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The Influence of Roughness Height and Manning Roughness on Hydraulic Parameters in Open Channels

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ABSTRACT There is currently a growing focus on endeavors aimed at optimizing the utilization of our present water resources, and implementing novel projects to achieve maximum efficiency. Sophisticated applications are necessary to determine the flow resistance in open channels for project design, and control process. For the purpose of studying sediment movement in open channels, rivers, and waterways, an accurate assessment of bed shear stress is necessary. Shear stress may be calculated using a variety of techniques, however since hydraulic factors vary, the results are not comparable. Moreover, determining the flow resistance for the project design, and control process in open channels necessitates using sophisticated applications. It is imperative to possess knowledge of the channel and flow characteristics to ascertain the hydraulic roughness, which embodies the resistance of the flow. To study the effect of these parameters on bed shear stress, a series of laboratory experiments were conducted. The comparison of results reveals a wide range of shear stress estimates obtained through these methods. Moreover, the height of roughness, and the surface characteristics of base bed significantly influence the cutting velocity. A laboratory flume with dimensions of 8 meters in length, 40 cm in width, and 40 cm height was utilized to conduct a total of 72 experiments. These experiments involved 4 different slope values, 3 flow rates, and 2 types of sediment with particle sizes of 10, 20, and 30 mm, both in rounded and angular. During the experiment, Froude number values were examined, and it was determined that, in 72 experiments the flow regime can be considered subcritical. The data analysis shows that, in relation to the basic equation for shear stress computation, the proportion of inaccuracy in shear stress determination rises as particle size increases.

Key Words: Flow rate, Experimental Flume, Roughness Coefficient, Manning, angular and rounded sediments

Introduction

Previous research diligently endeavored to augment the efficacy and versatility of water resources. Consequently, the endurance of these resources emerges as a pivotal concern due to prolonged water consumption. The precision of flow measurement and the conduct of water in unobstructed pathways are of immeasurable importance in the context of water resource management and flood analysis. Similarly, investigations into these topics are noteworthy (Yerdelen, 2015). The hydraulic and hydrological evaluation of flow stands as the paramount factor to ensure the efficient utilization of water resources. Within this framework, it becomes imperative to scrutinize the dynamic conditions pertaining to open channel flows. Manning equation, renowned as the most appropriate formula for studying flow in open channels, boasts numerous design applications Merry (2019) The roughness coefficient, denoted as 'n', in this equation undergoes changes based on prevailing channel conditions. The level of roughness in open channel flow exhibits variations contingent upon factors such as the roughness of bed material, the cross-section and size of the channel, the type and density of flow obstructions, sediment accumulation, and other relevant considerations. Nevertheless, the chief determinants affecting the roughness coefficient are the slope of channel and the roughness of the bed surface Gauta (2021). Numerous geophysical and environmental engineering applications are significantly influenced by bed shear stress. In addition, it is a turbulence scaling parameter and fundamental variable in river research, as it is closely associated with erosion and changes in channel morphology. To ascertain the critical erosion and sedimentation threshold, as well as the extent of sedimentation and erosion, a thorough assessment of the sediment is required to determine the hydrodynamic forces employed as bed shear stress. Moreover, shear stress plays a pivotal role in accurately estimating sediment transport in rivers, waterways, and canals. This parameter assumes a crucial role in the design of stable channels within sedimentary sections, as the transfer phenomenon presents a dual-component challenge.

1. Shear stress calculations related to fluid or liquid properties
2. Sediments and flow mechanical characteristics

Shear velocity, roughness height, and water depth are the parameters of significant importance that show high sensitivity. However, establishing a definitive baseline for measuring water depth proves to be challenging. The estimation of shear rate is directly proportional to the estimation of shear tension on the substrate. A series of experiments were conducted to measure shear velocity in open channel flows with a fixed uneven substrate in order to investigate this relationship. The flow can be classified as hydraulically fluid, transitional, or turbulent. Hydraulically smooth flow occurs when surface disturbances are minimal, causing all roughness elements to be submerged beneath the linear layer Chiu (1989). In such cases, the flow remains smooth as long as the surface roughness is negligible, and buried under the smooth or viscous layer, rendering the bed

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roughness inconsequential to the velocity distribution. This observation was supported by research conducted by Schlichting & Gersten (2000) on smooth surfaces. They found that bed roughness had no effect on velocity distribution.

Since the height of the rough layer introduces uncertainty and complexity, partial velocity profiles with total depth are usually analyzed in order to determine the shear velocity in flows with a rough substrate. Researchers, such as Wilcock (1996) and Grami (1999) used the logarithmic profile method in rivers with a sandy bed to ascertain the shear velocity.

In their laboratory study on flow along sand-reinforced beds, Rowinski (2005) compared these methods and concluded that the logarithmic profile method was unsuitable in these cases. They highlighted the challenge of using single-point measurements to determine the shear rate due to the irregularity of the coarse-grained sand beds.

