International Journal of Civil and Structural Engineering– IJCSE
Volume 3 : Issue 1 [ISSN : 2372-3971]
Publication Date: 18 April, 2016

Experimental analysis on flow resistance for different macro-scale roughness arrangements

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Abstract - **Macro-roughness elements superimposed on the original river bed are increasingly being applied as a restoration measure in natural streams. Under these conditions, due to the interaction of these large boulders with the flow, the classic resistance formulae are no longer valid, preventing their use for design purposes. The paper shows the results of an experimental study conducted on a rough channel with the insertion of protruding boulders, under different hydraulic and geometric conditions, for a total of 66 tests. The effects on flow resistance of channel slope, discharge, boulder size, density and arrangement were investigated in order to obtain useful information (in terms of boulder arrangement, concentration and dimension) for designing bed stabilization systems in natural streams.**

Keywords – macro-scale roughness, flow resistance, boulders, arrangements

I. Introduction

Artificial macro-scale roughness elements are increasingly being used for river training, as they help to stabilize the stream bed and bank slope, restore biodiversity and river ecology, and promote a better aesthetic landscape. In fact, flow interaction with large-scale roughness can be easily found in nature, such as step-pool systems in mountain streams. In these conditions, characterized by the presence of large boulders protruding from channel bed, flow depth is usually of the same order of magnitude of roughness size. Previous investigations (Bathurst 1978, Bathurst *et al.* 1981, Lawrance 1997) identified three different roughness conditions, based on the relative submergence of the boulders, i.e. on the ratio of flow depth *h* and the characteristic particle size d_{84} (or roughness height, *k*), as follows:

- small-scale roughness ($h/d_{84}>4$ or $h/k \gg 1$): roughness elements introduce only a boundary scale roughness, without altering the vertical flow velocity profile, as they are small compared to water depth;
- intermediate-scale roughness ($1.2<h/d_{84}<4$ or $1<h/k<4$): roughness elements are submerged, but their presence affects the vertical flow velocity profile, due to the relatively shallow water depth.
- large-scale roughness ($h/d_{84}<1.2$ or $h/k<1$): water depth is markedly shallower than roughness elements, which protrude through the flow.

In this last condition the classic flow resistance formulae cannot be applied, as the assumption of a logarithmic velocity profile is no longer valid.

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Previous experimental works (e.g. Bathurst *et al.* 1981, Ferro 2003, Pagliara and Chiavaccini 2006, Canovaro *et al.* 2007, Canovaro and Solari 2007, Pagliara *et al.* 2008) have shown that, besides the characteristic diameter, roughness geometry (including both boulder concentration Γ and spatial arrangement) affects flow resistance in macro-scale roughness conditions.

The present paper shows the results of an experimental study carried out to investigate the effects of the presence of macro-roughness elements on flow resistance, under different hydraulic conditions, boulder sizes and arrangements, with the aim of giving practical indications that can be useful in designing bed stabilization systems in natural streams.

II. Experimental setup

The experiments were carried out in a recirculating rectangular flume 6 m long, 0.50 m wide and 0.22 m deep, with bed slope set between s_1=3.5% and s_2=7%. The discharge, measured using a calibrated magnetic flow meter located in the supply line, was varied between 9.92, 13.10 and 16.20 l/s. Water levels and flow velocities were measured at 5 cm intervals in two cross-sections located respectively 1 m away from the inlet and the outlet of the channel. For each cross-section, space-time averaged values of these quantities were considered during each run.

In a first phase (reference condition, Γ=0) the channel was covered by a granular layer of uniform material having a median size of 10 mm, with no sediment transport occurring during the tests.

