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OPEN CHANNEL FLOW RESISTANCE

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ABSTRACT

The effects of Cross-Sectional Shape boundary non uniformity and flow unsteadiness in addition to viscosity and wall roughness are considered in open channel flow resistance.

Subjects Headings: Boulders, Channels, Drag, Flow resistance, Flumes

KEYWORDS: Friction Factor, Hydraulic Geometry, Roughness

INTRODUCTION

Flow Characteristics

The roughness is intermediate scale if the relative submergence lies between about four and `5, the latter limit marking the boundary with small scale roughness

For Large Scale Roughness: $\frac{d}{S_{50}} < 4$

Where $\frac{d}{S_{50}}$ = Relative Submergence

Intermediate Scale Roughness: $4 < \frac{d}{S_{50}} < 15$

In which d = Mean depth of flow and S_{50} = The size of the short axis which is bigger than or equal to 50% of short axes.

Flow Resistance Theory: The roughness geometry and channel geometry which determine the combined effect of the elements on the flow.

Roughness Geometry: The combined effect of the element on flow resistance depends on the proportion of the bed material which has a significant form drag and is determined by the geometry and disposition of the elements.

Experimental Setup & Procedures: Data were obtained for 0.5”and 0.75” roughness bed.

Flume: The flume is open and 1.168m wide and 9.54m long. Each roughness bed was constructed by smearing masonite boards with fiberglass resin. The boards were then screwed to the bed of the flume.

Experimental Procedure: For each bed, five to seven flows were measured for three different slopes (2,5 and 8%). At each flow, depth was gaged at a single cross section, so that mean flow and channel properties could be calculated.

In Flows with Large: Scale roughness, the cross-sectional area of flow is significantly affected by the projections of the elements into the flow.

Table 1: Flume Data for 0.5 Inch Roughness Bed

Sl. No.	Channel Slope (1)	Discharge in Cubic Meters per Second (2)	Mean Velocity in Meters per Second (3)	Mean Depth d in Meters (4)	Hydraulic Radius $R=\frac{A}{P}=\frac{Wd}{W+2d}$
1	0.02	0.00241	0.146	0.0141	0.014
2	0.02	0.01274	0.391	0.0279	0.027
3	0.02	0.03046	0.584	0.0446	0.041
4	0.02	0.05746	0.785	0.0627	0.056
5	0.02	0.07197	0.877	0.0702	0.063
6	0.05	0.00143	0.161	0.0076	0.008
7	0.05	0.00522	0.296	0.0151	0.015
8	0.05	0.01737	0.619	0.0240	0.023
9	0.05	0.03249	0.823	0.0338	0.032
10	0.05	0.04896	1.017	0.0412	0.038
11	0.08	0.00196	0.201	0.0084	0.008
12	0.08	0.00610	0.392	0.0133	0.013
13	0.08	0.01355	0.563	0.0206	0.020
14	0.08	0.03576	0.965	0.0317	0.030
15	0.08	0.06061	1.225	0.0424	0.040
16	0.08	0.07065	1.301	0.0465	0.043

Roughness depends upon $\frac{d}{D_{50}}$ and $\frac{d}{D_{84}}$. For large scale roughness $\frac{d}{D_{50}}$ <2 and $\frac{d}{D_{84}}$ <1.2 where d is the mean depth of flow and $\frac{d}{D_{50}}$ = the size of the median axis which is bigger than or equal to 50% of median axis. Similarly D_{84} = The size of the median axis which is bigger than or equal to 84% of median axis. Similarly for Intermediate Scale roughness 2< $\frac{d}{D_{50}}$ <7.5 and 1.2 < $\frac{d}{D_{84}}$ <4.