Moreover, there appears to be a lack of research investigating and comparing these methods in streams with very rough beds containing coarse sand, even though such situations are common in rivers with irregular bed levels. The shear velocity estimates calculated by various approaches exhibited substantial discrepancies in previous laboratory experiments conducted under uneven bed flow conditions (0.5 cm). Therefore, it is crucial to examine the feasibility of employing this method under the condition of a coarse sand bed.

Material and Methods

Experiments were conducted in a channel that had a length of 8 meters, a width of 0.4 meters, and a height of 0.4 meters. The experiments involved three different flow rates (10, 20, and 30 liters per second), and four different slopes (0.005, 0.01, 0.015, and 0.02) on three different gradings (10, 20, and 30 mm). These experiments were carried out two categories sharp and round corners sediments.

The channel used for these experiments was a tilting flume with a metal bottom and transparent fiberglass walls, Fig1. Water from an exterior tank was concurrently introduced into two tanks using a centrifugal pump and an intake hose. One of the tanks was linked to the 40 cm flume. At the beginning of tank, there was a triangular overflow that allowed for the measurement of the flow rate (refer to Figure 1). By altering the slopes, flow rates, and the type of channel bed (either stones with rounded or sharp grains), tests were conducted. The size of stones remained the same in both cases.

During these tests, data on speed and shear stress were collected and recorded using a Pitot tube. The flow roughness coefficient was also determined using flow resistance equations, specifically Manning's equation. Three granulation groups were implemented for each substrate particle type in order to accomplish the research objectives. Regarding each experiment involved three discharges and four slopes, a total of 72 experiments were conducted. The velocities were measured in three sections of the flume at intervals of 2 meters using a pitot tube.

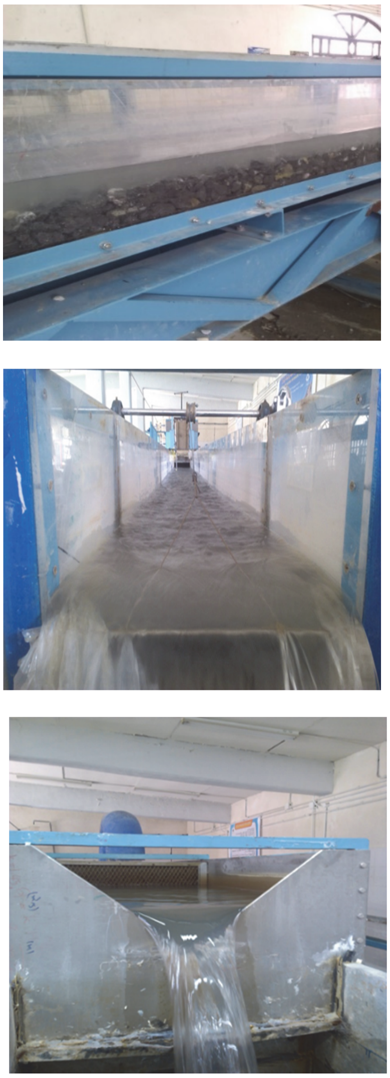

Fig.1 (a) Experimental flume, (b) the flume gate, (c) triangular weir respectively

Shear Stress

In this research, 4 methods were used for calculation shear stress. Chow (1959) defined shear velocity as follows:

$$u^* = \sqrt{\frac{\tau_0}{\rho}} \quad (1)$$

So $\tau = \gamma RS$ (2)

For the hydraulic the rough bed Chein and Wan (1998) defined shear velocity as follows:

$$\frac{u}{u^*} = 8.5 + 2.5ln\left(\frac{y}{K_S}\right) \quad (3)$$

And Keulgan (1938) showed. Shear velocity as follows:

$$\frac{u}{u^*} = 6.25 + 5.75log\left(\frac{R}{K_S}\right) \quad (4)$$

And Schlichting (1955) defined shear velocity as follows:

$$\frac{u}{u^*} = \frac{1}{k}ln\left(\frac{y}{k_s}\right) \quad (5)$$

Where u is flow velocity, u^* shear velocity, y is water depth, k_s is roughness height , R is hydraulic radius, s is the bed slope, γ is weight density of water , ρ is flow density.

