An Investigation of Unsteady Flow over an Obstacle using Imaging System

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Abstract

Experiments have been undertaken to investigate unsteady flows (such as dam-break flow) over an obstacle with wet beds downstream. An image analysis system based on tracer particles was used in the laboratory to analyse and visualise the instantaneous flow pattern and characteristics in the area of interest in the downstream channel. We study the problem experimentally at two different scales in a horizontal channel of rectangular section; a vertical flat plate separating the two levels of water is suddenly withdrawn (upwards). Depth ratios of 0.45 and 0.55 were investigated for an average upstream depth value of 10 cm. The experimental measurements of the flow structure and characteristics in the downstream wet-bed were obtained.

Results include visualization of the instantaneous flow pattern and characteristics in the area of interest in the downstream channel. Higher values and complexity of the most flow structure and characteristics were obtained for the lower downstream water depth case than for the case with higher downstream water depths. Measurements from the experimental imaging system were analyzed by using two different techniques such as PTV and PSV for comparison, which demonstrates a good agreement between two experimental results. The comparisons between analytical solutions and experimental measurements for the testing flume under dry and wet-bed flow conditions will be presented later to publish in ISI Journal paper as you promised.

Key words: Unsteady flow, Dam-break flow, Imaging system, Obstacle, Experimental work

