Open-Channel Discharge Characteristics and Secondary Flow Development Over a Biotope-Scale Heterogeneous Channel Bed

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Abstract: Understanding the effect of variations in bed roughness on overall channel resistance plays an important, though little researched, part in accurately modelling river flow. Changes in bed material, from sediment to gravel for example, mean that river bed roughness is generally heterogeneous, with both lateral and streamwise variation. The research described herein extends the authors’ previous work, which experimentally investigated the effect of full-length, longitudinal strip roughness, by examining the flow in a channel with both lateral and streamwise step changes in bed roughness.

An idealised heterogeneous channel with a “checkerboard” bed roughness pattern was constructed in a 22m long, 0.6m wide experimental channel at the University of Birmingham. When scaled with respect to the channel width, the streamwise length of each section approximately corresponds to changes in bed roughness which may be observed in a natural river. The structure of the 3-D velocity field has been measured at a number of channel cross-sections and has enabled the development of the mean streamwise velocity distribution and secondary flow cells to be observed. With the current roughness distribution, the development of secondary flow cells near the rough-smooth boundary appears to occur over a relatively short distance. While detailed analysis of the results is in the preliminary stages, a noticeable difference in the stage-discharge curves of the full-length and checkerboard configurations is seen, particularly at lower discharges, where differences of up to 15% are observed.

Key-Words: Open-channel, heterogeneous, secondary flow, turbulence, Quadrant-Hole, stage-discharge

1 Introduction

The flow in a natural river can be affected significantly by heterogeneity of the river channel. For example, changes in bed roughness can lead to the formation of internal shear layers which in turn affect the lateral momentum transfer which can ultimately reduce the conveyance capacity of the channel. In a straight open channel, secondary flows of the second kind [3] are known to occur in channels with a homogeneous roughness distribution.

Similar flow structures may be hypothesised in the case of flow over a transversely horizontal, heterogeneously rough channel bed. Indeed, secondary flow cells have been observed to form over full-length longitudinal ridges (e.g., [1]) and strip roughness (e.g., [2-5]), while an examination of the horizontal Reynolds’ stress has shown the existence of a transverse shear layer at the rough-smooth boundary (RSB) between strip roughness [4, 5]. The stage-discharge relationship has been shown to be significantly affected by full-length strip roughness, with a 25% reduction in discharge by stage [6].

While this work is undoubtedly valuable, heterogeneity in a natural river is a streamwise phenomenon as well as a lateral one. James and Jordanova [7] have examined such channels in the context of lumped parameters (e.g., Manning’s $n$) but, to the authors’ knowledge, only Vermaas [4] has examined such a system with an aim to understand the physical processes occurring. In order to investigate this, Vermaas used the more complex (though still very much simplified) model of a “checkerboard” bed. In the aforementioned work, the section length ($L_s$), i.e., streamwise length of each roughness element, was $4m$ and the width of the channel ($B$) was $2m$ (i.e., $L_s = 2B$). The choice of this section length was based on previous work undertaken by Vermaas [7] and enabled both developing and fully-developed flow over the checkerboard sections to be investigated. Based on this, the adoption of such a section length is understandable. However, it may not be representative of conditions which can be found in natural rivers.

The concept of physical biotopes (i.e., riffles, runs, pools, glides) occurs frequently in the fields
of river ecology and eco-hydraulics and has been advocated as the basic unit of river habitat [12]. Jowett [8] has shown that in approximately two-thirds of cases, these biotopes can be correctly identified from the flow characteristics such as velocity and Froude number. As such, the rate of change of physical biotope would seem to be a good indicator of changes in channel characteristics such as bed roughness. Padmore [9] quantified the rate of change of biotope in a wide selection of natural rivers and discovered that a mean biotype length of approximately three channel widths occurred frequently in nature. Hence, a section length of three times the width of the channel would be more akin to what could be expected to occur in natural rivers.

Section 2 of the paper outlines the experimental method used in the current work while Section 3 discusses the results obtained from initial preliminary data analysis. Finally, appropriate conclusions are drawn in Section 4.

2 Experimental Method

The experimental method, apparatus and data processing have been described in detail in [5]. However, for the benefit of the reader a brief summary is presented below.

