International Journal of Sediment Research 30 (2015) 93–99

Contents lists available at ScienceDirect

International Journal of Sediment Research

journal homepage: www.elsevier.com/locate/ijsrc

Original Research Paper

Effect of slope angle of an artificial pool on distributions of turbulence

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ARTICLE INFO

Article history:
Received 3 June 2014
Received in revised form
17 September 2014
Accepted 12 March 2015
Available online 10 June 2015

Keywords:
Slope angle of pool
Velocity distribution
Reynolds stress
Quadrant analysis
Secondary currents

ABSTRACT

Experiments were carried out over a 2-dimentional pool with a constant length of 1.5 m and four different slopes. The distributions of velocity, Reynolds stress and turbulence intensities have been studied in this paper. Results show that as flow continues up the exit slope, the flow velocity increases near the channel bed and decreases near the water surface. The flow separation was not observed by ADV at the crest of the bed-form. In addition, the length of the separation zone increases with the increasing of entrance and exit slopes. The largest slope angle causes the maximum normalized shear stress. Based on the experiments, it is concluded that the shape of Reynolds stress distribution is generally dependent on the entrance and exit slopes of the pool. Also, the shape of Reynolds stress distribution is affected by both decelerating and accelerating flows. Additionally, with the increase in the slope angle, secondary currents are developed and become more stable. Results of the quadrant analysis show that the momentum between flow and bed-form is mostly transferred by sweep and ejection events.

1. Introduction

Natural channels rarely have flat beds. Pools are one of the possible river bed-forms, pools are low points in the topography, with slow convergent flows, less water surface slopes and fine bed material. Leopold and Wolman (1957) and Montgomery et al. (1995) indicated that pools and other macro scale bed-forms such as bars scale with channel width. Keller and Melhorn (1978) claimed that these bed-forms are associated with lateral mobility of the channel (Booker et al., 2001; Clifford & Richards, 1992; Clifford, 1996; Keller, 1971; MacWilliams et al., 2006). Pools are important for aquatic ecology, the variable velocity, depth and turbulence maintain diverse substrates, thermal refuge and conditions essential for various aquariums.

Findings of past experimental studies indicate that the instantaneous flow structures are altered by non-uniformity of the flow caused by bed forms. Pools cause changes in the mean velocity and turbulence intensity. As a consequence, the sediment transport will be affected (MacVicar & Roy, 2007; MacVicar & Rennie, 2012; Yang & Chow, 2008). In general, bed-forms cause a defect of momentum that diffuses outward in the downstream direction. In a pool, the flow depth will increase in the entrance slope and then decrease in the exit slope. In the section of the entrance slope, decelerating flow with a positive pressure gradient exists. However, in the section of the exit slope, accelerating flow with a negative pressure gradient occurs. Flow separation occurs near the bed-form crest, followed by a reattachment of the flow. The location of reattachment point is a function of flow dynamics and characteristics of bed-form. At the reattachment point, a new internal boundary layer begins to grow within the wake region. In the pool, however, the susceptible region for flow separation is the entrance slope where the deceleration flow exists.

In the outer zone ($z/h > 0.2$) where z is distance from the bed and h is the flow depth, streamwise velocity remains relatively high during decelerating flow and relatively low during accelerating flow. The Reynolds stress increases above the bed with decelerating flow and decreases above bed with accelerating flow in comparison with that for uniform flow (Kironoto & Graf, 1995; Song & Chiew, 2001).

Flows in natural rivers may contain three dimensional large scale turbulent structures. Different processes occurring at the same time can generate these structures (Albayrak & Lemmin, 2011). Secondary currents are large scale streamwise vertical structures that form counter-rotating cells across the section. Secondary currents affect the distribution of bed shear stress, Reynolds stress profiles and turbulent intensity across the channel. They affect the flow field of the whole depth and the flow pattern of the free surface flow. These flow patterns contribute to

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http://dx.doi.org/10.1016/j.ijsrc.2015.03.008

Nomenclature

Fr	Froud number
Re	Reynolds number
w	channel width
h	water depth
d_{50}	mean grain size
D	bedform height
H	hole size
u_*	shear velocity
u_{max}	maximum velocity
RMS	root of mean square of flow velocity
u',v',w'	velocity fluctuations
U,V,W	mean velocity

sediment transport, reform bed and may influence the exchange of momentum (Nezu & Nakagawa, 1993). In a wide open channel flow, Nezu and Rodi (1985) observed that secondary currents do not exist in the center of fully developed open channel flow with an aspect ratio (width to depth) of 5 or more. Nezu and Nakagawa (1993) demonstrated that secondary currents are more stable over rough beds than over smooth beds.