Table 1 The characteristics of angular sediments

No	Name of test	Slope	Flow Rate	Depth	Particle size	Maximum velocity	Average velocity	Minimum velocity
			Lit/s	cm	mm	m/s	m/s	m/s
1	$S_1Q_1Da_1$	0.005	10	5.6	10	0.44	0.42	0.55
2	$S_1Q_2Da_1$	0.005	20	9.5	10	0.57	0.55	0.62
3	$S_1Q_3Da_1$	0.005	30	12	10	0.64	0.62	0.44
4	$S_2Q_1Da_1$	0.01	10	5.5	10	0.46	0.45	0.54
5	$S_2Q_2Da_1$	0.01	20	8	10	0.56	0.55	0.64
6	$S_2Q_3Da_1$	0.01	30	10	10	0.66	0.65	0.43
7	$S_3Q_1Da_1$	0.015	10	5.5	10	0.46	0.44	0.57
8	$S_3Q_2Da_1$	0.015	20	8	10	0.61	0.59	0.65
9	$S_3Q_3Da_1$	0.015	30	10	0	0.7	0.68	0.65
10	$S_4Q_1Da_1$	0.02	10	5	10	0.48	0.46	0.45
11	$S_4Q_2Da_1$	0.02	20	7	10	0.63	0.6	0.58
12	$S_4Q_3Da_1$	0.02	30	9	10	0.72	0.69	0.65
13	$S_1Q_1Da_2$	0.005	10	9	20	0.45	0.42	0.65
14	$S_1Q_2Da_2$	0.005	20	11	20	0.55	0.54	0.41
15	$S_1Q_3Da_2$	0.005	30	13.5	20	0.61	0.6	0.53
16	$S_2Q_1Da_2$	0.01	10	7	20	0.44	0.44	0.58
17	$S_2Q_2Da_2$	0.01	20	9	20	0.56	0.54	0.43
18	$S_2Q_3Da_2$	0.01	30	11	20	0.63	0.61	0.53
19	$S_3Q_1Da_2$	0.015	10	6	20	0.45	0.44	0.59
20	$S_3Q_2Da_2$	0.015	20	8	20	0.56	0.55	0.42
21	$S_3Q_3Da_2$	0.015	30	10.5	20	0.65	0.63	0.51
22	$S_4Q_1Da_2$	0.02	10	6.5	20	0.46	0.45	0.61
23	$S_4Q_2Da_2$	0.02	20	8.5	20	0.6	0.58	0.43
24	$S_4Q_4Da_2$	0.02	30	9.5	20	0.68	0.68	0.55
25	$S_1Q_1Da_3$	0.005	10	9.5	20	0.43	0.41	0.65
26	$S_1Q_2Da_3$	0.005	20	12	30	0.55	0.54	0.530.41
27	$S_1Q_3Da_3$	0.005	30	14	30	0.61	0.59	0.58
28	$S_2Q_1Da_3$	0.01	10	7.5	30	0.45	0.42	0.42
29	$S_2Q_2Da_3$	0.01	20	9.5	30	0.55	0.53	0.51
30	$S_2Q_3Da_3$	0.01	30	11.5	30	0.63	0.61	0.6
31	$S_3Q_1Da_3$	0.015	10	6	30	0.44	0.43	0.41
32	$S_3Q_2Da_3$	0.015	20	8.5	30	0.57	0.55	0.53
33	$S_3Q_3Da_3$	0.015	30	11	30	0.66	0.63	0.61
34	$S_4Q_1Da_3$	0.02	10	7	30	0.46	0.45	0.44
35	$S_4Q_2Da_3$	0.02	20	9	30	0.57	0.55	0.53
36	$S_4Q_3Da_3$	0.02	30	10	30	0.67	0.66	0.64

Table 2 The of characteristics of rounded sediment

No	Name of test	Slope	Flow rate	Depth	Particle size	Maximum velocity	Average velocity	Minimum velocity
			Lit/s	cm	mm	m/s	m/s	m/s
1	$S_1Q_1Dr_1$	0.005	10	6	10	0.46	0.44	0.44
2	$S_1Q_2Dr_1$	0.005	20	9	10	0.62	0.56	0.59
3	$S_1Q_3Dr_1$	0.005	30	12	10	0.7	0.65	0.64
4	$S_2Q_1Dr_1$	0.01	10	5	10	0.48	0.46	0.43
5	$S_2Q_2Dr_1$	0.01	20	7.5	10	0.57	0.6	0.53
6	$S_2Q_2Dr_1$	0.01	30	9	10	0.68	0.69	0.63
7	$S_3Q_1Dr_1$	0.015	10	5	10	0.49	0.47	0.44
8	$S_3Q_2Dr_1$	0.015	20	7.5	10	0.62	0.6	0.58
9	$S_3Q_1Dr_1$	0.015	30	10	10	0.74	0.71	0.69
10	$S_4Q_1Dr_1$	0.02	10	5	10	0.55	0.54	0.53
11	$S_4Q_2Dr_1$	0.02	20	6.5	10	0.68	0.64	0.63
12	$S_4Q_3Dr_1$	0.02	30	9	10	0.75	0.72	0.7
13	$S_1Q_1Dr_2$	0.005	10	7.5	20	0.45	0.44	0.41
14	$S_1Q_2Dr_2$	0.005	20	10.5	20	0.59	0.56	0.49
15	$S_1Q_3Dr_2$	0.005	30	12.5	20	0.68	0.64	0.57
16	$S_2Q_2Dr_2$	0.01	10	7	20	0.48	0.45	0.45
17	$S_2Q_2Dr_2$	0.01	20	9	20	0.59	0.58	0.56
18	$S_2Q_3Dr_2$	0.01	30	10.5	20	0.67	0.67	0.63
19	$S_3Q_1Dr_2$	0.015	10	6	20	0.5	0.46	0.46
20	$S_3Q_2Dr_2$	0.015	20	8	20	0.62	0.59	0.59
21	$S_3Q_3Dr_2$	0.015	30	10	20	0.72	0.7	0.69
22	$S_4Q_1Dr_2$	0.02	10	5.5	20	0.49	0.48	0.46
23	$S_4Q_2Dr_2$	0.02	20	7	20	0.61	0.61	0.55
24	$S_4Q_3Dr_2$	0.02	30	9.5	20	0.69	0.71	0.66
25	$S_1Q_1Dr_3$	0.005	10	9	30	0.47	0.43	0.41
26	$S_1Q_2Dr_3$	0.005	20	11	30	0.58	0.55	0.55
27	$S_1Q_3Dr_3$	0.005	30	13	30	0.66	0.63	0.63
28	$S_2Q_1Dr_3$	0.01	10	7.5	30	0.44	0.44	0.42
29	$S_2Q_2Dr_3$	0.01	20	.5	30	0.58	0.57	0.56
30	$S_2Q_3Dr_3$	0.01	30	11	30	0.66	0.64	0.62
31	$S_3Q_1Dr_3$	0.015	10	6.5	30	0.48	0.46	0.44
32	$S_3Q_2Dr_3$	0.015	20	8.5	30	0.59	0.59	0.54
33	$S_3Q_3Dr_3$	0.015	30	10.5	30	0.68	0.66	0.64
34	$S_4Q_1Dr_3$	0.02	10	6	30	0.49	0.47	0.64
35	$S_4Q_2Dr_3$	0.02	20	7.5	30	0.6	0.6	0.59
36	$S_4Q_3Dr_3$	0.02	30	9.5	30	0.7	0.7	0.69