The experiments were undertaken in the 22m long, 0.614m wide open channel at the University of Birmingham. This channel is fed from a constant-head tank in the laboratory roof, with the discharge, \( Q \), controlled by a manual valve and measured by an ABB Kent-Taylor 4” electromagnetic valve. The water enters a stilling tank before entering the channel mouth via a baffle designed to remove irregularities in the flow and a polystyrene board on the water surface to damp surface waves. Outflow is controlled by a tailgate, allowing uniform, normal flow conditions to be achieved (see [10] and [15] for further details).

The channel bed was constructed using 10mm thick, smooth plastic sheeting and gravel of size \( d_{75} = 10 \text{mm}, d_4 = 5 \text{mm} \) (as characterised by sieve analysis). The smooth sections of the channel consisted of two layers of plastic, with the rough section being made up of a layer of plastic with gravel glued on top. Thus, the channel bed was at (approximately) the same height over both the rough and smooth sections. The two bed configurations examined are illustrated in Figure 1, and referred to as BC1 and BC2.

Two Nortek Acoustic Doppler Velocimeters (ADVs) were used to measure the instantaneous values of the three velocity components (streamwise, lateral and normal to the bed; \( u, v \) and \( w \) respectively) and were sampled at a rate of 200Hz. Mean velocities and turbulent fluctuations were obtained through Reynolds decomposition, i.e., \( u = U + u' \), where \( U \) and \( u' \) represents the mean and fluctuating components of the streamwise velocity respectively. One of the ADVs was used to validate flow conditions and was thus maintained at a fixed position within the channel, with its measurements used to check for any large scale fluctuations in the flow. The second, “mobile” probe was traversed across the points of a 10mm spaced grid at a particular cross-section in the channel. For the full-length configuration as outlined in [8], a single cross-section was used at a distance of 17.75m from the channel entrance. Not only does this distance correspond to findings for development lengths in experimental channels (see [11], for example), additional vertical \( U \) distributions measured upstream and downstream of the measured cross-section confirmed that the flow was fully developed.

The ADV data was filtered using the Phase-Space Thresholding method of Goring & Nikora [12] to remove spikes. A rotation correction procedure was also used to correct for small inaccuracies in the orientation of the probe. More details may be found in [5].

In addition to the ADV measurements, measurements of \( U \) were made with a Pitot-Static tube in the upper regions, where the ADV would not fit.

For BC2 a number of cross-sections were used to permit the investigation of development of the flow from a roughness change. These cross-sections are shown in Figure 2. Two cross-sections (CS2 and CS4) were measured for the full span, with these being chosen as closest to the streamwise position of the full-length configuration cross-section, i.e., BC1. The remaining cross-sections were measured at the central section, around the RSB (the region of most interest).
Assuming that the flow is mirrored over alternating streamwise sections (with the rough-smooth sides reversed), CS 4 (once mirrored) is equivalent to CS 5; the partial section at CS 5 was measured to confirm this.

3 Results and Discussion

The stage-discharge curves for the two bed configurations are shown in Figure 3. As may be seen, in both cases the curves conform to the standard shape, with rapid increases in stage with discharge at low discharges, and an approximately linear relationship at high discharges. The differences between the two are best shown in terms of a percentage difference in stage (Figure 4), which indicates that the difference is small for high discharges (and correspondingly high water depths) but significant at lower discharges. The experimental error in this curve is ±3%. At high discharges this could form a significant part of the difference seen, though equally the difference could be greater than shown. The reduction of this difference with water depth is as would be anticipated from the literature describing the effect of differing roughness on the stage-discharge curves for homogeneously rough channels (see [13], for example).

James and Jordanova [7] concluded that, for a channel with $N$ different types of bed surfaces, an estimation of Mannings’ $n$ of the form:

$$n = \left( \frac{\sum_{i=1}^{N} (A_i n_i^a)}{\sum_{i=1}^{N} A_i} \right)^{\frac{1}{a}}$$

(1)

(\text{where } A_i \text{ is the area covered by the } i^{th} \text{ type and } a \text{ is a constant) “is acceptable considering the uncertainty and variability of other input variables”}. While “acceptable” is subjective, additional analysis of the data of Bhembe and Pandey (taken from [14]) in the context of the current study shows that the estimated stage-discharge curve is steeper in the high discharge region. This results in increasing divergence from the experimental data with stage. It is also worth noting that Bhembe and Pandey only used single discharge for their experiments, and no experimental errors are reported.