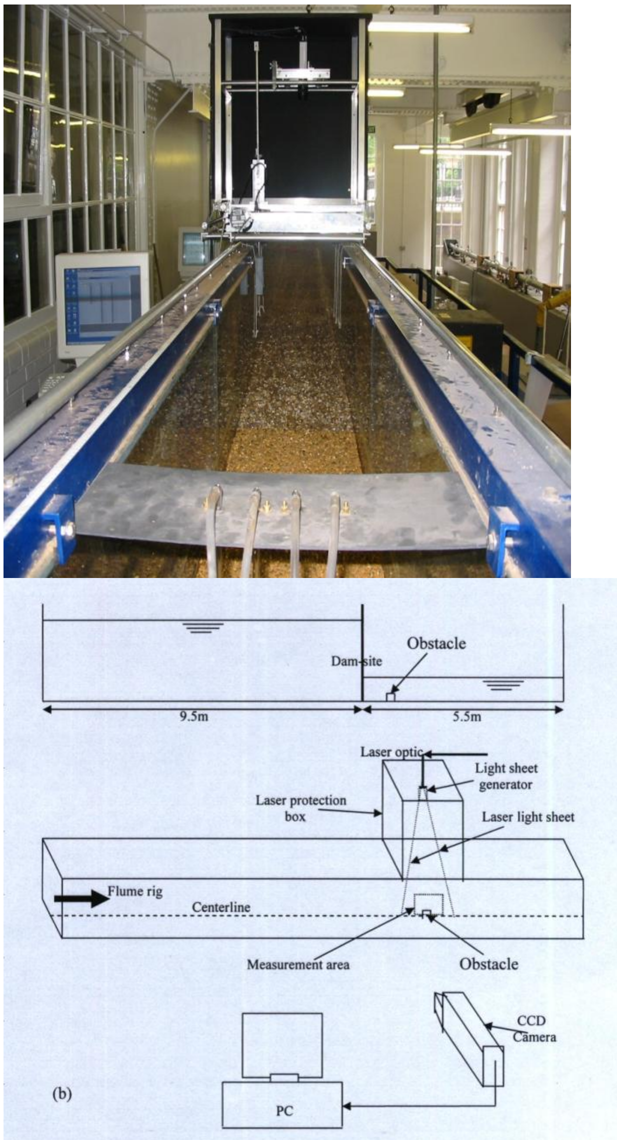
1. Introduction

Predictive mathematical model investigations of the effect of unsteady flows (such as dam-break floods) have been carried out by several researchers for the last several decades and some important results have been obtained, see for example Su & Barnes (1970) and Bellos & Sakkas (1987). Since field data for this flow is very difficult to obtain, it is necessary to collect experimental data to verify the mathematical models. Several experimental investigations of the dam-break flow have been reported in the last four decades, see Derssler (1954), Bell *et al* (1992) and Lauber & Hager (1998).
Physical models are often observed as being more expensive than a computational equivalent. Examples of computational model studies the dam-break flows can be found in Soulis (1992) and Glaster (1993) who compared these with recent experimental data for dam-break flows. On the other hand, a range of novel experimental methods based on signal and image analysis system have been developed for measuring flow velocities which are particularly useful in unsteady flows such as dam-break flow. Such data can be used for the validation of numerical calculations. In whole field measurement techniques, the flow field is illuminated with a thin light sheet from a powerful source and might be filmed photographically or digitally. Once several particles appear in the illuminated area, then the velocity vectors can be obtained for this area using tracking algorithm techniques based on auto-correlation, cross-correlation or Young's fringe method see Adrian (1989).
In this paper, the main objective is to investigate the instantaneous whole-field velocity of unsteady flows (such as dam-break floods) by tracking particles seeded in the flow, after the bore has become established. Previous work concentrated on the initial stages of dam-break flow, theoretically, numerically and experimentally sees Stansby *et al* (1998). A measuring system enables individual particles in the flow to be tracked directly. Particle Tracking Velocimetry (PTV) and Particle Streak Velocimetry (PSV) methods are applied for a digital system. In this study, the PSV was used, measuring streaks to obtain maximum average of the particle movements for two downstream wet bed cases. The automated PTV method was suited to certain subcritical flows which were assessed by comparing with PSV measurements. Finally, the experimental velocity measurements and free surface profile will be compared with computational calculation later.

2.Experimental Work

The experimental rig was an open channel flume with a horizontal bed. The test facility consisted of a 15 m length of 0.4 m by 0.4 m rectangular cross section flume. Parts of the upstream and downstream walls of the dam site were made with clear Perspex to view the flow. The upstream end of the flume was closed but the downstream end had different level weirs for the downstream wet-bed conditions. The dam site was set up at 9.5 m from the upstream end. A thin movable metal plate (3 mm thick) was used to simulate the instantaneous dam-break. A rope was attached to the top of the dam plate and loops through a pulley down to a 7 kg weight which was released from about 0.8 m above the laboratory floor. The experiments were made with an upstream depth (H) of 0.1 m and downstream depths of 0.45H and 0.55 H.
In this study, an instantaneous whole flow field plane visualisation and velocity measurements of the area of interest were investigated using PTV and PSV techniques. These methods are based on tracer particles which are added to the flow and then illuminated with a powerful light source. The particles were spherical, 80 micron in diameter, solid polystyrene seeding

powder with a relative density of 1.0 ±0.2, which made the particles neutrally buoyant in water and able to follow the flow. The particles were mixed in the flow rig before running each test. The light source for illumination in the field of view was a 4 watt Argon ion laser. The light sheet generator produced a vertical plane light sheet with the width of 1-3 mm along the flume at about middle of the flume. A JVC TK-1085E colour CCD camera was used to record a 8.4 cm by 6.9 cm picture field. The experimental arrangement of a principal requirement in the laboratory set-up is shown in figure 1.



(a)

Fig 1: Experimental facility of unsteady (dam-break) flow, (a) Photo of the experimental requirement, (b) Sketch of the laboratory arrangement

Each image (frame) is a series of discrete digital values that are stored in a two dimensional array of numbers. This array of individual element numbers (pixels) with an integer color (grey level) is represented as the digital image. The image resolution having 512 x 512 pixels with 256 (8 bit) grey levels. The digital image can be processed on the computer. Each digital data element (pixel) is denoted by a number, which represents the amount of light intensity of a small area of the visual image. The sampled number of each pixel conventionally gives the level of darkness or brightness of the small area. Zero represents black, the maximum value, 256, denotes white and intermediate values designate various shades of grey.

