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THE EFFECT OF BOULDER SPACING ON FLOW PATTERNS AROUND BOULDERS UNDER PARTIAL SUBMERGENCE

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ABSTRACT: This study focuses on documenting the influence of boulder spacing on flow patterns within an array of boulders in mountain streams. Boulder arrays modify the flow structures in their vicinity, which in turn regulate the depositional patterns. However, a critical literature review reveals that the effects of boulder spacing on flow have been overlooked. Herein, we hypothesize that the developing flow structures around boulders are controlled by the boulder spacing. The objective of this study is to map the surface flow structures around partially submerged boulders for two different boulder spacing scenarios: (1) $\lambda/d_c = 6$ and (2) $\lambda/d_c = 10$ (where $\lambda$ denotes the spacing between the boulders and $d_c$ is the boulder diameter). For each scenario, the flow structures are mapped using an IR camera. The IR camera records the motion of ice-cube tracers, which is subsequently analyzed with the Large Scale Image Velocimetry (LSIV) software. The result is a surface velocity field produced by a sequence of successive frames. The flow experiments show that when $\lambda/d_c = 6$, the shear layers emanating from the upstream boulders extend all the way to the downstream boulders, whereas when $\lambda/d_c = 10$, the flow reattaches prior to reaching the downstream boulders.

Keywords: mountain streams, relative submergence, boulder spacing, IR camera.

INTRODUCTION

In many restoration projects, it is a widely spread practice to install arrays of boulders (rocks) into the stream body to minimize the effects of upstream hydraulic structures (e.g. dams, weirs) and restore degraded ecosystems (SHAMLOO et al. 2001). Installation of boulders is a useful tool in engineering practice that can be used to replicate the natural environment, improve fish habitats and support ecosystem diversity by creating in-stream regions that provide feeding and spawning resources to the fish populations (NOWELL and JUMARS 1984, KATOPODIS 1996).
Despite their easy and cost-effective installation, the design of arrays of boulders for restoration purposes involves significant empiricism as the hydraulics around the rocks remains poorly understood. A key parameter governing the hydraulics and sediment transport processes within the boulder array is the relative submergence. Relative submergence is defined as the ratio of the flow depth (H) to the boulder (rock) characteristic diameter (d_c), H/d_c. Mountain streams are characterized by shallow flows due to the limited hydrologic inputs during most of the year. At these shallow flows, the boulders remain partially submerged, thus operating under the Low Relative Submergence (H/d_c < 1) regime.

In flow-boulder interactions within an array of boulders, there also exist interactions between neighboring boulders, which are intimately associated with the spacing, λ, between the boulders (MORRIS, 1955; HASSAN and REID, 1990). However, little research has been conducted on these boulder-to-boulder interactions, especially under the Low Relative Submergence (LRS) regime. In this study, it is hypothesized that the boulder spacing affects the flow structures developing around rocks under the LRS regime.

For shallow flows in steep mountainous streams, where the flow depth is typically smaller than the diameter of the boulders (H/d_c < 1), the flow patterns around the boulders can be reflected on the water surface (SHAMLOO et al., 2001; PAPANICOLAOU and KRAMER, 2005). This study investigates the surface flow patterns around boulders in a qualitative and quantitative manner by taking advantage of a relatively new technique, the InfraRed Large Scale Image Velocimetry or IR–LSIV. The basic principle behind the IR–LSIV is that the temperature convective velocities are equal to the fluid surface velocities for fluids such as water, which are typically characterized by low thermal diffusivity (HESTRONI et al., 2001). An IR camera can visualize the surface flow patterns by detecting thermal structures developing on the water surface. To enhance the thermal structures on the water velocity, water is seeded with a temperature tracer, i.e., ice cubes or hot water, which differs in temperature from the ambient water. Analysis of the videos showing the water surface thermal structures via the LSIV technique (FUJITA et al., 1997) can yield quantitative information about the water surface patterns. Because the IR–LSIV is a very recent technique (HESTRONI et al., 2001; JACKSON et al., 2009), a sensitivity analysis was conducted to determine the optimal number of (video) frames to be analyzed, as well as the optimal value of the searching radius, that produce consistent results.