The detailed, cross-section results for BC1 have been discussed in [5] but are repeated here for comparison. In the following figures, the smooth side spans $0 \text{mm} \leq y \leq 307 \text{mm}$ (LHS) and thr rough side between $307 \text{mm} < y < 614\text{mm}$. For BC2, CS 4 the relative streamwise velocity, $U_r (\equiv U/(Q/A))$, distribution near the bed is qualitatively similar to that seen for BC1, i.e., the flow near the bed is significantly slower over the rough bed than the smooth (Figure 5). A distortion of the contours corresponding to upward and

![Figure 2: Measured Cross-Sections for the Checkerboard Configuration (x' is distance from the section change)](image)

![Figure 3: Stage-Discharge Curves for the Two Bed Configurations](image)

![Figure 4: Percentage Difference in Stage](image)

![Figure 5: Contours of Disturbance](image)
downward secondary flows (Figure 6) is evident above the RSB, though the distortion seen for BC1 at $y/B \equiv 0.25$ does not appear due to the main secondary flow cell seen in BC1 not forming. At the start of the section (CS1 – not shown – and CS2) there is strong up-flow over the rough bed in the central region. Up-flow was also seen by Vermaas, across at least half the rough side of the channel [4], whereas in the current study it appears more localised. As the near-bed flow moves from the smooth to the rough surface at the section switch it slows. Similarly, the flow on the other side of the channel will accelerate. By continuity, flow must move away from the new rough bed, upwards and towards the smooth side. This up-flow, which exaggerates the secondary flow from the previous section, may be caused by retardation of the flow near the bed by the rough bed.

By CS3 (not shown) the flow in the central region is indistinct but shows some signs of down-flow on the rough side. This develops until, by CS4, the characteristic rough-side down-flow and smooth-side up-flow are seen.

In the BC1 case an initial Quadrant-Hole analysis (see, for example, [15]), examining the ratio of shear stress contributions from ejection and sweep events to other interactions, showed clear propagation of turbulence vertically from the rough bed and horizontally across a vertical shear layer at the RSB.

In the BC2 case, however, the horizontal propagation (not shown) across the shear layer is not in evidence, with the ratio being approximately unity over the central region of the channel. Vertical propagation (Figure 7) from the rough bed is still seen, but the distribution varies along the section. At CS2, where the rough bed has changed into smooth ($y/B < 0.5$) the vertical propagation shows signs of separation from the bed. With no new turbulence being created by the bed, the propagation in the central region is likely to be the remnant of turbulence emanating from the rough bed. At CS4 propagation from the (new) rough bed becomes evident. Turbulence theory ascribes such propagation to coherent structures (hairpin vortices) (e.g., [16]) and it would appear that these take time to develop, in a similar way to development of a boundary layer at the start of a channel. An examination of turbulence intensity will provide further insight into the form of the turbulence.

4 Conclusions

The stage-discharge curve for a channel with a “checkerboard” roughness distribution (and ultimately the conveyance) has been shown to differ significantly from that for a channel with a bed made up of full-length strip roughness. Detailed, 3D measurements of instantaneous velocities over cross-sections of a checkerboard
Figure 6: Lateral Velocity Vectors (BC1 (top), BC2-CS2) and BC2-CS44 (bottom); Arrow length relative though not to scale

Figure 7: $u'w'$ Quadrant-Hole Ejections and Sweeps to Other Events Ratio (BC1 (top), BC2-CS2, BC2-CS4 (bottom)
channel show that both the streamwise and lateral velocities react quickly to the change in bed as the rough and smooth sections switch sides.

Secondary flows develop within the relatively short section length (3B) used. However, initial Quadrant-Hole analysis reveals little horizontal propagation of turbulence between the flow on the two sides of the channel. Vertical propagation occurs over the rough bed, and swiftly dies out when the bed smoothes, highlighting the bed as the source of turbulence.

The checkerboard configuration has a lower discharge (by stage) than the full-length strip configuration, indicating that resistance is greater in such a channel. However, the lack of turbulence propagation when compared to the full-length strip configuration, and the less clearly defined secondary flow structure, implies that another mechanism is contributing to resistance. Significant up-flow at the start of the rough side of a section suggests that this resistance is due to macroscale “blocking” of the smooth bed flow by the following rough section.

Further data analysis, including turbulence flux and turbulence intensity calculations is required before drawing final conclusions regarding the flow structure.

References: