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EVALUATION AND OPTIMISATION OF A NOVEL SELF-CLEANSING COMBINED SEWER OVERFLOW SCREENING SYSTEM USING COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

The paper describes the results of a programme of numerical studies that were undertaken in order to assess and optimise the fluid-dynamic performance of a novel non-powered self-cleansing combined sewer overflow (CSO) screening system, the Hydro-Jet Screen™. The Hydro-Jet Screen™, like many other CSO systems, was developed such that it could be readily installed into either a purpose built or existing rectangular chamber. By means of simulating the system using computational fluid dynamics (CFD) software, a design configuration was identified in which the occurrence of 'stagnant' or 'recirculating' regions was minimised. The objective of the study was to reduce the likelihood of occurrence of debris accumulation and retention within the chamber, both during and after a storm spill event. Observations of the operation of both model and prototype scale units have indicated good qualitative correspondence with the predictions in terms of overall flow patterns, and have confirmed the superiority of the recommended design in terms of its self-flushing capabilities.

KEYWORDS

Combined sewer overflow; screening; computational fluid dynamics

INTRODUCTION

During the hydraulic design of civil, and indeed, many fluid mechanical processes or systems, the potential effect on performance of secondary flow structures has often been overlooked, in some cases with significant consequences (Simm, 1983). However, with modern day computing capabilities, and the evolution of computational fluid dynamics (CFD) code from its roots in academia into the hands of the industrial engineer, such information is becoming increasingly, and more practically accessible.

The paper describes a programme of work that was undertaken in which the CFD software Fluent (Version 4.31) was effectively applied for the evaluation and optimisation of the fluid-dynamic operation of the Hydro-Jet Screen™, a novel non-powered self-cleansing CSO screening system (Smith, 1998; Andoh *et al.*, 1999). The work has relevance to the application of such techniques to chamber design, and indeed, to that of other hydraulic structures.

The Hydro-Jet Screen™ was originally developed as an effective low cost, low maintenance, non-powered screening system for CSO application, and evolved from the Hydro Swirl-Cleanse™ (Smith and Andoh, 1997), a similar (although functionally superior) system employing a combination of both hydro-dynamic (rotary) separation, as well as physical screening to perform its function. Driven by the increasingly stringent requirements of the European Urban Wastewater Treatment Directive relating to the quality of discharged effluents to watercourses during storm events (EC, 1991), the system was developed specifically to meet the 6 mm in two directions aesthetic pollutant requirement outlined in AMP2 (former National Rivers Authority and Water Services Association 'Asset Management Plan'; NRA, 1993). In the UK, there is a requirement for the Water Service Companies to rectify two thirds of the identified 4000 unsatisfactory CSO's by the year 2005, dictating much interest in the system.

The Hydro-Jet Screen™ system has been subject to an extensive testing and evaluation programme, both by HRD Ltd, and also independently at the UK National CSO Test Facility at Hoscar Wastewater Treatment Works, Wigan (UKWIR Ltd, 1997). Its performance, assessed in terms of its efficiency when tested on raw sewage, has been shown to be superior to that of other CSO systems (Saul, 1998).

OPERATION OF THE HYDRO-JET SCREEN™

A schematic representation illustrating both the form and function of a single-sided Hydro-Jet Screen™ during a spill event is shown in Figure 1. The rectangular channel on the left hand side (sectional view) represents the dry weather channel, incorporating both an inlet and pass-on flow pipe. This device would only overflow during a storm event (of pre-defined intensity), in which case both the dry-weather channel discharge, and the screenings channel discharge terminate in a common location such that screenings can be re-entrained into the primary stream (the continuation flow). The screened overflow, free from aesthetic pollutants, is discharged to the receiving watercourse. The mechanism by which the screen back-washes is essentially a cyclic process. The key element responsible for this is the novel, patented discharge siphon, shown on the right hand side in the illustration.

The siphon initially prevents the screened effluent from discharging to the watercourse. This results in a rise

