Report for 2001IA1021G: Complementary Investigations for Implementation of Remote, Non-Contact Measurements of Streamflow in Riverine Environment

Publications

- Conference Proceedings:
    - Polatel, C., M. Muste, V.C. Patel, T. Stoesser, W. Rodi. 2005. Double-averaged velocity profile over large-scale roughness, XXXI International Association of Hydraulic Engineering and Research Congress, Seoul, Korea.
    - Polatel, C. 2005. Indexing by free surface velocity: A prospect for remote discharge estimation, XXXI International Association of Hydraulic Engineering and Research Congress, Seoul, Korea.
    - Stoesser, T., W. Rodi, C. Polatel, V.C. Patel, M. Muste. 2005. Large eddy simulations of the flow over two-dimensional dunes, XXXI International Association of Hydraulic Engineering and Research Congress, Seoul, Korea.
    - Polatel, C., T. Stoesser, M. Muste. 2005. Velocity Profile Characteristics in Open Channel Flow over Two-Dimensional Dunes with Small Relative Submergence, World Water and Environmental Resources Congress 2005, Anchorage, AK.
    - Balachandar, R., C. Polatel, B. Hyun, K. Yu, C. Lin, W. Yue, V.C. Patel. 2002. LDV, PIV and LES Investigation of Flow Over a Fixed Dune, in ETH Sedimentation and Sediment Transport Symposium, Monte Verita, Switzerland.
    - Polatel, C., M. Muste, V.C. Patel. 2006. Velocity indexing over large-scale roughness by free surface velocity, 7th International Conference on HydroScience & Engineering, Philadelphia, PA.
    - Polatel, C., M. Muste, V.C. Patel, T. Stosser, W. Rodi. 2006. Free surface respnse to large-scale bed roughness, 7th International Conference on HydroScience & Engineering, Philadelphia, PA.
- Other Publications:
    - Polatel, C. 2003. Signature of Bed Characteristics on Free Surface Velocity in Open Channel Flows, International Association of Hydraulic Research Congress XXX,

Thessaloniki, Greece.

- Dissertations:
    - Polatel, C., 2006. Large-Scale Roughness Effect on Free-Surface and Flow Characteristics in Open-Channel Flows, PhD Dissertation, The University of Iowa, Iowa City, IA.

Report Follows

Complementary Investigations for Implementation of Remote, Non-contact Measurements of Streamflow in Riverine Environment

Marian Muste, Allen Bradley, Anton Kruger, Ralph Cheng

Problem and Research Objectives

Estimation of flow discharges in natural streams using conventional approaches requires measurements of the flow depth, velocity distribution over the depth, and stream cross-section bathymetry. The emerging remote measurement technologies have potential to measure remotely, non-contact the free-surface velocity (radar, image-based methods, lidars) and bathymetry (ground-penetrating radars). Consequently, the need for describing the velocity distribution in the water column (or its surrogate, the velocity index, which is the ratio between the depth-averaged velocity and the free-surface velocity) for various flow regimes and bed roughness characteristics has emerged.

The main objective of this research was to establish velocity indices for flows in open channels with smooth and rough beds for a range of bulk flow velocities and depths. A secondary objective was to relate the free-surface appearance (texture) with the bulk flow velocity, bed roughness characteristics and its relative submergence. The research project was conducted to support the USGS Hydro-21 initiative for implementation of remote, non-contact, real-time estimation of stream discharges in natural streams.

Methodology

The research objectives were accomplished by conducting a series of experimental and numerical simulation tests for various open-channel flow conditions over bed roughness resembling that in natural streams. The geometry of the tested large-scale roughness elements is provided in Figure 1. The experiments were performed in a hydraulic flume with varying flow depth and bed roughness. Rectangular ribs and two-dimensional, dune-shaped obstacles were placed on the flume bottom to simulate different bed roughness conditions. Laser Doppler Velocimetry (LDV) measurements were made to obtain the vertical velocity profiles at various roughness element locations. Large-Scale Particle-Image Velocimetry (LSPIV) measurements were made to determine the velocity distribution at the free-surface. Additional experiments using image based techniques were used to capture the "signature" of the bed roughness elements on the free-surface appearance. Large-Eddy Simulation (LES) was used to numerically simulate flow over the same roughness elements to complement the experimental results for a wider range of flow conditions. Details of the numerical and experimental procedures are provided in Polatel (2006).

