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Role of macroturbulence to sustain turbulent energy in decelerating flows over a gravel bed

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ABSTRACT

New experimental data and turbulence analyses are used to elucidate the role of macroturbulence to sustain energy in streamwise decelerating and vertically expanding open channel flows over a gravel bed such as those found in river pools. Quality assurance of the turbulence measurements was verified by the close comparison between results of time-averaged quantities calculated with the measurements and published semiempirical equations for decelerating flow over gravel beds. The presence of macroturbulence within the flow is verified using turbulence decomposition, spectral analysis, and the distribution of time-averaged quantities. The vertical expansion velocity provided 40% of the turbulent energy production in the vertical suggesting that the expansion velocity interacts with macroturbulence in the outer region to generate and redistribute energy. Spectral analyses show that net turbulent energy is primarily lost through the decelerating flow at 1 to 10 Hz frequencies associated with the bursting process and dissipative scales while the primary streamwise energy reduction is less pronounced in the macroturbulence range. Vertical and transverse turbulent energy within the macroturbulence range actually becomes more energetic as the flow decelerates. Macroturbulence makes up ~50% of the total streamwise turbulent kinetic energy, and the loss of macroturbulence energy through the decelerating flow lags well behind that of the decreasing intensity of bursting as identified with quadrant analysis. Taken together, the results of this study suggest that macroturbulence is a defining feature of the fully rough expanding flow that sustains itself from bed-derived bursting as well as flow nonuniformities.

1. Introduction

The behavior of turbulent eddies in streamwise deceleration and vertical expansion regions of open channel flow is recognized to help control fluvial processes in river pools as well as backwater zones (Thompson et al., 1998; MacVicar and Roy, 2007). However, the vast majority of turbulence studies of flow over gravel beds have focused on uniform flow conditions, and we recognize that assumptions of uniform-like eddy structures will yield unsatisfactory approximations when applied to nonuniform reality (Nezu, 2005; Church et al., 2012). Our motivation in this study was to elucidate the role of depth-scaled turbulent structures, termed macroturbulence, within gradual vertical expanding flows over gravel beds. The overall goal was to investigate macroturbulence for streamwise decelerating and vertically expanding open channel flow and thereafter elucidate the role that macroturbulence plays to sustain turbulent energy in the outer region of the flow field.

The velocity distributions and turbulent eddy processes in hydraulically rough uniform flows over gravel beds have been well documented in the literature (Hurther et al., 2007; Rodriguez and Garcia, 2008; Belcher, 2009). These studies indicate that shedding from individual roughness elements induces a roughness region that extends ~$2.5D_{84}$ (Belcher and Fox, 2009). The amalgamation of multiple shed eddies produces hairpin packets that eject away from the bed, and in many instances, reach the free surface and affect the entire flow structure (Shvidchenko and Pender, 2001; Hurther et al., 2007; Belcher, 2009). The outer flow region is populated with quasi-streamwise roll cells and remnants of the near-bed bursting process. We recognize that outer region turbulence exists as a continuum from the viscous scale to at least the channel depth. However, consistent with the literature, we discretize instantaneous turbulent motions into two broad classes (Nezu and Nakagawa, 1993; Adrian et al., 2000; Belcher, 2009) including: (i) the bursting process consisting of eddies shed from individual roughness elements with low momentum fluid packets moving away from the bed (ejections) and high momentum fluid moving toward the bed (sweeps); and (ii) macroscale structures or 'macroturbulence' comprising the entire flow depth with a rolling motion and advecting in the streamwise direction (Shvidchenko and Pender, 2001; Fox and Patrick, 2008). These two prominent instantaneous processes are defined by a separation of scales but are believed to be intimately linked as bursting motions enhance large-scale flow structures and large-scale

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List of symbols

$D_{u,v,w}$	empirical coefficients for streamwise, vertical, and transverse turbulent intensities
D_{50}	particle diameter for which 50% of particles are finer
D_{84}	particle diameter for which 84% of particles are finer
D	uniform flow depth
F	production of turbulent energy by the vertical velocity gradient
Fr	$U_m(gH)^{-1/2}$ is the Froude number
G	primary production of turbulent energy
H	flow depth
H'	hole size used to separate strong motions from velocity fluctuations
K^+	$k_s U_* \nu^{-1}$ is the shear Reynolds number
Re	$U_m H \nu^{-1}$ is the Reynolds number
$S_{u,v,w}$	streamwise, wall normal, and transverse velocity spectrum
T_B	$3HV^{-1}$ bursting period defined by outer variables
TKE	turbulent kinetic energy
T_s	moving average time-step used to isolate macroturbulence
U	time-averaged streamwise velocity component
U_{avg}	cross-sectional mean velocity
U_{max}	maximum streamwise velocity
U'	root mean square of streamwise velocity fluctuations
U_*	shear velocity
V	time-averaged wall normal velocity component
V_{mag}	magnitude of the time-averaged velocity vector
V_{exp}	expansion velocity induced by the deceleration
V'	root mean square of wall normal velocity fluctuations
W	time-averaged transverse velocity component
W'	root mean square of transverse velocity fluctuations
b	log-law constant of integration for hydraulically rough flows
k_s	equivalent roughness height
m	empirical coefficient used to fit power law to velocity distribution
u	instantaneous streamwise velocity component
u'	instantaneous fluctuating component of streamwise velocity
$\overline{u'v'}$	primary Reynolds shear stress component
v	instantaneous wall normal velocity component
v'	instantaneous fluctuating component of wall normal velocity
w	instantaneous transverse velocity component
w'	instantaneous fluctuating component of transverse velocity
x,y,z	stream wise, wall normal, and transverse directions
β	Clauser pressure gradient parameter $\beta = \frac{H}{U_*^2} g(-S_0 + \frac{\partial H}{\partial x})$
Π	Coles wake strength
κ	von Karman constant
ω	frequency

motions are thought to initiate bursting by pumping high momentum fluid toward the bed (Roy et al., 2004; Belcher, 2009; Adrian and Marusic, 2012).

