Optimise inlet condition and design parameters of a new sewer overflow screening device using numerical model

M. A. Aziz, M. A. Imteaz, Nazmul Huda and J. Naser

ABSTRACT

After heavy rainfall, sewer overflow spills to receiving water bodies cause serious concern for the environment, aesthetics and public health. To overcome these problems this study investigated a new self-cleansing sewer overflow screening device. The device has a sewer overflow chamber, a rectangular tank and a slotted ogee weir to capture the gross pollutants. To design an efficient screening device a numerical computational fluid dynamic (CFD) model was used. A plausibility check of the CFD model was done using a one-dimensional analytical model. Results showed that an inlet parallel to the weir ensured better self-cleansing than an inlet perpendicular to the weir. Perforations should be at the bottom of the weir to get increased velocity and shear stress to create a favourable self-cleaning effect of the screening device. Increasing inlet length from 0.3 to 1.5 m reduced wave reflection up to 10%, which increased flow uniformity downstream and improved self-cleansing effect. The orientation of the ogee weir with the rectangular tank was found most uniform with a 1:3 (horizontal:vertical) slope. These results will help to maximise functional efficiency of the new sewer overflow screening device. Otherwise it would be too expensive to alter after installation and at times difficult to customise accordingly to existing urban drainage systems.

Key words | CFD modelling, ogee weir, screening device, sewer solids

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INTRODUCTION

Most urban sewer systems built in the 18th century used a simplified one-way material flow. During wet weather conditions, combined sewer overflows (CSOs) to receiving water bodies cause serious concerns regarding environmental, aesthetic and public health problems. To overcome such challenges some of the adopted mitigation options include temporary holding tanks at sewage treatment plants, real-time control of sewer systems, enlarged upstream sewers to provide transient storage, separation of storm and sewage flows and various screening devices in CSO chambers. In most cases screening is the only economically viable method (Michael *et al*. 2001). These issues trigger the need to research different types of screening devices and screening handling systems. A state-of-the-art review of these screeners can be found in the work of Saul (2003); a recent update on this literature can be found in the work of Madhani *et al*. (2011).

Reported literature suggests that screens need to be a self-cleansing mechanism; otherwise, placed in combined sewer environments, these are subject to blinding (Aziz *et al*. 2013a; Simon & Phillips 2008). Usually most 'conventional' screening systems utilise electro-mechanical components to facilitate such a process (Phillips & Simon 2010). However, given the harsh unmanned remote environment of the sewer overflow device locations, this is clearly not ideal (Aziz *et al*. 2013b). Blocking and seizure are common maintenance problems of moving parts, and electrical failure will dictate an onerous maintenance commitment in many cases (Aziz *et al*. 2013b). To overcome such problems a novel self-cleansing, less expensive, low maintenance with no moving parts sewer overflow screening device is proposed. The aim of this study is to investigate the optimum inlet and design parameters of the novel sewer overflow screening device using computational fluid dynamics (CFD) modelling.

With the advancement of computational power in recent years CFD has become a proven technology to investigate hydraulic behaviour of hydraulic structures and CSO design (Stovin & Saul 2000; Dewals *et al*. 2008; Matthieu *et al*. 2009). One key advantage of the CFD-based approach

doi: 10.2166/wst.2014.422

is that three-dimensional (3D) solid–liquid two-phase flow problems under a wide range of flow conditions can be evaluated rapidly, which is almost impossible experimentally (Thinglas & Kaushal 2008). This technique has been successfully used for accurate prediction of the flow pattern, storage tanks (Dufresne *et al.* 2009) and the solids separation of CSOs and storage structures (Harwood & Saul 1999; Aziz *et al.* 2013b).

The proposed sewer overflow screening device has overcome the common drawbacks in the available devices like inadequate screening capacity, external power requirement and high cost (Aziz *et al.* 2013b). Simon & Phillips (2008) developed a sewer overflow screening device with temporary holding tanks for transient storage and real-time control of sewer systems. Our study proposed a novel upgrade of the above device which would consist of a sewer overflow chamber, a rectangular tank and a slotted ogee weir to capture the gross pollutants and will require no external power source for any mechanical or electrical components and would be self-cleansing (Andoh & Saul 2003). Before constructing the proposed novel sewer overflow screening device for experiments, its design criteria were optimised using a 3D CFD model. Plausibility of the numerical model was tested using a one-dimensional (1D) analytical model based on well-established physical laws. The main purpose of this study was to optimise proposed gross pollutant trapping devices to get maximum sewer solid trapping efficiency, including the following sub-objectives:

- Compare inlet orientations either parallel or perpendicular to the ogee weir to determine their effects on self-cleansing.
- Understand hydrodynamic flow properties to get the maximum self-cleansing effect and ideal location for perforation in the device.
- Determine the optimum inlet length to reduce wave reflections and improve functionality of self-cleansing effect.
- Optimise ogee weir design orientation based on standard US Army Engineers Waterways Experimental Station design best practice guideline.