The local vertical velocity distributions obtained from experiments and numerical simulations were used to determine a "representative" velocity profile for each roughness element and flow case. The representative velocity profile characterizes the flow over a rough bed from a "hydraulic" point of view. Specifically, the representative velocity distribution will be the basis for calculation of the discharge in river reach where these types of roughness exist. The representative profile was obtained by spatially-averaging mean (temporal) velocity profiles over the roughness wavelength. The double-averaged

velocity profile was then fitted using a two-layer, power-law model for providing an analytical form for the representative profile, and to further compare the flow over different roughness conditions as well as to establish an indexing velocity linking the free-surface velocity to the bulk flow velocity.

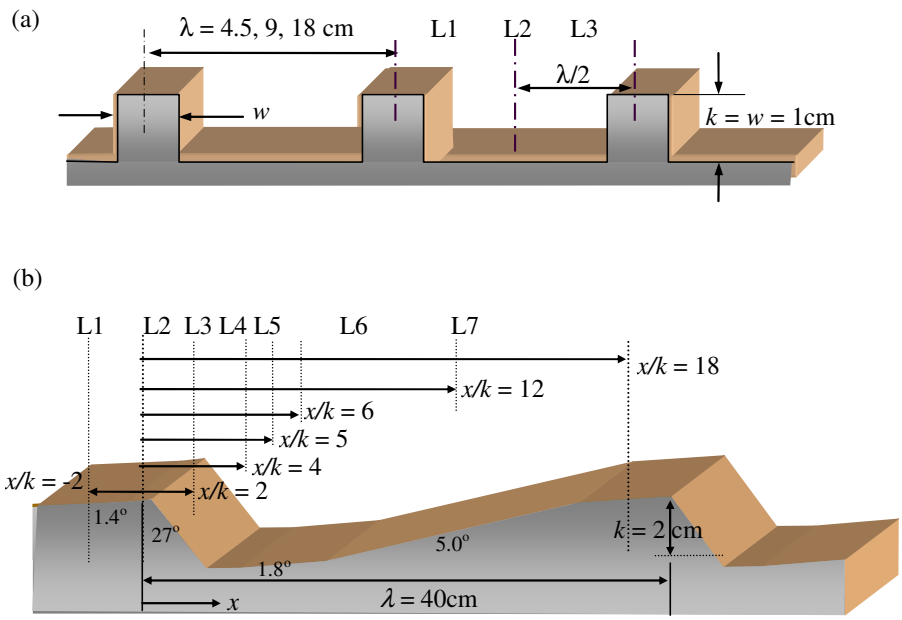


Fig. 1. Characteristics of the large-scale roughness elements investigated in the study: a) ribs; b) dunes

The flow conditions investigated experimentally in the study are summarized in Tables 1,2,3,4,5,6,7. The legend for the notations in the tables is the following: h is the flow depth, U_0 is the free-surface velocity, U_{Bulk} is the bulk flow velocity, U_{LDV} is the velocity measured with the LDV, Fr is the Froude number, Re is the Reynolds number (Fr and Re are based on flow depth, d, and bulk flow velocity), AR is the flow aspect ratio (the ratio of channel width to flow depth), u_* is the bed shear velocity, and S_0 is the channel slope.

Table 1 Flow conditions for shallow open-channel flows over flat bed

Code	***h (m)***	***U_0 (m/s)***	***U_{Bulk} (m/s)***	***Fr***	***Re***	***AR***	***u_* (m/s)***	***S_0***
S01	0.025	0.044	0.029	0.06	718.4	24.38	0.0050	2.81E-4
S02	0.025	0.106	0.085	0.17	2119.8	24.38	0.0073	6.81E-4
S03	0.025	0.205	0.173	0.35	4322.4	24.38	0.0100	4.32E-2
S04	0.025	0.384	0.336	0.68	8389.5	24.38	0.0174	8.58E-2

Table 2 Flow conditions for constant velocities over flat bed experiments.

