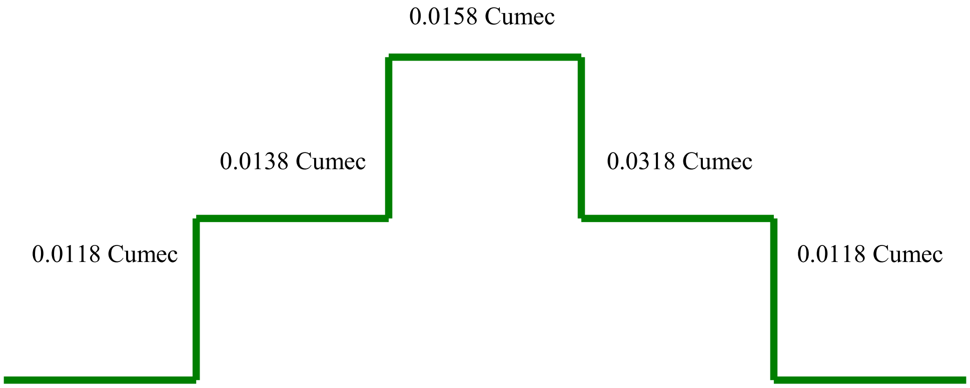
$U = 0.0096\ [\ r_b^{2/3}\ S^{1/3}\ ]^{-0.9418}$, which can also be expressed as , ...(12)

$U = 0.0096\ /\ (r_b^{0.628}\ S^{0.314})$ ...(13)

where U is mean velocity in m / s, $r_b$ is bed hydraulic radius in m and S is bed slope.

**TABLE 1** : (Data obtained from Flume Study) D50 = 0.285 mm, Slope = 0.002

| **Discharge in cumec** | **Depth in m** | **Hydraulic Radius in m** | **Average velocity in m / sec** | **Bed Hydraulic Radius ($r^b$) in m** | **Bed friction factor ($f^b$)** | **Grain friction factor ($f_b'$)** | **Ripple friction factor ($f_b''$)** | **Bed form** | **Average Ripple height (H) in m** | **Average Ripple Length (L) in m** | **Modifid Relative Roughness ($r_b$ L / $H_2$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0118 | 0.08157 | 0.05987 | 0.32294 | 0.074876 | 0.1127 | 0.02766 | 0.085 | Ripple | 0.00942 | 0.0924 | 77.967 |
| 0.0138 | 0.1749 | 0.0984 | 0.1758 | 0.1691 | 0.8593 | 0.02145 | 0.8378 | Ripple | 0.0102 | 0.09153 | 148.79 |
| 0.0158 | 0.304 | 0.1293 | 0.1156 | 0.2987 | 3.5071 | 0.01826 | 3.49 | Ripple | 0.0105 | 0.09427 | 255.41 |
| 0.0138 | 0.2371 | 0.11545 | 0.12967 | 0.2321 | 2.167 | 0.01982 | 2.1472 | Ripple | 0.00947 | 0.0867 | 224.39 |
| 0.0118 | 0.1379 | 0.085499 | 0.19105 | 0.1328 | 0.5708 | 0.0237 | 0.5471 | Ripple | 0.00958 | 0.08344 | 120.737 |



Depth of flow = 0.1 m , b / d = 0.45 m / 0.1m = 4.5
Duration of each stage is 1 hour during rise and 1 hour during recession

