# RESISTANCE TO FLOW OVER SUBMERGED OBSTACLES IN A STEEP CHANNEL

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## Abstract

An experimental study is presented of flow over various kinds of submerged artificial large scale roughness elements in a channel of 16.5% slope with supercritical approach flow. Eight different shapes of obstacles are tested, namely standard baffle blocks, cubes, half-cubes, vertical plates, cylinders, thin rods, and half–spheres parallel or normal to the flow; their density along the bottom is also variable. Based on depth measurements, the effective Manning's roughness coefficient n as well as the Darcy-Weisbach's friction factor f are determined for a range of discharges. The results are presented in non-dimensional plots and the effect of main geometrical parameters on flow resistance is discussed.

**Keywords**: Open channel flow, Large scale roughness, Roughness coefficient, Friction factor, Energy dissipation, Steep channel

## Introduction

Flow in steep channels has high velocities, so energy dissipation is normally required. As an alternative to localized dissipation in conventional structures, such as stilling basins, gradual dissipation may be employed by means of successive steps, cascades, submerged obstacles, riprap layers etc (Vischer, 1995). The flow over large artificial roughness elements has received limited attention so far. Peterka (1958) studied the effect of protruding blocks in chutes of high slope, up to 50%. Herbich & Shulits (1964) conducted experiments in a channel at slopes 0.003 to 0.03, for several arrangements of cubic blocks, and introduced a dimensionless parameter, θ, as the ratio of the total projected area of the blocks divided by the respective area of the channel bottom. Their results were presented in diagrams of the dimensionless resistance coefficient (Darcy-Weisbach's f or normalized Manning's n) vs Reynolds number for various θ values. Sayre & Albertson (1961) placed thin plates normal to the flow at several patterns in channel slopes 0.001 to 0.003. By fitting a logarithmic law to their data, they were able to determine a characteristic roughness length X which incorporates the roughness height and the effect of pattern.

Considerable research has been carried out on the effect of natural large scale roughness in boulder- or gravel-bed rivers in mountainous terrain. In most cases a log law was adopted, of the form:

$$\sqrt{\frac{8}{f}} = c_1 \log\frac{y}{D} + c_2 \qquad (1)$$

where f is the friction factor, y the depth of flow and D a characteristic length of the bed roughness (often $D_{84}$ or $D_{50}$). Values of the coefficients $c_1$ and $c_2$ have been obtained by several investigators based on either field or laboratory experiments (e.g. Bathurst 1985, Rice et al 1998). A similar equation was proposed by Pagliara et al (2010) for the resistance coefficient in rock chutes, whereas Pagliara & Chiavaccini (2006) related the friction coefficient to energy dissipation on block ramps. Somewhat relevant research has also been carried out concerning drag and resistance characteristics of flow through vegetation. For example, Järvelä (2002) presented experiments in a large laboratory channel, concerning the friction factor f due to rigid or flexible elements of vegetation. His results show the dependence of f mainly on the Reynolds number and relative depth. Kouwen & Unny (1973) and Okamoto & Nezu (2010) investigated the value of f for flexible vegetation.

This paper presents an experimental investigation of flow over a variety of submerged obstacles in a steeply sloping channel focusing on resistance characteristics, following recent experimental work by Christodoulou & Papathanassiadis (2009), Vassilakos (2010) and Kostidou (2010).

## Experiments

The experiments were conducted in the Laboratory of Applied Hydraulics of the National Technical University of Athens. The experimental setup consisted of a supply tank and a 0.25 m wide channel made of plexiglas, in three segments. The main segment where measurements were taken had a length L = 3.55 m and slope 16.5%. This was connected upstream and downstream to shorter segments, of about 1 m length, at slopes approximately 5%. The flow was regulated by a sluice gate at the exit of the supply tank, so that the flow depth near the end of the upstream segment of the channel was close to uniform. Thus, the incoming flow to the steep channel was clearly supercritical, with Froude number about 3.3. The discharge was measured by a Venturi meter and a differential manometer installed on the main supply line of the Laboratory, and ranged between 15 and 60 l/s. The Reynolds number was generally large, of the order of $10^5$. A sketch of the experimental setup is shown in Fig. 1.