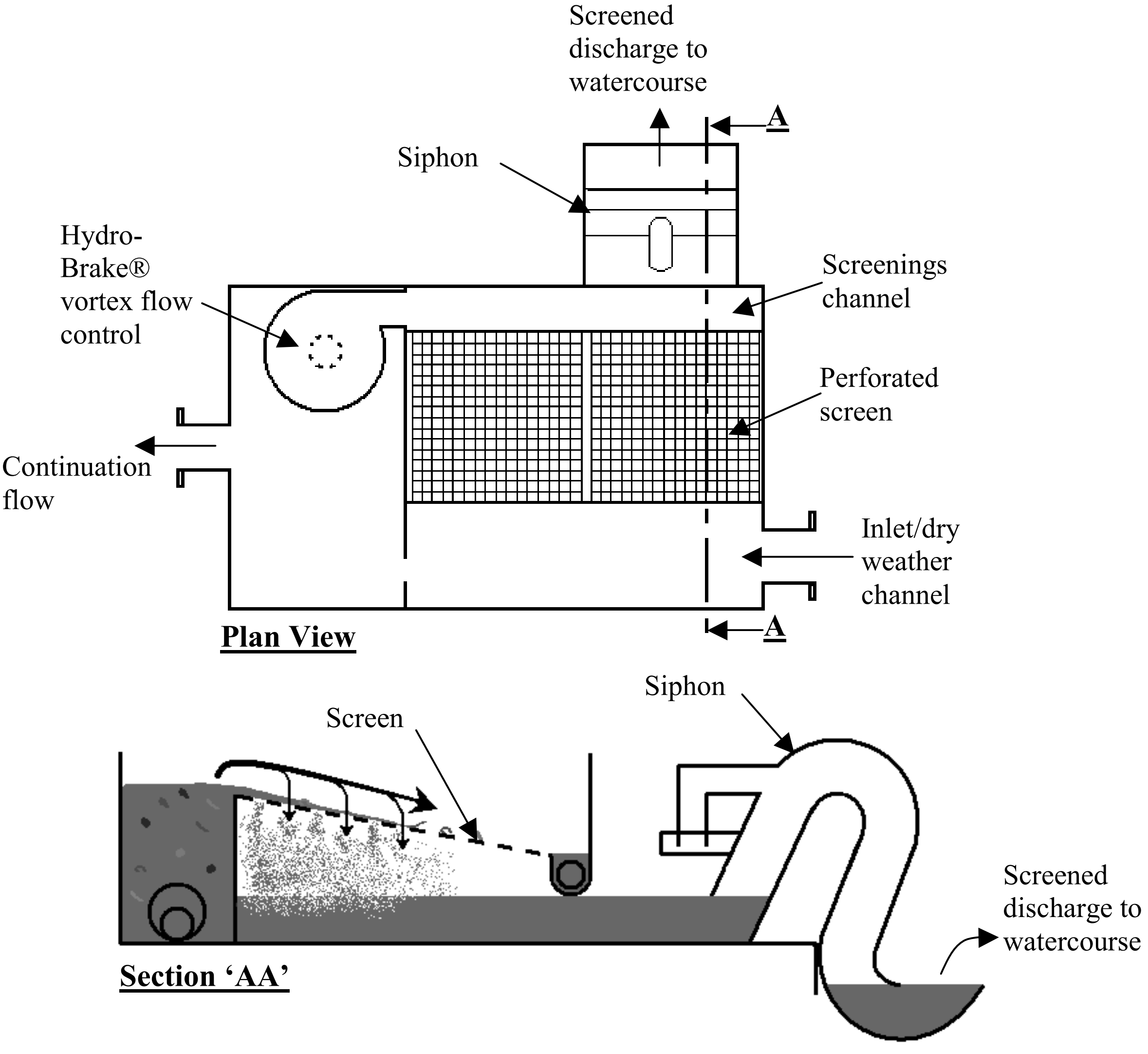

Figure 1 Plan and sectional views through the Hydro-Jet Screen™

in the water level beneath the mesh panel. The rising water level has the effect of displacing the pocket of air beneath the mesh panel, and this assists in lifting any debris trapped on the mesh. The scouring action due to the cross-flowing water directs the debris towards a collection trough, which ultimately discharges, via a vortex flow control, through to the continuation flow and on to treatment. When the water level has risen to the crest of the siphon, the siphon primes, discharging the screened effluent to the watercourse. This lowers the water level and the air brake pipe causes the siphon to shut-off before the cycle repeats.

SIMULATION OF THE HYDRO-JET SCREEN™

Objectives

The principal aim of the research programme was to analyse the nature of the flow patterns within the Hydro-Jet Screen™ such that its overall hydraulic performance could be reviewed and optimised. Rectangular chambers are renowned for their tendency to induce the formation of eddy and recirculating structures, and this can result in debris accumulation if not appropriately addressed. Rotary systems, by the nature of their operation, tend not to be subject to the same problems.

In the case of a CSO screening system, it is desirable that 'screened' debris is effectively removed from the immediate vicinity following its capture, and propelled in the direction of the continuation flow. As well as avoiding the scenario of debris retention within a CSO structure following a storm event, this is also conducive to maintaining a functional, non-blinded screen during the event.

The Hydro-Jet Screen™ model

From a modelling point of view, the Hydro-Jet Screen™ is actually a very complicated system. It incorporates time-varying water levels and associated discharge characteristics, free surface boundaries, two phase flows, porous boundaries, as well as complex turbulent flow patterns. It would be impractical to model the unit in its full complexity, and thus various simplifiying assumptions were made during the current work;

- The system was simulated for a case in which the water level above the screen corresponded with that in the inlet channel; an approximation of the scenario at the moment of syphon initiation.
- Given the above approximation, two of the three system discharges were defined with constant velocity boundaries. The third discharge was defined as a 'fixed pressure' boundary.
- The surface water level was approximated using a zero-friction wall. Although this does not allow an uneven surface profile, it considerably reduces the problem complexity. This approach is well known to users of CFD.
- The system was analysed for the fluid flows only; no two phase studies were performed.