METHODOLOGY

Screening mechanism

The screening mechanism was designed to segregate some of the common sewer solids overflow reported in the literature (Aziz *et al.*2013a) including cigarette butts, cotton balls, bottle tops, bottle cans, condoms, tampons, wipe papers, toilet papers and dish wipes. Figure 1 shows the overflow sewerage device in the first phase. The screener used

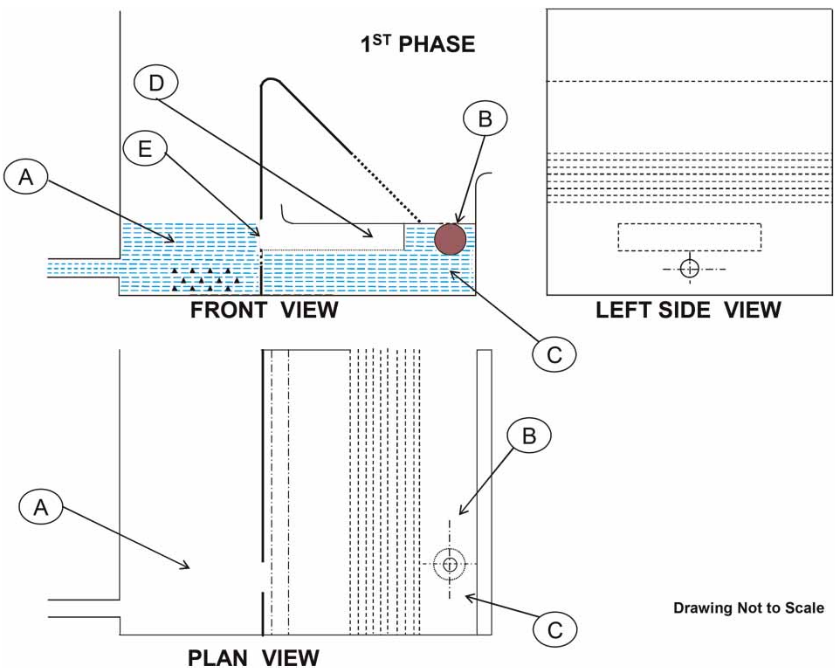

Figure 1 | Schematic diagram of the proposed sewer overflow screening device.

perforated plates (Faram & Andoh 2001; Andoh *et al*. 1999) with round holes at the bottom. As sewage builds up in the left chamber (A), water pressure will push the floatable ball upward in the right chamber (B), which is connected to the left chamber via a pipe (C).

As the floatable ball goes upward, it will block the hole on the upper surface. The plan view of the proposed device shows the left and right box chambers with the vertical dotted lines (right) representing the screening device. The thick horizontal dotted lines represent the pipe connecting the left and right chambers. The thick smaller circle is the hole at the bottom of the right chamber (B) and the dotted circle is the floatable ball. The sewage builds up in the left chamber (A) until it becomes full, at which time the sewage overflow will pass over a weir-type structure. Figure 2 shows the second phase of the scenario with the overflowing sewage.

Towards the bottom of the sloping weir, the screen will exclude the solids while allowing the water to pass through the screen, bypassing the right chamber (B) and then exiting to the creek or waterway through two bypass channels (D). It also shows the third phase of the scenario, when the flow has subsided and the sewage level in the left chamber (A) is receding. Once the sewage level drops down to a certain level, the buoyancy pressure on the ball will reduce and the ball will drop, allowing the trapped pollutants to exit