Note: S_1,S_2,S_3, S_4 is the bed slope equal 0.005, 0.01, 0.015 and 0.02, D_{r1} D_{r2} D_{r3} rounded sediments with size 10 mm, 20 mm and 30 mm, respectively. $D_{a1}D_{a2}D_{a3}$ is the angular sediment with size 10 mm, 20 mm and 30 mm, respectively, Q_1, Q_2 and Q_3 is discharge flow 10,20 and 30 liter per second, respectively.

Results and Discussion

1. Velocity distribution profiles in two sharp and rounded modes

A flow with a rough bed occurs when the roughness exceeds six times the value of δ. In this type of flow, Reynolds shear value surpasses 70. The vertical distribution of flow velocity in these channels is solely affected by particle size, with viscosity playing no role in flow conditions. This flow is referred to as a completely mixed flow. In this research, the hydraulic regime is rough, and rough elements are introduced into a turbulent environment. Consequently, the majority of flow resistance is determined by the drag shape, velocity profile, and roughness Schlichting & Gersten (2000). The velocity profile graphs (U water velocity and Z water depth from the bottom of the bed) in figure 2 show an increase in speed from the bottom of the bed towards the water surface, both in sharp and round corners. In comparison to dusty particles, sharp-cornered particles exhibit a significantly higher speed profile due to the formation of a boundary layer that is significantly thicker in sharp-edged particles than in dusty particles. Thus, in the graphs, the velocity in the dusty bed is higher at the same depth as compared to the bed of sharp corners. The deviation of the velocity profiles from the origin and point (0, 0) is due to the presence of a rough surface.