**Fig. 5** : Experimental Hydrograph

**Fig. 6** : Plan view photograph of the bed forms

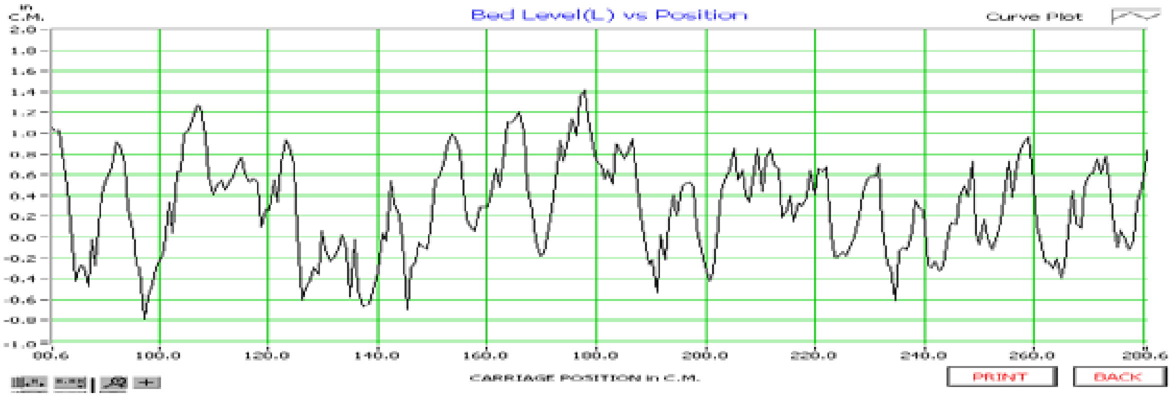


**Fig. 7** : Bed level versus carriage position

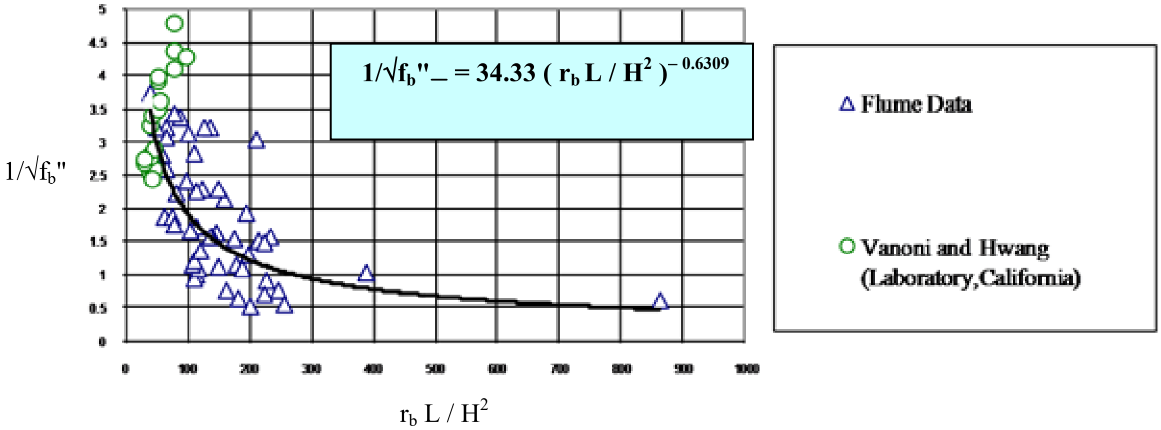


**Fig. 8 :** 1/ $\sqrt{f_b}$" versus modified relative roughness ($r_b$ L / $H^2$ ) for experiments with rippled beds

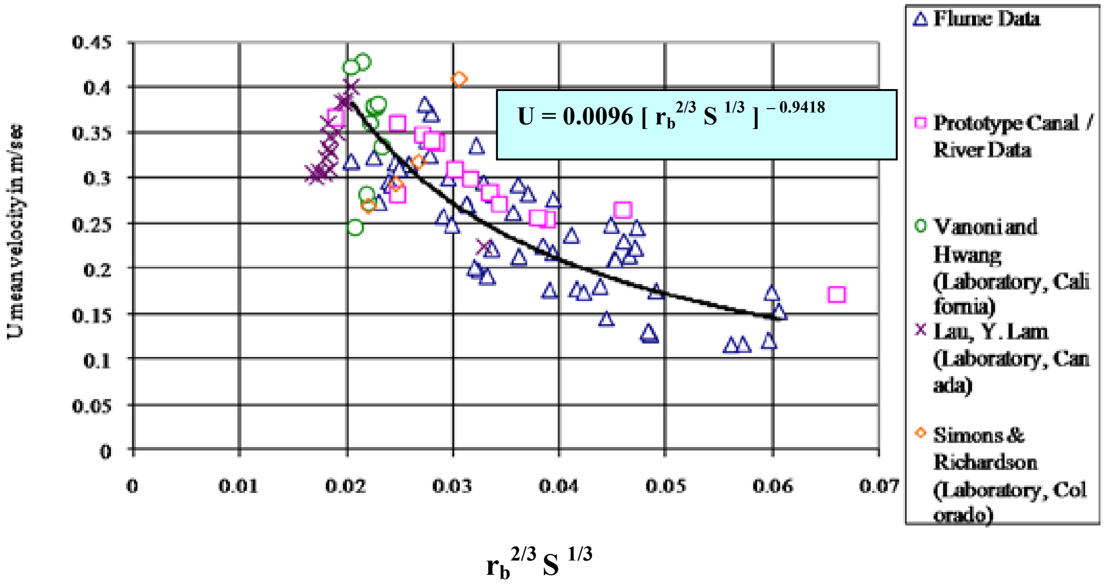


**Fig. 9** : U mean velocity plotted against the parameter ($r_b^{2/3}$ $S^{1/3}$)  for experiments with rippled beds

## 6.0 VERIFICATION OF THE DEVELOPED EQUATIONS

The validity and general applicability of the developed equations (10) and (12) were verified and confirmed by data from field canals and laboratory flume studies reported by other investigators such as Vanoni and Hwang (1967), Y.L. Lau (1988), Simons and Richardson (1962) [shown in Fig. 8 & 9] . The channels included in their analysis had slopes ranging from 0.005% to 1.0% and sediment sizes from fine sand to fine gravels including different laboratory materials. In most of the data tested for validity, the predicted velocities generally did not deviate from the measured values by more than ± 20% though in few cases, the deviation might be as much as or just greater than ± 30% , this applies equally to both laboratory and prototype data (as shown in Fig 10). Applicability to natural river data was also verified.

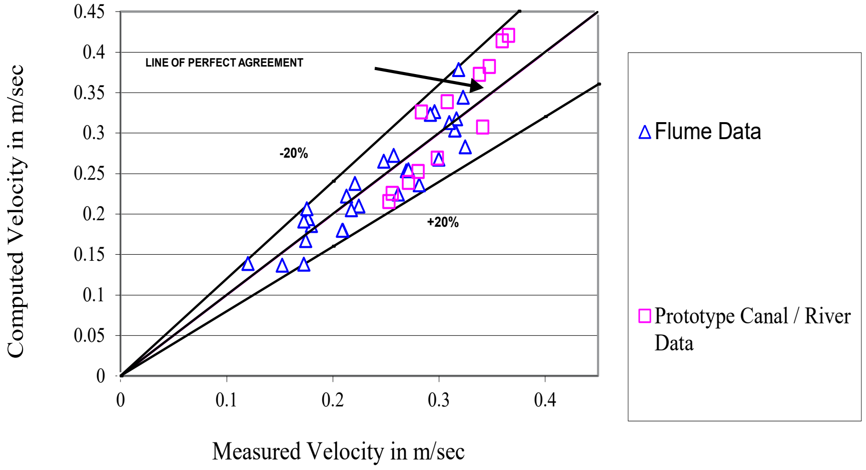


**Fig. 10** : Comparison of Computed and Measured Velocity

## 7.0 CONCLUSION

The following conclusions are drawn from the above experimental investigation and discussions.

(i) Resistance to flow in alluvial channels can be expressed as a unique function of modified relative roughness i.e. rb L / H2

