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Turbulent flow over the trough region formed by a pair of forward-facing bedform shapes

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HIGHLIGHTS

- Turbulent flow within the trough region constructed by two forward-facing waveforms.
- Mean flows, Reynolds shear stress and overall drag are analyzed.
- Semi-empirical relations for turbulent intensities and shear stresses are provided.
- Spectral analyses are performed at various points along the waveforms.

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ABSTRACT

The present paper explores the turbulent flow characteristics and overall drag over the trough region of a pair of adjacent 2-D forward-facing dune-shaped artificial structures with two different stoss-side slopes and aims to make a comparative study. Structures considered here were of equal base length (λ) with a common gentle slope of 6° at the downstream face. The stoss-side angles were respectively 50° and 90°. Experiments were conducted at the Fluvial Mechanics Laboratory (FML) of Indian Statistical Institute (ISI), Kolkata. The velocity data were collected using a 3-D Micro-Acoustic Doppler Velocimeter (ADV) at the flume centerline to analyze the mean flows, Reynolds stresses and the overall drag at a Reynolds number, $Re_h \approx 1.44 \times 10^5$. One-dimensional profiles of turbulent flow parameters demonstrate that the flow separation bubble and a thin perturbed shear layer between the negative velocity region and outer layer with high velocity are the main sources of turbulence production. A change in turbulence characteristics between the two crest positions is identified. A greater amount of flow resistance is observed in the case of the structure having higher stoss-side slope. The spectral analysis reveals that peak power spectral density generally occurs at 0.25–1 Hz for the stream-wise velocity component and at 0.9–3.0 Hz for the cross-stream and vertical velocity components. Power spectra showed better defined peaks near the shear layer in the separation cell where it reaches to maximum which is two to three times greater than its values in the upstream and further downstream region. Strouhal numbers are calculated using the frequencies of eddies and vortices with different sets of characteristic length and velocity scales; and compared with the previous results of other researchers.

1. Introduction

In the alluvial channels, various kinds of bedforms like ripples, dunes, bars or biological organisms like shells, wood fragments or pebbles and small steps like structures are frequently observed on the bed. These objects significantly affect the overall flow field inducing separation and recirculation bubbles near the boundary due to the adverse pressure gradient. Detailed turbulent statistics, separation of flow and drag over complex geometries like wavy hilly surfaces, artificially made dunes or ripples, backward- and forward-facing steps with sharp and rounded faces, sudden contraction of pipe under various flow conditions have been tested both experimentally and numerically. Problems of flows over two/three-dimensional backward-facing steps with sharp edges, rounded faces, etc. have received much attention in many engineering fields like hydraulics, aerodynamics, ocean engineering (Barkley et al. [1], Poole and Escudier [2], Casarsa and Giannattasio [3] and many others).

Turbulent flows over moving or rigid bedform structures in riverine environment have been studied by many investigators

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Notations

$A, B, C, \ldots, L$	$\Rightarrow$ Stream-wise selected locations for the ADV measurements for both DSFFS & DVFFS.
P, Q	$\Rightarrow$ Extra two locations for the ADV measurements for DSFFS.
M, N, O, P, Q, R	$\Rightarrow$ Extra six locations for the ADV measurements for DVFFS.
$\bullet$	$\Rightarrow$ Profile of mean stream-wise and vertical velocity of DSFFS.
$\triangle$	$\Rightarrow$ Profile of mean stream-wise and vertical velocity of DVFFS.
g	$\Rightarrow$ Acceleration due to gravity.
h	$\Rightarrow$ Flow depth.
h'	$\Rightarrow$ Crest height.
Re	$\Rightarrow$ Reynolds number.
Fr	$\Rightarrow$ Froude number.
u, v, w	$\Rightarrow$ Instantaneous velocity components.
U, V, W	$\Rightarrow$ Mean Velocity components.
u', v', w'	$\Rightarrow$ Fluctuating velocity components.
u_*	$\Rightarrow$ Shear velocity.
u_{*T}	$\Rightarrow$ Spatially averaged shear velocity.
U_m	$\Rightarrow$ Maximum velocity.
z_o	$\Rightarrow$ Equivalent bed roughness.
λ	$\Rightarrow$ Wavelength or base length of the structures.
κ	$\Rightarrow$ Von Karman constant.
σ_u, σ_w	$\Rightarrow$ Root mean square velocity components.
I_u, I_w	$\Rightarrow$ Normalized stream-wise & vertical turbulent intensity.
$\tau_{uw_{dim}}$	$\Rightarrow$ Dimensionless Reynolds shear stress.
$\hat{\kappa}$	$\Rightarrow$ Normalized turbulence kinetic energy (TKE).
R_{uw}	$\Rightarrow$ Coefficient of correlation.
$\langle U \rangle$	$\Rightarrow$ Spatial averages of centerline mean velocity.
τ_T	$\Rightarrow$ Total boundary shear stress.
Sr	$\Rightarrow$ Strouhal number.