In a second phase, macro-roughness elements constituted of three sets of boulders characterized by different sizes *H* (H_1=4.50 cm, H_2=3.70 cm and H_3=2.50 cm) were introduced along a 3 m reach between two cross-sections located respectively at abscissa 1.50 and 4.50 m of the channel (Fig. 1). Boulder concentration Γ (Pagliara and Chiavaccini 2006) was ranged from 0 to 0.19. These elements were positioned according to a regularly spaced transversal stripe pattern and, for the different sets of boulders, the spacing *L* between two consecutive stripes was varied between 12.5 and 60 cm as follows:

- Configuration H_1-1, H_1-2and H_1-3: transversal stripes composed of H_1 size boulders with spacing *L*=60, 45 and 22.5 cm respectively;
- Configuration H_2-1, H_2-2 and H_2-3: transversal stripes composed of H_2 size boulders with spacing *L*=50, 37 and 18.5 cm respectively;
- Configuration H_3-1, H_3-2 and H_3-3: transversal stripes composed of H_3 size boulders with spacing *L*=30, 25 and 12.5 cm respectively;

In addition to these 'step-pool' configurations, two other geometries were tested for comparative purposes:

Figure 1. Tested macro-scale roughness configurations: transversal stripes (different boulder sizes and spacings), groynes and random arrangements.

- Configuration RH_1: unstructured geometry composed of 170 H_1 size boulders randomly arranged in the measuring reach;
- Configuration GH_1: 22.5 cm long transversal stripes constituted of H_1 size boulders arranged like groynes with spacing L=45 cm.

According to Lawrance (1997), macro-scale roughness conditions were observed for H_1 and H_2 boulder sizes, with *h/k* values ranging from about 0.6 to 0.9; these values increased up to 1 and 1.5 for the H_3 boulder size, leading to an intermediate-scale roughness condition.

III. Results and conclusions

In order to analyze the effects of the presence of the boulders on flow resistance, the dimensionless Chezy coefficient *C* was used for comparing the performance of all the tested configurations:

$$C = \frac{C'}{\sqrt{g}} = \sqrt{\frac{8}{f}} \tag{1}$$

where *C'* is the classical dimensional Chezy coefficient, *g* gravity and *f* the Darcy-Weisbach friction factor.

In line with other previous studies (Rouse 1965, Canovaro *et al.* 2007, Canovaro and Solari 2007), the influence of roughness concentration Γ on *C* was investigated with the aim of finding Γ values which maximize flow resistance (i.e. minimize *C*). The results are summarized in Fig.2, which shows the behavior of *C* as a function of Γ for the three tested discharges. All plots are characterized by a non-monotonic trend of *C* as a function of Γ: starting from the maximum values observed in the reference conditions (Γ=0), *C* tended to decrease until reach a minimum for $\Gamma = 0.05 \div 0.10$.

