Effects of Streamwise Ridges on Hydraulic Resistance in Open-Channel Flows

Andrea Zampiron, Ph.D. Student, *School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* andrea.zampiron@abdn.ac.uk

Vladimir Nikora, Professor, *School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* v.nikora@abdn.ac.uk

Stuart Cameron, Research Fellow, *School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* s.cameron@abdn.ac.uk

Wada Patella, Ph.D. Student, *School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* r01wp17@abdn.ac.uk

Isacco Valentini, M.Eng. Student, *Department of Civil Engineering, Università degli Studi di Padova, Padova, Italy and School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* isacco.valentini@studenti.unipd.it

Mark Stewart, Honorary Research Fellow, *School of Engineering, King's College, University of Aberdeen, Fraser Noble Building, AB24 3UE Aberdeen, Scotland, U.K. Email:* mstewart@abdn.ac.uk

Abstract: This Technical Note reports new experiments focused on hydraulic resistance in open-channel flows over beds covered with streamwise ridges. Extensive bulk friction factor measurements, combined with particle image velocimetry (PIV) for selected cases, were carried out to investigate the effects of spanwise spacing, relative submergence and surface roughness of the ridges. Two types of ridges were investigated, both characterised by triangular cross-sections but featuring different surface roughness. Compared to friction factor estimates neglecting any changes in flow structure promoted by the ridges, the measured friction factors were found to be higher by 10% at ridge spacings of approximately $1.6H$ and lower by up to 20% at spacings smaller than $0.7H$ (H is flow depth). No influence of relative submergence and ridge surface roughness on these findings was observed. The PIV data suggest that the revealed effects are likely related to secondary currents instigated and modulated by the bed ridges.

Introduction

Streamwise ridges can often be observed in natural and man-made mobile-bed open channels, where they appear across the whole channel at intervals of approximately two flow depths. These ridges are known to be capable of generating depth-scale secondary currents (SCs) (e.g., Nezu and Nakagawa 1984, 1993; Colombini 1993; Colombini and Parker 1995; Wang and Cheng 2006), which may affect turbulence structure, mixing, and hydraulic resistance (e.g., Nikora and Roy 2012). The generation of SCs is not restricted to streamwise ridges (which introduce topographical changes in the cross-section) but may also occur in the case of spanwise variations in bed surface roughness without changing bed topography (e.g., Colombini & Parker 1995; Anderson et al. 2015; Stroh et al. 2016; Bai et al. 2018; Chung et al. 2018). Recently, SCs have been also observed in the presence of streamwise (e.g., Goldstein and Tuan 1998) or diverging/converging riblet patterns (e.g., Nugroho et al. 2013; Kevin et al. 2017, 2019).

Complementing open-channel studies, streamwise ridges have also attracted the attention of researchers studying boundary layers (e.g., Vanderwel and Ganapathisubramani 2015; Medjnoun et al. 2018; Hwang and Lee 2018) and closed-channel flows (e.g., Yang and Anderson 2018), who focused on the effects of different ridge properties (e.g., shape or relative width and height of the ridges) on the generated SCs. In particular, Vanderwel and Ganapathisubramani (2015) investigated the effects of the spanwise spacing of streamwise rectangular ridges on the flow structure and found that they can instigate SC cells, i.e., time-averaged streamwise vortices, that scale with the ridge spacing. This result highlighted that streamwise ridges are not only capable of generating SCs but also of controlling them.

Since SCs compliment viscous and turbulent stresses in delivering fluid momentum to the bed (and therefore in generating drag), we might expect some influence of the ridge spacing on flow resistance. The aim of this work is therefore to assess the effects of spanwise spacing, relative submergence, and surface roughness of streamwise ridges on hydraulic resistance in open-channel flows. Extensive hydraulic measurements of the bulk friction factor were carried out, complemented with specially designed experiments involving particle image velocimetry (PIV). In the next section, a necessary conceptual background is outlined. Then, the experimental details are provided. The data analysis procedure is explained next, followed by the presentation and discussion of the results. The last section summarises the main outcomes of the work.