A 3-dimensional model was set up of the system. This was based on the dimensions of a trials unit which had a screen length of 1.6 m and a peak design flow capacity of 100 l/s. During the simulation programme however, the boundary conditions were defined to represent an inlet flowrate of 65 l/s (mean velocity of 1.32 m/s in a Ø250 mm pipe), an inlet channel discharge flowrate of 10 l/s, a screenings channel discharge flowrate of 9 l/s, and a screened discharge flowrate of 46 l/s.

The screen was simulated using a porous wall, defined with a thickness of 7 mm, and an effective open area of 18 percent. This was to represent a 5 mm thick steel screen with Ø6 mm perforations that had been coated with a 1 mm thick polymer coating.

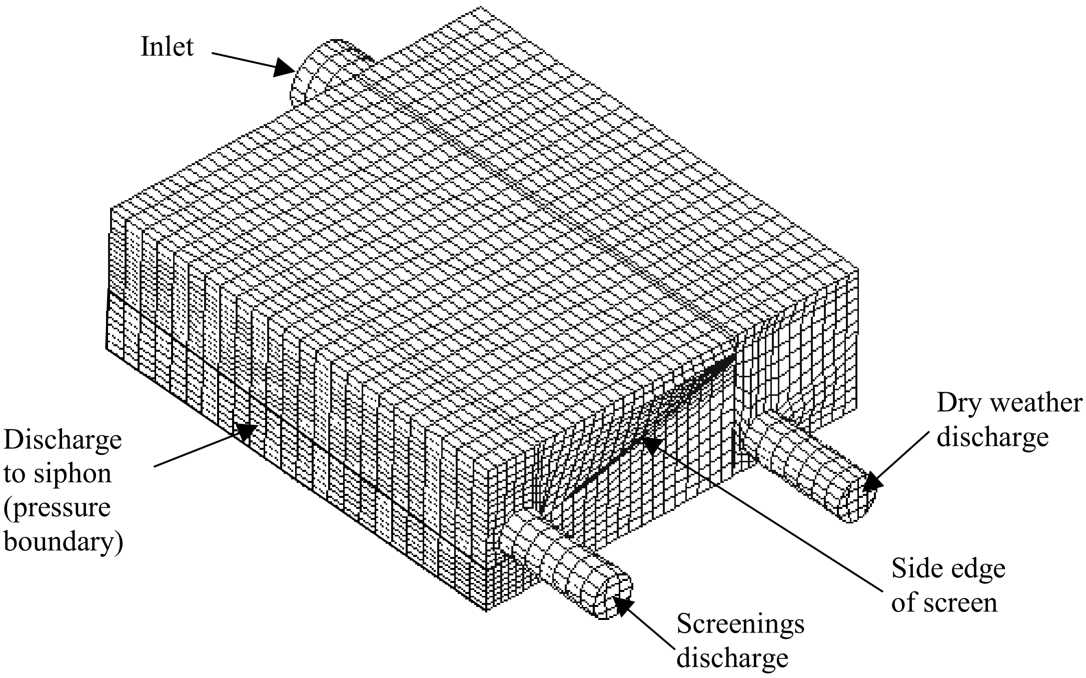

Figure 2 Typical computational grid

The porous boundary model in Fluent operates effectively by applying a momentum sink to the momentum equations in the defined region. In result, this creates a pressure drop that is proportional to the fluid velocity. In the Hydro-Jet Screen™ simulation, this was defined such that the flow would encounter least resistance when approaching the boundary in a perpendicular direction. Given this, the boundary properties are regarded as being uniform, and therefore not able to represent the concept of 'perforations'.

Computational grids consisting of typically around 50,000 cells were used for the modelling. The external appearance of one of the grids used is shown in Figure 2. Due to the rectangular form of the Hydro-Jet Screen™, this was readily constructed from hexahedral (six-sided) elements. Throughout the investigation, the RSM (Reynolds' stress model; Fluent, 1995) approach was applied due to its well documented ability to provide the best results for turbulent flows compared to the less sophisticated 'eddy' viscosity models.

Base configuration predictions and experimental validation

As a basis for comparison, the initial simulation considered a unit in which no additional weir/baffle components were incorporated. This was consistent with the original configuration of the 100 l/s trials unit. A number of dominant flow features were identified from the studies.