Code	***h (m)***	***U_{LDV}***	***U_0 (m/s)***	***U_{Bulk} (m/s)***	***Fr***	***Re***	***AR***	***u_* (m/s)***	***S_0***
S06	0.06	0.506	0.490	0.445	0.50	26700	10.16	0.0213	3.83E-04
S08	0.08	0.504	0.489	0.449	0.51	35920	7.62	0.0229	1.70E-04
S10	0.10	0.496	0.485	0.455	0.46	45500	6.10	0.0247	1.70E-04

Table 2 Flow conditions for flow over ribs with λ = 0.045 m at (location L1)

Code	*h (m)*	*λ (m)*	U_{LDV} *(m/s)*	U_0 *(m/s)*	U_{Bulk} *(m/s)*	*Fr*	*Re*	*AR*	u_* *(m/s)*	S_0
R01	0.055	0.045	0.474	0.46	0.370	0.50	20350	11.08	0.053	0.00348
R02	0.075	0.045	0.505	0.49	0.396	0.46	29723	8.13	0.051	0.00327
R03	0.095	0.045	0.503	0.49	0.406	0.42	38526	6.42	0.049	-

Table 3 Flow conditions for flow over ribs with λ = 0.09 m (location L1).

Code	*h (m)*	*λ (m)*	U_{LDV}	U_0 *(m/s)*	U_{Bulk} *(m/s)*	*Fr*	*Re*	*AR*	u_* *(m/s)*	S_0
R04	0.055	0.09	0.350	0.34	0.289	0.39	15915	11.08	0.050	2.49E-03
R05	0.075	0.09	0.447	0.43	0.376	0.44	28200	8.13	0.055	2.55E-03
R06	0.095	0.09	0.514	0.49	0.440	0.46	41800	6.42	0.059	2.61E-03

Table 4 Flow conditions for flow over ribs λ = 0.18 m (location L1).

Code	*h (m)*	*λ (m)*	U_{LDV} *(m/s)*	U_0 *(m/s)*	U_{Bulk} *(m/s)*	*Fr*	*Re*	*AR*	u_* *(m/s)*
R07	0.055	0.18	0.359	0.35	0.307	0.42	16896	11.08	0.047
R08	0.075	0.18	0.434	0.42	0.364	0.42	27321	8.13	0.053
R09	0.095	0.18	0.512	0.49	0.434	0.45	41273	6.42	0.054

Table 5 Flow conditions for flows over dunes (location L1).

Code	*h (m)*	U_{LDV} *(m/s)*	U_0 *(m/s)*	U_{Bulk} *(m/s)*	*Fr*	*Re*	*AR*	u_* *(m/s)*
D01	0.06	0.418	0.41	0.369	0.48	22140	10.2	0.0339
D02	0.08	0.467	0.44	0.394	0.44	31520	7.6	0.0323
D03	0.10	0.477	0.475	0.425	0.43	42500	6.1	0.0299

Table 6 Flow conditions for flows over dunes roughened with sand particles and wiremesh (location L1).

Code	*h (m)*	U_{LDV} *(m/s)*	U_0 *(m/s)*	U_{Bulk} *(m/s)*	*Fr*	*Re*	*AR*	u_* *(m/s)*
Sand	0.10	0.505	0.48	0.436	0.44	43600	6.1	0.040
WM	0.10	0.525	0.515	0.466	0.47	46600	6.1	0.036

Analysis Approach

The analysis for the study is based on the following approach (see Figure 2): the detailed instantaneous flow from field obtained with numerical or experimental measurements was firstly time-averaged at characteristics locations over the roughness elements. Next, the obtained velocity profiles were averaged firstly over the roughness wavelength, then over the depth.

