VELOCITY AND TURBULENCE MEASUREMENTS IN A SCOUR HOLE USING AN ACOUSTIC DOPPLER VELOCITY PROFILER

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ABSTRACT

The detailed structure of the 3-D flow (mean velocity, turbulence, and Reynolds stress components) in a scour hole formed by a plane jet is measured using a high resolution Acoustic Doppler Velocity Profiler (ADVP), which can simultaneously measure the profiles of quasi-instantaneous velocity components. The use of pulse-to-pulse coherent technique provides high spatial (O(6mm)), temporal (O(30Hz)) and velocity (O(1mms^{-1})) resolutions. The measurements reveal the importance of the apron on the behaviour of the jet and the structure of the flow. The proper orthogonal decomposition (POD) method is used to extract dynamically significant information on the large-scale coherent structures.

1. INTRODUCTION

The understanding of the scouring process of the sediment bed by a horizontal jet is important in the design of the foundations of hydraulics structures. Until very recently, the researchers were only interested in the parameterization of the equilibrium scour hole geometry (maximum scour depth, deposition height, length of the scour hole, etc.). A review of these studies can be found in Karim and Ali (2000). Recently, researchers have shown interest in the 3D flow pattern within the scour hole. Ali and Lim (1986) and Liriano and Day (2000) have carried out point-velocity measurements using a commercial Acoustic Doppler Velocimeter.

The present study is a part of a PhD thesis project on the experimental investigation of the interaction between flow and mobile sediment bed. The aim of the study being an understanding of the relationship between the flow structure and the scour-hole geometry, the profiles of the three components of the instantaneous velocity vector were measured in an equilibrium scour hole downstream of a plane turbulent horizontal jet. The mean velocity field, and the turbulence characteristics were then evaluated from these measurements. The Proper Orthogonal Decomposition (POD) method was used to investigate the spatiotemporal properties of the velocity field in order to extract information on coherent structures.

2. EXPERIMENTAL SETUP AND ADVP INSTRUMENT

The scouring experiments were carried out in a 17m-long tilting flume with a 0.8m-high and 0.5m-wide rectangular cross section (Fig.1). The raised false floors were built at the upstream and downstream ends of the flume. The 5m-long and 0.30m-deep mobile-bed test reach created in the middle part of the flume was filled with sand having a uniform diameter of 2mm. A submerged plane jet, with or without an apron, was created by passing a constant discharge under a dismountable sluice gate placed on the fixed bed upstream of the test reach.

The equilibrium scour hole was obtained by a continuous operation of the submerged jet under clear-water scour condition during a period of 5 to 6 days approximately. The scour-hole evolution was recorded using a digital video camera. After reaching the equilibrium scour depth, the flow was stopped and the scoured sand bed was fixed by spraying a glue.

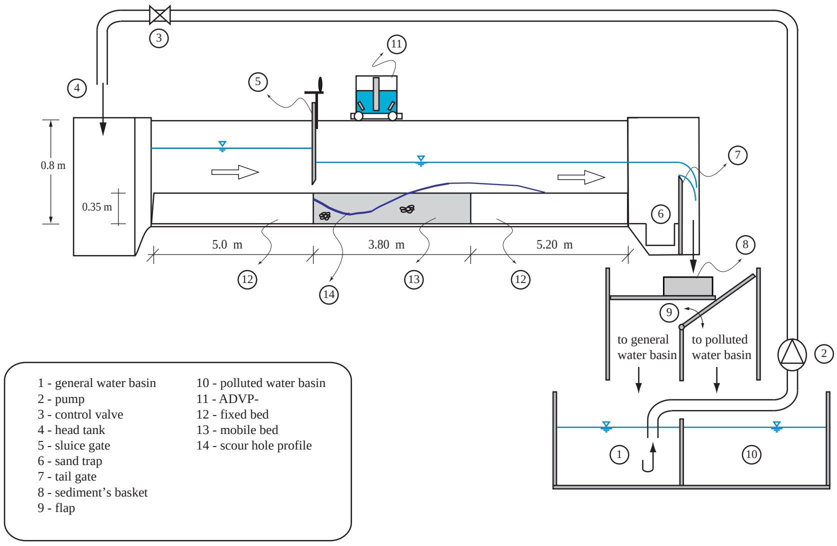

Figure 1. General view of the experimental setup

Flow measurements in the fixed scour hole were then made using both an Acoustic Doppler Velocimeter (ADV) and an Acoustic Doppler Velocity Profiler (ADVP) for the discharge used for creating the scour hole. The hydraulics parameters for the two experiments illustrating the findings of the present study are listed Table 1 (see Kurniawan et al., 2001).