Figure 3 shows the predicted flow characteristics (in terms of length-scaled velocity vectors) along the central vertical plane of the inlet channel. The model suggests the formation of a recirculating flow structure in this plane. From the inlet, the main body of the fluid is shown to pass horizontally towards the end wall at

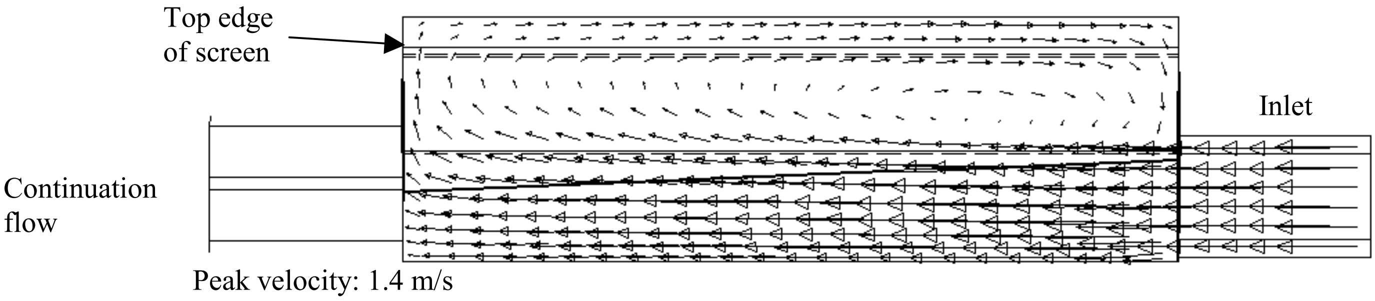

Figure 3 Base model prediction: flows in the central vertical plane of the inlet channel

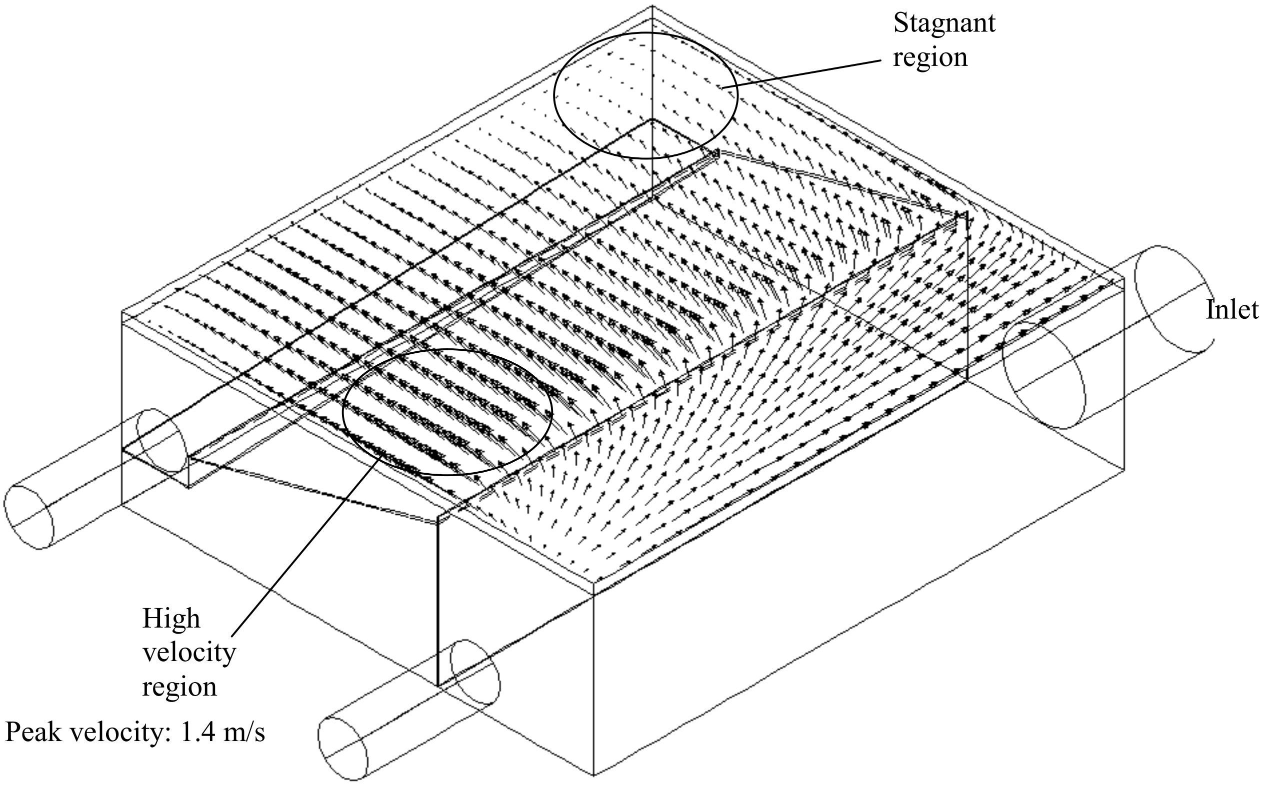

Figure 4 Base model prediction: flows in the upper horizontal plane prior to optimisation

which point it is deflected upwards, and then back along the flow surface. Regarding the predictions in the upper horizontal plane, shown in Figure 4, this has a significant impact on the overall flow patterns within the model. A region of peak velocity is predicted to occur across the downstream end of the screen, yielding a somewhat uneven flow distribution. This is accompanied with a stagnant zone adjacent to the upstream wall above the screenings channel, clearly identified in the Figure.