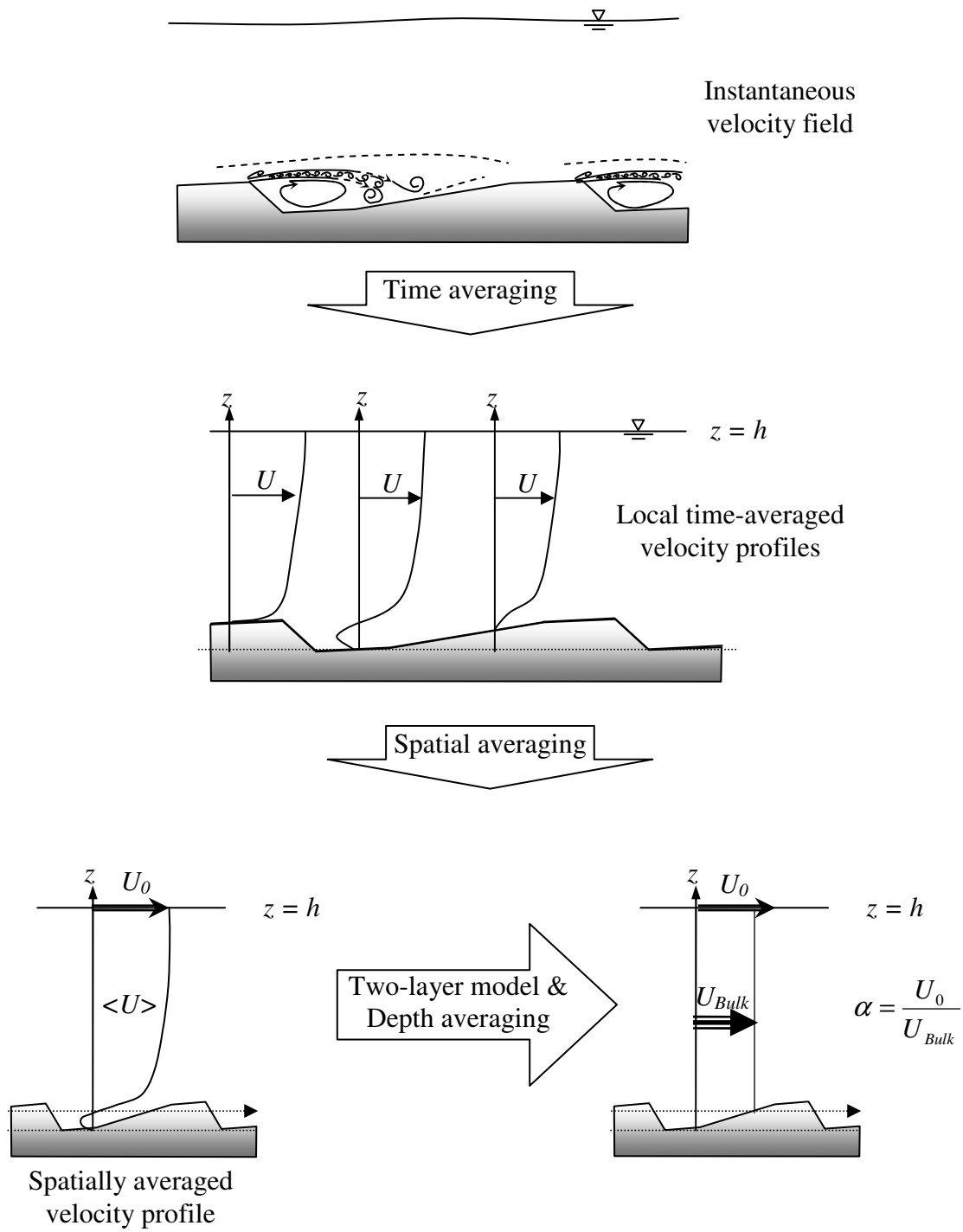


Fig. 2. Sequence of time/space averaging employed to obtain bulk flow characteristics.

Principal Findings and Significance

Free Surface Texture

The numerical and experimental results show that the free surface has embedded in its texture the bed roughness signature. This conclusion is substantiated by the plots in Figures 3 and 4. The signature is a function of the relative roughness submergence.

