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Experimental Study on Hydraulic Jumps With and Without Sediment

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ABSTRACT

In the present study we try to obtain the internal flow field and examine the phenomena while the hydraulic jump is developing. Channel experiments with inclination angle of 5 degree are designed, where the jumps are produced by setting a weir at the end of the channel. Two types of water supply are considered, in the inflow condition I pure water is supplied, whilst sediments are added into the water in the inflow condition II. The velocity measurement and water surface variation are achieved by means of the Digital Particle Image Velocitmetry (DPIV) technique, for which an open-source software "PIVLab" is employed. In experiments of inflow condition I, the toe of the jump oscillates where a roller exists and the flow exhibits highly turbulent. When the water is mixed with sediments (inflow condition II), a mixture shear layer exists near the flow bottom. Once the jump is going to develop, it is interesting to find that sediment begins to deposit in the vicinity of the jump toe. The deposit heap of sediment develops upwards and extends in the downstream direction. In this study we shall present the detailed evolution of the corresponding velocity fields and the whole process of the development of sediment deposition. The measurements will serve as the solid evidences and be the raw material for developing the shear shallow flow models.

KEY WORDS: hydraulic jumps; non-hydrostatic pressure; sediment deposit.

INTRODUCTION

For open channel flows, hydraulic jumps appear at the transition from the supercritical stage to subcritical one. Steady hydraulic jump can be numerically reproduced by applying the standard Saint-Venant Equations (or Shallow-Water equations, SWEs). However, the steady hydraulic jump is rarely observed in channel experiments. It is due to the strong assumptions of uniform velocity distribution and a hydrostatic pressure along the flow thickness in the SWEs. The non-uniform distribution of the velocity might be induced by the inevitable roughness on the bottom surface, so that shear layer exists near the flow bottom. A shear shallow flow model is therefore proposed (Richard and Gavrilyuk, 2012, 2013 in Journal of Fluid Mechanics), in which it mathematically proves that the non-uniform distribution of velocity along the flow depth does not admit the assumption of hydrostatic pressure in the shallow water equations. In the present study we try obtain the internal flow field and examine the phenomena while the hydraulic jump is developing. Channel experiments with inclination of 5 degree are designed, where the jumps are produced by setting a weir at the end of the channel. Two types of water supply are considered, in the inflow condition I pure water is supplied, whilst sediments are added into the water in the inflow condition II. The velocity measurement and water surface variation are achieved by means of the Digital Particle Image Velocitmetry (DPIV) technique, for which an open-source software "PIVLab" is employed. In experiments of inflow condition I, the toe of the jump oscillates where a roller exists and the flow exhibits highly turbulent. It is known that the jump is a complex turbulent flow and highly dependent on the flow conditions in the vicinity of the jump toe, especially the bottom condition. When the water is mixed with sediments (inflow condition II), a mixture shear layer develops near the flow bottom where deposit might take place. Once the jump becomes fully developed, it is interesting to find that sediment begins to deposit in the vicinity of the jump tow where the flow is extremely turbulent. The deposit heap of sediment develops upwards and extends in the downstream direction. In this study we shall present the detailed evolution of the corresponding velocity fields and the whole process of the development of sediment deposition. The measurements will serve as the solid evidences and be the raw material for developing the shear shallow flow models.

EXPERIMENTAL FACILITY AND INSTRUMENTATIONS

Experimental method and equipment

The experimental investigation mainly focused on the characteristics of the two-dimensional hydraulic jumps. Hence, the experiments were performed in a narrow rectangular channel. A 1.4 m long by 2 cm wide inclinable flume made by plexiglass was used for experiment. The flume inclination was set to 5 degree. A water supply system with a reservoir is equipped to provide a constant discharge, ca. 90 m2/s, at constant water head, see Fig. 1 for the experimental setup. Two types of supply condition are considered, where pure water inflow is adapted in the condition I, sediments are added into the water in the inflow condition II. The Ottawa sand (ASTM C778 20/30, diameter: 0.60-0.85 mm) was used as the sediment with flow rate of 4.7 g/s. The flow rates in the two conditions are listed in Tab. 1.

