

Flow over gravel dunes

ABSTRACT

Aims: Flow over gravel dunes is investigated. Measured velocity and Reynolds stress distributions over gravel dunes are compared to those for sand bedforms under similar geometric and hydraulic conditions.

Place and Duration of Study: Experiments were carried out at the hydraulics laboratory at the Isfahan University of Technology, Iran, during the summer of 2012.

Results: Results show that the dune surface roughness plays a significant role in the streamwise velocity near-bed region ($z/H < 0.3$), but it has no influence on the velocity distribution in outer flow region ($z/H > 0.3$). While flow separation is clear in the troughs of sand bedforms, it is not evident over gravel bedforms and this has important implications in consideration of drag and flow resistance. The convex distribution shapes of Reynolds shear stress over the trough and stoss regions of gravel bedforms are comparable to those of sand bedforms with similar distributions for $z/H > 0.5$, but significant scatter for $z/H < 0.5$. The greater dune surface roughness increases peak values of Reynolds shear stress over the trough, crest and stoss dune regions.

Keywords: Velocity profile; Reynolds shear stress; gravel and sand bedforms.

ABBREVIATIONS

2D: Two Dimension; ADV: Acoustic Doppler Velocimeter; SNR: Signal Noise Ratio; B&B: Bennett & Best; d_x = diameter of bed particles for which x% of a sample is finer than this diameter; h = bedform height; λ = bedform wavelength.

1. INTRODUCTION

Understanding the roughness effect of bedforms on flow structure is important for engineering purposes and river restoration projects. Knowledge of roughness is essential for predicting flood or low-flow water depths and it is a driver of turbulence which influences aquatic biota, incipient motion of sediment, bed stability and the transport of sediments, pollutants and nutrients. Typically, bedform drag is considered to dominate in sand rivers and surface roughness is significant for gravel beds. Because very high shear stresses are required to move gravel there are relatively few measurements of flow over gravel dunes. Furthermore, the hydraulic implications of river works such as surfacing sand dunes with gravel are not well documented.

The main characteristics of flow structure over fixed 2D bedforms include: accelerating flow over the stoss region, a turbulent wake and shear layer originating from flow separation at the crest and extending downstream, decelerating flow in the lee region and an outer, overlying wake region [12]. With bedforms, vertical profiles of mean velocity and Reynolds stress have different hydraulic characteristics from those over a flat bed.

Information on gravel dunes is not widely available because there is an obvious difficulty in monitoring or reproducing experimentally, the deep and rapid flow conditions necessary for large-amplitude dunes to develop. Carling [5] conducted an extensive literature review and credited the lack of information on gravel dunes to their rare occurrence and the confusion of dunes with other gravel features such as antidunes and gravel bars. His review of bedforms with a median size greater than 2 mm shows that gravel dunes have developed in laboratory conditions with median grain sizes up to 28.6 mm. He reported steep lee sides on gravel dunes with smaller growing dunes having angle-of-repose lee sides [6]. Good field examples of natural gravel dunes which display these characteristics are given by Vershinin *et al* [14].

Potentially useful investigations of bedform characteristics include: the development of numerical models of flow over bedforms [11], and partitioning of the total boundary shear stress into skin friction and form drag components [3,16]. Turbulence associated with bedforms is significant for both the entrainment and transport of sediment and for controlling the formation and hydraulic stability of bedforms [12,13]. In addition, knowledge of the mean flow and turbulence associated with various roughnesses is important to understand velocity and Reynolds stress distributions over bedforms.

The lack of sufficient experimental data for gravel bedforms has prevented comparisons with sand bedforms. The objective of the present investigation is to show the influence of grain size on the velocity and Reynolds shear stress distributions over gravel and sand dunes under similar hydraulic and geometric conditions.