Table 2: Flume Data for 0.75 Inch Roughness Bed

Sl. No.	Channel Slope (1)	Discharge in Cubic Meters per Second (2)	Mean Velocity in Meters per Second (3)	Mean Depth d in Meters (4)	Hydraulic Radius $R=\frac{A}{P}=\frac{Wd}{W+2d}$
1	0.02	0.00580	0.222	0.0223	0.021
2	0.02	0.01181	0.348	0.0290	0.028
3	0.02	0.02482	0.484	0.0439	0.040
4	0.02	0.04047	0.586	0.0591	0.054
5	0.02	0.05348	0.656	0.0698	0.063
6	0.05	0.00381	0.230	0.0141	0.013
7	0.05	0.00843	0.363	0.0199	0.019
8	0.05	0.02037	0.583	0.0299	0.029
9	0.05	0.03333	0.782	0.0365	0.035
10	0.05	0.04586	0.904	0.0434	0.041
11	0.05	0.05460	0.979	0.0477	0.044
12	0.08	0.00207	0.186	0.0095	0.009
13	0.08	0.00631	0.380	0.0142	0.014
14	0.08	0.01007	0.430	0.0200	0.019
15	0.08	0.02825	0.807	0.0299	0.029
16	0.08	0.04518	1.032	0.0375	0.035
17	0.08	0.04879	1.064	0.0392	0.037

Table 3: Flume Date for 0.5 Inch Roughness D_{50}=0.0088m, D_{84}=0.0115m

Serial No.	Mean Depth d in Meters	$\frac{d}{D_{50}}$	$\frac{d}{D_{84}}$
1	0.0141	1.602	1.226
2	0.0279	3.170	2.426
3	0.0446	5.068	3.878
4	0.0627	7.125	5.452
5	0.0702	7.977	6.104
6	0.0076	0.864	0.661
7	0.0151	1.716	1.313
8	0.0240	2.727	2.087
9	0.0338	3.841	2.939
10	0.0412	4.682	3.583
11	0.0084	0.955	0.730
12	0.0133	1.511	1.157
13	0.0206	2.341	1.791
14	0.0317	3.602	2.757
15	0.0424	4.818	3.687
16	0.0465	5.284	4.043

Table 4: Flume Data for 0.75 Inch Roughness Bed D_{50}=0.013m, D_{84}=0.0193m

Sl. No.	Mean Depth d in Meters	$\frac{d}{D_{50}}$	$\frac{d}{D_{84}}$
1	0.0223	1.715	1.155
2	0.0290	2.231	1.503
3	0.0439	3.377	2.275
4	0.0591	4.546	3.062
5	0.0698	5.369	3.617
6	0.0141	1.085	0.731
7	0.0199	1.531	1.031
8	0.0299	2.300	1.549
9	0.0365	2.808	1.891
10	0.0434	3.338	2.249
11	0.0477	3.669	2.472
12	0.0095	0.731	0.492
13	0.0142	1.092	0.736
14	0.0200	1.538	1.036
15	0.0299	2.300	1.549
16	0.0375	2.885	1.943
17	0.0392	3.015	2.031

RESULTS AND ANALYSIS

Hydraulic radius is the depth of low from the channel bottom to the point where velocity is half of the max^{m} velocity of flow.

Average value of hydraulic radius R= 0.029 metre for 0.5inch roughness bed.

Average value of hydraulic radius R = 0.031 metre for 0.75 inch roughness bed.

Since roughness is more for 0.75 inch roughness bed for large size hence there is more increase in mean depth of flow for 0.75 inch roughness bed hence there is more increase in hydraulic radius for 0.75 inch roughness bed as compared to 0.5 inch roughness bed since hydraulic radius depends upon mean depth of flow.

Larger size of roughness material increases the mean depth of flow which is useful for irrigation and water distribution purpose i.e. capacity of the channel increases. Larger size of roughness materials reduce the mean velocity of flow hence the erosion of the channel bed is prevented. Since there is reduction is mean velocity of flow for 0.75 inch roughness bed of 1.102 times as compared to 0.5 inch roughness bed there is increase is mean depth of flow for 0.75 inch roughness bed of 1.047 times as compared to 0.5 inch roughness bed and there is 1.069 times more increase in hydraulic radius for 0.75 inch roughness bed as compared to 0.5 inch roughness bed.

Increase in depth is due to roughness of the channel bed whereas hydraulic radius is associated with free surface.