Table 1. Hydraulic parameters of the experiment

Test	Q $[m^3/s]$	L_a [cm]	h_v [cm]	U_o [m/s]	Fr_o [-]	h_1 [cm]	h_2 [cm]	d_{50} [mm]	Fr_d [-]	d_s [cm]	L_s [cm]
B	0.015	0	5.0	0.846	1.21	25.85	22.2	2.0	4.70	16.8	62.5
C	0.015	10	5.0	0.843	1.20	25.80	22.2	2.0	4.69	13.1	56.6

The ADVP conceived and developed at LRH (Lhermitte and Lemmin, 1994) measures the instantaneous velocity vector at a number of layers within the water column. This instrument has been successfully used to measure the velocity distributions, turbulence characteristics and coherent structures in various free surface flows (Song et al, 1994; Hurther et al., 1996; Yulistiyanto, 1997; Istiarto, 2001; Blanckaert, 2002).

The tristatic configuration of ADVP, used in the present study, consists of one emitter, T_3, and four plane receivers, T_1^-, T_1^+, T_2^-, T_2^+, which are placed symmetrically around the emitter (Fig. 2). This configuration is placed in a water-filled housing covered by a mylar film at the bottom. Mounted on a carriage, the instrument is positioned at the desired location along the flume with the Mylar bottom barely touching the water surface.

The three dimensional instantaneous velocity, is measured by the ADVP as a pair of two-dimensional instantaneous velocities, $\vec{V}_1(\hat{u}_1,\hat{w}_1)$ and $\vec{V}_2(\hat{u}_2,\hat{w}_2)$. Both velocities are identified by their components along the longitudinal direction, $\hat{u}_1$ or $\hat{u}_2$ and along the vertical direction, $\hat{w}_1$ or $\hat{w}_2$ of the respective plane. Using geometrical relationships, these are combined to give the target velocity, $\vec{V}(\hat{u},\hat{v},\hat{w})$. Details can be found in Rolland (1994).

The instantaneous velocity profile was obtained by recording successively the back-scattered signals according to a fixed time interval (time gate), ΔT_{gate}, corresponding to different layers within the water column. This ΔT_{gate} defines the thickness of the measuring volume, Δd, to be calculated from the relation $\Delta d = \Delta T_{gate} \cdot c_s/2$, where ΔT_{gate}=8 [μs] is the time gate and c_s=1486 [m/s] the sound speed in water. In the present experiment, the pulse-repetition frequency (PRF) was done at 1000 [Hz]. A value of number of pulse-pairs (NPP) of 32 is used, resulting in a measuring frequency, f_v, of 31.25 [Hz]. The measurement duration for individual profiles was 60[sec]-180[sec]. Due to the size of the housing, the measurements were started at x = 20 [cm] from the sluice gate. The profiles were measured at every 2 [cm] up to x = 200 [cm].

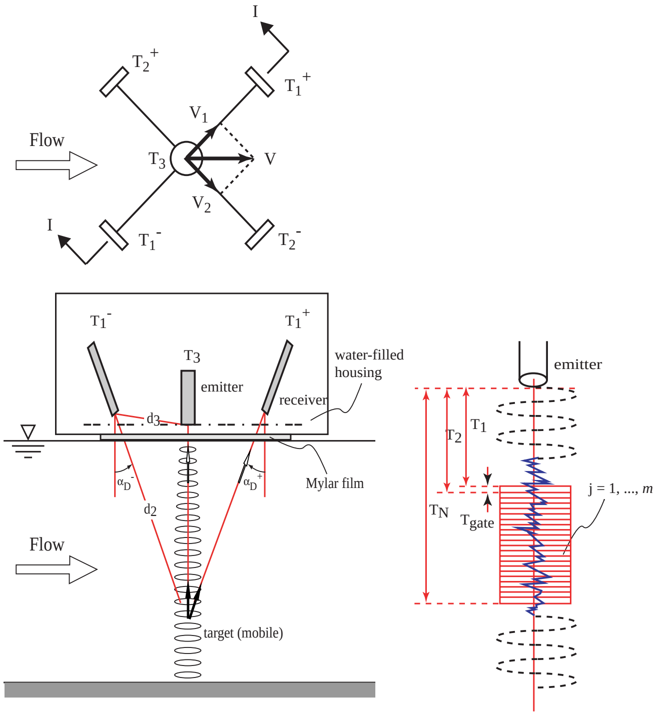

Figure 2. The configuration of *tristatic* mode

3. RESULTS AND DISCUSSIONS

Only the results for the runs listed in Table 1 are presented in this paper. Note that, the velocity data for x/h_v < 4 were obtained from ADV-Nortek instrument and they are not included in POD analysis. The ADVP measurements cover the region $x/h_v \geq 4$.