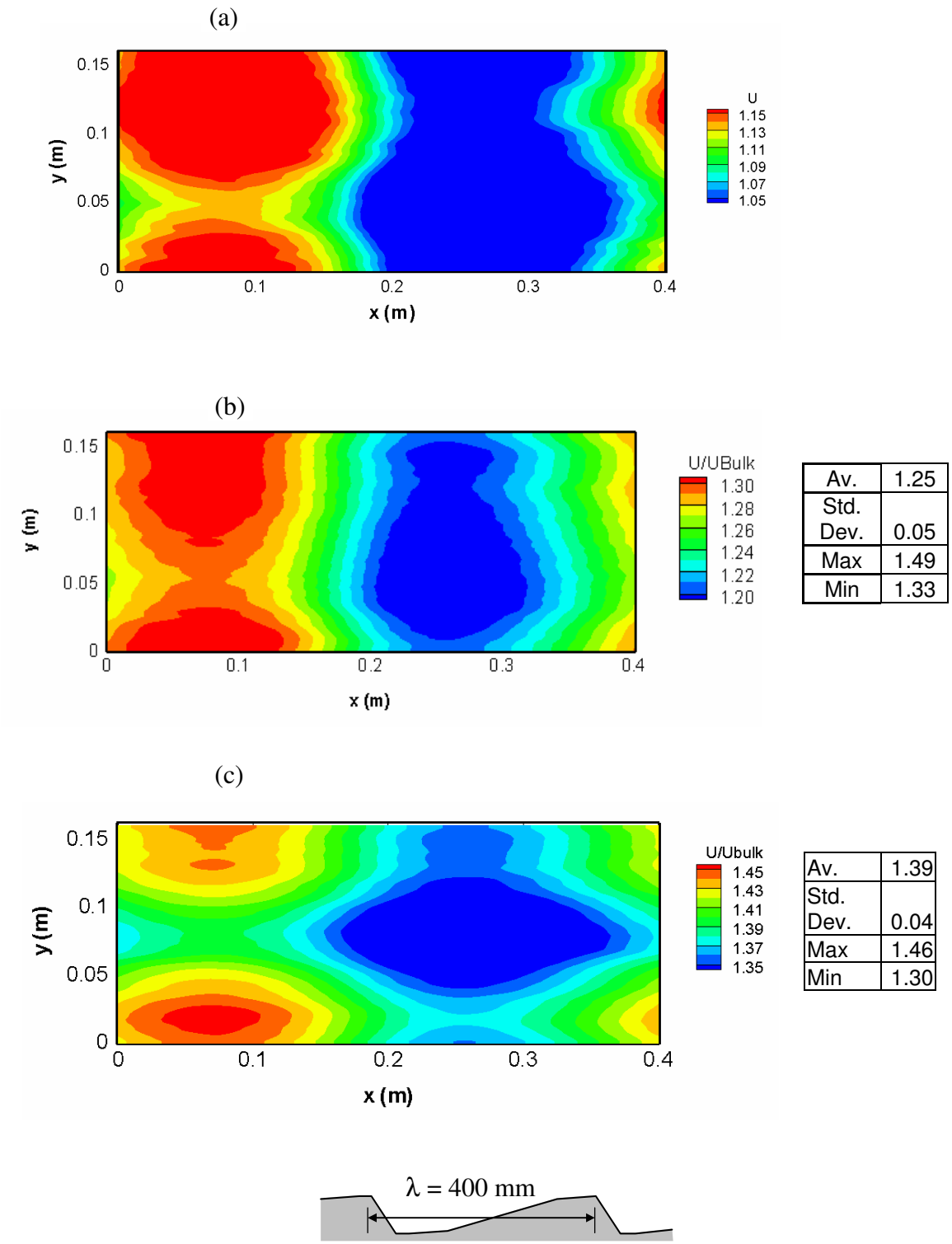


Fig. 3. LES results for normalized free-surface velocity distribution for flow over dunes with flow depth of (a) 6 cm, (b) 8 cm, (c) 10 cm.