The overarching objective of this study is to investigate the influence of boulder spacing on the developing flow structures around a rock within an array under the LRS regime. The specific objectives of this research can be summarized as (1) qualitative assessment of the flow interaction between neighboring rocks, (2) sensitivity analysis for the IR–LSIV method, and (3) preliminary estimates of the velocity field around a representative group of boulders, utilizing the
IR-LSIV technique for two different packing densities: 2 and 1%.

METHODOLOGY

A number of flume experiments were designed and conducted in order to address the study objectives. Two experimental scenarios, under the LRS regime, were considered and investigated: (1) $\lambda/d_c = 6$ and (2) $\lambda/d_c = 10$ (Figure 1), where $\lambda$ is the spacing between neighboring boulders and $d_c$ is characteristic diameter of the boulders ($d_c = 55$ mm), corresponding to a 2 and 1% packing density (MORRIS, 1955; BYRD et al., 2000; and YAGER et al., 2007), respectively. During each experimental run, the bed slope and the flow depth were kept constant at 0.0159 and 0.044 m, respectively. The flow conditions used in this experimental study (Table 1) were selected to match the conditions from a previous study (Papanicolaou and Kramer 2005).

<table>
<thead>
<tr>
<th>Run</th>
<th>$H/d_c$</th>
<th>$H$ (m)</th>
<th>$Q$ (m$^3$/s)</th>
<th>$S$ (m/m)</th>
<th>$U_{bulk}$ (m/s)</th>
<th>Fr</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>0.044</td>
<td>0.0207</td>
<td>0.0159</td>
<td>0.5170</td>
<td>0.7956</td>
<td>7.02E+04</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>0.044</td>
<td>0.0250</td>
<td>0.0159</td>
<td>0.6244</td>
<td>0.9609</td>
<td>8.48E+04</td>
</tr>
</tbody>
</table>

Experimental setup

This laboratory flume study is conducted at IIHR-Hydroscience and Engineering facilities in the University of Iowa. For the purposes of this research a 21-meter-long, 91-cm-wide, 53-cm-deep experimental flume with an adjustable slope (up to 15%) was used. The side walls of the flume were built with acrylic glass, allowing a side view of the developing flow structures. The boulder section was 5.2 m in length and located 10.9 m from the upstream edge of the flume. An array of 48 and 22 uniform-size boulders was placed atop a flat, immobile, porous, uniform roughness bed, representing the 2 and 1% packing densities, respectively (Figure 1). The bed was comprised of well-packed, colorless glass beads with characteristic diameter $d_b = 19.1$ mm. During all experiments, uniform flow conditions were preserved by placing a set of metal bars, along the flume transverse direction, at the flume exit section, one on top of the other.

The surface flow structures developing around boulders were recorded via an IR camera. The videos created was loaded to the LSIV software, where the surface velocity fields were constructed. The LSIV software makes use of thermal tracers to estimate the flow velocity vectors. In this study, ice cubes were first used as tracers, but the results were not at all satisfactory (Figure 2). Therefore, hot water droplets were finally employed. The hot water
tracers were feeding 0.50 m upstream of the test section. The IR camera was placed on a metal frame above the test section, and the videos were recorded at a rate of 30 frames per second for a total duration of approximately 35 seconds. The Final Cut Pro software was then used to convert the videos into sequences of images. These images were loaded to the LSIV software, which analyzes the successive images to produce the surface velocity field vectors.

