INSIGHTS INTO FLOW FIELD INTERACTIONS OF SURCHARGED MANHOLES

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Abstract. Flow patterns within surcharged manholes determine energy losses, and control the transport and dispersion of soluble material. The latter aspect is increasingly important as legislation relating to river quality and the impact of urban drainage systems becomes more stringent. Guymer *et al.* (2005) identified a transition within surcharged manholes between a low surcharge pre-threshold 'fully-mixed' flow regime and a high surcharge post-threshold flow regime characterised by an upper dead zone. Lau *et al.* (2007) presented computational fluid dynamics (CFD) data for a comparable manhole. Laboratory measurements of the flow field have been made using particle image velocimetry (PIV) in five planes (two horizontal and three vertical) for the pre-threshold surcharge conditions in a 218 mm ID laboratory manhole. CFD data is presented alongside experimental PIV data to provide a complementary description and to facilitate a greater insight into the flow field structure. A simple travel time technique is applied to different regions of the inlet pipe to illustrate the effect of pipe cross-sectional position in creating longitudinal dispersion effects across the structure.

1. Introduction

The efficient design and management of urban drainage systems with respect to water quality processes requires knowledge of both the solute retention time and, for temporally varying concentrations, the effects of mixing should be incorporated. Within uniform conduits, these may be estimated using the discharge and cross-sectional shape. However, within urban drainage structures, such as manholes, where there are sudden changes in cross-sectional shape, estimation of solute travel time and the associated mixing across the structure is less straightforward. This is especially so under high flow conditions when the system becomes surcharged.

Recent laboratory and field studies quantifying retention times within urban drainage systems have employed tracing techniques to measure and analyse changes in temporal concentration distributions across the structures (Boxall *et al.*, 2003 and Guymer *et al.,* 2005). To elucidate the mechanisms responsible for differences in retention times requires knowledge of the full 3D flow field within each structure. Observations of the movement of a solute tracer within a model manhole help to provide a qualitative description of the flow field. However, much of the previously reported work has measured the integrated effect of the structure on a temporal concentration distribution between locations up- and down-stream of the structure. The analysis has adopted a "black box" approach, fitting different transfer functions to the recorded distributions.

Guymer *et al.* (2005) suggested that *"at surcharge elevations below the threshold value solutes experience a large degree of mixing within the stored volume, whilst at surcharge elevations above the threshold value a large proportion of the tracer is advected through the manhole, experiencing little mixing."* Data from the current PIV study confirms that under high surcharge conditions the flow field is symmetrical and comprises one large vertically rotating flow cell. As a result, this paper will concentrate on the more interesting and complex flows in low surcharge, pre-threshold conditions.

Lau *et al.* (2007) evaluated the feasibility of utilising a CFD-based approach to modelling the flow field and solute transport characteristics of a surcharged manhole structure. Discrete phase modelling was adopted and results were compared with published laboratory data characterising the dispersion effects of surcharged manholes over a range of surcharge depths.

The CFD data presented in Lau *et al.* (2007) clearly showed the asymmetric horizontal recirculation zones that developed under low surcharge conditions. However, without experimental validation data, there is inevitably some uncertainty about the accuracy of simulation results. Preliminary indications showed that the CFD results adequately replicated the measured downstream temporal concentration profiles, and that a threshold surcharge depth, corresponding to a change in hydraulic regime within the manhole, could also be identified. However, direct measurements of velocities have not previously been reported. The aim of the work reported here was to characterise the flow behaviour of a surcharged manhole using Particle Image Velocimetry (PIV) and couple this new data with an improved CFD application to gain new insights into the full flow field.

2. PIV study

The laboratory model comprised a transparent perspex 218 mm diameter circular manhole structure with no benching. The centre-line of the 24 mm diameter inlet and outlet pipes passed through the vertical axis of the manhole, and the pipe inverts were level with the base of the manhole. In total five planes through the flow field were studied for a surcharge of 28.1 mm. Lau *et al.* (2006) provide further details of the laboratory configuration.