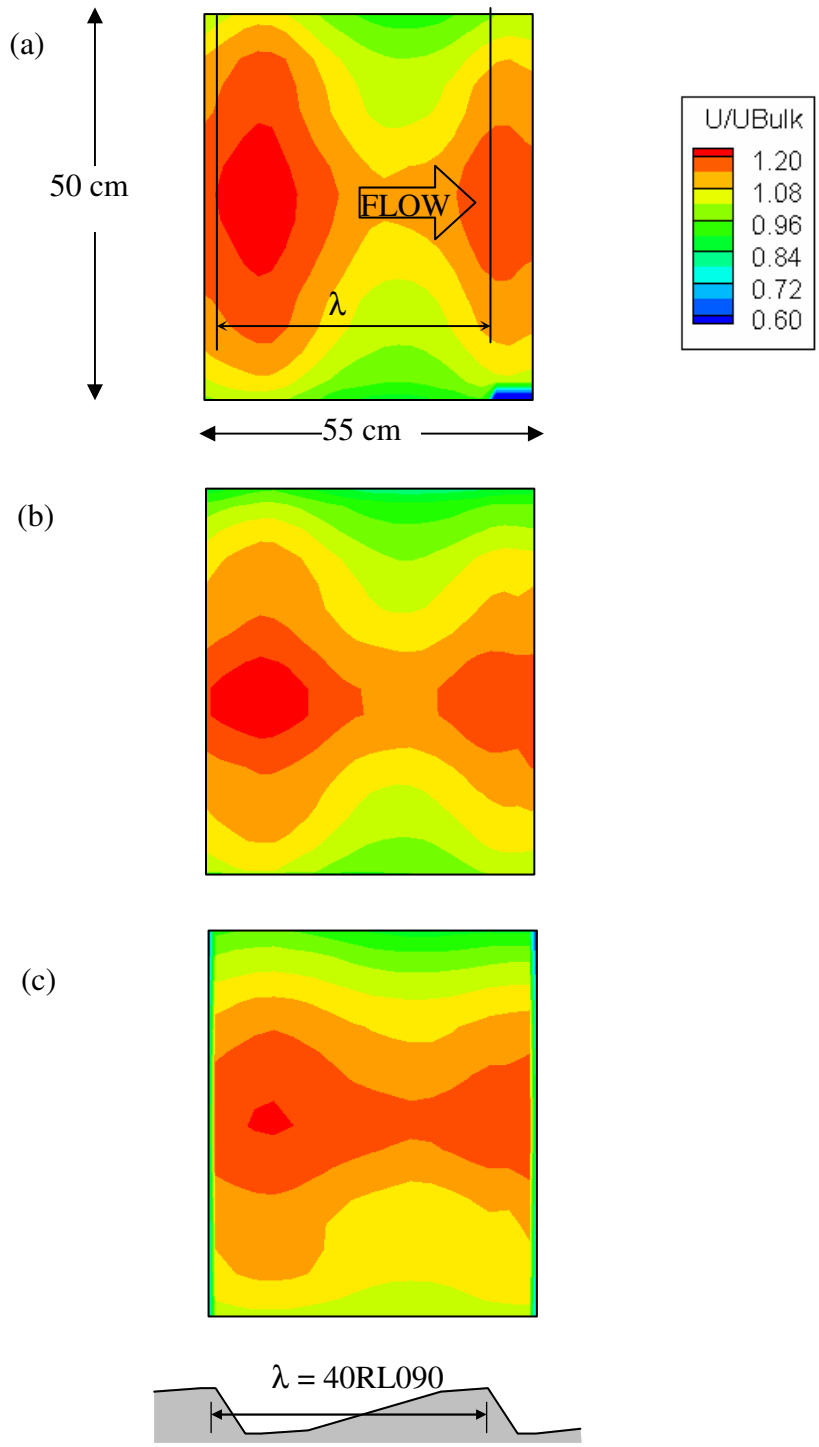


Fig. 4. LSPIV results for normalized free-surface velocity distribution for flow over dunes with flow depth of (a) 6 cm, (b) 8 cm, (c) 10 cm.

The large and small scale ripples are indicative of the flow regime and the presence of the roughness elements on the bed. The texture of the free surface formed by the ripples can be quantitatively estimated using power spectra of the free-surface waviness captured by the imaging devices (Polatel, 2006). Power spectra of this kind for flow over smooth bed and ribs are illustrated in Figures 5 and 6, respectively.

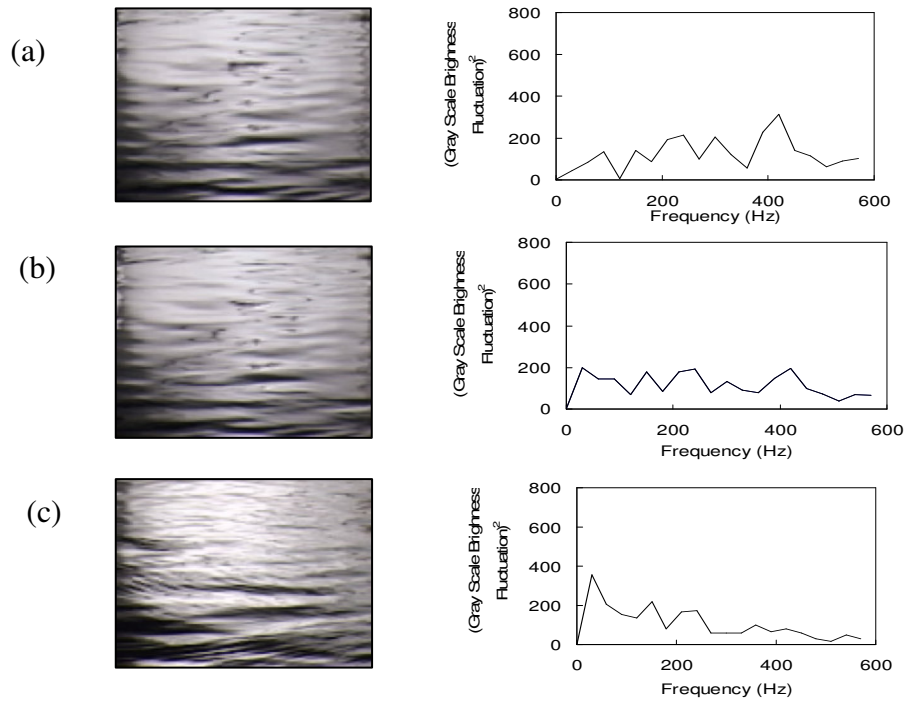


Fig. 5. Power spectra for the free-surface texture recordings for flow over smooth bed with flow depth of (a) 6 cm, (b) 8 cm, (c) 10 cm