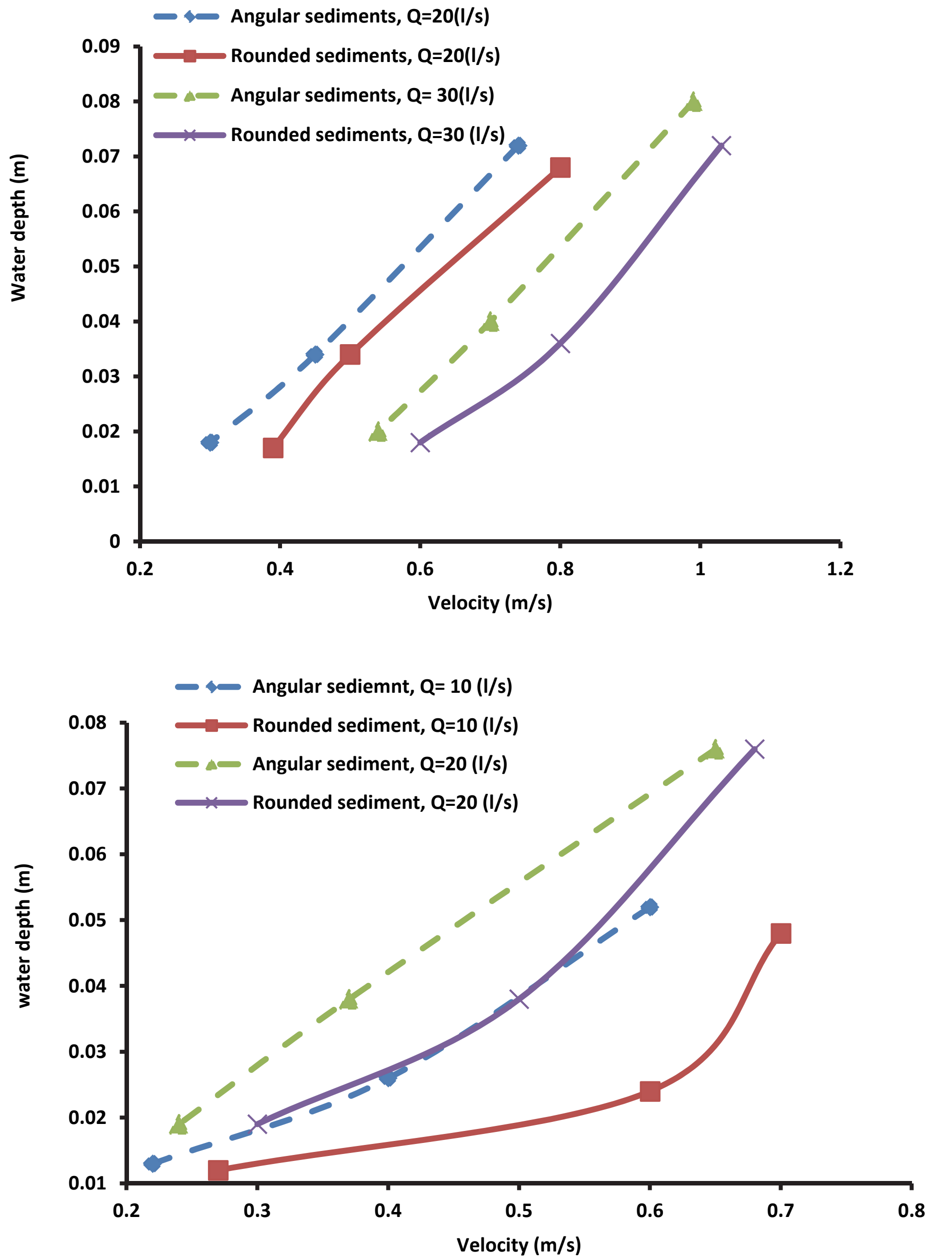

Fig.2 The velocity profiles VS water depths in angular and rounded bed

2. Relationship Between Slope and Roughness Coefficient

Figures 3 & 4 illustrate the graphs illustrating the relationship between the channel slope and the roughness coefficient. These graphs were replicated under varying flow rates and different sediment samples. Based on Merry (2017) study, it was determined that the roughness coefficient of the channel with a 1:200 slope is greater than the roughness coefficient of the channel with a 1:500 slope. In the study of Yilmaz (2023), as the slope demonstrates an increase, the roughness coefficient is anticipated to correspondingly increase at a specific flow rate. Furthermore, the field experiment conducted by Hessell (2003) yielded comparable findings. The study examined the effect of slope on the manning coefficient, utilizing the 6-64% slope of the Chinese Loess Plateau as the focal point of investigation. By increasing slope, the roughness coefficient increased. Consequently, it was deduced that the roughness coefficient exhibited a linear growth pattern in tandem with the slope increment. Upon comparing the graphs, it was discerned that the Manning roughness coefficient on x-axis experiences an augmentation as the flow rate diminishes, while the slope values exhibit a direct correlation with the roughness coefficient.

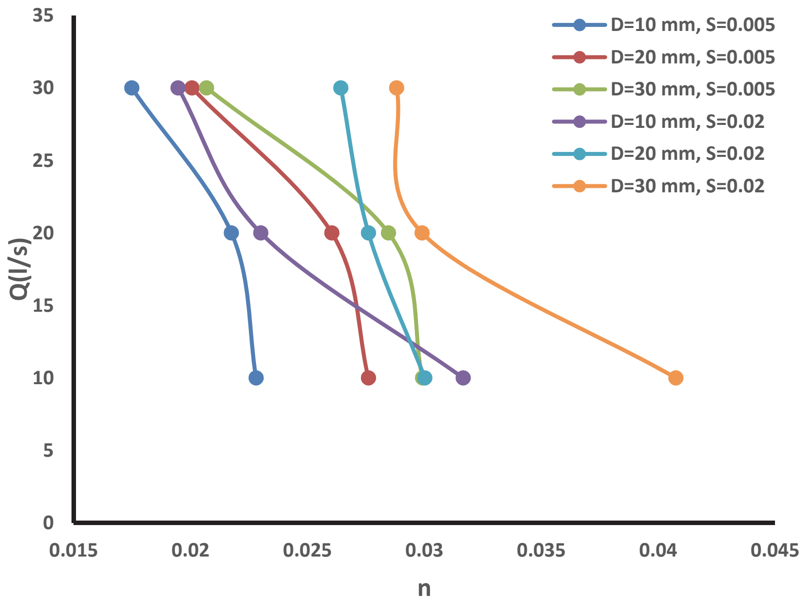

Fig.3 The relationship between the channel slope and the roughness coefficient in angular sediment