Figure 1: Variation of Parameter Hydraulic Radius with Mean Depth of Flow for 0.5 Inch Roughness Bed

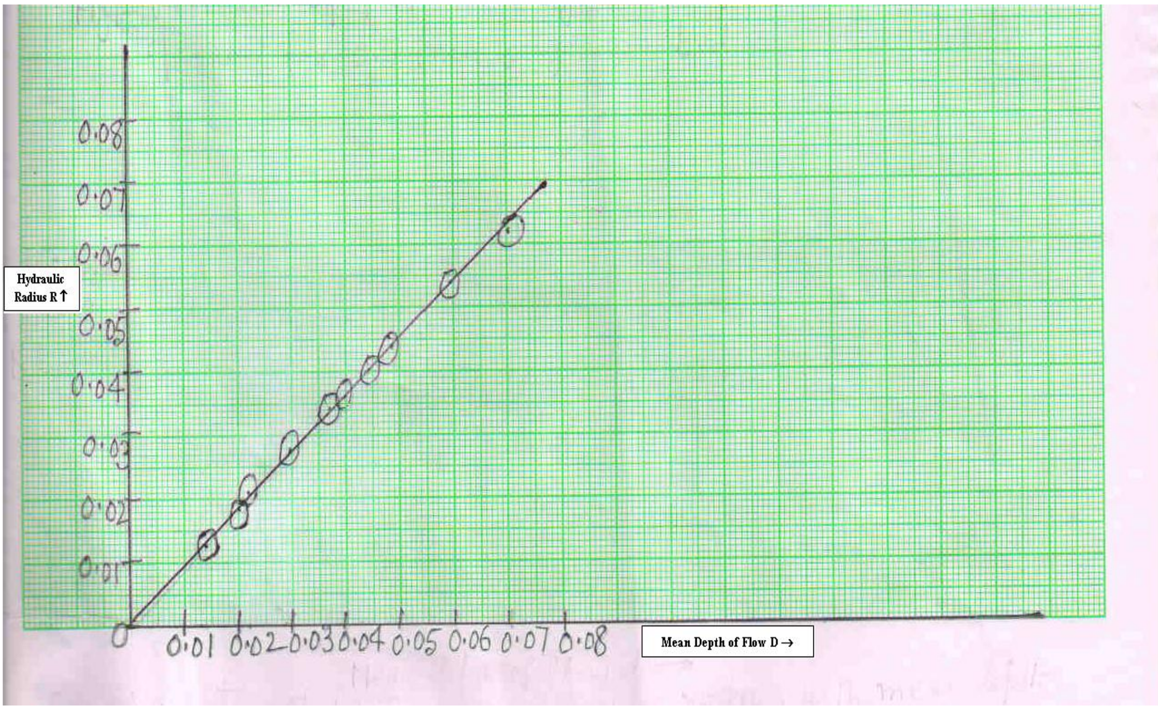

Figure 2: Variation of Parameter Hydraulic Radius with Mean Depth of Flow for 0.75 Inch Roughness Bed