Background

Hydraulic resistance can be quantified by a number of coefficients such as Manning's n, Chézy's C or Darcy–Weisbach's friction factor f (e.g., Graf and Altinakar 1998). In this Technical Note, we use the Darcy-Weisbach friction factor f, which relates to n and C as $f = 8gC^{-2} = 8gn^2R^{-1/3}$, where $R = A/P$ is hydraulic radius, $A = B\overline{H}$ is cross-sectional area of the flow, B is channel width, $\overline{H}$ is mean flow depth, P is total wetted perimeter, and g is gravity acceleration. In open-channel flows, the friction factor f usually incorporates the contributions from both channel bed and sidewalls (or banks). The problem of finding the friction factor due to the bed roughness only (i.e., excluding effects of side walls and associated secondary currents) is known as "side-wall correction" (e.g., Guo 2015, 2016). Although there is no rigorous analytical solution to this problem, it can be shown that the friction factor f_b due to the bed roughness only is in the range (Guo 2015; Stewart et al. 2018):

$$f_l \le f_b \le f_u \tag{1}$$

where the lower limit is given by the conventional friction factor $f_l = 8gRS_b / U^2$; the upper limit is defined as $f_u = 8gR_bS_b / U^2$, which can be interpreted as a friction factor of an equivalent flow where the total friction force is assigned to the bed only; $U = Q / A$ is bulk flow velocity; Q is flow rate; S_b is bed slope; and $R_b = A / P_b$ is bed hydraulic radius, where P_b is the wetted perimeter of the bed only, which explicitly accounts for the contribution of the ridges to the wetted perimeter (in contrast to the frequently used approximation of P_b by the channel width B).

If the flow aspect ratio (ratio of channel width to flow depth) is sufficiently large, the flow in the central part of the flume is affected by bed roughness only and thus the true bed friction f_b can be directly estimated as:

$$f_b = 8\frac{u_{*b}^2}{\hat{U}^2} = 8\frac{gR_bS_b}{\hat{U}^2} \tag{2}$$

where $u_{*b} = \sqrt{gR_bS_b}$ is bed-related shear velocity; $\hat{U} = \bar{H}^{-1}\left(y_2 - y_1\right)^{-1}\int_{y_1}^{y_2}\int_{z_b}^{z_{ws}} \bar{u}(y,z)\,\mathrm{d}z\mathrm{d}y$ is velocity averaged within the central part of the flow where sidewall effects can be neglected; $\bar{H}$ is the mean flow depth defined as $\bar{H} = \left(y_2 - y_1\right)^{-1}\int_{y_1}^{y_2}(z_{ws} - z_b)\mathrm{d}y$; y_1 and y_2 are transverse coordinates of left- and right-side boundaries of the averaging domain; $z_b(x,y)$ is local bed surface elevation; z_{ws} is water surface elevation; $\bar{u}$ is streamwise local time-averaged velocity; and x, y and z are streamwise, transverse and vertical coordinates, respectively. Note that the parameters defined above relate to conditions when channel cross-section does not change along the flow, as otherwise additional streamwise averaging may also be required. In our study, we use Eq. (1) to obtain the bounds of the bed friction factor f_b from the measurements of $\bar{H}$, S_b, and $U = Q / A$, while Eq. (2) is used to estimate f_b directly from the PIV data for selected scenarios.

Experiments

Open-Channel Facility and Bed Roughness

The experiments were carried out in the 'RS' open-channel facility (e.g., Stewart et al. 2018) in the Fluid Mechanics Laboratory of the University of Aberdeen. This glass-sided open-channel flume is 0.4 m wide with a working length of 10.75 m. Water is circulated through the system by a single centrifugal pump that can sustain flowrates up to 22 l/s. An adjustable gate with vertical vanes at the exit section of the flume is used for establishing and maintaining uniform flow conditions.