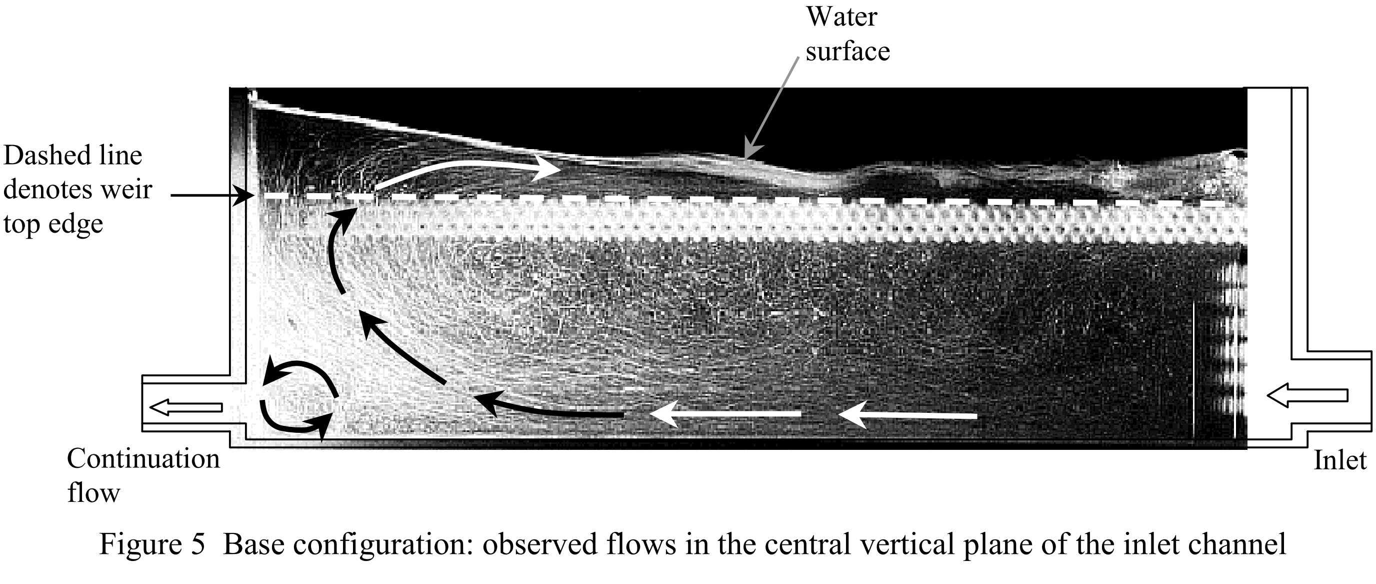

Figure 5 Base configuration: observed flows in the central vertical plane of the inlet channel

Similar phenomena to those described above have been observed on both the model and prototype scale units. Although best observed by the naked eye, a series of photographic studies were carried out in order to provide data for presentation purposes. These focussed on the operation of a small scale perspex unit. This had a screen length of 0.4 m, and an approximate hydraulic capacity of 3 l/s.

Using a slide projector to provide illumination, and seeding the flow with aluminium powder, Figure 5 represents the view along a vertically illuminated plane in the inlet channel. As was indicated by the predictions, the incoming flow reverses in direction following impact with the far wall. This results in a 'bulge' in the upper flow surface. This is also observed on a larger scale, although it is less pronouned. The predictions, by nature of the assumptions made are not able to show this effect, although the result, dictated by momentum conservation considerations, is similar. Figure 6 shows a plan view of the perspex unit during operation. In this case, plastic beads had been added to the system. The main features of the design are identified, as are the key flow features. This illustrates clearly how, as the flow in the inlet channel hits the downstream wall, it is deflected backwards up the channel and also diagonally across the screen. The result of this is that a stagnant region forms in the upstream corner above the screenings channel, and, as shown in the Figure, this had a tendency to collect and retain particulate matter. For the purposes of the study, these observations provided a degree of confidence in subsequent predictions.