Table 1. Inflow condition for both conditions

	Condition I	Condition II
Water	90.48 (g/s)	89.60 (g/s)
Sand	--	4.7 (g/s)

An adjustable laser (up to 1W) with wavelength 532 nm was used with optical setup to create a vertical laser sheet down the channel at 1/4 of the width near the wall of camera side for the velocity analysis by particle image velocimetry (PIV). The PIV is a flow visualization technique in which the flow is seeded by tracers and filmed by a high-speed camera (e.g. Willert and Gharib, 1991). The flow velocities are determined by comparing the distribution of tracers in two consecutive images, where the PIVlab software (Thielicke and Stamhuis, 2014) was utilized. In experiments, the images were taken by a high-speed CMOS camera with a lens of focal length 50 mm at a speed of 1,000 frames per second (fps). Spherical hollow glass powder (diameter: 30 μm) was added to water as tracers for detecting the fluid velocity.

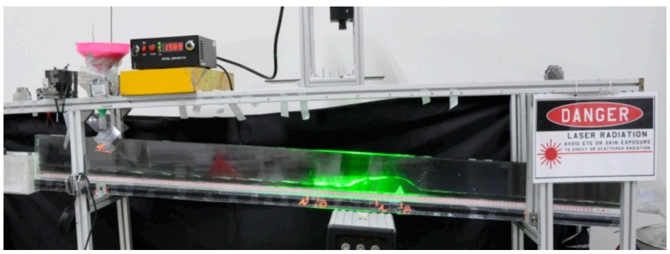

Fig. 1 Experimental setup, where the channel includes the reservoir, weir and laser lighting system.

EXPERIMENTAL RESULTS

Inflow Condition I: Pure Water

Fig. 2 shows the water surface and the PIV-measured velocity fields at two time levels ($t=t_0^I+0.005$ s and $t_0^I+1.345$ s) in the pure water inflow condition. Because of large amount of velocity data, we analyzed the velocities within 1 cm range as shown in the panels. The toe of the jump oscillates where a roller exists and the flow exhibits highly turbulent. It is clear that the distribution of velocity along the flow depth is not uniform.

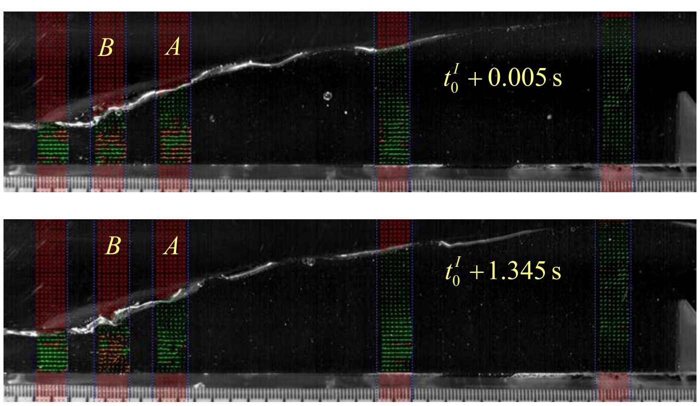

Fig. 2 Hydraulic jump and the PIV-measured velocity fields.

Since the flow is turbulent, the representative velocities are given by mean values which are calculated within a 1-cm band. Fig. 2 depicts the velocity profiles of tangential component at sections A (upper panels) and B (lower panels), where the lines in color light blue indicate the water level and the bars represent the standard derivation of measurement. Backflows are found in the upper part of the flow. Either in section A or B, the shapes of the velocity profile are rather similar. At section A the flow depth remains nearly invariant, the ones in section B vary due to the oscillation of the jump toe.