The bed of the flume was fully covered with a continuous plastic fabric sheet composed of micro hooks with height $\Delta \approx 1.1$ mm [Fig. 1(a)] and spatial concentration of $\approx 0.8\%$ (calculated as the ratio of the volume occupied by the hooks to the total volume of the hook canopy). Due to the low spatial concentration of the micro hooks, their effect on $\bar{H}$ is neglected. The streamwise 'ridges' (i.e., plastic strips) were attached to the bed of the flume using a *hook-and-loop* fastener system (Fig. 1). This fastening technique enabled a high level of versatility as ridge locations and spacings s [Fig. 1(a)] could be relatively quickly changed. Two types of plastic strips, both of triangular cross-section, were tested. The first type, denoted here as *smooth ridges*, were made of rigid polypropylene (PP), while the second type, denoted as *rough ridges*, had the PP part covered with the same fabric as the bed. The smooth ridges were $b \approx 5.6$ mm wide and $h' \approx 3.8$ mm high [Fig. 1(a)], while the rough ridges were slightly larger with a width of ≈ 6.5 mm and a height of ≈ 5.0 mm. The loop component of the gripping fabric was cut into ribbons with the same width as the ridges and attached to the bottom of the ridges using double-sided adhesive tape. The resulting total height h [Fig. 1(a)] was ≈ 6.0 mm for the smooth ridges and ≈ 7.2 mm for the rough ridges. The streamwise ridges continuously covered the entire length of the flume.

Hydraulic Resistance Measurements

The measurements of the friction factors f_l and f_u [Eq. (1)] were carried out for a range of flow conditions (Table 1) related to three cases: (1) no ridges on the bed; (2) smooth ridges on the bed; and (3) rough ridges on the bed. Three bed slopes S_b (0.1%, 0.2% and 0.3%) and seven ridge spacings s (20, 25, 40, 50, 80, 100, and 200 mm) were covered by the tests. The maximum flow depth H, defined as the distance between the water surface and the base of the micro hooks at $z = 0$ [Fig. 1(a)], varied in 5 mm increments from 15 mm to: 110 mm for $S_b = 0.1\%$, 80 mm for $S_b = 0.2\%$, and 70 mm for $S_b = 0.3\%$. Differently from $\overline{H}$, which depends on the bed geometry at fixed water surface elevations, H is affected neither by the presence nor by the spacing of the ridges, i.e., $\overline{H} \le H$.

Water surface and bed elevations were measured with a digital point gauge every meter along the flume. Water surface slopes were estimated from the water surface elevation profiles referenced to corresponding still water surface elevations. Water depths were calculated as the difference between the measured water surface and bed elevations. The water discharge Q was measured with an electromagnetic flowmeter (MagMaster, ABB), sampled at 0.5 Hz and averaged over a duration of 180 seconds. In our analysis we used only the data that satisfied two key conditions: (1) bed-related roughness Reynolds number $\mathsf{R}_b^* = u_{*b}\Delta / \nu \ge 30$ (ν is kinematic viscosity) and (2) flow aspect ratio $B / H \ge 5$, corresponding to hydraulically rough-bed flows with wide aspect ratios to minimise sidewall effects (e.g., Nezu and Nakagawa 1993). The threshold value of 30 for condition (1) was specifically identified for our experimental dataset by ensuring the independence of the friction factor from the bulk Reynolds number

$\mathsf{R} = U\bar{H} / \nu$, i.e., by comparing friction factors at the same flow depth and ridge spacing but different bed slopes or, in other words, at the same relative submergence but different roughness Reynolds number R_b^*.

Particle Image Velocimetry (PIV) Measurements

A subset of the scenarios covered by the bulk hydraulic measurements was further studied using a four-camera stereoscopic PIV system similar to that described in Cameron et al. (2017). The measurements were completed for the cases with no ridges and with smooth ridges at spacings of 20, 25, 50, 80, 100, and 200 mm. Maximum flow depth H and bed slope S_b were fixed to 50 mm and 0.2%, respectively. The measurement plane was orientated perpendicular to the flow direction and covered the entire flume cross-section at 7.15 m from the flume entrance [Fig. 1(b)]. Measurements were conducted for each of the selected spacings over a continuous duration of 2 hours with a sampling rate of 50 Hz.