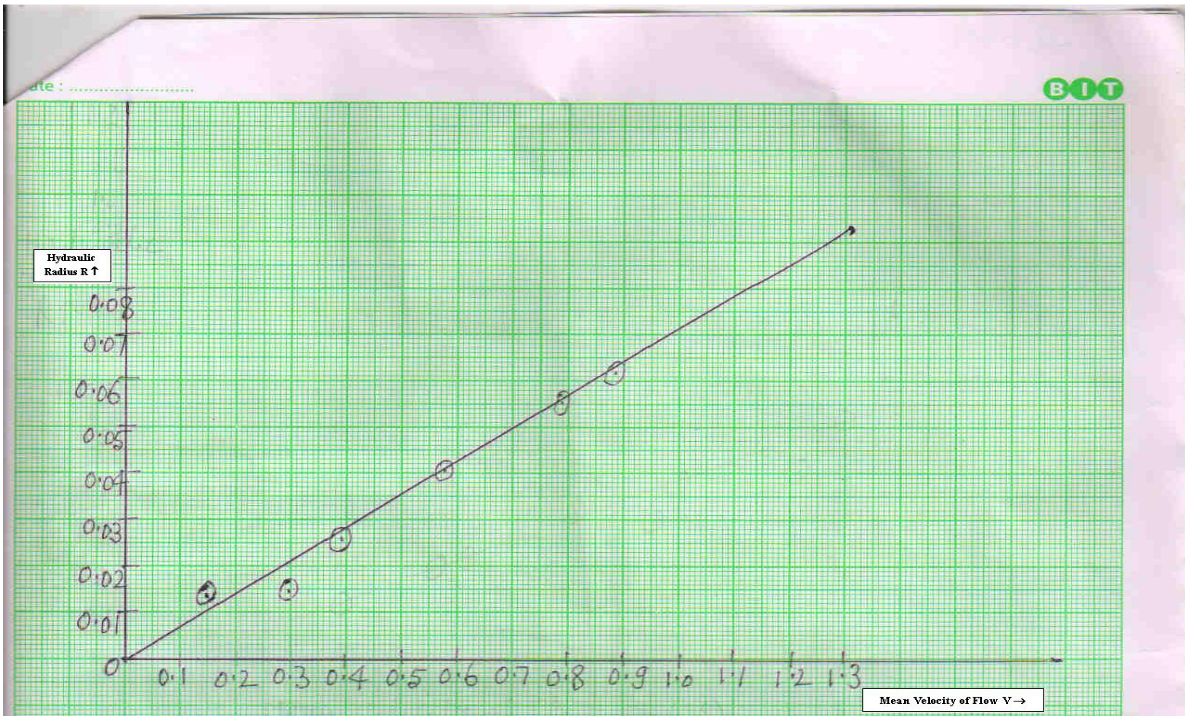

Figure 3: Variation of Hydraulic Radius with Mean Depth Velocity of Flow for 0.5 Inch Roughness Bed