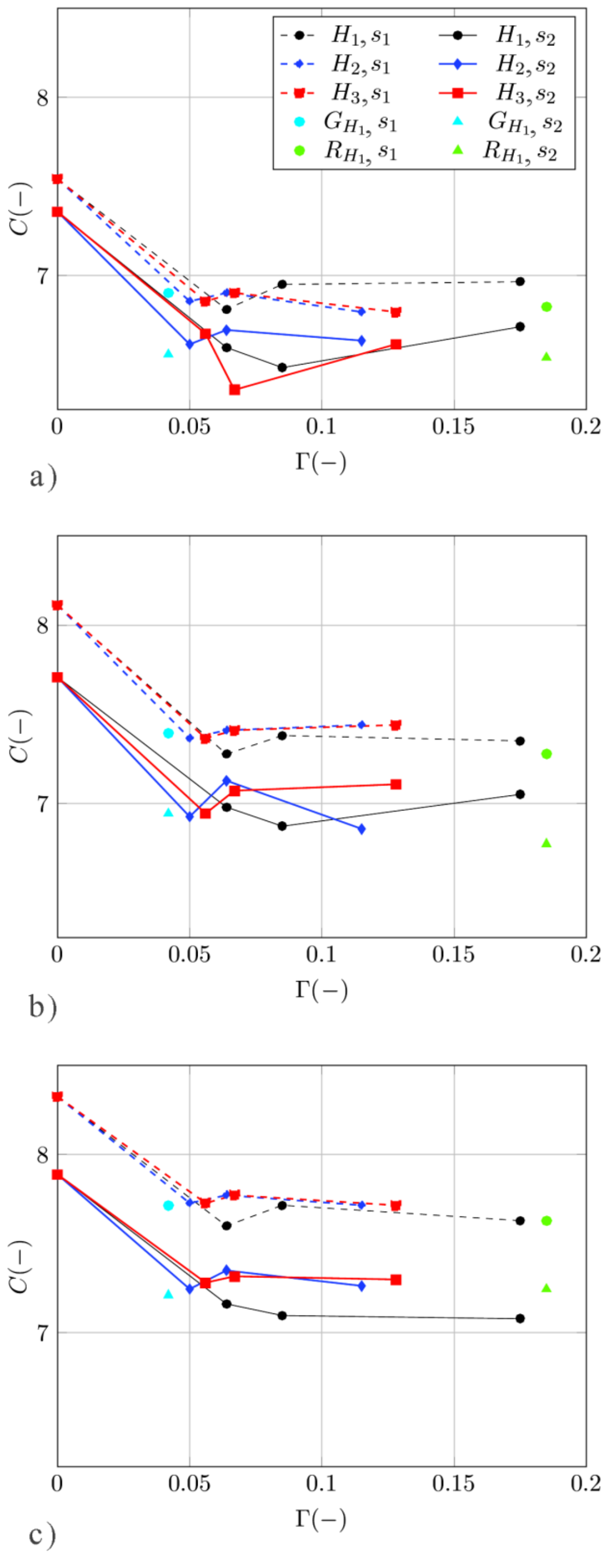

Figure 2. Dimensionless Chezy coefficient as function of boulder concentration Γ for different discharges: a) Q_1 = 9.92 l/s; b) Q_2 = 13.10 l/s; c) Q_3 = 16.20 l/s.

These results are in agreement with other investigations that found optimal Γ values around $0.15 \div 0.20$ (Rouse 1965) and $0.20 \div 0.40$ (Canovaro *et al.* 2007). Morris and Wiggert (1971) explained the presence of a maximum flow resistance by relating flow characteristics to the concentration of macro-roughness elements. They suggested that this condition could be attained in the transition from a "isolated roughness" (where flow resistance is proportional to the number of boulders) to a "wake interference" flow (where flow resistance is no longer proportional to the number of boulders, as the elements interfere with the others due to their proximity).

Although the plots of Fig. 2 show similar trends, it is evident how the macro-scale elements were more effective in reducing the *C* coefficient in the case of the larger slope s_2=7%. From a more detailed analysis of the behavior for each configuration, minor differences were found at s_1=3.5%, especially for transversal H_2 and H_3 boulder size geometries, with almost constant values of *C* for $\Gamma > 0.05$. For H_2 boulders, maximum flow resistance was attained at the same values of Γ observed both for s_1 and s_2 ($\Gamma = 0.05$), while for H_1 and H_3 geometries the minimum was slightly shifted to $\Gamma = 0.06 \div 0.08$ (up to 0.17 for Q_3) in the passage from s_1 to s_2. As regards the GH_1 and RH_1 configurations, despite the limited range of the experimental runs, two considerations are still possible: on one hand, the use of groynes (GH_1) seems to be a cost-effective solution, with values of *C* similar to those obtained with other arrangements, but with a smaller boulder concentration; on the other hand, the random disposition (RH_1) led to *C* values in line with the others (best performance for the run at discharge Q_2 and slope s_2), but at the cost of using more boulder elements ($\Gamma = 0.19$), even though this drawback can be compensated by a better aesthetic and more natural aspect.