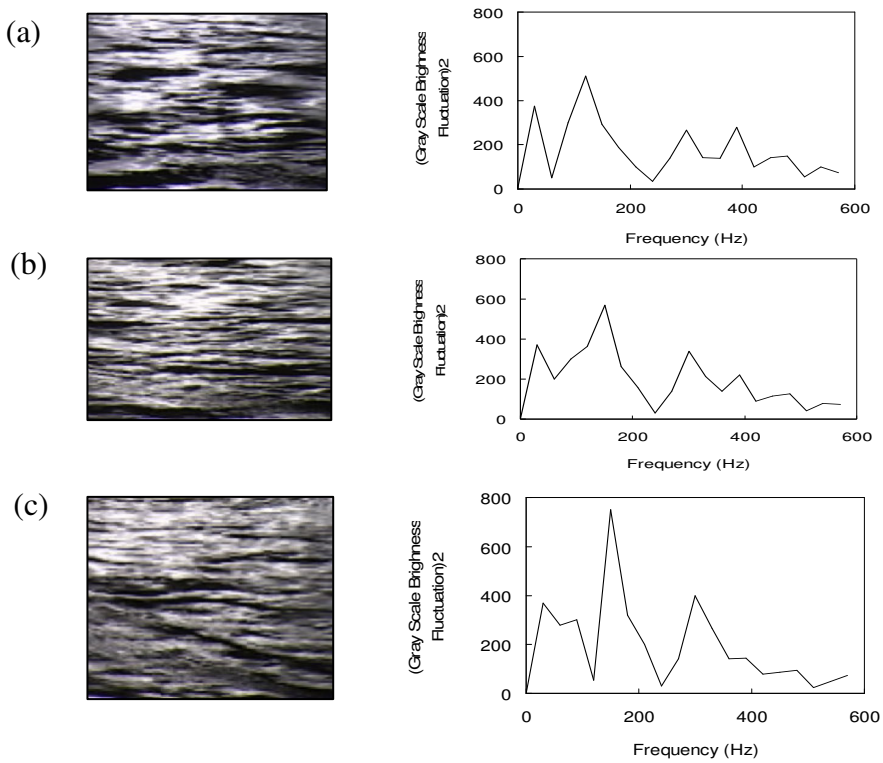
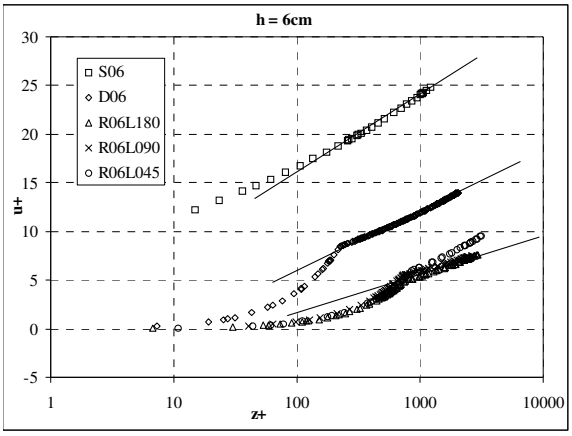


Fig. 6. Power spectra for the free-surface texture recordings for flow over rib roughness with $\lambda = 9$ cm with flow depth of (a) 6 cm, (b) 8 cm, (c) 10 cm

Power Law Fit for Two-layer Velocity Profile

The roughness function is traditionally used to describe the effect of roughness on mean velocity distribution. However, the u^+ vs. z^+ plot of our data shows that the effect of roughness is not limited to a shift from the smooth bed profile, but also the slope of the curve changes, as illustrated in Figure 7.

a)