3. Image Analysis System

The captured images were cleaned-up by filtering and then thresholding. Therefore, the background becomes black (grey level 0) and the foreground particle images become white (grey level 256). At this stage, all seeding particles appear in the frame image sequence as white colour. The images are now suitable for further processing. The technique of applying image analysis to obtain quantitative velocity flow field information from particle movement encompasses a number of different methods. They are differentiated by the form of the captured image and the analysis technique employed. The displacement of individual particles within a field of view over the known short time period yields information about the velocity vector field simultaneously over the whole plane for which the particle image data was gathered. The vectors displayed using the vector map software to an original image are recorded.

3.1 Particle Tracking Velocimetry (PTV)

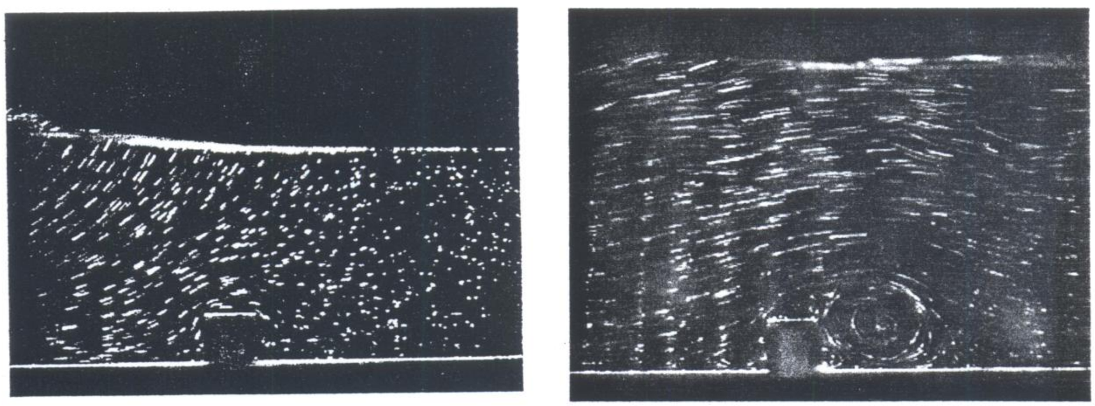
This method requires individual particles to be located in an image and successive images to be recorded on successive frames. The system analyses pairs of single exposed digital images to produce whole field maps of velocity vectors. Particle images at different times exist on the separate frames. There is no directional ambiguity in the calculated vectors and the direction of particle motion is easily found. There is also no lower limitation on particle motion between frames. The particle tracking technique is used to accurately determine the position of a particle in an image frame and compare it with its location at a known short time interval later (in a successive frame). The distance traveled by an individual particle is then calculated and the velocity found knowing the time interval between images. This process is repeated for all of the particles appearing in the frame sequence. Various correlation algorithms have been developed to allow the tracking of particles from frame to frame. Examples of these are Nishio et al. (1992) and Hassan et al. (1992).