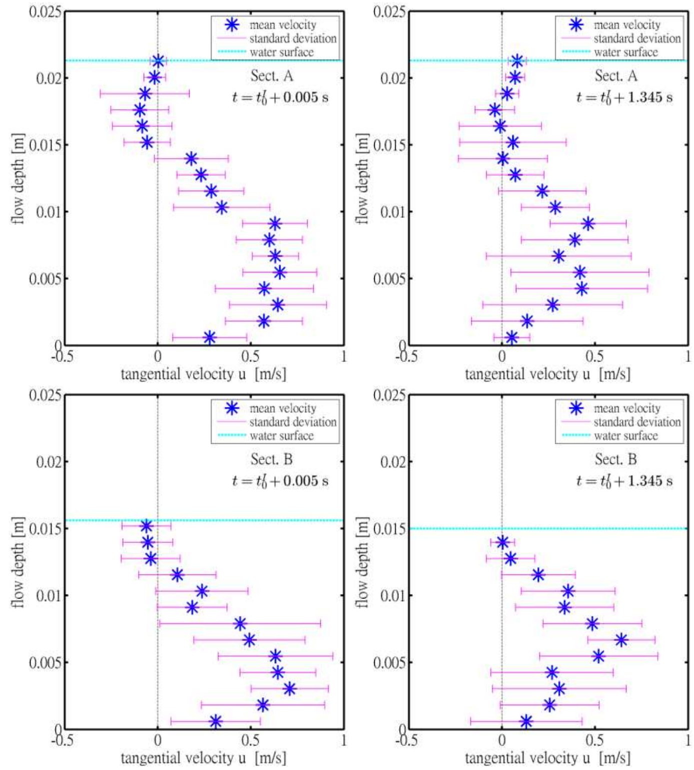

Fig. 3 Distributions of tangential velocity at sections A and B

Inflow Condition II: Sediment-Water-Mixture

Once the sediment is added into the flow, a mixture shear layer develops near the flow bottom and the flow behavior changes significantly. Fig. 4 illustrates the high-speed camera captured images and PIV-measured velocity fields at three time levels ($t=t_0^{II}+0.005$ s , $t_0^{II}+2.505$ s and $t_0^{II}+3.005$ s). At $t=t_0^{II}+0.005$ s , the sediment begins to deposit when the jump develops. Two deposition heaps were found: one locates in front the weir (the minor one) and the other one (the major one) developed just after the jump toe. With the evolution of the deposition heap, the jump travels toward upstream.

In the PIV measurement for the mixture layer, the sediments were treated as the tracers. The velocities are computed for ranges (D_1, D_2 and D_3 as shown in Fig. 4), where the depth mixture/deposition is at maximum value, and are expressed by mean values over a band of 2 cm. Fig. 5 shows the velocity profiles at the three time levels, where, as shown is Fig. 4, the light-blue lines indicate the water level and the bars represent the standard derivation. The mixture layer lies between the orange line and deep-red line. Below the deep-red line is the deposition heap. It is interesting to find that a quasi-linear velocity profile is found in the mixture layer and the interface is associated with a velocity jump. At D_2 and D_3, the velocity profiles are nearly of the same shape. Different from the ones by pure water, the upper layer moves faster than the lower one in the clear water layer.

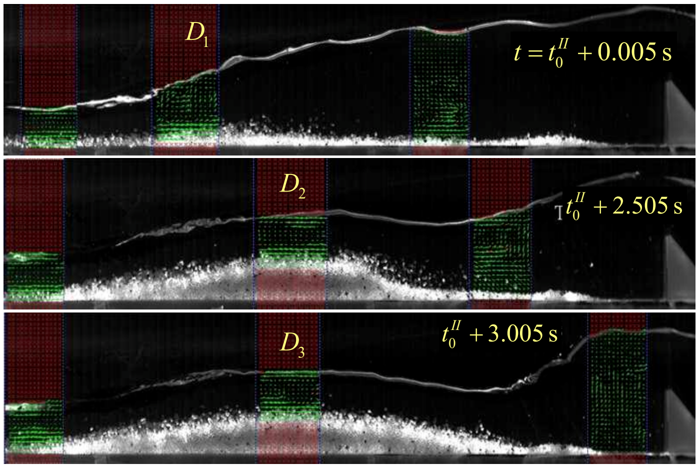

Fig. 4 Hydraulic jump, deposition heap and the PIV-measured velocity fields in inflow condition II.