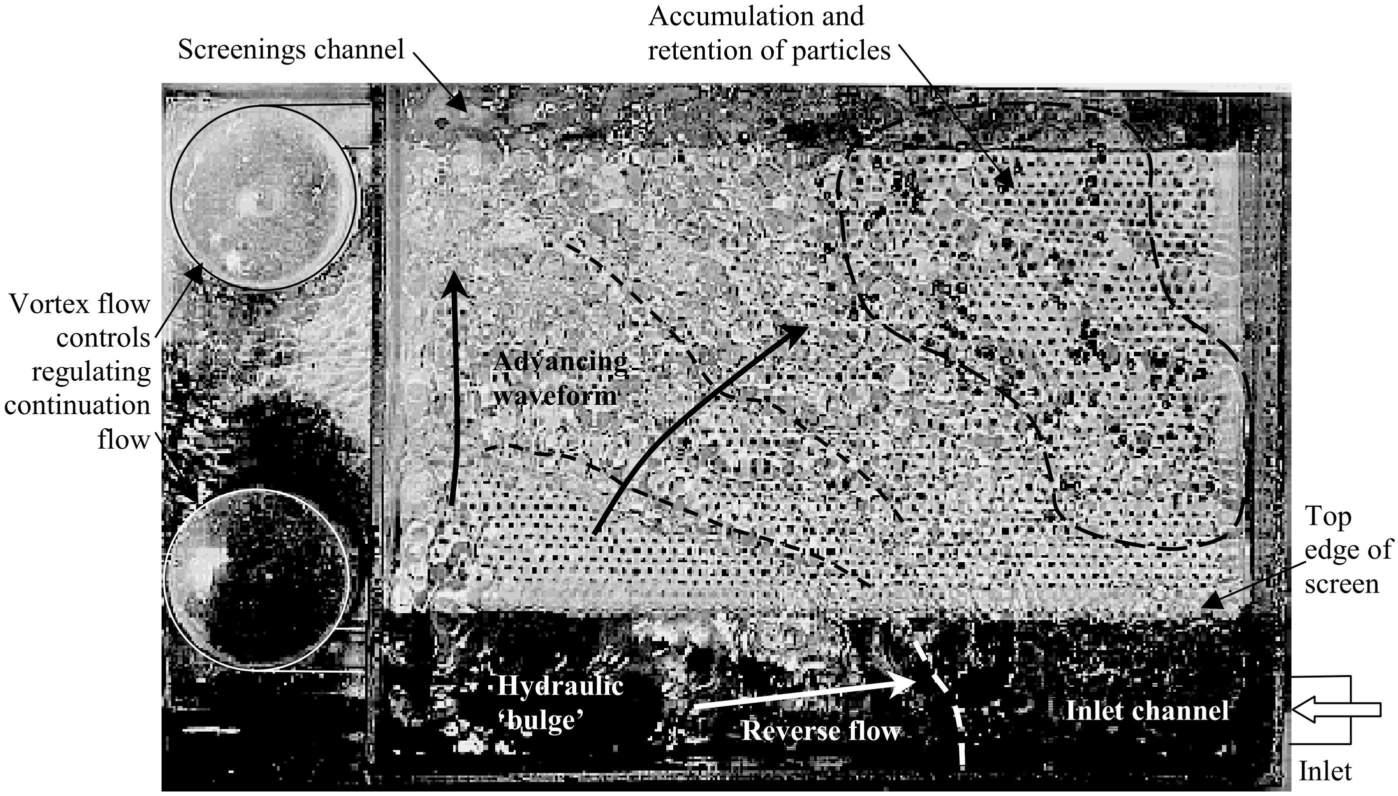

Figure 6 Base configuration: observed flows in the upper horizontal plane prior to optimisation

Alternative weir/baffle arrangements

In order to avoid the potential scenario of material accumulation and retention within the Hydro-Jet Screen™ system, a number of alternative weir/baffle arrangements were identified for further simulation. On the whole, it was found that seemingly minor adjustments had significant impact on the overall system flow characteristics.

During the developmental stages of the Hydro-Jet Screen™, one configuration tested incorporated an inlet pipe that entered the device from a direction perpendicular to the plane of the weir. It was found that the incorporation of a transverse baffle, protruding horizontally from the weir wall, and extending along its length, helped to even out the flows passing over the screen. This feature was consequently considered as a candidate for consideration in the parallel inlet unit. The flow predictions for the upper horizontal plane of this configuration are shown in Figure 7. Given that this configuration would be most appropriate for a two-sided scheme, a symmetry plane was placed along the inlet channel section of the model. The predictions indicate that, contrary to the desired effect, the flow spread across the screen is particularly uneven. This remained the case regardless of inlet flowrate and the scheme was subsequently rejected.