3.2 Particle Streak Velocimetry (PSV)

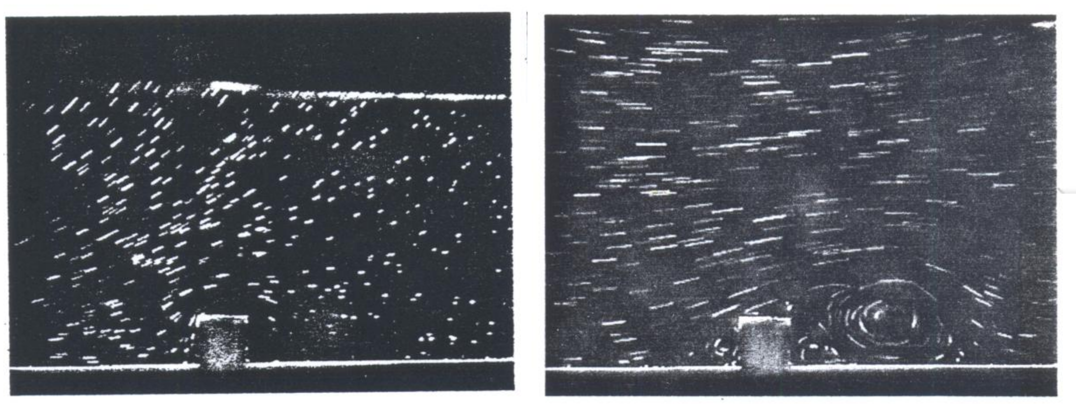
Seeding particles in the fluid medium may be recorded on a single frame of photographic or video film by using a relatively long exposure time. The application of particle streak in fluid mechanics has been used for qualitative flow visualisation as illustrated in Van Dyke (1982). Particle streak images can be digitised for development into the quantitative measuring technique known as Particle Streak Velocimetry (PSV). This method is usually used when the medium fluid has a seeding particle concentration less than that for PTV. This method does not require individual streak images to be overlapped and distinguished from each other. PSV enables accurate individual streak lengths to be determined and then analysed. As the exposure time is known, it becomes possible to obtain the velocity associated with a particle streak. The processing of the streak images includes filtering the images to eliminate noise and thresholding to separate the streak from the background. The white streaks corresponding to the particles can then be located and measured, see Kobayashi & Saya.(1988). The image analysis for locating streak images and measuring their lengths with known exposure time to obtain the velocity field has been demonstrated in a wide variety of flow situations, see Green & Gerrard (1993).

4. Results and Analysis

The most interesting of the experimental results will be shown here. More details regarding the experimental data can be found in Chegini *et al* (2004). In this paper, visualisation and measured velocity fields are presented by analysing images using PTV and PSV methods. The free surface profiles in the initial stages of the dam-break flow from the digitised images have already been published see Stansby *et al* (1998). Surface elevations at various longitudinal positions were also measured using resistance probes and essentially confirmed the results from the digitized images. Surface profile plot with the identified area (8.4 cm x 6.9 cm) of the recording digitised images at centred 85 cm downstream of the dam-site for the downstream wet-bed initial flow conditions. Figure 2 shows typical time series of the raw digitised images at location x=85 cm downstream of the dam-site for different initial flow depth ratios.