Figure 1 – Experimental setup for (a) $\lambda/d_c = 6$ and (b) $\lambda/d_c = 10$

Figure 2 – Flow patterns captured with the IR camera, using ice cubes as tracers

A sensitivity analysis was performed to estimate the optimal number of frames and the searching radius value that introduce the minimum numerical error to the LSIV method in computing the bulk velocity ($U_{bulk}$) compared to the true bulk velocity. A different number of frames were analyzed (e.g., 50, 100, 250, 500, and 800 frames) and search radius values (e.g.,...
20, 25, 30, 35 and 40 pixels) were considered in two runs, one without boulders present, corresponding to two bulk velocities \( U_{\text{bulk1}} = 0.451 \text{ m/s} \) and \( U_{\text{bulk2}} = 0.595 \text{ m/s} \), and one with boulders. These bulk velocities were selected for the sensitivity analysis because they were of comparable magnitude with the ones considered for the experimental runs \( U_{\text{bulk}} = 0.51 \text{ m/s} \) and \( U_{\text{bulk}} = 0.62 \text{ m/s} \). The optimal number of frames and search radius used in this study were the ones that gave the minimum error compared to the bulk velocity measured from the flume flow meter (MAGFLO® MAG 3100 Electromagnetic digital flow meter, accurate to within 0.25% of the flow) and the flume dimensions (Jackson et al., 2009).

RESULTS
The flow structures developing around a group of representative boulders for \( \lambda/d_c = 6 \) and \( \lambda/d_c = 10 \) are presented in Figure 3a and 3b, respectively. For \( \lambda/d_c = 6 \), the different colors in Figure 3a represent different water temperatures. The blue and the violet colors indicate cooler water regions, while the brighter colors, cyan, green, yellow and red, represent regions with progressively hotter water. The boulders in the flow field are denoted by solid black circles. Hot water (white and red colors) was seeded right upstream of the rocks and mixed with the cooler water in the flume while it was advected downstream. The shear layers forming at the downstream side of the boulders are indicated with the cyan color. Because the shear layers consist of high momentum fluid, the seeded hot water was advected downstream faster, hence the higher water temperature corresponds to the cyan color. Figure 3a shows that for \( \lambda/d_c = 6 \), the shear layers forming around the upstream boulders, illustrated as regions with cyan color, extend to the downstream boulders and interfere with the surface flow structures around the downstream boulders. In the wake region of the central upstream boulder, the fluid is characterized with purple color, which denotes cooler and thus decelerated water. Because of the recirculation region forming downstream of the boulder and the shear layers that form around the boulder, the seeded hot water does not mix with the cooler ambient water in the boulder wake region.

Figure 3 – IR camera depiction of the developing flow patterns for (a) \( \lambda/d_c = 6 \) and (b) \( \lambda/d_c = 10 \)
Figure 3b shows a snapshot of the surface water temperature when the rock spacing is $\lambda/d_c = 10$. In Figure 3b, the black and deep purple colors indicate cooler water regions, while the lighter purple, blue, cyan, green, yellow and white colors represent regions with progressively hotter water. Shear layers developed at the wake region of the boulders, forming an inner, low momentum and outer, high momentum regions. The water region forming behind the boulders is characterized by cooler, decelerated water. As can be observed from Figure 3b, the effects of the shear layers emanating from the boulders upstream did not interfere with the flow structures developing around the downstream rocks due to the fact that the shear layers reattached with the main flow far upstream of the downstream rocks. Moreover, the water flowing between the two upstream boulders was not affected by the presence of the developing shear layers. Therefore, for the case of $\lambda/d_c = 10$, no interference between neighboring boulders was observed, and thus the packing density corresponding to this experimental scenario (1%) created an isolated roughness regime, where the wake developed by one boulder had no effect on its neighboring boulders.