2. EXPERIMENTAL DETAILS

Experiments were carried out at the hydraulics laboratory at the Isfahan University of Technology, Iran, in a horizontal recirculating flume with no sediment transport. The flume was 7-m long, 0.3-m wide, and 0.3-m deep. The bed and walls of the flume were made of glass. A pump delivered a flow discharge of 0.02 m³/s to a constant head box upstream of the flume and a tail gate located at the end of flume was used to control water depth. An IRAN MADAR (Mag Ab 3000) electromagnetic discharge meter was fitted on the inlet pipe to continuously monitor discharge. For all experiments the flow depth (H) was adjusted to be 10 cm at the dune crest section.

A Nortek down-looking Acoustic Doppler Velocimeter (ADV) was used to measure instantaneous three dimensional velocity components. Error in mean velocity was less than ± 2.5 mm/s (or $\pm 1\%$). Velocities were recorded for each point with a sampling frequency of 200 Hz and a sampling duration of 120 s. WinADV was used to filter out data with an average correlation coefficient of less than 70% and average SNR of less than 15 dB [15]. Vertical profiles of overlying velocity were measured along one bedform at the centerline of the flume. In total, 37 velocity profiles were spaced at 0.01 m in the dune trough and 0.03-m apart along the stoss of the bedform. For each vertical profile, 21 points were measured, starting from 3 mm above the bed.

Gravel dunes range from less than 0.6 m to greater than 100 m in length and from less than 0.1 m to 16 m in height [5]. The present experiments are for dunes typical of small growing gravel dunes with steep lee sides (30 degrees). Carling *et al.* reported h/λ ranged from 0.023 to 0.14 where h is bedform height and λ is the bedform length [6]. An h/λ ratio of 0.04/0.63 = 0.064 was used in this research. Nine 2D fixed-bed gravel dunes were constructed in the flume with a lee slope angle of 30°. The gravel used had a median diameter, d_{50} , of 10 mm and d_{84}/d_{16} ratio was 1.51. All measurements were made between the sixth and seventh dune crests with numbering starting at the most upstream bedform. Figure 1 shows the gravel dunes and the flume.



Fig. 1. Bedforms on flume bottom

Table 1 gives a summary of the experimental gravel dune conditions compared with a similar experiment for sand dunes which have similar hydraulic and geometric parameters [4].

Table 1. Summary of experimental conditions

	Bennett & Best (1995)	This study
Flow depth (H), m	0.10 (crest)	0.10 (crest)
Mean velocity (U), m/s	0.57 (crest)	0.57 (crest)
Froude number (Fr)	0.58 (crest)	0.58 (crest)
Reynolds number (Re)	$57 \cdot 10^3$ (crest)	$57 \cdot 10^3$ (crest)
Mean shear velocity (u_*), m/s	$0.041U_B$ $0.025U_{SF}$	0.027
Friction factor (f)	0.032	0.050
Dune wavelength, (λ), m	0.63	0.63
Dune height (h), m	0.04	0.04
h/λ	0.063	0.063
Median grain size (d_{50}), mm	0.22	10