Given the different behaviors observed for the transversal stripes configurations for the two tested slopes, we investigated the influence on flow resistance of geometric parameters like boulder size and spacing, by combining them in the ratio *(H/L)/s*, according to other experimental studies on step-pool systems (e.g. Abrahams *et al.* 1995). Plots of Fig.3 show interesting additional information to that provided in Fig. 2. It is possible to note that for the 3.5% slope, the trend was almost constant in the range of the tested *(H/L)/s* (from about 2 to 6), while large scatter and smaller *C* values were evident for the 7% slope, with maximum flow resistance observed for *(H/L)/s* ≈1.5. These results confirmed the existence, for step-pool configurations, of an optimal value of the ratio *(H/L)/s* ranging from 1 to 2 (Abrahams *et al.* 1995) which maximizes flow resistance and stream bed stabilization.

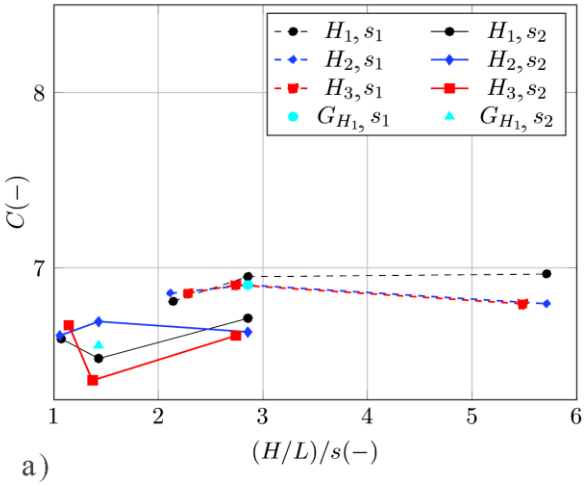

Figure 3. Dimensionless Chezy coefficient as function of the *(H/L)/s* ratio for different discharges: a) Q_1 = 9.92 l/s; b) Q_2 = 13.10 l/s; c) Q_3 = 16.20 l/s.

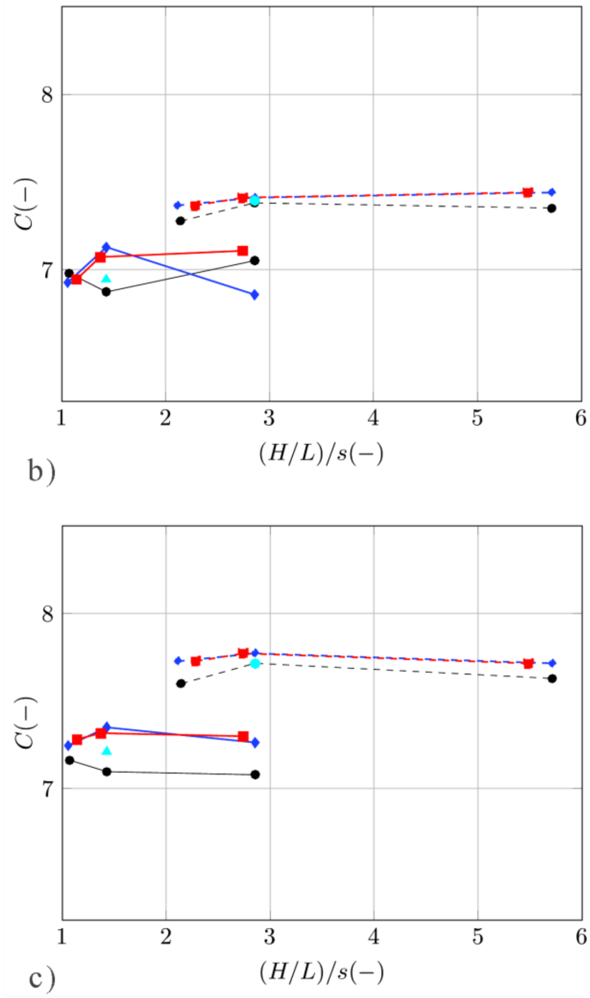

Figure 3. *(continues)* Dimensionless Chezy coefficient as function of the *(H/L)/s* ratio for different discharges: a) Q_1 = 9.92 l/s; b) Q_2 = 13.10 l/s; c) Q_3 = 16.20 l/s.

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