Although detailed analysis of the flow structure is outside of the scope of this Technical Note and will be reported elsewhere, here we show mean velocity fields for some selected cases (flows over beds without ridges and with ridges at spacings of 20, 50 and 100 mm, Fig. 2) as complementary information for the hydraulic resistance data presented in this Technical Note. Similar to boundary layer flows over rectangular streamwise ridges (Vanderwel and Ganapathisubramani 2015; Hwang and Lee 2018), the triangular ridges in our study also generate SCs with cell sizes that scale with the ridge spacing. In our case, however, the SCs did not disappear at small spacings (e.g., s = 20 mm) as in Vanderwel and Ganapathisubramani (2015). The direction of rotation of the SC cells is consistent with the previous studies of flows over streamwise ridges (e.g., Nezu and Nakagawa, 1984, 1993; Wang and Cheng 2006; Vanderwel and Ganapathisubramani 2015; Hwang and Lee 2018), with upflows over the ridges and downflows over the inter-ridge gaps. Since SCs contribute to the total momentum transfer in the flow, we may expect a dependency of the friction factor on the ridge spacing. Their potential effects on the friction factor will be explored in the following sections. In this Note, the PIV measurements are used to estimate the true bed friction factor f_b using Eq. (2) by considering a region of $\approx$ 200 mm in the central part of the channel where the effects of the sidewalls on the flow are negligible (Fig. 2).

Data Analysis and Results

Data Handling

Placing the ridges on the rough bed modifies it by (1) increasing the bed wetted perimeter and, in the case of smooth ridges, (2) altering the bed surface roughness, which not only affects the roughness-related friction, but may also change the properties of the SCs induced by the ridges. In the previous section we showed that the result of these modifications is the emergence of SCs that scale with the ridge spacing (Fig. 2). Thus, the measured friction factors (f_b, f_l and f_u) incorporate contributions of ridge-induced SCs as well as accounting for changes in bed roughness. In order to help interpret the results, a friction factor (f_{EST}) that neglects any effects related to ridge-induced SCs was estimated and used for comparison. Any difference between measured and estimated friction factors therefore can likely be related to the presence of SCs generated by the ridges (Fig. 2). The procedure used for obtaining f_{EST} is outlined below.

The flow cross-section was divided into ridge and inter-ridge subsections bounded by vertical separating planes (Fig. 3). The estimated friction factor was obtained considering the flow within each subsection free of ridge-induced SCs and excluding any momentum transfer (on average) from one subsection to another. Such an approach has been widely used in hydraulic applications and is known as "divided channel method" (e.g., Chow 1959). From the mass conservation law it follows that:

$$\hat{U}_{Tot}\left(A_{Rid}+A_{Sp}\right)=\hat{U}_{Rid}A_{Rid}+\hat{U}_{Sp}A_{Sp} \tag{3}$$

where $A_{Rid}=b\overline{H}_{Rid}$ and $A_{Sp}=(s-b)\overline{H}_{Sp}$ are cross-sectional areas of ridge and inter-ridge subsections, $\overline{H}_{Rid}$ and $\overline{H}_{Sp}$ are mean flow depths within corresponding subsections; and $\hat{U}_{Tot}$, $\hat{U}_{Rid}$, and $\hat{U}_{Sp}$ are mean velocities averaged over respective areas $A_{Rid}+A_{Sp}$, A_{Rid}, and A_{Sp} (Fig. 3). Combining Eqs. (2) and (3) and assuming that the friction slope (which is equal to S_b in the case of steady uniform flow conditions) is the same for all subsections, the estimated friction factor for the whole bed is defined as:

$$\sqrt{\frac{1}{f_{EST}}}=\sqrt{\frac{1}{f_{Rid}}}\sqrt{\frac{P_{Rid}+P_{Sp}}{P_{Rid}}}\left(\frac{A_{Rid}}{A_{Rid}+A_{Sp}}\right)^{1.5}+\sqrt{\frac{1}{f_{Sp}}}\sqrt{\frac{P_{Rid}+P_{Sp}}{P_{Sp}}}\left(\frac{A_{Sp}}{A_{Rid}+A_{Sp}}\right)^{1.5} \tag{4}$$

where P_{Rid} is the wetted perimeter of the ridge subsection characterised by a friction factor f_{Rid}; and P_{Sp} is the wetted perimeter of the subsection between the ridges characterised by a friction factor f_{Sp}.

The surface of the smooth ridges is considered to be hydraulically smooth and thus f_{Rid} (for both PIV and bulk friction factor measurements) can be estimated using Blasius' equation (e.g., Yen 2002):

$$f_{Rid} = \frac{0.224}{\mathsf{R}_{Rid}^{0.25}} \tag{5}$$

or Colebrook-White's equation (e.g., Colebrook 1939, Henderson1966):

$$\frac{1}{\sqrt{f_{Rid}}} = 2\log_{10}\left(\frac{4\mathsf{R}_{Rid}\sqrt{f_{Rid}}}{2.51}\right) \tag{6}$$

Substituting the ridge specific bulk Reynolds number $\mathsf{R}_{Rid} = \hat{U}_{Rid} R_{Rid} / \nu$, where $R_{Rid} = \bar{H}_{Rid} b / P_{Rid}$ is the ridge specific hydraulic radius and $\hat{U}_{Rid} = \sqrt{1/f_{Rid}}\sqrt{8gR_{Rid}S_b}$, in Eqs. (5) and (6), we obtain, respectively:

$$f_{Rid} = \left[\frac{0.224}{\left(\sqrt{8gS_b}R_{Rid}^{1.5}/\nu\right)^{0.25}}\right]^{\frac{1}{0.875}} \tag{7}$$

and:

$$\frac{1}{\sqrt{f_{Rid}}} = 2\log_{10}\left(\frac{4\sqrt{8gS_b}R_{Rid}^{1.5}}{2.51\nu}\right) \tag{8}$$

No significant differences in the estimates based on Eqs. (7) and (8) were noted; thus, only values from Eq. (7) are used in this study.

For the cases where PIV measurements were made (smooth ridges), the overall friction factors obtained using Eq. (4) are denoted as f_{ESTb}. The friction factor related to the ridges (i.e., f_{Rid}) was calculated using Eq. (7). The mean flow depth in the inter-ridge subsections ($\bar{H}_{Sp}$, Fig. 3) matched the mean flow depth $\bar{H}$ with no ridges on the bed (i.e., $\bar{H}_{Sp} = \bar{H} = H \approx 50$ mm) and therefore the friction factor of the rough fabric surface between the ridges (i.e., f_{Sp}) was taken equal to the bed friction factor (f_b) measured with PIV without the presence of ridges.

For the cases where bulk friction factor measurements were made, the estimated friction factors are denoted as f_{ESTu}. In the case of smooth ridges, f_{Rid} was calculated using Eq. (7), similar to the scenarios with PIV measurements. The friction factor f_{Sp} was taken equal to the upper bound of the bed friction factor (f_u) measured in the absence of ridges with $\bar{H}$ matching $\bar{H}_{Sp}$, as without ridges on the bed $\bar{H}_{Sp} = \bar{H} = H$. In the case of rough ridges, f_{Rid} was taken equal to f_u measured in the absence of ridges with $\bar{H}$ matching the mean flow depth of the ridge subsections ($\bar{H}_{Rid}$, Fig. 3). Since $\bar{H}_{Rid}$ is generally different from any of the directly investigated flow depths, the required data were estimated by interpolation using the best fit equation $f_u = 0.164(\bar{H} / \Delta)^{-0.298}$ obtained for the scenario without ridges. Note that our analysis of bulk measurements below is based on the ratio f_u / f_{ESTu}, but similar results can be obtained using the lower bound of the bed friction factor (f_l) instead (i.e., $f_l / f_{ESTl} \approx f_u / f_{ESTu}$ where f_{ESTl} is the estimated friction factor based on f_l; see "Key Findings").