The qualitative results of Figure 3 are also quantitatively investigated via the LSIV technique. First, a sensitivity analysis was performed to estimate the optimal number of frames, as well as the value of the searching radius required for the LSIV technique. In Figure 4 the sensitivity analysis curves are presented. Figure 4a shows that when the analysis is based on more than 500 frames, the error in the bulk velocity estimation is less than 10% for both $U_{\text{bulk}} = 0.451$ m/s and $U_{\text{bulk}} = 0.595$ m/s. Moreover, Figure 4a and 4b show that for both $U_{\text{bulk}} = 0.451$ m/s and $U_{\text{bulk}} = 0.595$ m/s the error in the $U_{\text{bulk}}$ estimation reduces to approximately 5%, when the searching radius is greater than 25 pixels. The results in Figure 4 show overall that 25 pixels and 500 frames are the optimal values for the searching radius and the number of frames, respectively, which are then used to carry out the LSIV analysis.

Figure 4 – LSIV sensitivity analysis for estimating the optimal number of frames and the value of the search radius for (a) $U_{\text{bulk}} = 0.451$ m/s and (b) $U_{\text{bulk}} = 0.595$ m/s.

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The surface velocity fields corresponding to $\lambda/d_c = 6$ and $\lambda/d_c = 10$, were obtain via the LSIV technique around a representative group of rocks and are presented in Figures 5a and 5b, respectively. Figure 5a reveals that for $\lambda/d_c = 6$, a wake region with decelerated fluid formed immediately downstream of the rocks. This region was characterized by small surface velocities and was separated from the rest of the flow field by the arms of the forming shear layer. Figure 5a captures both the stream wise interactions between upstream and downstream boulders and the transverse interference between boulders located at the same row. The green, yellow and orange colors represent progressively higher velocities, occurring almost at the center of the outer regions, where the effects from the wake regions are minimal.

In Figure 5b, which represents the surface velocity field for $\lambda/d_c = 10$, the effects of the forming shear layers are localized, since the shear layers occupy a limited area of the flow field in the wake region of the rocks. The shear layers reattach with the main flow far upstream of the downstream boulders. Thus, the effects of the shear layers to the downstream boulders and to the boulders being at the same row are negligible. The blue color denotes very small surface velocities that occur in the inner region, the cyan color separates the inner and the outer regions, while the rest of the flow field is characterized by higher surface velocities, represented by the green, yellow, orange and red colors.

**CONCLUSIONS**

The overreaching objective of this experimental study was to map the surface flow structures around partially submerged boulders, for two different spacing arrangements: $\lambda/d_c = 6$ and $\lambda/d_c = 10$. The objectives of this study were accomplished by using an IR camera to record the surface...
flow structures and the LSIV technique to build the corresponding surface velocity field. Prior to the LSIV method, a sensitivity analysis was conducted in order to estimate the optimal number of frames and the value of the searching radius that introduce the minimum numerical error to the LSIV technique.

The observed surface flow patterns via the IR camera were also quantitatively investigated by constructing the corresponding surface velocity fields. Both the qualitative and quantitative results suggest that for $\lambda/d_c = 6$, interference between neighboring rocks occurs. More specifically, the shear layers emanating from the upstream boulders extend to the downstream boulders and affect the surface flow structures developing around the downstream boulders. According to these findings, for a packing density of 2%, the presence of the upstream rocks might still affect the surface flow patterns around the downstream rocks. This raises an interesting question of whether a spacing between neighboring boulders of $\lambda/d_c = 6$ indeed produces an isolated roughness regime for the boulders (MORRIS, 1955). In the isolated roughness regime, the individual boulders do not affect the flow field of the immediately downstream boulders.

For the second experimental scenario, where $\lambda/d_c = 10$, the shear layers emanating from the upstream boulders reattached with the main flow prior to the downstream boulders, and thus, no interference between neighboring boulders was observed. These qualitative results were also quantitatively reconfirmed via the surface velocity field produced by the LSIV method, where the effects of the upstream emanating shear layers were negligible to the downstream boulders.

In summary, for the Low Relative Submergence (LRS) regime, the spacing arrangement of the boulders in the stream affects the developing flow patterns around neighboring boulders. These interesting findings warrant future research, which will focus on the investigation of the parameters that control the depositional patterns for the Low Relative Submergence (LRS) regime and the improvement of the IR camera and LSIV technique.

REFERENCES