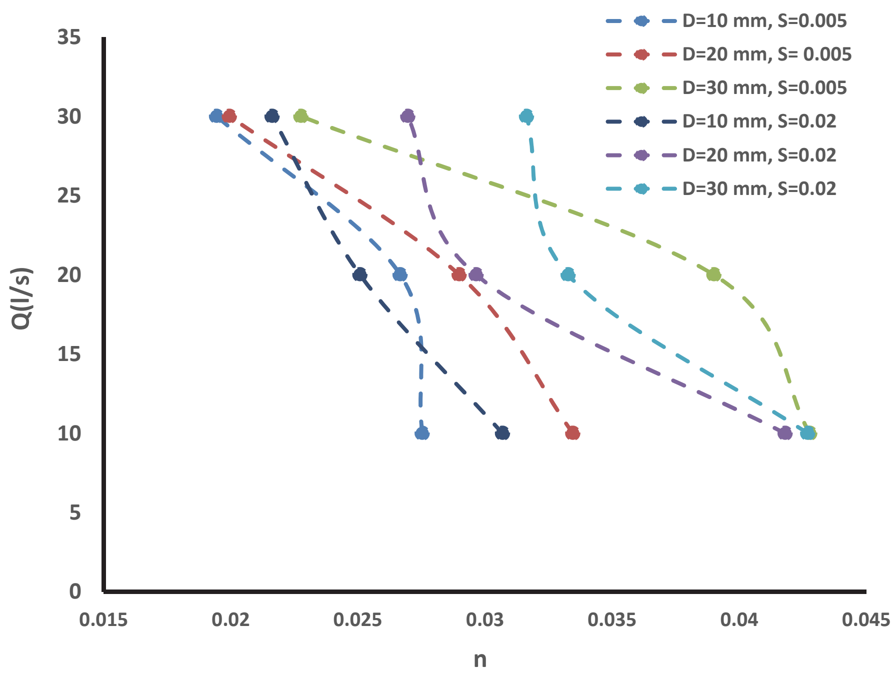

Fig.4 The relationship between the channel slope and the roughness coefficient in rounded sediment

3. Relationship Between Flow Rate and Roughness Coefficient in angular and rounded sediments

In Figure 5, the relationship between flow rate and roughness coefficients in experiments conducted with three sediment sizes and four discharge flows for two types of angular and rounded sediment is presented. Previous research by Merry (2017), Jarret (1985) and Ibrahim (2014) established a negative correlation between flow rate and roughness coefficient at a specific slope value. Building upon this knowledge, Yilmaz (2023) conducted twelve tests considering three different slopes. The results revealed that as the roughness coefficient increases, the flow velocity in the channel decreases, leading to a reduction in flow values. This study observed that the roughness coefficient decreased as the flow rates decreased for both angular and rounded sediments. Furthermore, the roughness coefficient increased with larger sediment sizes, with angular sediment experiencing greater changes compared to rounded sediment.

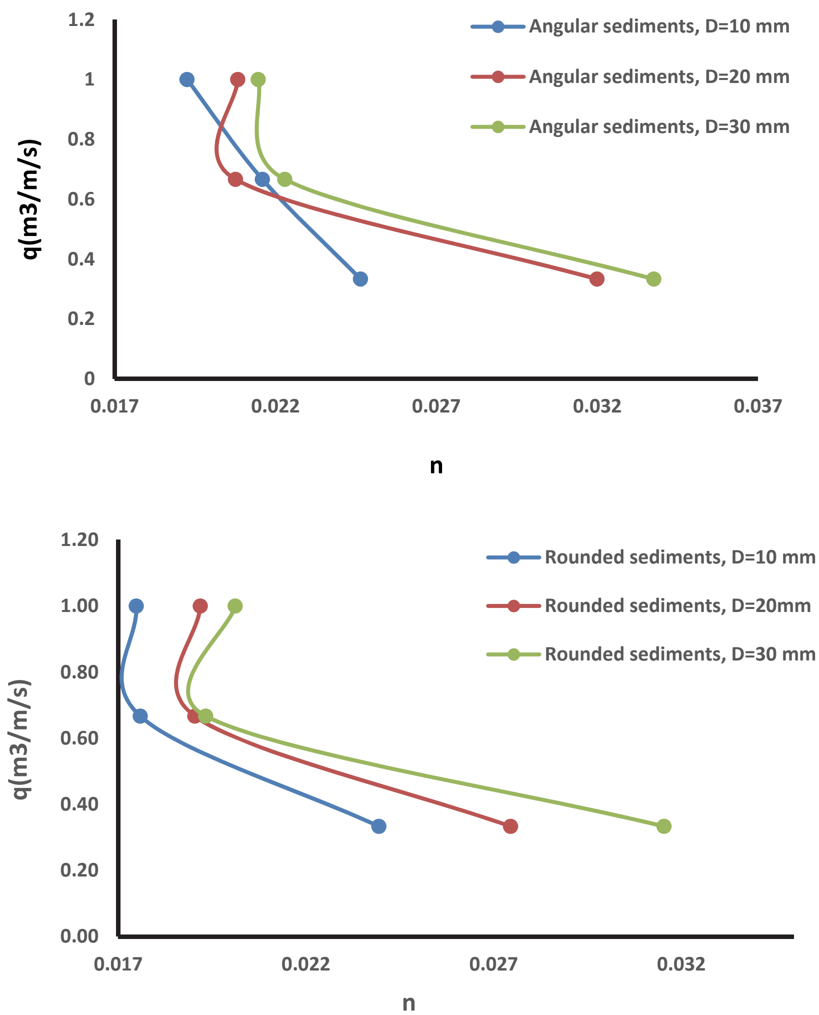

Fig.5 the relationship between the channel slope and the roughness coefficient in rounded sediment

4. Shear Stress

Considering direct correlation between bed shear stress and shear rate, the utilization of shear rate estimation becomes instrumental in expressing shear stress. Four distinct approaches were used to determine shear speed, and the outcomes were juxtaposed in two scenarios: round-cornered and sharp-cornered beds. The methods used are elaborated in Table 3.