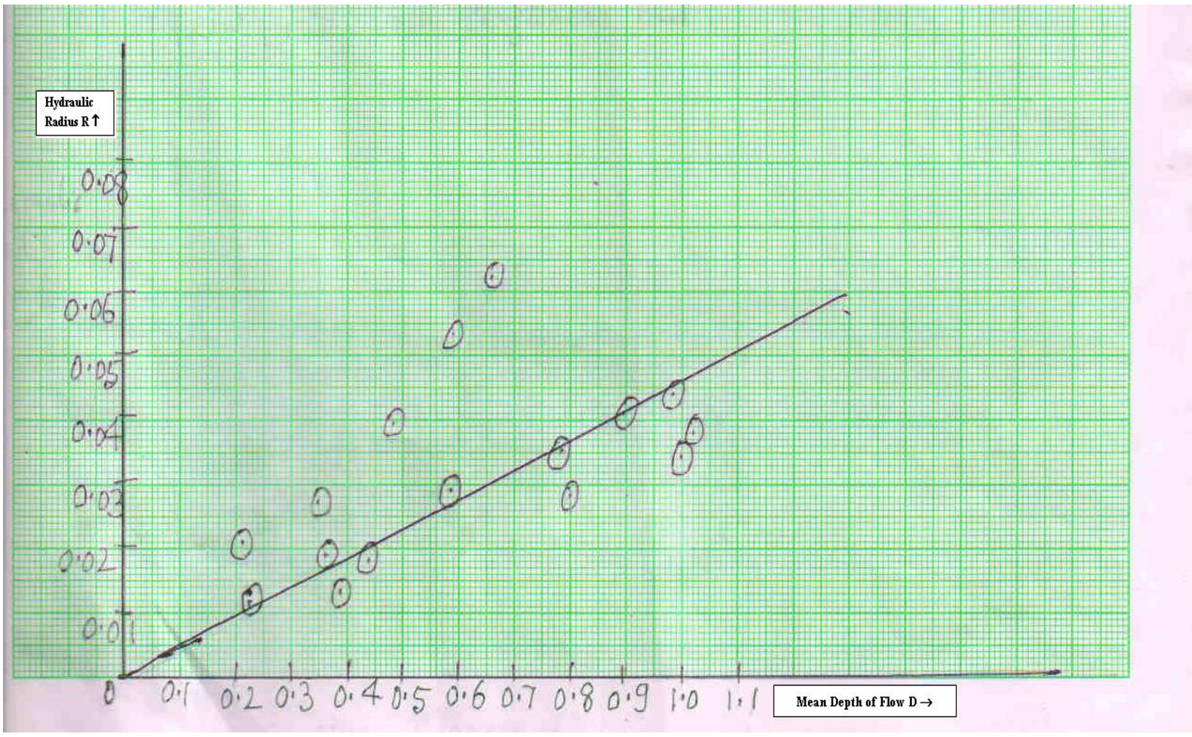

Figure 4: Variation of Hydraulic Radius with Mean Depth Velocity of Flow for 0.75 Inch Roughness Bed

Figure 1: As mean depth of flow increases hydraulic radius increases because hydraulic radius depends upon mean depth of flow. Hydraulic radius is the depth of flow taken from the channel bottom to a point where velocity is half of the maximum velocity.

Figure 3: As mean velocity of flow increases hydraulic radius increases since hydraulic radius depends upon max^{m} velocity of flow.

0.5 Inch Roughness Bed

Equations

$$Q = 1.415\left(\frac{d}{D_{50}}\right)^{0.707} - 1.712\left(\frac{d}{D_{84}}\right)^{0.707} + \frac{Q_{max}}{2.482} \quad \text{(A)}$$

$$Q_{max} = 2.227\left(\frac{d}{D_{50}}\right)^{0.449} - 2.511\left(\frac{d}{D_{84}}\right)^{0.449} + 2.482Q \quad \text{(B)}$$

$$d = 1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994} + \frac{d_{max}}{2.208} \quad \text{(C)}$$

$$d_{max} = 2.227\left(\frac{d}{D_{50}}\right)^{0.449} - 2.513\left(\frac{d}{D_{84}}\right)^{0.448} + 2.208d \quad \text{(D)}$$

$$V = 0.761\left(\frac{d}{D_{50}}\right)^{1.314} - 1.084\left(\frac{d}{D_{84}}\right)^{1.312} + \frac{V_{max}}{2.00} \quad \text{(E)}$$

$$V_{max} = 1.475\left(\frac{d}{D_{50}}\right)^{0.678} - 1.768\left(\frac{d}{D_{84}}\right)^{0.678} + 2.00V \quad \text{(F)}$$

$$\frac{d}{D_{50}} = 1.307\left(\frac{d}{D_{84}}\right) \quad \text{(G)}$$

$$\left(\frac{d}{D_{50}}\right)_{max} = 5.068\left(\frac{d}{D_{84}}\right)^{0.450} \quad \text{(H)}$$

0.5 Inch Roughness Bed

Relationship between Q_{max}, hydraulic radius and mean depth

$$Q_{max} = \frac{2.361(R)^{0.460}}{2.208(d)^{0.453}} \times 2.482Q \quad (1)$$

Relationship between mean depth of flow (d) with hydraulic radius and mean depth of low -1

$$d = \frac{.1.096R}{d} \times \frac{d_{max}}{2.208} \quad - \quad (2)$$

$$d = 1.096(R)$$

Relationship between d_{max} with hydraulic radius and mean depth of flow:

$$d_{max} = \frac{2.36(R)^{0.460}}{2.208(d)^{0.453}} \times 2.208d \quad (3)$$

or another form of d_{max}

$d_{max} = 0.358\ (R)^{0.460}$

Relationship between mean velocity of flow with hydraulic radius and mean depth of flow:

$$V_{max} = \frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{max}}{2.00} \quad (4)$$