3.1 Velocity Distributions

Fig. 3 shows the distribution of the magnitude of the 2D mean velocity for the tests B and C. For the Test B, without apron, the measurements show that the flow issues from the sluice gate as a plane, turbulent free-jet and impinges on the bed at about x = 40 [cm]. Downstream of the impingement point the main flow continues as a plane, turbulent wall-jet. These results are in good agreement with those of Ali and Neyshaboury (1991) and Liriano and Day (2000). For the Test C, with apron, however, the jet is deflected towards the surface and there is no impingement on the bed. Rajaratnam and Berry (1977) makes a similar observation.

3.2 Reynolds Stresses Distributions

The Reynolds stress, $\tau_{zx} = -\rho \overline{u'w'}$, is readily calculated from the measured u(z,t) and w(z,t) data. The Fig. 4 shows the spatial distribution of the Reynolds stress, normalized with ρU_o^2, on the vertical central plane, for the Tests B and C. Qualitatively these distributions compare quite well with the data reported by Rajaratnam (1976). The maximum Reynolds stress is

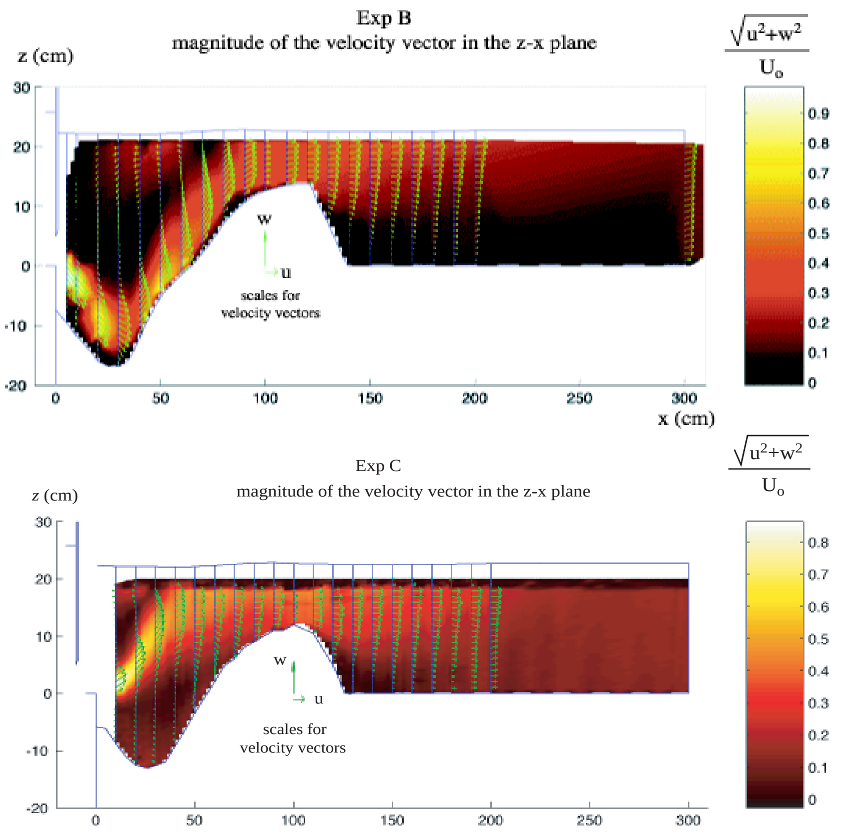

Figure 3. Magnitude of velocity vector in the *z-x* plane

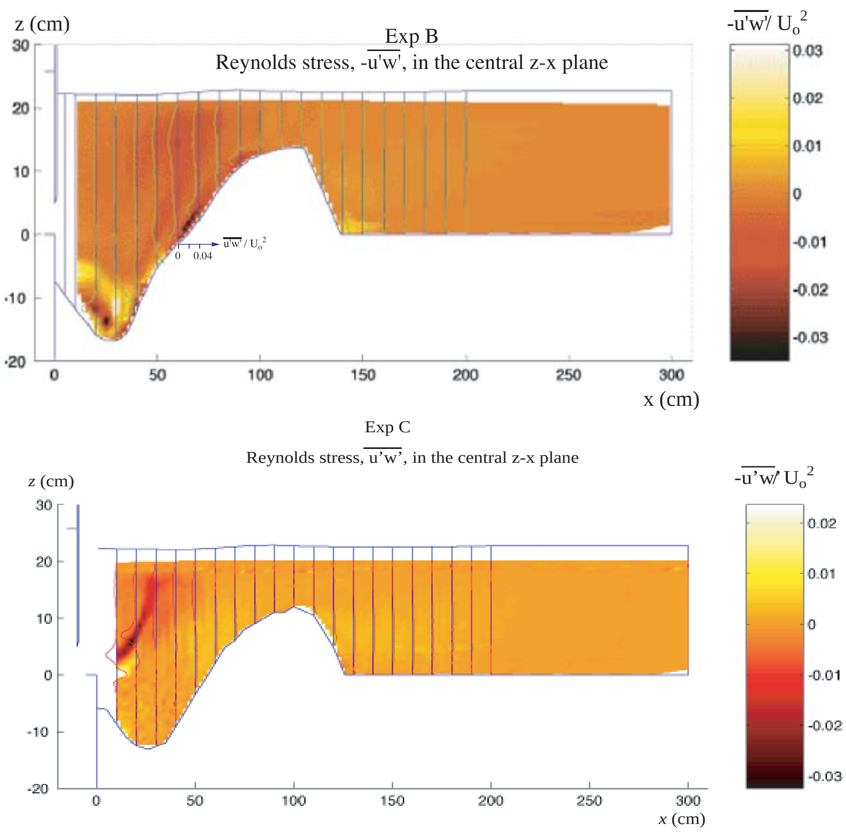

Figure 4. Magnitude of Reynolds stress in the *z-x* plane

usually situated at the line of maximum velocity. In the vicinity of the bed the Reynolds stress is vanishing considerably, implying the incapacity of transporting sediments for the equilibrium scour-hole situation. The negative Reynolds stresses are observed in the upper part of the scour hole where the velocity gradient is negative.

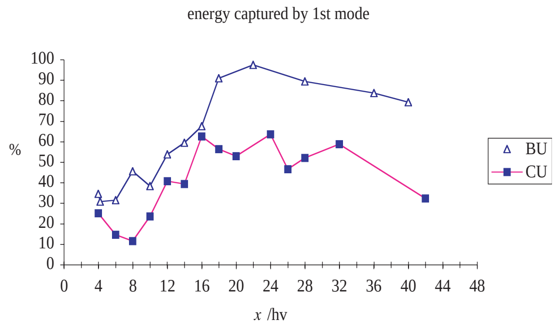

Figure 5. Energy captured by 1st POD mode

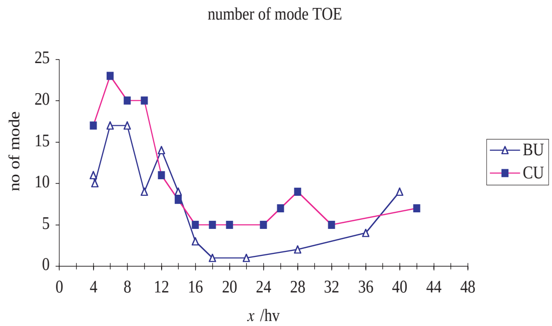