The friction factors involved in the calculation of f_{EST} for each case are summarised in Table 2. In the following section, we first discuss the flow scenarios as used in the PIV experiments and then generalise the key findings by employing extensive bulk hydraulic measurements of the friction factors.

Key Findings

Fig. 4(a) shows bed friction factor f_b from the PIV data together with f_{ESTb} as a function of relative strip spacing s / H. Note that in this and in the following figures, the data from flows over bed without ridges are plotted assuming $s = B = 400$ mm. The estimated friction factor f_{ESTb} clearly differs from f_b, showing that the changes in flow structure introduced by the ridges (Fig. 2) significantly contribute to hydraulic resistance. Fig. 4(b) presents the upper bound of the bed friction factor (f_u) and corresponding estimated friction factor (f_{ESTu}) for both rough and smooth ridges from bulk measurements for the same maximum flow depth as in the PIV measurements, i.e., $H \approx 50$ mm. Comparing the data at small s / H, one can note that the estimated friction factor f_{ESTu} for rough-surface ridges is higher than that for smooth-surface ridges, revealing the effects of the ridge surface properties on the total bed friction factor. Once again, f_u is generally different from f_{ESTu}, showing a trend similar to that for the PIV data in Fig. 4(a).

In Fig. 4(c), the measured friction factors, shown in Figs. 4(a) and 4(b), are presented normalised by the respective f_{EST}. The normalised friction factors offer the advantage of being independent of any changes in viscous and/or pressure drag at the bed due to changes in bed wetted perimeter and/or surface roughness, which are taken into account by f_{EST} (see "Data Handling"). Thus, modifications in the flow structure induced by the ridges on the channel bed (such as the appearance of SCs, Fig. 2) will result in higher ($f/f_{EST} > 1$) or lower ($f/f_{EST} < 1$) measured flow resistance (f) compared to that when such modifications are not present (f_{EST}). Considering the normalised values, no clear differences can be observed between PIV and bulk hydraulic measurements ($f_b/f_{ESTb} \approx f_u/f_{ESTu} \approx f_l/f_{ESTl}$), i.e., f/f_{EST} values obtained using lower and upper bounds for the bed friction factor closely match ($f_u/f_{ESTu} \approx f_l/f_{ESTl}$). Thus, the relative contribution of the ridges to the friction factor can be reasonably estimated even when only bulk friction factor measurements are available. The data for smooth and rough ridges are also very similar, suggesting that the two ridge types lead to comparable modifications of the flow structure. At $s/H \approx 1.6$, f is larger than f_{EST} by approximately 10% [Fig. 4(c)]. It is likely that this increase in the friction factor is caused by the SC cells that, occupying nearly the entire water depth (Fig. 2), maximise the rate of momentum delivery to the bed (and hence the momentum sink rate at the bed which is equal to the drag force per unit area). The occurrence of the maximum f/f_{EST} at a s/H value smaller than 2 is probably due to the ridges being a confining factor to the SC cell size together with the water surface dampening effect. For s/H less than ≈ 0.7, f becomes smaller than f_{EST} by up to 15-20%. Such a significant reduction in the friction factor is unexpected and needs to be addressed in future studies. For instance, it is possible that SCs modify the turbulence structure in the entire water column regardless of the SC size, suppressing turbulence-related momentum delivery to the bed at small ridge spacings.