T=0.96 s (a) T=1.14 s

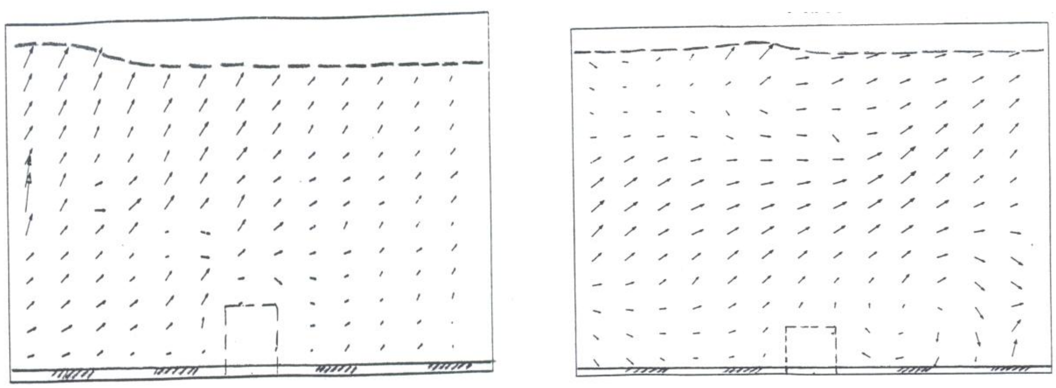


T=1.08 s (b) T=1.54 s

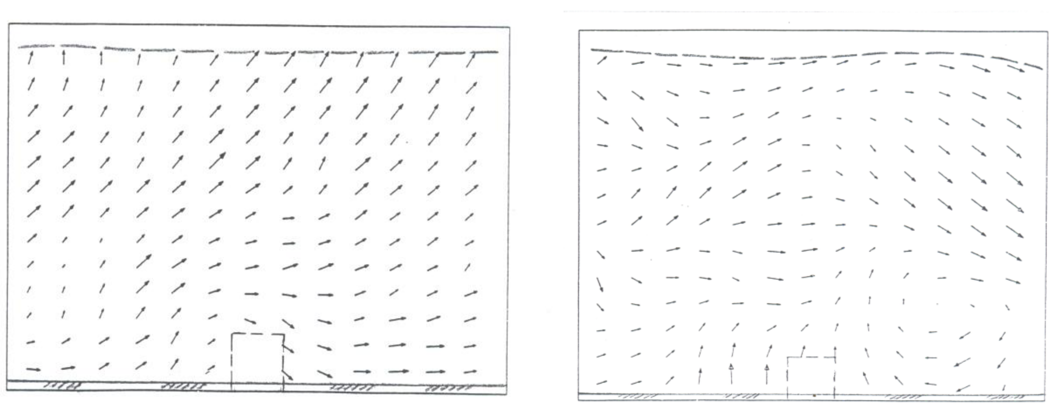
Fig 2: Typical time series of the digitised images at 85 cm downstream of the dam site with initial upstream water depth condition of 10 cm, (a) H_{ds}=0.45 H_{us} and (b) H_{ds}=0.55H_{us}

These digitised images of the flow are processed to obtain the time series of the whole flow field. Note that x=0 corresponds to the dam-site. The longitudinal cross section fluid motion is shown by the laser sheet which produces an illuminated screen of finite thickness. To aid illumination, seeding powder is dropped on the water around the area of interest. The powder is neutrally buoyant in water. The velocity fields are here defined by the tracking of the particle.

Some frames of the digitised flow field images were analysed to obtain the velocity information by the particle tracking technique for a downstream initial depth of 4.5 cm and 5.5 cm which presents the subcritical flows. The typical results are shown in figures 3 as frames progresses.



T=0.96 s (a) T=1.14 s



T=1.0 s (b) T=1.58 s

Fig 3: Typical velocity field obtained by PTV at 85 cm downstream of the dam site with initial upstream water depth condition of 10 cm, (a) H_{ds}=0.45 H_{us} and (b) H_{ds}=0.55H_{us}

Observation of the results from the particle tracking technique and digitised images emphasises the similarity as expected. The digitised flow field images of the wave propagation in the downstream initial conditions also show clearly that the flow particles in the stationary area had moved before the wave as confirmed by PTV results.

The digitised flow field images used to obtain the velocity field for the fixed camera position at 85 cm downstream of the dam-site. Some images suggest these regions are in fact a mixture of spray and particles. The results show white long straight and mixed lines with some brighter areas. These are due to high speed and turbulent flow with entraining air. Since the above problems and the sequence frame time image is too long, for this case, the Particle

Tracking Velocimetry (PTV) technique cannot match between the two sequence frames. Since the images were not clear enough as explained, the Particle Streak Velocimetry (PSV) method was applied to obtain the maximum average of velocity. The streak images were measured at several frames on the imaging system whilst the digitising procedure took place. As the relationship between pixels and object distance and exposure time were known the velocity could be determined. Taking the reading of the length of the straight lines, the results can be plotted on a graph, as shown in figure 4, based on streak line measurement technique.