A high speed camera operating at 500 frames per second with a spatial resolution of 1024 x 1024 pixels was used in conjunction with a scanning laser light sheet to illuminate the water. The flow was seeded with Polyamide (50µm diameter), density matched to water and from this the time averaged two dimensional velocity vectors for each measurement plane were obtained. Two horizontal (pipe centre-line and at mid-surcharge height) and three vertical planes (pipe centre-line and at the left and right hand quarter points of the circle parallel to the inlet and outlet pipes axes) were considered, to describe the three-dimensional flow field within the circular manhole.

3. Insights into the flow field through integration of CFD and PIV

A CFD simulation of the 218 mm manhole was produced using the Fluent (6.2) software. The model included 0.26 m of upstream and downstream pipes, and the inlet velocities were defined according to a full-developed pipe flow profile based on a discharge of 0.351 l/s (the same discharge used in the PIV study). The model comprised a structured mesh of 300,000 cells and used a symmetry boundary condition for the free surface. The flow field within the surcharged manhole was solved using the Reynolds Stress Model associated with second order spatial discretisation schemes.

Fig. 1 compares CFD predictions with PIV results from three of the five planes. Fig. 1a, a plan view at pipe centre-line elevation, shows the inflow from the right with a strong central jet, deviating towards the right as it passes across the manhole. There is good general agreement between the CFD and PIV data showing a strong clockwise circulation in the right-hand section of the manhole and a weaker circulation in the same direction in the left-hand portion. It is important to note that the CFD predictions are temporal mean flow fields whilst the PIV data are mean flows over a 6 s period. This may explain why the jet appears to deviate more in the PIV compared with the CFD. In repeat PIV studies, the degree of deviation of the jet was observed to oscillate, but always towards the same side of the centre-line.

Fig. 1b shows the vertical plane through the pipe centre-line and, again, reasonable agreement between the two approaches. The PIV perhaps shows the in-plane inlet jet velocities decaying quicker compared with the CFD predictions. Fig 1c shows less agreement between the two techniques, in both magnitude and pattern. Low velocity secondary circulations present challenges for both techniques and further interpretation of the results is required.

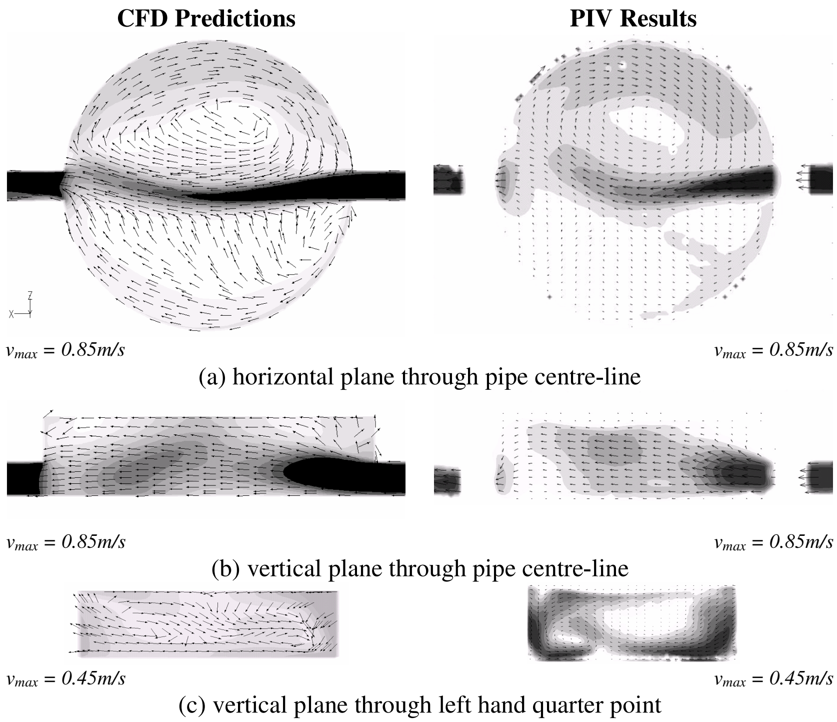

Figure 1 CFD and PIV flow fields for three planes under low surcharge, pre-threshold conditions.