The calculations for shear velocity were conducted using four methods, as indicated in table 3. Subsequently, the outcomes were examined for both sharp-cornered and round-cornered rough bed conditions.

Table 3 All of calculation shear velocity's methods

Method 1	$u^* = \sqrt{gRS_0}$
Method 2	$\frac{u}{u^*} = 8.5 + 2.5\ln\left(\frac{y}{k_s}\right)$
Method 3	$\frac{u}{u^*} = 6.25 + 5.75\log\frac{R}{k_s}$
Method 4	$\frac{u}{u^*} = \frac{1}{k}\ln\left(\frac{y}{k_s}\right)$

The data presented in the graphs in figure 6, indicate that the shear speed in methods 2 and 3 is highly influenced by the position of base surface used for measuring water depth. In contrast, methods 1 and 4 demonstrate a lower level of sensitivity compared to the reference level. Therefore, it is noteworthy that the cutting speed in methods 2 and 3 exhibit similarities at certain values of the base surface. The results indicate that methods 2 and 3 yield comparable shear rates at the base of the bed for a specific set of hydraulic parameters. These findings align with the research conducted by Biron (2004), who conducted experiments on a rough bed in a rectangular flume.

Furthermore, a comparison was made between the remaining methods and the first method, and the percentage of error was calculated for two scenarios: sharp corner and round corner. These findings are presented in Table 4.