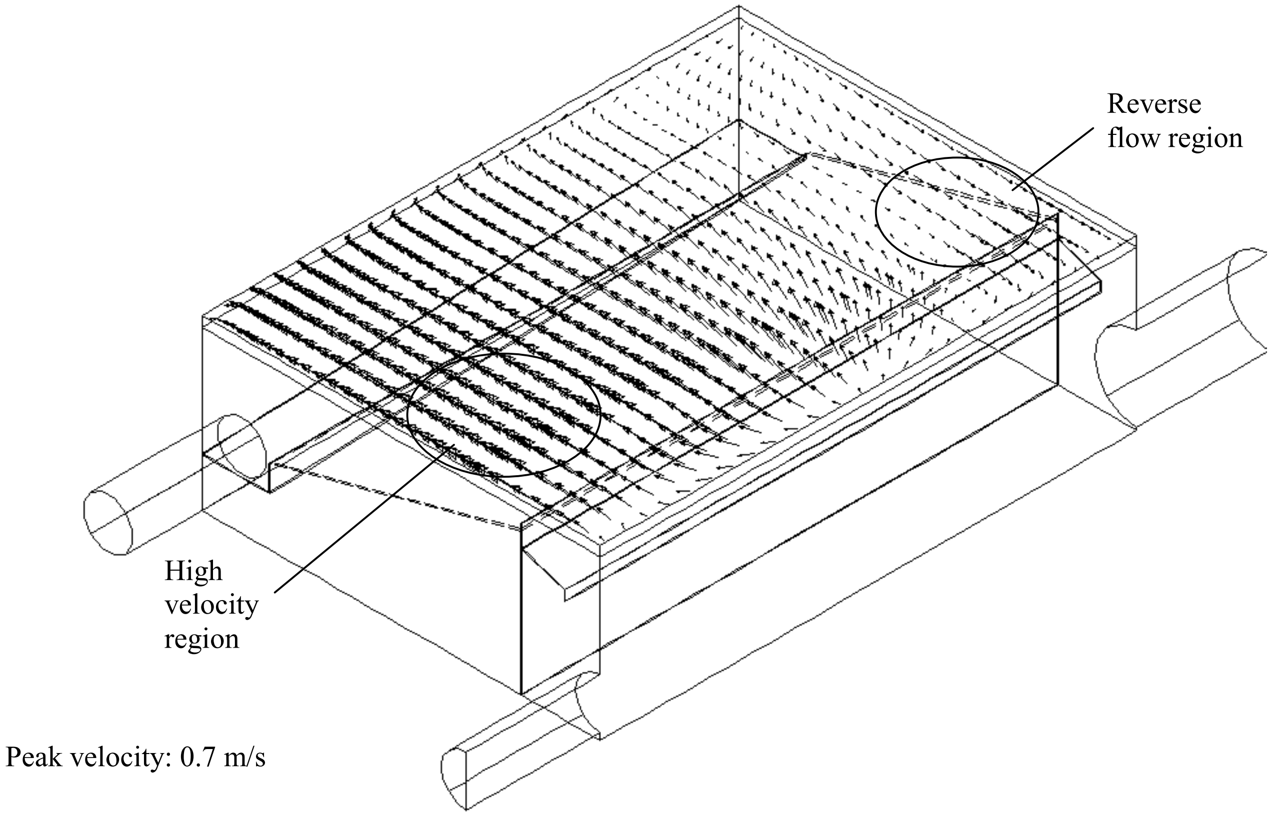

Figure 7 Predicted effect of using a protruding baffle arrangement: upper horizontal plane

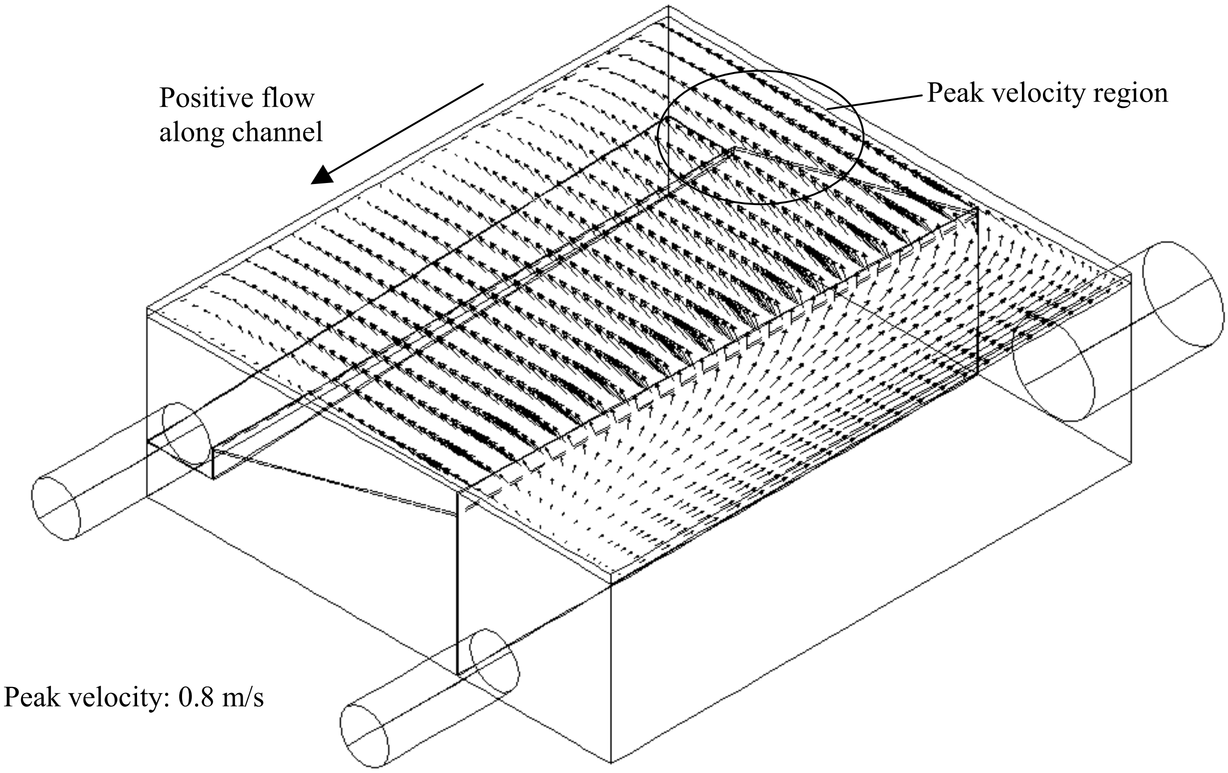

Figure 8 Predicted effect of using an inclined weir: upper horizontal plane

A straightforward and easily implemented modification to the unit was considered in which the angle of a weir plate, positioned along the top edge of the screen, was deviated from the horizontal. Figure 8 shows the predictions of the flow patterns in the upper horizontal plane, with the weir defined such that its height increases linearly along the length of the screen. The result, as shown, is that the flows over the screen