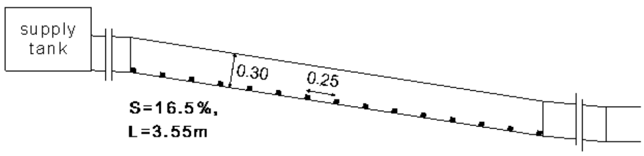



Figure 1: Sketch of experimental setup

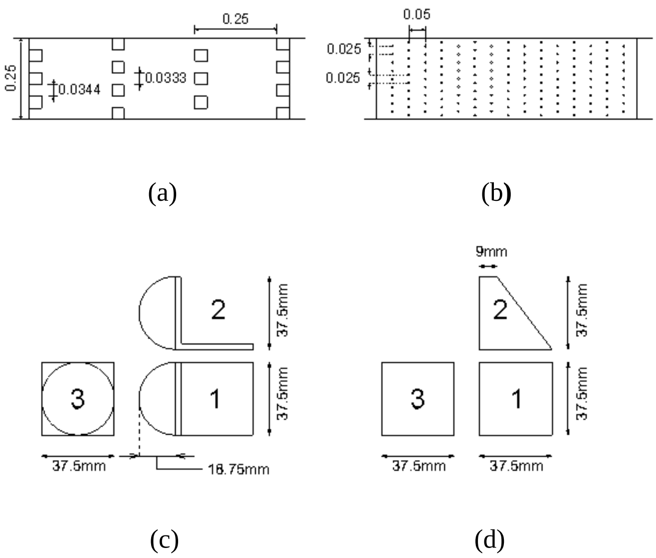


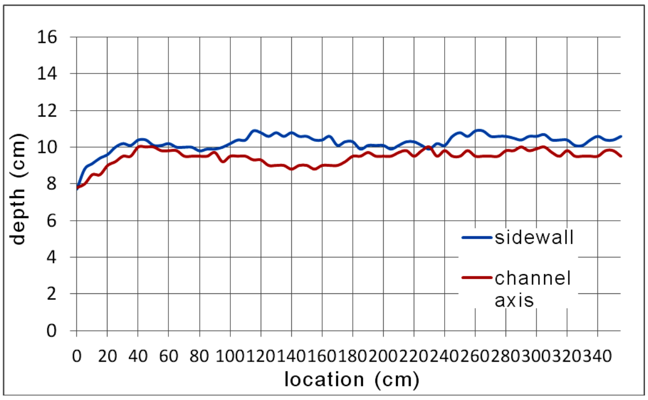

Figure 2: (a) Basic arrangement of obstacles, (b) Dense arrangement of rods, (c) Hemisphere normal to flow, (d) Baffle block

Seven types of obstacles were tested, namely standard-shaped baffle blocks, cubes, thin plates normal to the flow, vertical cylinders, half-cubes, hemispheres normal and parallel to the flow. The detailed forms of the baffle block and of the hemisphere normal to the flow (attached to a thin vertical plate) are shown in Figs. 2(d) and (c), respectively. In all cases the elements were placed in regular patterns forming rows normal to the flow. For the first four types, the height h, as well as the width w facing the flow across the channel was 3.75 cm, while the spacing d between them was slightly less, as shown in Fig. 2(a). The diameter of the hemispheres was also 3.75 cm, whereas the half-cube dimensions were 3.75 x 3.75 cm in plan and 1.9 cm in height. Thus, the height of the half-cube and of the hemisphere when placed parallel to the flow was half that of the other elements. The distance s between successive rows was set equal to the width of the channel (0.25 m), so the basic arrangement of the elements in plan view is as shown in Fig. 2(a). For the baffle blocks also a denser pattern was tested, in which the distance s between rows was half the channel width. Finally, to assess the resistance of rigid vegetation, two patterns of thin rods of 0.5 cm diameter and 4 cm height were studied, one with s= 5 cm as shown in Fig. 2(b) and another with s=10 cm. Thus, a total of 10 series of experiments were carried out.

## Results and Discussion

### Flow profile

The depth of flow was measured along the channel axis and sidewalls at 5 to 10 cm intervals. In general, the free surface along the steep channel reach had considerable undulations. For any given type of roughness element, these were more pronounced for low discharges and decreased appreciably when the distance between successive rows decreased. Preliminary observations showed that the first row of obstacles caused excessive disturbance of the flow and high waves especially for small discharges; consequently in most cases the first row was modified to a height half of that of the remaining rows. Given that modification, in all cases the depth tended to an almost constant value in the lower part of the steep channel, indicating that nearly uniform flow has been attained. As an example, the measured depths for the flow over the standard arrangement of baffle blocks and the dense pattern of rods are shown in Fig. 3 (a,b).