(Grey-scale contours of in plane velocity magnitude in ten equal increments, zero to v_{max} m/s)

This brief summary of the results confirms the reasonable general agreement between the CFD and PIV data, providing some confidence in a qualitative interpretation of the CFD results. One of the benefits of a CFD model is that it may be 'sliced' through any plane of interest, enabling detailed examination of the flow field. It may be used to investigate flow fields within structures for which access or safety issues may make instrumentation impossible. For example, in the present case, it would be virtually impossible to measure the flow pattern on a plane perpendicular to the pipe axis using PIV equipment, (CFD prediction shown in Fig. 2), though these planes may be critical to understanding the system's flow field and solute transport characteristics.

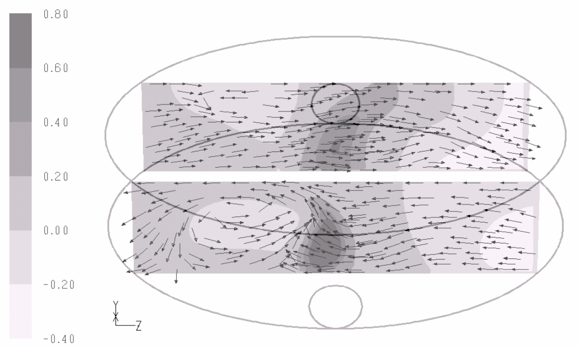

Figure 2 CFD velocity vectors in vertical planes (yz) perpendicular to pipe axis.
(looking downstream, contours show x velocity, vectors show velocity in yz plane)

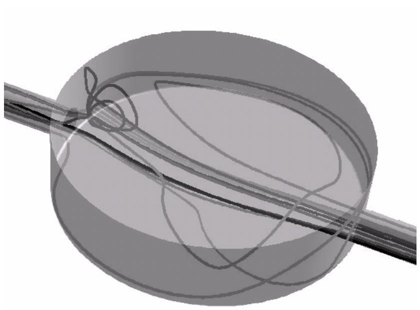

Figure 3 Path-lines for low surcharge, pre-threshold condition

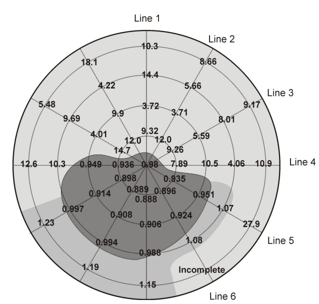

Figure 4 Residence time for path lines relative to injection position

Preliminary inspection of mean flow path-lines, Fig. 3, suggests preferential paths being followed depending upon the position of a parcel of water as it enters the manhole. Even in the low-surcharge case, there are complex vertical recirculations, particularly at the inlet and outlet. At the outlet parcels of water positioned at the top edge of the jet appear to be entrained briefly into a small recirculation zone above the outlet. Flow to the right of the jet is more likely to be entrained in the large right-hand recirculation. At the inlet the return flow from the right-hand recirculation is forced to pass over the incoming jet, with the lower particles becoming re-entrained within the jet. Having passed over the inlet jet, this leads to strong down currents in the left half of the chamber, with a low level flow of material moving back to be re-entrained within the jet at the outlet. The strong cross-currents above the inlet jet and the down-current in the left half of the manhole are both evident in the velocity vectors shown in Fig. 2.

4. Implications on Residence Time Distribution

To examine this more closely, the particle tracking utility within the CFD package was used to follow individual parcels of flow from known input points. Input points were set up a short distance upstream from the manhole and six transect lines were used, each comprising nine points. The central point on each transect corresponds to the central axis of the pipe. The travel times associated with fluid injected at each of these positions are shown in Fig 4. Those injected in the central to bottom-left zone are most likely to experience a rapid transit – and these are assumed to be retained within the core of the jet. Towards the top and sides of the pipe some long retention times are experienced (around 30 times greater than the jet-entrained material) – these are assumed to be associated with re-circulating particles.

5. Conclusions

- PIV measurements, coupled with a CFD model, offer complementary approaches to an enhanced understanding of flow patterns (and solute transport) within urban drainage structures.
- PIV measurements on five planes (three vertical and two horizontal) provide confidence in the validity of the CFD predictions for a laboratory manhole under low surcharge conditions.
- CFD data provide insights into the complex three-dimensional flow patterns, which assist interpretation of the observed solute transport.

References

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