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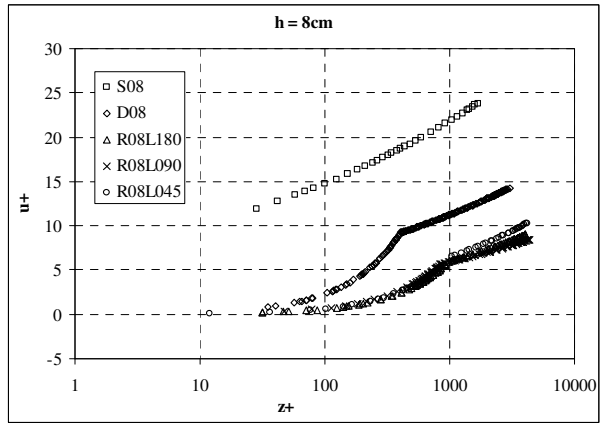

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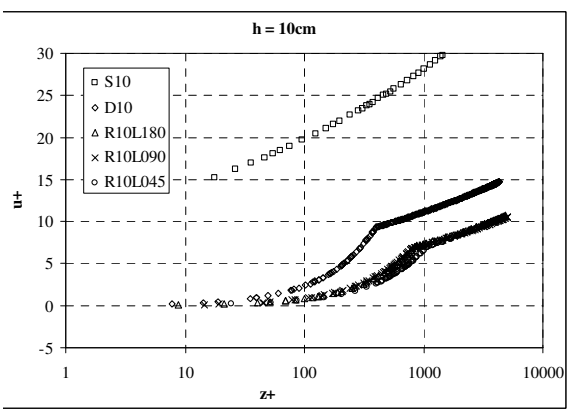

Fig. 7. Power law fit for velocity profiles of the flows over smooth, ribs, and dunes: a) h = 6 cm; b) h = 8 cm; c) h= 10 cm

Velocity Index

Velocity indices for the flow investigated in this study vary in the 0.802–0.938 range. The obtained velocity indices are presented in Table 7 and plotted in Figure 8. The experiments demonstrate that ratio of free surface velocity to depth-averaged velocity depends on the channel bed roughness. The results show, as expected, that the flow over smooth bed has higher velocity indices than those of flow over rough beds. The results also indicate that the velocity index is dependent on the relative submergence of the roughness elements, with higher velocity indices for larger relative submergence.

Overall, the study provides valuable information for implementation of remote discharge measurement methodologies and sheds light on important hydrodynamics characteristics of the open-channel flow over large-scale roughness.

Table 7 Summary of the velocity indices

	Code	***α***
Smooth Bed	S01	0.659
	S02	0.802
	S03	0.844
	S04	0.875
	S06	0.908
	S08	0.918
	S10	0.938
RL045	R01	0.804
	R02	0.809
	R03	0.828
RL090	R04	0.850
	R05	0.874
	R06	0.898
RL180	R07	0.878
	R08	0.878
	R09	0.887
2D dunes	D01	0.900
	D02	0.895
	D03	0.895
	Sand	0.908
	WM	0.905

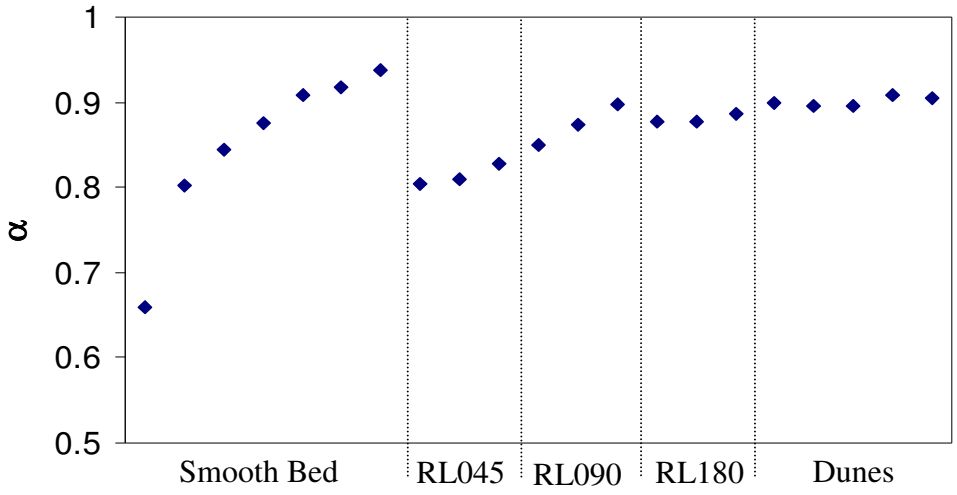

Fig. 8. Graphical representation of the velocity indices obtained from the experimental study