Relationship between V_{max} and hydraulic radius and mean depth of flow:

$$V_{max} = \frac{1.505(R)^{0.674}}{1.462(d)^{0.684}} \times 2.00v \tag{5}$$

Relationship between V_{min} and hydraulic radius and mean depth of flow:

$$V_{min} = \frac{0.287(R)^{2.071}}{0.443(d)^{2.55}} \times \frac{V_{max}}{8.911} \tag{6}$$

$$V_{max} = 0.6d \tag{7}$$

$$V_{max} = 1.462\,d \tag{8}$$

$$V_{min} = 0.443\,d \tag{9}$$

MATHEMATICAL FORMULATION TO GET DIFFERENT PARAMETERS

0.5 Inch Roughness Bed

Mathematical Formulation for Hydraulic Radius (R)

We know

$$Q_{max} = 2.227\left(\frac{d}{D_{50}}\right)^{0.449} - 2.511\left(\frac{d}{D_{84}}\right)^{0.449} + 2.482Q \tag{1}$$

Again,

$$Q_{max} = \frac{2.361\,(R)^{0.460}}{2.208\,(d)^{0.453}} \times 2.482\,Q \tag{2}$$

Hence from (1) & (2)

$$\frac{2.361(R)^{0.460}}{2.208(d)^{0.453}} \times 2.428Q = 2.227\left(\frac{d}{D_{50}}\right)^{0.449} - 2.511\left(\frac{d}{D_{84}}\right)^{0.449} + 2.482Q \tag{3}$$

Taking d = $1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994} + \frac{d_{max}}{2.208}$ (4)

and $\frac{d}{D_{50}} = 1.307\left(\frac{d}{D_{84}}\right)$ (5)

Substituting $\frac{d}{D_{50}}$ from equation (5) in equation (4) and d_{max} = 0.0720 metre

We get d = 0.0318 metre

Now substituting d = 0.0318 metre and $\frac{d}{D_{50}} = 1.307\left(\frac{d}{D_{84}}\right)$ in equation (3) and also average value of discharge of flow Q = 0.029 m^3/sec in equation (3) we get hydraulic radius R = 0.031 metre which in nearly equal to average value of hydraulic radius R = 0.029 metre.

Hence this mathematical formulation gives more conservative value to hydraulic radius R. Hence this mathematical formulation can be used to determine value of hydraulic radius R.

Determination of most appropriate value of hydraulic radius (R) : -

We know

$$V_{mean} = \frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{\max}}{2.00} \quad (1)$$

and d = 1.096 R (2)

Using equation (2) in equation (1)

We get $\frac{0.680(R)^{1.261}}{0.755\{1.096(R)\}^{1-325}} \times \frac{V_{\max}}{2.00} = V_{mean} = \frac{V_{\max}}{2.00}$

Hence $\frac{0.680(R)^{1.261}}{0.755\{1.129 R^{1.325}\}} = 1.00$

Hence R = 0.029_m which is equal to average value of hydraulic radius R = 0.029 metre

Hence equation (1) & equation (2) are taken into account for Mathematical formulation and also $V_{mean} = \frac{V_{\max}}{2.00}$ to obtain the most appropriate value of hydraulic radius R.

Mathematical Formulation to Get the Value of Mean Depth of Flow (d)

$$V_{mean} = \frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{\max}}{2.00} \quad (1)$$

Again

$$V_{mean} = 0.761\left(\frac{d}{D_{50}}\right)^{1.314} - 1.084\left(\frac{d}{D_{84}}\right)^{1.312} + \frac{V_{\max}}{2.00} \quad (2)$$

d = 1.096 R (3)

From (1) & (2)

$$\frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{\max}}{2.00} = 0.00 + \frac{V_{\max}}{2.00}$$

Since $0.761\left(\frac{d}{D_{50}}\right)^{1.314} - 1.084\left(\frac{d}{D_{84}}\right)^{1.312}$ = 0.00

By substitution of average value of = $\frac{d}{D_{50}} \& \frac{d}{D_{84}}$

Hence $\frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{max}}{2.00} = \frac{V_{max}}{2.00}$

Or $\frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} = 1.00$

Now from equation (3)

$$\frac{0.680\left\{\frac{d}{1.096}\right\}^{1.261}}{0.755(d)^{1.325}} = 1.00$$

Or $\frac{0.680\{0.912d\}^{1.261}}{0.755(d)^{1.325}} = 1.00$

Hence d = 0.0318m which is equal to average mean depth of flow.