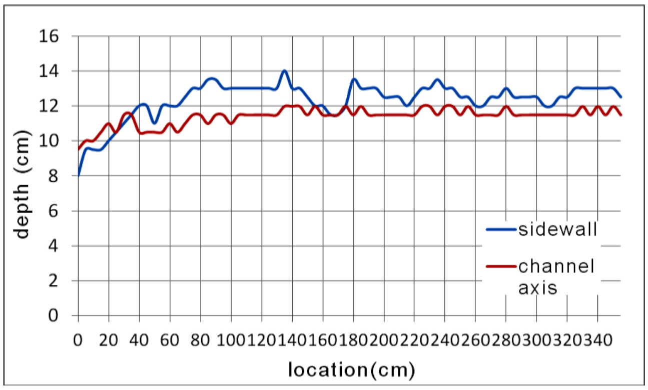




Figure 3: Measured depth along the channel for (a) rods (dense), Q= 52.5 l/sec, (b) baffle blocks, Q= 55 l/sec

**Roughness coefficient**

Evaluation of the equivalent roughness coefficient expressing the effect of the submerged obstacles was based on the consideration of a uniform flow depth y equal to the average depth measured in the lower reach of the steep channel. Application of the Manning formula

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (2)$$

(where A is the cross-sectional area, R the hydraulic radius and S the bottom slope) for the respective set of discharge and flow depth allows the calculation of the effective Manning's n coefficient for each experiment. Further, the respective Darcy-Weisbach's friction factor f was calculated taking into account that:

$$\frac{1}{\sqrt{f}} = \frac{R^{1/6}}{n\sqrt{8g}} \qquad (3)$$

Fig. 4 shows the variation of the computed n vs the discharge Q for all series of experiments. It is seen that: (i) For any type of roughness element, the value of n is higher for small discharges and tends to become constant as the discharge increases. This behavior indicates the higher effect of the roughness elements when they are little submerged compared to when the flow depth is much larger than their height. (ii) The highest resistance is offered by the thin vertical plates, followed closely by the baffle blocks and cubes. The two types of elements with smaller height yield significantly smaller values of n. (iii) The elements with rounded edges result in smaller n values compared to similar sized ones with sharp edges. Thus the resistance of cylinders and of hemispheres normal to the flow with same height and projected area as the cubes, baffle blocks and thin plates is considerably lower. Similarly, the value of n for the hemispheres parallel to the flow is appreciably lower compared to the half-cubes. (iv) The resistance of vertical rods in the patterns studied is comparable to those of other obstacles of about half their height.

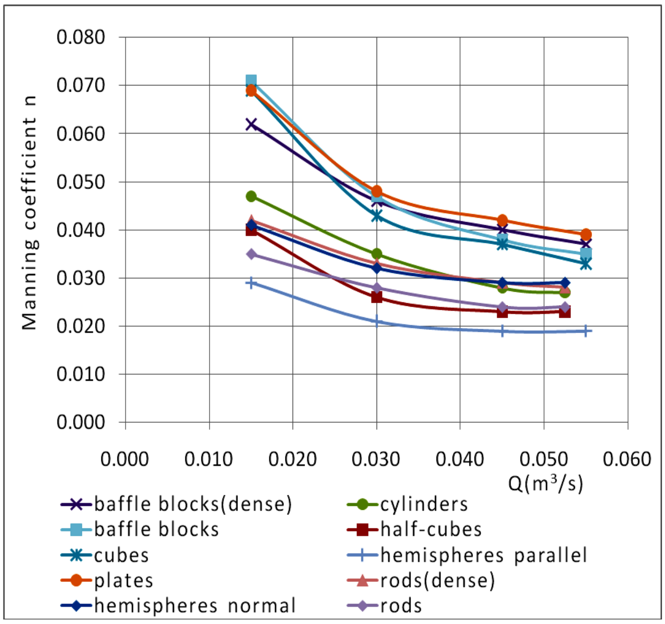



Figure 4: Variation of Manning's n with discharge

**Dimensionless results**

For better generalization, non-dimensional forms of the results are presented below. Fig. 5 is a plot of the normalized depth, y/h, vs the non-dimensional parameter $nq/(h^{5/3}S^{1/2})$, where q is the discharge per unit width. The bottom slope S is introduced to allow possible comparison with results obtained at different slopes. In fact, Fig. 5 includes data from Herbich & Shulits (1964) representing the effect of cubic elements (15 cm size) at two row spacings (pattern I, s=30 cm; pattern II, s=38 cm) in a channel with much smaller slope (0.003 to 0.01). It is evident that all data corresponding to a certain height h collapse on a single line regardless of the shape of the obstacle; however this correlation is a consequence of the way of determining n via the measured depth in each case.