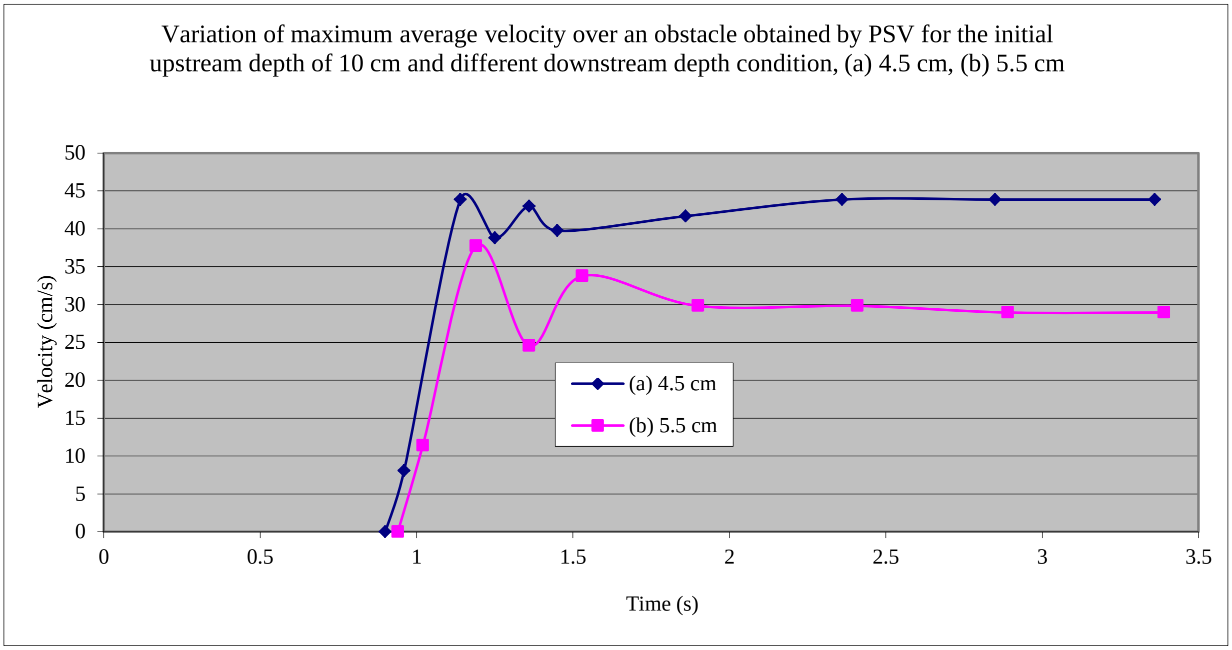


Fig 4: Variation of the streamwise velocity against time obtained by PSV for different initial water depth flow condition.

This figure shows that the velocity increased quickly at the beginning and then decreased with some variation, to a more or less stable value. This figure also emphasizes the bore velocity wave in the front of the flow propagation in the downstream section. The results show that the initial slope of the velocity variation with time decreases as the downstream initial water depth increases. For all depth ratios, the velocity fields eventually became quite stable after the bore develops downstream. In general, these comparisons are considered to be satisfactory for the downstream subcritical flow region.

5. Conclusions

An image analysis system has been applied to unsteady flows (such as dam-break flow) for investigation of the instantaneous whole flow field visualisation and measurement of the velocities and the free surface profiles (elevations). The whole flow field velocity data may be used to assess the ability of a computer model to simulate flow structure. The system has limitations for the seeding particles which correspond to the high water speed and turbulent flow with entraining air.

Experimental flow visualisation of unsteady flows (such as dam-break flow) has shown interesting movements of the flow particles in the stationary area before the arrival of the wave. These features are confirmed by PTV results and have not been reported previously. As the experiments show, the front wave interaction with the downstream wet-bed flow conditions produce a complex phenomenon, but the velocity profiles has become established after a front wave. A general comparison between the results obtained from PTV (figure 3) and the maximum average of the velocity obtained by PSV (figure 4), shows reasonable agreement for the cases with the depth ratios of 0.45 and 0.55.

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