Hence these three equations will be used for mathematical formulation of mean depth of flow.

Mathematical Formulation for Max^{m} Value of Mean Depth of Flow d_{max}: -

$$d = 1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994} + \frac{d_{max}}{2.208} \tag{1}$$

d = 1.096 R (2)

From (1) & (2)

$$\frac{d_{max}}{2.208} = 1.096R$$

Since $1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994}$ = ZERO by substituting the average value of $\frac{d}{D_{50}}$ and $\frac{d}{D_{84}}$ from 0.5 inch roughness bed.

Hence d_{max} = 2.208 [1.096 R]

= 2.208 × 1.096 × 0.029

= 0.0702 metre

Hence we get same value of d_{max} by mathematical formulation from equation (1) & equation (2) compared to d_{max} for 0.5 inch roughness bed.

Another Mathematical Formulation for Mean Depth of Flow d

$$d = 1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994} + \frac{d_{max}}{2.208} \qquad (1)$$

$$d_{max} = \frac{2.36(R)^{0.460}}{2.208(d)^{0.453}} \times 2.208d \qquad (2)$$

Or $$\frac{d_{max}}{\frac{2.36\,(R)^{0.460}}{2.208\,(d)^{0.453}} \times 2.208}$$

Hence from equation (1)

$$\frac{d_{max}}{2.208} = d_{max} \times \frac{2.208(d)^{0.453}}{2.36(R)^{0.460}} \times 2.208 \qquad (3)$$

Since $1.01\left(\frac{d}{D_{50}}\right)^{0.994} - 1.318\left(\frac{d}{D_{84}}\right)^{0.994}$ = ZERO

by substitution of average value of $\frac{d}{D_{50}}$ *and* $\frac{d}{D_{84}}$ from 0.5 inch roughness bed.

Using $d = 1.096R$ in equation (3)

we get d = 0.0294 ≈ 0.0318m i.e. average value of mean depth of flow d = 0.0318m for 0.5 inch roughness bed.

Mathematical Formulation for Max^{m} Discharge of Flow Q_{max}

$$Q_{max} = \frac{2.361(R)^{0.460}}{2.208(d)^{0.453}} \times 2.482Q \qquad (1)$$

$$Q = 1.415\left(\frac{d}{D_{50}}\right)^{0.707} - 1.712\left(\frac{d}{D_{84}}\right)^{0.707} + \frac{Q_{max}}{2.482} \qquad (2)$$

From equation (2)

$Q = \frac{Q_{max}}{2.482}$ Since $1.415\left(\frac{d}{D_{50}}\right)^{0.707} - 1.712\left(\frac{d}{D_{84}}\right)^{0.707}$ = Zero

by substituting the average value of $\frac{d}{D_{50}}$ *and* $\frac{d}{D_{84}}$ from 0.5 inch roughness bed.

From equation (1)

$$Q = \frac{2.208\ Q_{\max}\ (d)^{0.453}}{2.361\ (R)^{0.460} \times 2.482}$$

Now from $\quad Q = \frac{Q_{\max}}{2.482} = \frac{0.07197}{2.482} = 0.029$

Hence $\quad \frac{2.208\ Q_{\max}(0.0318)^{0.453}}{2.361(0.029)^{0.460} \times 2.482} = 0.029$

Hence $\quad Q_{\max} = 0.0719\ \ metre$

Taking d = 0.0318_m and hydraulic radius = 0.029m and Q = 0.029 m^3/sec

Hence equation (1) and equation (2) can be taken for mathematical formulation for Q_{max}.