Figure 6. Number of POD modes which catch at least 90% of total energy

3.3 POD analysis and coherent structures

Consider a velocity measurement with ADVP on a vertical. The N instantaneous u-velocity measurements from m gates along the vertical are stored in the N×m matrix A. The singular value decomposition (SVD) is applied to calculate the eigenvalues (singular values), λ_k , of this matrix A. If $\phi_k(z)$'s are the spatial eigenfunctions or modes corresponding to the eigenvalues λ_k, according to the POD method, the spatiotemporal velocity data can be decomposed as follows (Holmes, et al., 1996)

$$u(z,t) \approx \sum_{k=1}^{m} a_k(t)\, \phi_k(z) \tag{1}$$

where a's are temporal coefficients and z is the spatial coordinate along the vertical. Each mode makes an independent contribution to the total flow energy. The total energy captured in the POD decomposition (sum of all the eigenvalues), E, and the relative energy captured by the kth mode, E_k, is defined as

$$E = \sum_{k=1}^{m} \lambda_k \quad ; \quad E_k = \lambda_k / \sum_{k=1}^{m} \lambda_k = \lambda_k / E \tag{2}$$

In Fig. 5, the amount of energy captured by the first mode (the most energetic mode) is plotted against dimensionless distance x/h_v for the tests B and C. In both tests, for the region $x/h_v < 17$ the energy captured by the first mode is relatively low; meaning that a lot of modes are involved in the dynamics of this region. For $x/h_v > 17$ the first mode captures considerably more energy. The number of modes required to capture 90% of the total energy are plotted in Figure 6 as a function of x/h_v. The results presented in Figures 5 and 6 are relatively in good agreement with the values reported by Caraballo, et al. (2001) for a circular jet flow.