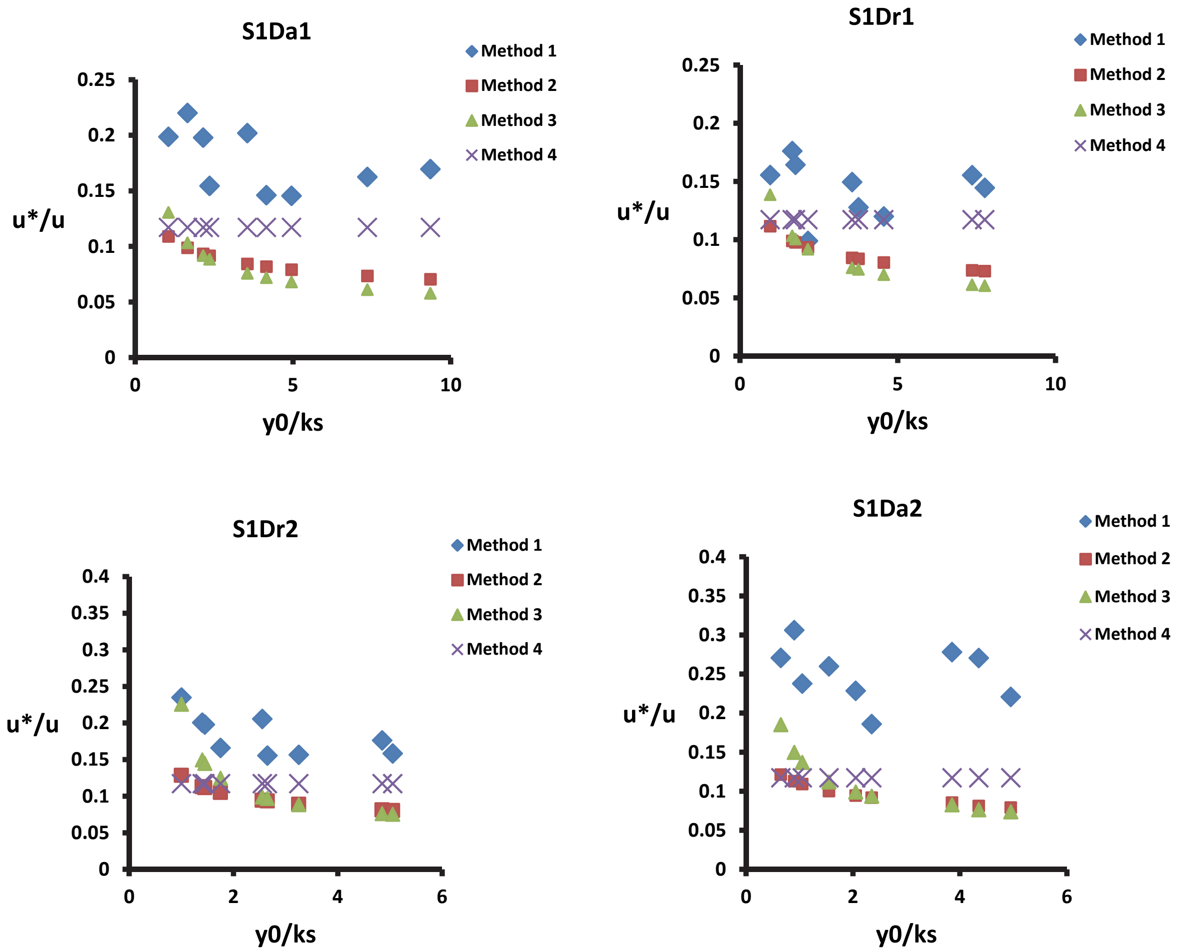

Fig.6 Diagrams (u*/u) V.S (y0/ks) with 4 methods

Table 4 The comparison among methods with percentage of error

Methods	Error (a) 10 (l/s)	Error (a) 20 (l/s)	Error (a) 30 (l/s)	Error (r) 10 (l/s)	Error (r) 20 (l/s)	Error (r) 30 (l/s)
$u^* = \sqrt{gRS_0}$	41	26.9	45	39.3	47.2	44.1
$\frac{u}{u^*} = 8.5 + 2.5\ln\left(\frac{y}{k_s}\right)$ $\frac{u}{u^*} = 8.5 + 2.5\ln\left(\frac{y}{k_s}\right)$	57.7	43.2	58.2	48	63	59
$\frac{u}{u^*} = 6.25 + 5.75\log\frac{R}{k_s}$	56.7	28.2	49.8	29.5	60	30
$\frac{u}{u^*} = \frac{1}{k}\ln\left(\frac{y}{k_s}\right)$	41.1	27.8	47.9	41.7	48.3	45.5

5. Effect of relative submergence on Darcy-Weisbach Coefficient

Based on Figure 7, we can anticipate a consistent pattern of the relative submergence and Darcy-Weisbach coefficient for two-bed surfaces. This pattern consistently demonstrates an inverse correlation between the values of f and y/ks across all the Figures.

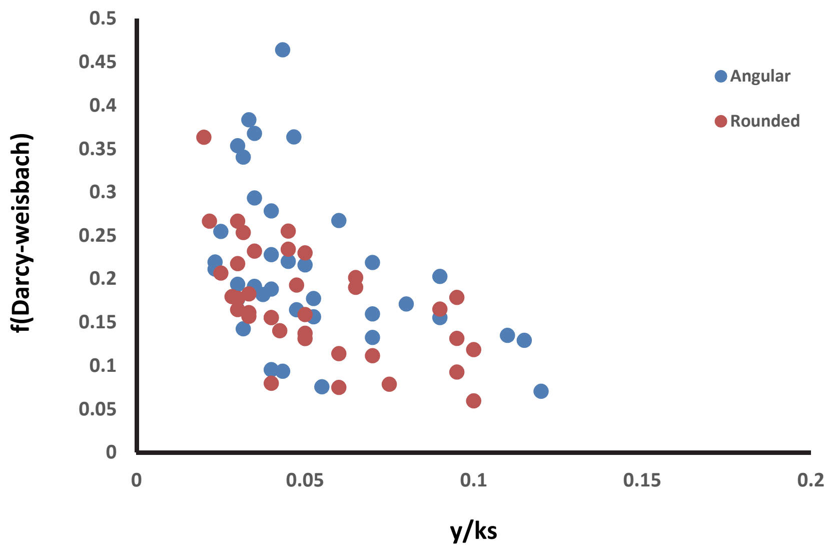

Fig.7 Effect of Aspect ratio on roughness coefficient for the slope of 0.005 and 0.01

Conclusion

Determining the roughness coefficient in the Manning equation, commonly employed in open channel flows, is subject to variation based on numerous parameters. To effectively compute this coefficient, it is crucial to have information about the flow characteristics as well as the channel. In this particular study, the association between the roughness coefficient and the channel slope, grain diameter, and various flow rates is thoroughly examined through the utilization of graphs derived from 72 experimental data. Based on laboratory studies, it was observed that within a channel of identical slope, the flow rate and roughness coefficient exhibit an inverse relationship. Thus, at a specific slope value, the roughness coefficient displayed an increase corresponding to an increase in median particle size. The slope values directly correlated with the roughness coefficient in experiments with consistent flow rates. It was determined that the Froude number ranged from 0.41 to 0.78. In the subcritical flow regime, the Froude number and the roughness coefficient show an inverse correlation for the same slope. Besides, as the slope increases, Froude number and the roughness coefficient increase for the same grain size. The roughness coefficient up to the particle size of 20 mm has a small difference between the sharp corner and round corner states so that the difference between the sharp corner and round corner states will increase as the size increases. The slope of the speed changes in the bed of the corner is lower than that of the sharp corner. The speed increases from the bottom of the bed towards the water surface in both the sharp and round corners. Hence, the speed at different depths on the bed of the round corner is higher than that of the sharp corner. The amount of bed shear stress has increased with the increase in bed particle size, and the shear stress is higher in the case of a sharp corner bed than in a round corner. Based on the results of this research, it can be said that in all the experiments, the shear stress of bed for round-shaped particles decreased by 3.62% compared to sharp-cornered particles.

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