Mathematical Formulation for Maximum Mean Velocity of Flow V_{max}

We know

$$V_{\max} = 0.761\left(\frac{d}{D_{50}}\right)^{1.314} - 1.084\left(\frac{d}{D_{84}}\right)^{1.312} + \frac{V_{\max}}{2.00} \tag{1}$$

Again,

$$V_{mean} = \frac{0.680\ (R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{\max}}{2.00} \tag{2}$$

Hence from equation (1) and (2)

$$\frac{V_{\max}}{2.00} = \frac{0.680(R)^{1.261}}{0.755(d)^{1.325}} \times \frac{V_{\max}}{2.00}$$

Since $\quad 0.761\left(\frac{d}{D_{50}}\right)^{1.314} - 1.084\left(\frac{d}{D_{84}}\right)^{1.312}$

= ZERO by substituting the average value of $\frac{d}{D_{50}}\ and\ \frac{d}{D_{84}}$

Hence $\quad \frac{V_{\max}}{2.00}\ and\ \frac{0.680\ (R)^{1.261}}{0.755\ (d)^{1.325}} \times \frac{1.301}{2.00}$

Where V_{max} = 1.301 m/sec

Now $$\frac{V_{max}}{2.00} = \frac{0.680\ (0.0290)^{1.261}}{0.755\ (0.0318)^{1.325}} \times \frac{1.301}{2.00}$$

Where hydraulic radius (R) (average value) = 0.0290 metre and average value of mean depth of flow d = 0.0318 metre

Hence $$\frac{V_{max}}{2.00} = 0.6505$$

∴ V_{max} = 1.301 m/sec

Which is same to V_{max} given for 0.5 inch roughness bed. Hence equation (1) and equation (2) are taken for mathematical formulation for V_{max}.

Mathematical Formulation for Mean Velocity of Flow (V_{mean})

$$V_{max} = \frac{1.505\ (R)^{0.674}}{1.462\ (d)^{0.684}} \times 2.00V \qquad (1)$$

Again,

$$V_{max} = 1.475\left(\frac{d}{D_{50}}\right)^{0.678} - 1.768\left(\frac{d}{D_{84}}\right)^{0.678} + 2.00V \qquad (2)$$

Since $1.475\left(\frac{d}{D_{50}}\right)^{0.678} - 1.768\left(\frac{d}{D_{84}}\right)^{0.678}$ = ZERO by substituting the average value of $\frac{d}{D_{50}}\ and\ \frac{d}{D_{84}}$ from 0.5 inch roughness bed.

Hence from equation (1) and (2)

2.00V = $$\frac{1.505(R)^{0.674}}{1.462\ \{1.096(R)\}^{0.684}} \times 2.00V$$

Where d = 1.096(R)

Hence 2.00V = $$\frac{0.1384}{1.462\ \{1.065\ R^{0.684}\}} \times 1.3$$

Or 2.00V = $$\frac{0.1384}{1.557R^{0.874}} \times 1.300 \qquad (3)$$

Taking average value of hydraulic radius R = 0.0290 metre. Average value of mean velocity of flow V = 0.65 m/sec

Hence from equation (3)

V = 0.65 m/sec

Hence same as that of mean velocity of flow for 0.5 inch roughness bed.

Equation (1) and equation (2) and d = 1.096 R can be taken for mathematical formulation to determine average value of mean velocity of flow.

0.5 Inch Roughness Bed

- Average value of hydraulic radius R = 0.029 metre
- Average value of mean depth of flow d = 0.318 metre
- Average value of mean velocity of flow V = 0.65 m/sec
- Average value of $\frac{d}{D_{50}} = 3.582$
- Average value of $\frac{d}{D_{84}} = 2.740$
- Average value of discharge of flow Q = 0.029 m^3/sec

CONCLUSIONS

The mean depth of flow and hydraulic radius increase for large roughness material. Also mean velocity of flow decreases for large roughness material. Hence larger size roughness material provides large capacity of the channel and larger size roughness material is useful in steep slope for reduction in mean velocity of flow.

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APPENDIX – 1: NOTATION

The following symbols are used in this paper

d	=	Mean depth of flow in meters
Q	=	Discharge in cubic meters per second
V	=	mean velocity of flow in meters per second
D_{50}	=	the size of the median axis which is bigger than or equal to 50% of medium axis.
D_{84}	=	The size of the median axis which is bigger than or equal to 84% of median axis.
R	=	Hydraulic radius
A	=	Flow cross sectional area
W	=	Width of the channel
P	=	wetted perimeter