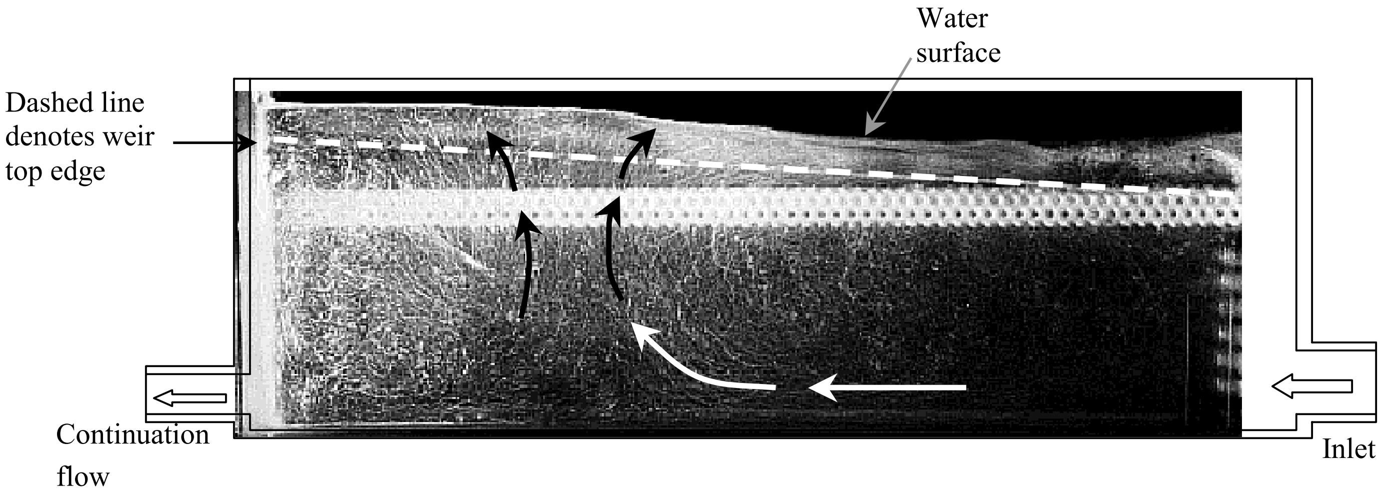

Figure 9 Inclined weir configuration: observed flows in the central vertical plane of the inlet channel

become far more evenly distributed. With a marginally higher flow velocity over the upstream end of the screen, the streamlines tend to follow a clockwise path, and this dictates a screenings channel flow that passes in the direction of the discharge. During the flow visualisation studies, this configuration was also considered. Figure 9 illustrates the flow patterns in the inlet channel vertical plane, revealing a relocation in the position of the flow circulation center compared to that in the base configuration. Of note, the level of the water surface is seen to remain relatively parallel along the length of the weir, dictating the resulting even flow distribution over the screen. When beads were added to the system, significant improvements were noticed in the ability of the Hydro-Jet Screen™ chamber to clear itself following a backwash cycle.

PRACTICAL IMPLICATIONS

Following the combined CFD and experimental programme, the option of fitting Jet-Screen units with an inclined weir plate along the top edge of the screen was adopted. During trials performed using the 100 l/s pilot scale unit, this was confirmed as being the most effective means of maintaining a continuously flushed system, despite its simplicity compared to the other options considered.

Subsequent to carrying out the work, and based on experimental observations, an algorithm has been developed to enable appropriate sizing of the weir offset for different scales of unit.

CONCLUSIONS

The work described in the paper has significance at a number of different levels.

On the product level, the programme of studies has successfully enabled the Hydro-Jet Screen™ CSO screening system to be optimised in terms of its ability to remain continuously flushed and free from debris accumulation and retention during its operation. This has implications to the wastewater treatment community.

On the fluids-engineering level, the work provides a further contribution towards validation of the use of CFD codes for the analysis of hydraulic systems, and provides a good example of where this approach has been used for direct engineering advantage.

In the field of hydraulic civil engineering, specifically relating to the design of sewer and associated CSO systems, the work brings attention to the potential effects of secondary flow structures, and demonstrates how modern techniques can be applied for their analysis and subsequent fine tuning. In particular, the sensitivity of such systems to seemingly minor design adjustment is identified.

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