Since $f_b/f_{ESTb} \approx f_u/f_{ESTu} \approx f_l/f_{ESTl}$, the extensive bulk resistance measurements could be used to expand the ranges of R, H/Δ and s/H covered by the data in Fig. 4. Figs. 5(a, smooth ridges) and 5(b, rough ridges) show that f/f_{EST} exhibits the same dependency on s/H as already observed for $H \approx 50$ mm in Fig. 4, suggesting that the effects of the relative ridge spacing on f/f_{EST} are largely independent from H/Δ and R (at least for the studied ranges of these parameters). The excellent agreement between smooth-surface and rough-surface ridges [Fig. 5(c)] indicates that the effects of the ridge spacings on the flow resistance is dominant and the same for both ridge types. The reduction in the friction factor at small s/H is even higher compared to the PIV-studied scenarios, with drag reduction up to $\approx 20\%$. The trend of the data in Fig. 5 suggests that the friction factor might keep decreasing to even lower values with decrease in s/H. The results presented in this Note together with general physical considerations suggest that the function f / f_{EST} within the whole range of possible spacings can be shaped as outlined in a sketch in Fig. 6.

Conclusions

This Technical Note reports the effect of the spacing of streamwise ridges on hydraulic resistance in open-channel flows. Compared to an estimated friction factor that does not account for changes in the flow structure induced by the ridges, it is found that ridge spacings around ≈ 1.6 flow depths lead to $\approx 10\%$ increase in the friction factor, while at spacings smaller than ≈ 0.7 flow depths the friction factor is reduced by up to $\approx 20\%$. The observed maximum in the friction factor at $s / H \approx 1.6$ suggests that the naturally emerging sedimentary ridges on the river beds (that have a similar spanwise periodicity; e.g., Colombini and Parker 1995) maximise hydraulic resistance, recalling a maximum resistance hypothesis for mobile bed flows (e.g., Davies and Sutherland 1983).

The obtained results imply that the effects of relative submergence and ridge surface roughness are likely to be of secondary importance. It is argued that the observed changes in flow resistance are associated with secondary currents induced by the ridges. Mean velocity fields, measured with PIV, support this conjecture and will be discussed in detail elsewhere. Thus, it is possible that the total drag in open-channel flows can be controlled through the induction and modulation of secondary currents and streamwise ridges might be a suitable tool for this purpose.

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Notation

A = total cross-sectional area;

A_{Rid}, A_{Sp} = areas of ridge and inter-ridge subsections;

B = channel width;

C = Chézy's resistance coefficient;

F = Froude number;

f = friction factor;

f_{EST} = estimated friction factor;

f_{ESTb} = estimated friction factor based on bed friction factor;

f_{ESTl} , f_{ESTu} = estimated friction factors based on bed friction factor lower and upper bounds;

f_{Rid} , f_{Sp} = friction factors characterising ridge and inter-ridge subsections;

f_b = bed friction factor;

f_l , f_u = bed friction factor lower and upper bounds;

g = gravity acceleration;

H = maximum flow depth;

$\bar{H}$ = mean flow depth;

$\bar{H}_{Rid}$, $\bar{H}_{Sp}$ = mean flow depths of ridge and inter-ridge subsections;

h , b = total height and width of the ridges;

h' = partial height of the ridges;

n = Manning's resistance coefficient;

P = total wetter perimeter;

P_{Rid} , P_{Sp} , P_b = wetted perimeters of ridge subsection, inter-ridge subsection and bed;

Q = flow rate;

R , R_{Rid} = bulk and ridge specific Reynolds numbers;

R_b^* = bed-related roughness Reynolds number;

R = hydraulic radius;

R_{Rid} , R_b = ridge and bed hydraulic radii;

S_b = bed slope;

s = ridge spacing;

U = flow bulk velocity;

$\hat{U}$ = streamwise mean velocity averaged in the central part of the flow;

$\hat{U}_{Rid}$, $\hat{U}_{Sp}$ = streamwise mean velocity averaged over ridge and inter-ridge subsections;

$\hat{U}_{Tot}$ = streamwise mean velocity averaged over combined ridge and inter-ridge subsections;

$\overline{u}$ = time-averaged streamwise velocity;

u_{*b} = bed-related shear velocity;

x, y, z = streamwise, spanwise and vertical coordinates;

y_1, y_2 = left- and right-side boundaries of the averaging domain;

z_b, z_{ws} = bed and water surface elevations;

Δ = height of the micro-hooks constituting the bed of the channel;

ν = fluid kinematic viscosity.