In Fig. 6 the same non-dimensional parameter containing n is plotted against the normalized critical depth $y_c/h$. It is seen that for each type of element the data have a linear trend, at approximately the same slope, and that there is a systematic shift from the sparse rods (smallest n for given $y_c/h$) to the thin vertical plates (largest n).

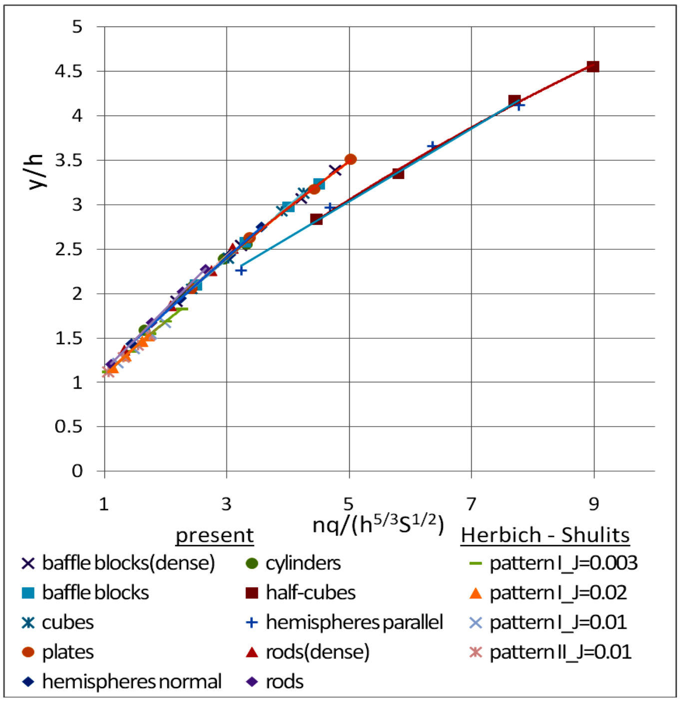



Figure 5: Non-dimensional plot of n vs flow depth

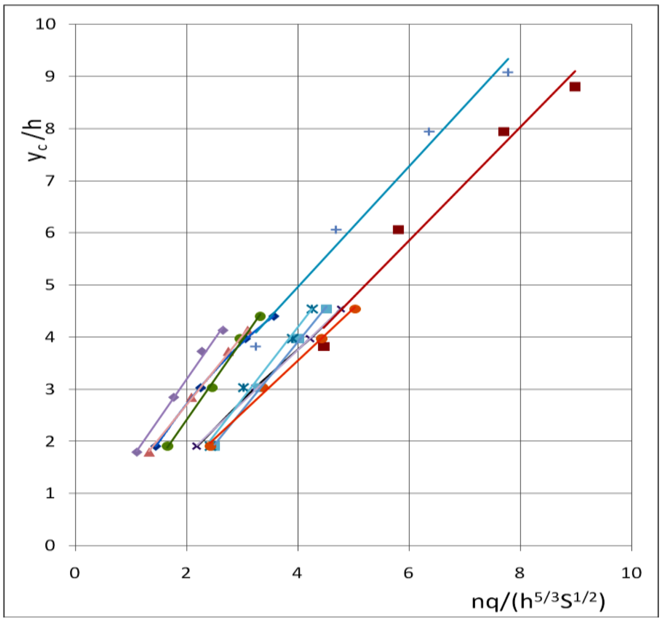



Figure 6: Non-dimensional plot of n vs critical depth; symbols as in Fig. 5

Finally, Fig. 7 shows the variation of $1/f^{1/2}$ with $y_c/h$. It is obvious that in the semi-log plot the relation is approximately linear, similar to eq. (1), and has the form:

$$\frac{1}{\sqrt{f}} = a \log \frac{y_c}{h} + b \tag{4}$$

The critical depth $y_c$ is uniquely determined from the unit discharge q, therefore Figures 6 and 7 can be used for predicting the effective roughness (in terms of n or f, respectively) for a certain discharge, height and pattern of the obstacles, without any measurement of depth. The coefficients a and b are calculated by linear best fit of the data and presented in Table 1. The values of a have little variation (2.2 to 3.2) for a certain height h but are considerably larger, about 3.8, for the two elements with smaller h (half-cubes and half-spheres parallel to flow).This indicates a faster decrease of f with increasing $y_c/h$ for the smaller size elements. Even smaller values of a are obtained from the results of Herbich & Shulits (1964), which suggest a possible dependence on the slope as well. Concerning the value of b, it tends to be smaller for sharp-edged elements, implying a larger f, however no firm conclusion can be reached at this point given the simultaneous variation of a.