(Lyn [4], Bennett and Best [5], Parsons et al. [6], Best [7], Poggi et al. [8], Ojha and Mazumder [9], Peet et al. [10], Stoesser et al. [11], Mazumder et al. [12], Keshavarzi et al. [13]). The turbulent flow and related bursting phenomena over an isolated asymmetric waveform structure were studied statistically by Mazumder and Mazumder [14] using the analysis of multivariate normal distribution. Mazumder [15,16] studied the turbulence of fluid flow in the trough region between a pair of adjacent asymmetric waveform structures using a statistical clustering technique based on geometry and interactions of turbulence bursting rate. Recently, Paul [17] made a comparative study of the turbulence and fractional contributions of bursting events to the Reynolds shear stress over the trough regions formed by a pair of scalene and a pair of isosceles triangular-shaped waveform structures.

Spectral and co-spectral analyses had been performed on the nature of oscillations that were embedded in the turbulent flow field at various points along the bedform profile. Simpson [18] suggested that the low-frequency signal resulted from wake flapping and the high-frequency signal from vortex shedding. Experiments of Krogstad et al. [19] revealed that the roughness of a structure primarily affected the shear stress, but it did not influence the power spectra. Krogstad and Antonia [20] showed that the co-spectra had a roughness effect very close to the wall. A spectral analysis was also applied to examine the correlation between the velocity components and sediment movements in near-bed environment. Kostaschuk [21] showed that the frequency spectra of near-bed velocity and optical back-scatter probe (OBS) data from the lee-side flow-reversal zone of a dune were composed of two distinct peaks. Investigations of Venditti and Bennett [22], Venditti and Bauer [23] illustrated that the power spectra showed larger and better defined peaks in the near-bed and recirculation regions. In their studies, the Strouhal number calculated from the various combinations of length and velocity scales revealed a broad similarity amongst eddies produced over the flow field and the bedform structures.

Ando and Shakouchi [24] conducted experiments on the forward-facing step through a sudden contraction of pipe using the LDA technique. Flows over smooth and rough surfaces of the forward-facing step (FFS) were tested by Camussi et al. [25], Sherry et al. [26], Ren and Wu [27] using different techniques such as LDV and PIV with different Reynolds numbers. These studies verified that the Reynolds number, the roughness of upper surface and the slope of the flow facing surface play important roles on the geometry, shape and size of separation bubble and the position of reattachment point. There are some data available predicting the effects of δ/h i.e. the ratio of boundary layer thickness δ to the step height h on the reattachment length X_r. Sherry et al. [26] studied the flow over the forward-facing step for several values of the ratio δ/h. They categorized the study into two groups: for $\delta/h > 1$, the reattachment length X_r was strongly dependent on the δ/h and for $\delta/h < 1$, the X_r was weakly affected by the ratio, and usually situated around $4h$ to $6h$.

In spite of all these studies, no experimental studies were performed to examine the mean flow, turbulence and drag over the trough region of a pair of steeper stoss-side slope bedforms under the reverse flow conditions, though such a study has the potential to be useful to the researchers who study the bedforms in natural environments, especially those that experience reverse flow conditions (Dinehart [28], Lefebvre et al. [29], Winter et al. [30]). How does the flow over the trough region of forward-facing bedform structures compare to that over the rare-facing ones? Therefore, a substantial investigation is required to understand the basic hydrodynamics experimentally in a flume over a pair of 2-D adjacent bedform structures oriented against the flow.

The aim of the present study is to determine the spatial changes in turbulence and overall drag over and within the trough region formed by a pair of adjacent 2-D forward-facing dune-shaped structures. Two different stoss face slopes (50° and 90°) of bedforms oriented against the flow with a common slanted lee face of 6° along downstream were considered separately under identical flow conditions. More precisely, to understand the turbulent flow and its characteristics over the trough regions between two artificial 2-D bedform structures, the two cases of bedforms were chosen with a common gentle lee slope of 6°: (1) asymmetric structures with 50° stoss-side angle, and (2) vertical (90°) stoss-side structures facing against the flow, which were akin to the bedforms measured in the seabed bathymetry in tidal environments (Lefebvre et al. [29]). The divergence of the stoss-side slopes between the two cases and the existence of the second structure placed adjacently downstream of the first, made significant differences in the mean flow and turbulence fields for the first and second bedforms. The stoss-side slopes of primary bedforms measured by Lefebvre et al. [29] were approximately 77° and the lee-side slopes were almost gentle (see Fig. 6 of Lefebvre et al. [29]). Therefore, the use of steep stoss-side slopes (50° and 90°) with a common gentle lee-side slope in the present study was justified because the slopes of the bedforms were of similar order which fall into the range of those measured in natural environments. The velocity data were analyzed to emphasize the turbulent statistics, overall drag and the power spectral density over the trough regions of such bedforms with different stoss-side angles, which were not studied earlier.

Although the choice of two artificial bedform shapes in the flow was not the actual representation to form the equilibrium flow conditions over many similar bedforms in the natural tidal flow regimes, this study would provide some understanding of the