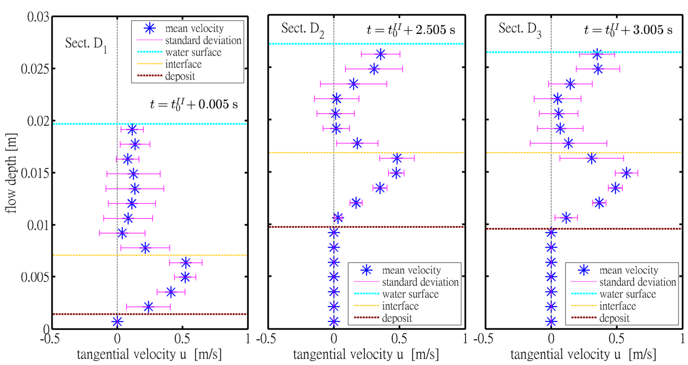

Fig. 5 Distributions of tangential velocity at sections D_1, D_2 and D_3, where the deep-red lines represent the location of the top surface of the deposition heap, and the lines in orange color indicate the interface between the mixture layer and clear water layer.

Taking the advantage of velocity information, one can determine the deposition heap, both the depth and the shape. Hence, the deposition rate and the volumetric deposition rate can be calculated. The left panel of Fig. 6 depicts the evolution of the top surface of the deposition heap (the red marker *) with the regressed curve (blue line), of which the slope means the deposition rate (green line). The decrease of depth is suspected to be due to the horizontal extension of the heap. The stagnant area in the images is recognized as the deposit body, so that one can compute the deposited volume. The right panel Fig. 6 describes the evolution of the area of the deposition heap (the red marker *) with the regressed curve (blue line), whose slope is equivalent to the volumetric deposition rate (green line). It is surprising that the deposition rate linearly decrease with time, but the volumetric deposition rate increase linearly.

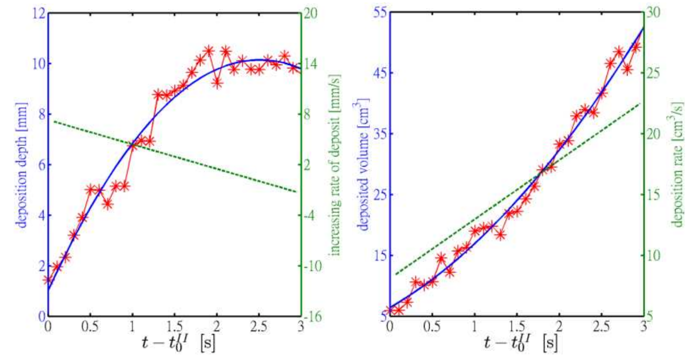

Fig. 6 Evolutions of the deposition depth (left panel) and deposited volume (right panel), where the slopes indicate the deposition rate and volumetric rate, respectively.

CONCLUSIONS

In the present study, hydraulic jumps were experimentally examined by a narrow channel inclined at 5 degree. The velocity fields of the clear water and mixture layers, as well as the evolutions of the deposition heap are achieved by utilizing a high-speed camera together with the Digital Particle Image Velocimetry (DPIV) technique. Two types of water supply are considered. In the pure-water condition, the shapes of the velocity profile are rather similar at the same section, where high speed layer lies near the bottom and backflows are found to be near the flow surface. In the inflow condition II, a quasi-linear velocity profile is found in the mixture layer and the interface is associated with a velocity jump. With the PIV technique and image processing method, the deposition rate and volumetric deposition rate are available. It is surprising that both of them decrease/increase linearly with time. These measurements may serve as the solid evidences and be the raw material for developing the shear shallow flow models.

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