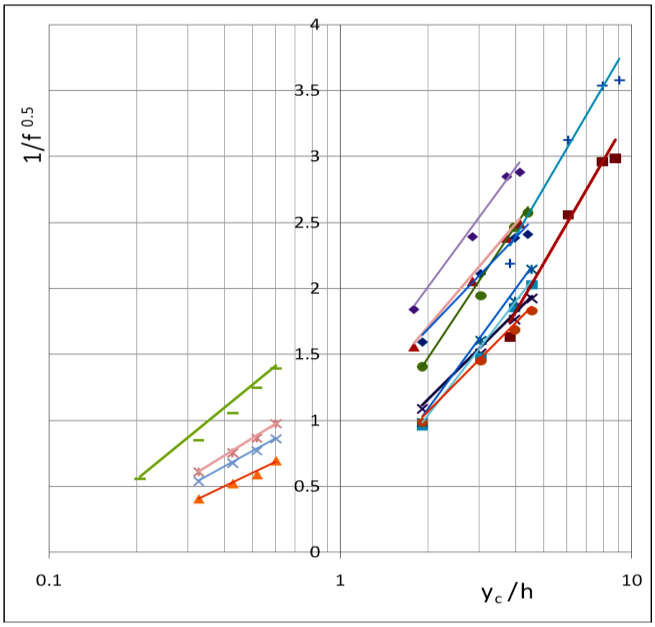



Figure 7: Variation of friction factor f with $y_c/h$; symbols as in Fig. 5

Table 1: Coefficients a, b of eq. (4)

| | a | b |
|---|---|---|
| baffle blocks (dense) | 2.1957 | 0.4638 |
| baffle blocks | 2.8408 | 0.1461 |
| cubes | 3.0058 | 0.1419 |
| vertical plates | 2.2284 | 0.3639 |
| hemispheres parallel | 3.8323 | 0.0188 |
| hemispheres normal | 2.3276 | 0.9588 |
| half-cubes | 3.8656 | -0.5674 |
| cylinders | 3.2844 | 0.4510 |
| rods (dense) | 2.5843 | 0.8979 |
| rods | 2.9817 | 1.0792 |
| HS pattern I_J=0.003 | 1.7904 | 1.7571 |
| HS pattern I_J=0.02 | 1.0582 | 0.9139 |
| HS pattern I_J=0.01 | 1.2046 | 1.1231 |
| HS pattern II_J=0.01 | 1.3658 | 1.2673 |

## Conclusions

Based on a large number of laboratory experiments concerning the flow resistance characteristics of a variety of submerged obstacles in a steep channel, the following main conclusions may be drawn:

1. The equivalent Manning's roughness coefficient n is larger for small discharges and tends to a constant value as the discharge increases, regardless of the type of obstacle. In all cases, the values of n are much larger than that of the channel boundary, implying a considerable increase in energy dissipation.
2. Several geometrical parameters affect the resistance characteristics, notably the height, projected area and shape of the element.
3. Increasing the height of similarly shaped elements implies an increase in roughness. The effect of height can be better expressed in terms of the ratio $y_c/h$, which relates h to the critical depth and hence the discharge, or y/h, which incorporates the influence of slope.
4. Elements with rounded edges result in smaller roughness compared to sharp-edged ones of similar size.
5. Non-dimensional plots of n with some of the main geometrical parameters are presented, which may be useful in practical applications.
6. A log-linear expression holds between the effective friction factor f and the relative height $y_c/h$. The respective coefficients are determined for each type of roughness element.
7. The effect of density of placement is evident in the case of thin rods, but less clear for baffle blocks; however variation of density was presently limited. Also, the effect of slope seems to be important, but could not be studied in this work, as the slope was fixed. Further research is needed to clarify the influence of these two parameters.

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