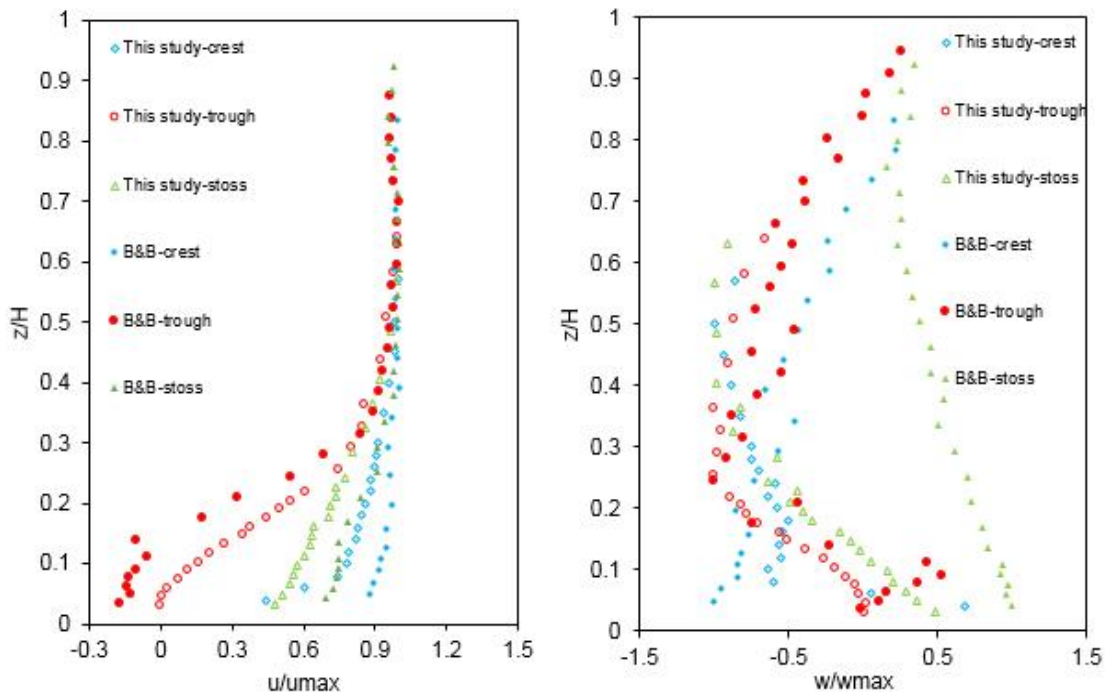
3. RESULTS AND DISCUSSION

3.1 Velocity Distributions

Because a higher energy gradient was needed to reproduce the same depth and mean velocity that occurred for the sand dunes, the maximum velocities over the gravel dunes were higher than those for the sand dunes. The maximum velocity at the crest of the gravel dunes was 10 percent larger than that over equivalent sand dunes. The difference between stoss or trough velocities was 5 percent.

Figure 2 shows vertical profiles of dimensionless streamwise and vertical velocity over the gravel bedform (the present study) compared with Bennett and Best's (B&B) 1995 data for similar sand bedforms [4]. In the figure, the mean point velocities are normalized by the

109 maximum velocity for each profile at crest ($x/\lambda=0$), trough ($x/\lambda=0.15$) and stoss ($x/\lambda=0.6$)
 110 locations. Due to flow separation and positive pressure gradient in the trough region, Figure
 111 2 displays considerable deviation of the velocity profiles, especially for the inner zone ($z/H =$
 112 0.3). In the trough of sand bedforms, streamwise velocities are clearly negative, showing
 113 flow separation, however, the flow separation is not evident for gravel bedforms. It should be
 114 noted that ADVs have difficulty making accurate measurements within separation zones
 115 where turbulence is high and mean flow is low, resulting in smaller measured recirculation
 116 and a smaller measured separation zone than in reality. Downstream of the trough,
 117 streamwise velocity gradually increases and achieves a maximum value at the bedform
 118 crest. For $z/H > 0.3$, the grain size has no significant role on streamwise velocity distribution.
 119 The vertical components of flow velocity ($w/w_{\max}$) do not present a specific pattern over crest
 120 and stoss of sand or gravel bedforms. However, a convex distribution is observed for vertical
 121 velocity distribution in the trough region for both sand and gravel bedforms. The high non-
 122 linear values of the vertical velocity distributions along the shear layer generate anisotropy in
 123 turbulence.
 124 The results show that streamwise velocities close to the bed follow the logarithmic law as for
 125 a flat bed [1,2,9]. Fitting logarithmic law parameters over gravel and sand dunes provides a
 126 good estimation of shear velocity and friction factor.
 127 Since the flow depths change along a dune, the mean velocity and shear velocity change
 128 along the bedform as well. The results reveal more than 30 percent variation in mean
 129 velocity and shear velocity in different regions (stoss, crest and trough) of gravel dunes. The
 130 logarithmic law cannot be applied locally using a single velocity profile, but it can be applied
 131 to spatially-averaged velocity profiles to estimate average shear velocity. Using spatial
 132 averaging to determine velocity and shear velocity, the friction factor over the gravel dunes
 133 was 0.05 which is 56 percent larger than that over the sand dune [8,10].
 134