To obtain a better understanding of fluvial hydraulics, it is useful to find out how the velocity and turbulence characteristics are affected by variation of entrance and exit slopes of pool. To our knowledge, no research work has been done in this regard. Thus, the objectives of this paper is to understand how the entrance and exit slopes of an artificial pool affect mean velocity Reynolds shear stress and turbulence intensity distributions for different slopes.

2. Materials and methods

2.1. Experimental setup

Experiments were carried out in an 8 m long, 0.4 m wide and 0.6 m deep flume at the Isfahan University of Technology, Iran. Accelerating and decelerating flows had already investigated in a flume with the same length, covered with gravel, but without bed forms (Afzalimehr & Anctil, 1999, 2000; Afzalimehr, 2010). The flow depth was controlled during the experiments by a tailgate located at the end of flume. A pump with a maximum flow capacity of 50 l/s circulated water from a sump to the flume. An electromagnetic flow meter was installed in the supply pipe connected to the flume to measure the discharge passing through the channel. At the uniform section, the flow depth and aspect ratio were 0.2 m and 2, respectively. The pools for experiments were selected on the basis of field data and past experiments. The pools were designed two dimensional due to isolate the effect of stream wise convective acceleration and deceleration flow and to remove confounding effect of width variations. Accordingly, the bed surface was flat in the direction normal to the side walls, and the side walls were made of vertical glass. Based on Carling and Orr (2000) study, the angle of entrance (proximal) slope and exit (distal) slope can be considered equal. They studied 285 pools of the Severn River in Shropshire England, and showed the angles of entrance and exit slopes are generally less than 6°. In addition, a few extreme values were up to 26°. Our field investigations in Zayandeh-rud River at the central Iran confirmed the angles between 5° and 20°. Accordingly, the angles of 5°, 10°, 15°, 20° selected for entrance and exit slopes; and the wavelength of two-dimensional bed form was 1.5 m for each experiment. Measurements were made at 14 sections in two axes of central axis of channel and 5 cm distance from the wall. The first section was located 10 cm upstream of the pool entrance, and the last section was located at 10 cm downstream of the pool exit. Fig. 1 shows the location of 14 sections along the pool. For each profile, 25–30 points were measured from 4 mm above the bed to 5 cm below the water surfaces. Gravel with grain size diameter of $d_{50}=10$ mm covered the flume bed, and the walls were constructed of Plexiglas. The flow discharge kept constant of 18.5 l/s during all experiments.

A down looking Acoustic Doppler Velocimeter (ADV), developed by NORTEK was used to measure the instantaneous three-dimensional velocity components. The measurement error of mean velocity is 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 volume of 5.5 mm^3. For each measurement point, measurement duration was 300 s, resulting in 600,000 instantaneous velocity measurements for each point. To obtain high quality data from the ADV, velocity and turbulence data were filtered by Goring and Nikora (2002) algorithm. The summary of flow characteristics for each run is presented in Table 1. Both Froude number (Fr_0) and Reynolds number (Re_0) were calculated at the upstream of the pool. Spatially-averaging method based on Smith and Mclean (1977) was used to calculate Froude number and Reynolds number over the pool (Franca et al., 2010). These values presented as $Fr_{bedform}$ and $Re_{bedform}$ in Table 1. Spatially averaged velocity profile was also used to estimate shear velocity values from the boundary layer characteristics method (Afzalimehr & Anctil, 2000) over the artificial pools.

2.2. Quadrant analysis

In turbulent flows, coherent structures occur randomly in space and varying with time. Hence, conditional sampling and statistics techniques have to be used in the detection and characterization of coherent structures. One of the most frequently used conditional sampling techniques is the quadrant analysis of the Reynolds shear stress (Lu & Willmarth, 1973; Willmarth & Lu, 1972).The quadrant analysis provides information on the processes of turbulence

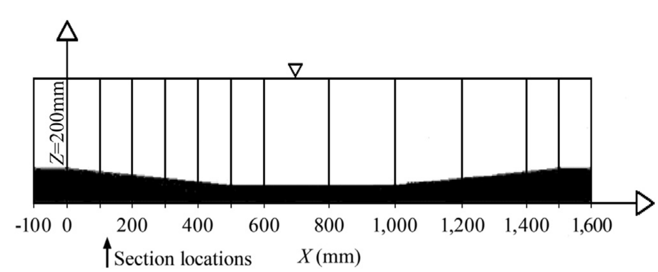

Fig. 1. Sampling design.

Table 1
Summary of the experiment runs.

Slope (deg)	Q (l/s)	h_0 (mm)	U (m/s)	W/h_0	Fr_0	Re_0	$Fr_{bedform}$	$Re_{bedform}$
5	18.4	200	0.231	2	0.165	46200	0.173	54323
10	18.9	205	0.231	1.95	0.163	47355	0.094	54769
15	18.7	208	0.225	1.92	0.157	46800	0.107	50535
20	18.7	196	0.238	2.04	0.171	46648	0.082	38888