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Table 1. Ranges of key hydraulic parameters covered by the bulk hydraulic resistance measurements.

S_b (%)	H (mm)	U (m/s)	H/Δ	s/H	B/H	F	R	R_b^*
0.1	15-110	0.12-0.49	14-100	0.18-13.33	3.6-26.7	0.35-0.47	1900-51600	11-36
0.2	15-80	0.14-0.58	14-73	0.25-13.33	5.0-26.7	0.44-0.65	2300-46200	15-43
0.3	15-70	0.16-0.57	14-64	0.29-13.33	5.7-26.7	0.58-0.74	2700-39900	19-50

Note: S_b is bed slope; H is maximum flow depth; U is streamwise bulk velocity (cross-sectionally averaged); B/H is flow aspect-ratio, B is channel width; H/Δ is relative submergence, Δ is the height of the roughness elements on the bed fabric; s/H is relative ridge spacing, s is ridge spacing; $\mathsf{F} = U/\sqrt{g\overline{H}}$ is Froude number, g is gravity acceleration, $\overline{H}$ is mean flow depth; $\mathsf{R} = U\overline{H}/\nu$ is bulk Reynolds number, ν is kinematic viscosity; $\mathsf{R}_b^* = u_{*b}\Delta/\nu$ is bed-related roughness Reynolds number, and u_{*b} is bed-related shear velocity.

Table 2. Summary of friction factors employed in the calculation of f_{EST} for each experimental case.

Measurement type	Ridge type	Measured friction factor	f_{Rid}	f_{Sp}	Estimated friction factor
Bulk friction factor measurements	Smooth	f_u , f_l	Eq. (7)	$f_u(\bar{H}_{Sp})$, $f_l(\bar{H}_{Sp})$ with no ridges	f_{ESTu} , f_{ESTl}
	Rough	f_u , f_l	$f_u(\bar{H}_{Rid})$, $f_l(\bar{H}_{Rid})$ with no ridges	$f_u(\bar{H}_{Sp})$, $f_l(\bar{H}_{Sp})$ with no ridges	f_{ESTu} , f_{ESTl}
PIV-based measurements	Smooth	f_b	Eq. (7)	f_b with no ridges	f_{ESTb}

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Fig. 1. (a) definitions of ridge spacing (s), background roughness height Δ, flow depths (H and $\overline{H}$) and geometrical parameters characterising the ridges (b, h' and h); and (b) PIV measurement section in the 'RS' flume.

Fig. 2. Contour maps of mean streamwise velocity $\overline{u}$ with vectors representing transverse and vertical mean velocities for the cases of bed without ridges and with ridges spaced 20, 50 and 100 mm. Vectors are shown in half cross-section only for clarity.

Fig. 3. Cross-section partitioning.

Fig. 4. (a) f_b and f_{ESTb} for smooth ridges (PIV); (b) f_u and f_{ESTu} for smooth and rough ridges (bulk measurements); and (c) f_b and f_u from (a) and (b) normalised by f_{ESTb} and f_{ESTu}, respectively. For all cases maximum flow depth (H) is fixed to 50 mm. The standard measurement errors of the friction factor values in (a) and (b) are appreciably smaller than the symbol size.

Fig. 5. Normalised friction factors from Fig. 4(c) supplemented with bulk hydraulic measurements of the friction factor for a range of flow depths: (a) smooth ridges; (b) rough ridges; and (c) combined data for smooth and rough ridges. Circular symbols are defined in Fig. 4(c).

Fig. 6. Sketch of f / f_{EST} as a function of s / H for rough-bed open-channel flows over streamwise ridges. Dashed line denotes the range of s / H not covered by the measurements.