It is interesting to note that the reconstruction the flow field using the first POD mode at x/h_v=6, shows the presence of large scale coherent structures indicating a pulsation of the jet. These may correspond to periodic rotational structures (see Faghani, 1997).

4. CONCLUSIONS

A tristatic ADVP was used to measure the 3D velocity field in an equilibrium scour hole created by a horizontal, plane turbulent jet issuing under a sluice gate. The tests were carried out for the cases with and without apron using the same tail-water depth. The measured velocity fields show important differences. In the case with the apron, the jet is deflected towards the free surface whereas the jet without apron flows downwards and impinges on the bed at $x/h_v=8$ approximately. It then continues as a wall-jet. Although not given here, the resulting equilibrium scour hole geometries for these two cases are also quite different.

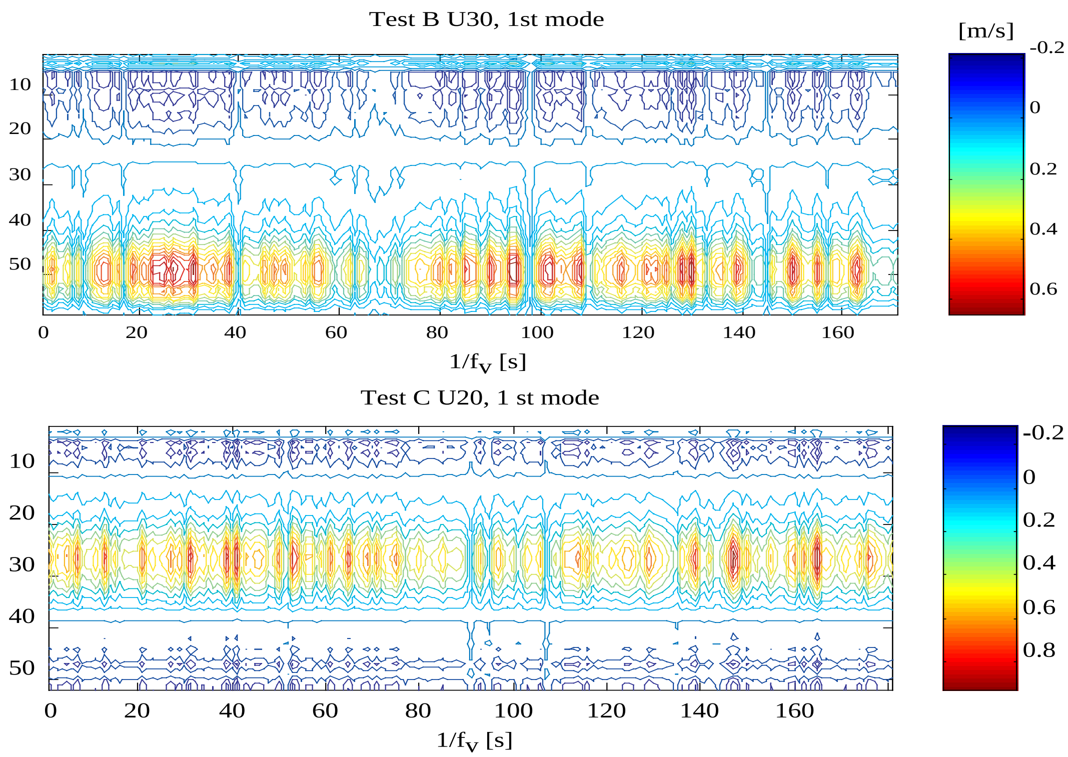

Figure 10. Contour of longitudinal velocity using the first POD mode at *x*/hv=6

The spatiotemporal signals obtained with ADVP were analysed using the POD technique. The results show that a large number of modes are needed to capture the flow dynamics in the near field. The reconstruction of the velocity measurements at $x/h_v=6$ using only the first mode shows the presence of periodically released rotational structures.

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NOTATION

Fr_o	= Froude number (-)
Fr_d	= densimetric Froude number (-)
L_a	= apron length (cm)
L_s	= scour length (cm)
PRF	= frequency of the pulse emission (Hz)
Q	= discharge (m^3/s)
T_1^-, T_1^+, T_2^-, T_2^+, T_3	= ADVP transducer
U_o	= initial jet velocity (m/s)
d_{50}	= mean diameter of the sediment (mm)
d_s	= maximum scour depth (cm)
h_V	= sluice gate opening (cm)
u, v, w	= time average of longitudinal, transversal and vertical velocity components (m/s)
$\hat{u}$, $\hat{v}$, $\hat{w}$	= instantaneous velocity components (m/s)