135
 136 **Fig. 2. Dimensionless velocity profiles for similar dunes comprised of 0.22mm sand**
 137 **(B&B) and 10mm gravel (This study).**

3.2 Reynolds Shear Stress Distributions

Figure 3 presents normalized Reynolds shear stress distributions in which shear velocity (u_*) was determined by double averaging [7]. Application of local shear velocity (estimated by a single velocity profile) in the presence of bedform may not adequately qualify shear velocity, however, extrapolating spatially-averaged log-law profiles provided an estimate of shear velocity for the different surface roughness sizes.

Figure 3 shows that the shear stress approaches zero under the water surface ($z/H = 0.7$) where the maximum streamwise velocity occurs. Convex forms of Reynolds stress distributions are observed for trough and stoss regions of both sand and gravel bedforms, showing an increasing trend near the bed up to $z/H = 0.2$ and a decreasing trend toward the water surface. No specific pattern was observed for Reynolds stress at the crest bedforms due to complex flow conditions in this region. Also, due to higher flow resistance over gravel bedforms, Reynolds stresses values are larger than those of Bennett and Best's [4] sand bedforms.

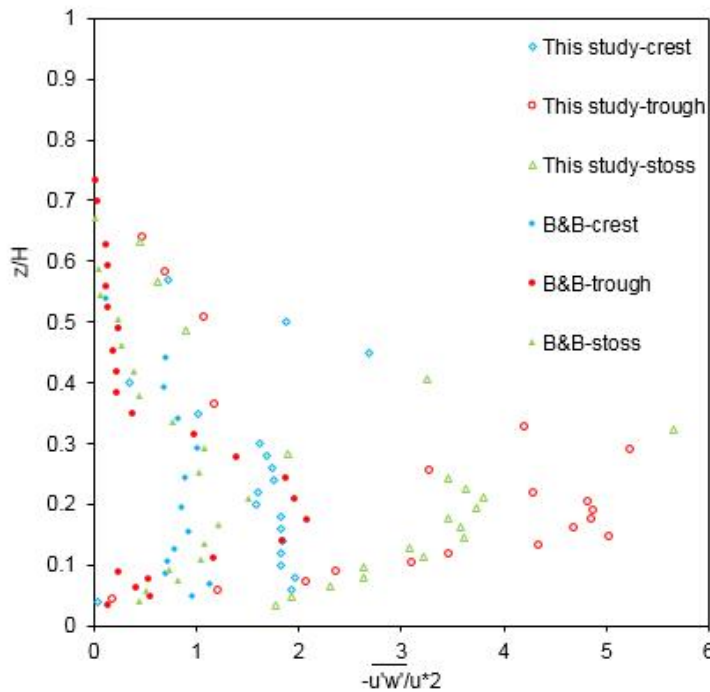


Fig. 3. Dimensionless Reynolds shear stress

4. CONCLUSION

This study shows that dune surface roughness size affects the velocity distribution for relative depths of $z/H < 0.3$ and flow separation cannot be clearly observed over gravel bedforms. This does not exclude the possibility that flow separation occurs over gravel bedforms, but it calls for further experiments and precise measurements to detect velocity distributions in the trough region of gravel bedforms. Estimation of the friction factor (f) using a spatial- averaging method revealed that f over the gravel dunes was 35 percent larger than that over the sand dunes.

The convex distribution of Reynolds stresses for trough and stoss of gravel bedforms are in agreement with those of sand bedforms (Bennett and Best [4]); however, complex flow conditions over the crest cause unusual patterns in this region. Roughness size causes larger Reynolds stress values in the trough, stoss and crest regions of gravel bedforms in comparison with those of sand bedforms for $z/H < 0.5$. There is high scatter of Reynolds shear stress data for $z/H < 0.5$ is due to anisotropic turbulence, the small aspect ratio and a non-equilibrium boundary layer in the wake region of the bedforms.

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