(ii) For a given depth, the maximum resistance to flow is offered by a rippled bed when the flow conditions are such that the ripples are in the most developed state. The resistance to flow will be less if flow conditions are such that either the ripples are not formed to their maximum dimensions or they are partly degenerated due to rearrangement in the process of forming dunes.

(iii) The points of maximum ripple resistance are reference points for comparison of flows of different depths over the same bed material.

(iv) Equation $1/\sqrt{f_b''} = 34.33\,(r_b\, L / H2\,) - 0.6309$ obtained from the flume data would predict the bed friction factor for natural streams for lower flow regime with reasonably good accuracy.

(v) Equation $U = 0.0096 / (r_b^{0.628}\, S^{0.314})$ obtained from the flume study has been verified with respect to prototype canal and river data for lower flow regime.

(vi) Observations on rivers and flume studies have shown us that the presence of suspended load tends to decrease the resistance in an alluvial stream. However, present experiments also revealed that with ripples on the bed, the effect of suspended load on the resistance to flow is of secondary importance. For the field, the reduction due to suspended sediment is of importance only for streams carrying a very high suspended load over a flat bed and is of minor importance when there are dunes on the bed.

(vii) The parameters modified relative roughness $(r_b\, L / H_2)$ and $r_b / eH$ are indices of the amount of resistance from ripple beds.

(viii) The effect of variability of the cross-sections and sinuosity are not studied in the present research work. Despite these deficiencies, it is believed that the results presented here will be helpful in understanding the resistance of alluvial bed covered with ripples.

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