Bursting motions have historically received more attention in uniform rough flows than macroturbulence until quite recently. For the latter, in-depth macroturbulence investigations for uniform open channel flow over gravel with moderate Froude number ranges (0.5 to 1) and relative submergence similar to gravel bed rivers (H / D_{84} from 3 to 15) have shown the pronounced presence of macroturbulence through the use of decomposed acoustic Doppler velocimeter data, decomposed digital particle image velocimetry data, and decomposed large-scale particle image velocimetry data (Fox et al., 2005; Fox and Patrick, 2008; Belcher, 2009; Fox and Belcher, 2011). In addition to the existence of macroturbulence, visualization, and measurements of macroturbulence for the uniform flow case have shown the functional role that macroturbulence plays for rough bed flows including connectivity to the bursting process, responsibility for downrushing of fluid to the bed, and the production of high and low momentum zones of fluid (Roy et al., 2004; Hurther et al., 2007; Belcher, 2009).

One open channel flow scenario for which macroturbulence has not been studied is the nonuniform flow when the fluid is decelerating in the streamwise direction and expanding in the vertical. Streamwise decelerating and vertically expanding open channel flow over a gravel bed consists of a boundary layer continually developing in the streamwise direction. As flow gradually expands in the vertical direction, streamwise velocity decreases to satisfy continuity. The continuity-induced positive wall normal velocity component is called the expansion velocity. Theoretically derived expressions determine the expansion velocity as a function of local streamwise velocity, bed normal position, and water surface slope (Song and Graf, 1994; Kironoto and Graf, 1995). The wall normal expansion velocity is a nonhelical flow of Prandtl's first kind (Church et al., 2012). The addition of the deceleration in the streamwise direction and vertical advection significantly alters the equations of turbulent momentum and energy from the idealized uniform flow case. The decelerating streamwise velocity represents a decreased energy source to dampen primary production of turbulence, while the expansion velocity potentially represents an increased energy source for the secondary production of turbulence.

A number of studies have shown that the structure of the time-averaged turbulence in vertically expanding flows differ from that of uniform flow by a number of features including: increased wake strength for the streamwise velocity distribution (Song and Graf, 1994; MacVicar and Rennie, 2012), nonlinearity of the primary Reynolds shear stress (Kironoto and Graf, 1995; MacVicar and Rennie, 2012), an amplification of the streamwise and vertical turbulent intensities in the upper half of the flow depth (Song and Chiew, 2001), and turbulence generation away from the boundary (MacVicar and Roy, 2007; Thompson, 2007). Implicit in the explanations of these past results for decelerating flow has been an emphasis upon the primary bulk momentum changes of the nonuniform flow, including a dampened streamwise velocity and net positive wall normal velocity, and their impacts on turbulent energy production via the bursting mechanism in the near bed-region. For example, the ratio of ejections to sweeps in the bursting process determined using quadrant analysis has shown that these processes are not significantly affected by decelerating flows (Afzalimehr et al., 2012). Thus, the bursting process in streamwise decelerating and vertically expanding flows is expected to retain its form but is dampened as energy production from the mean velocity gradient is reduced.

As mentioned, studies have not yet considered the mechanism of three-dimensional macroturbulence in streamwise decelerating and vertically expanding open channel flow, and the role of macroturbulence on sustaining and redistributing turbulent energy in pools and backwater zones is of interest to the community. The vortical nature of the macroturbulence suggests the potential to assist with turbulent energy production from an interaction with mean energy gradients and to redistribute energy in the vertical and transverse directions. Reasons that macroturbulence has not been explicitly considered or studied previously for nonuniform gradually decelerating open channel flow over gravel may be attributed to: (i) the lack of decomposed turbulence visualization results from digital particle image velocity measurements and acoustic Doppler velocimetry profiles until recently for open channel flows with gravels (Hurther et al., 2007; Belcher, 2009); (ii) the loss of the imprint of macroturbulence on Reynolds-averaged turbulence terms and thus the lack of knowledge of its presence in the flow (Church et al., 2012), and (iii) perhaps the lack of investigations where macroturbulence is easily identifiable using decomposition methods (Shvidchenko and Pender, 2001).

The overall goal was to provide the first study, to our knowledge, that investigates macroturbulence for streamwise decelerating and vertically expanding open channel flow over gravel and thereafter elucidate the role macroturbulence plays to sustain turbulent energy in the outer region of the flow. To meet this goal, our specific objectives of this study were: (i) to calculate turbulence time-averaged parameters