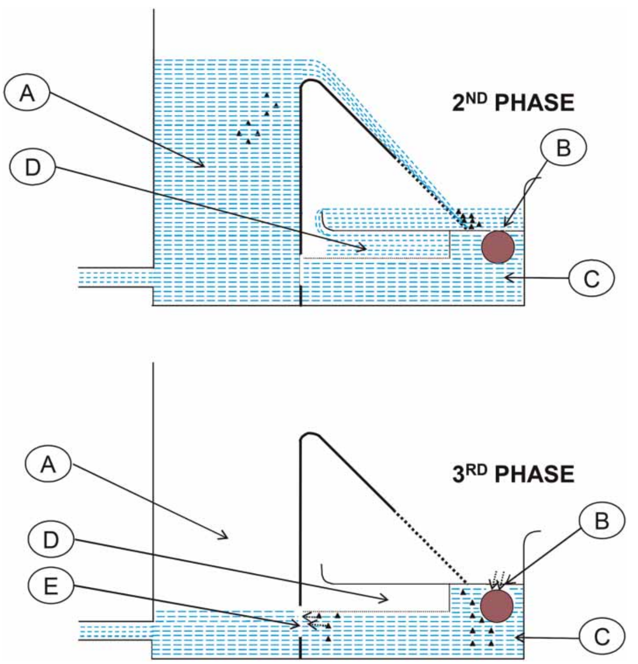

Figure 2 | Ogee weir (front view) is used to overflow the sewer water while pollutants are trapped in B.

into the right chamber (through the pipe 'C') and then be flushed back into the sewer system using a valve (E). The fluid pressure difference in the screening chamber A and the gravitational flow will take sewer solids back to the main sewer system. For maintenance of the device chamber, pipe C can be cleaned using vacuum suction. The application area of the investigated screen will be downstream of an existing sewer overflow location towards the receiving water.

Numerical CFD modelling

The hydrodynamic characteristics of the overflow sewer screening device were investigated using a CFD model by adopting the finite volume method in the Euler–Euler approach. The 3D multiphase flow numerical model was developed using a commercially available CFD package (AVL Fire 2008) to predict the flow over the ogee weir.

Model geometry and computational process

A 3D CFD model, similar to the schematic diagram shown in Figure 3, of the proposed sewer overflow screening device was developed by using a CFD tool, similar to the schematic diagram shown in Figure 3. The screening device has a rectangular tank (1 m × 0.2 m), an ogee weir and an inclined surface. The height of the ogee weir bottom is 0.75 m and the diameter of the inlet pipe is 0.2 m. A design flow rate of 40 L/s was considered for this analysis as boundary inflow. Outflow was assumed as a free flow and perpendicular to the outlet surface at the edge of the weir. Roughness height of the ogee weir surface assumed as 0.001 m and wall functions are based on the assumed logarithmic velocity distribution (refer to Figure 3).

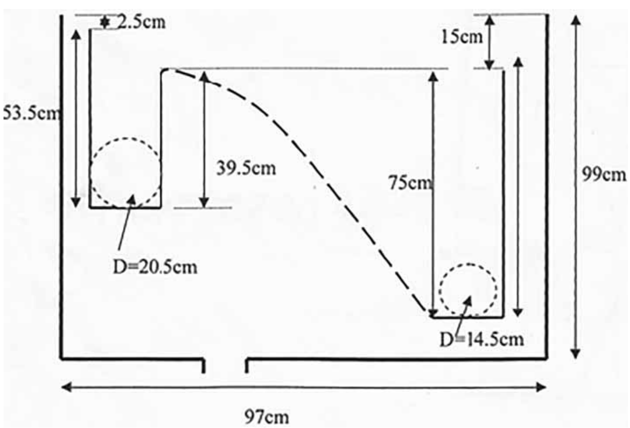

Figure 3 | Showing geometric details of the screener device.

Two different inlet positions, as shown in Figure 4, were chosen to analyse hydrodynamic characteristics for the proposed screening device. The model developed included the following features and assumptions:

- Unsteady state multiphase solution for momentum and continuity was considered.
- Standard k-ϵ turbulence model for the turbulence modelling was employed.
- A cell centred finite volume approach was used to discretise the governing equations and the resulting discretised equations were solved iteratively using a segregated approach.
- Pressure and velocity were coupled using the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm (Patankar and Spalding 1972).
- Least square fit approach was used for the calculation of the derivatives.
- For momentum and turbulence, the first order upwind differencing scheme was used whereas the central differencing scheme with second order accuracy was used for the continuity equation.
- Screening device walls were treated by standard wall functions with no slip condition. The CFD model did not consider the perforated holes on the sloping wall, which requires extreme memory and would slow down the model simulations.
- Air was considered to be the dispersed phase and water was considered to be the continuous phase.
- Grid independency tests were carried out and the results presented in this paper are grid independent.

The simulation was carried out considering unsteady state condition with time steps of $\Delta t = 0.05$ second. Total time period for each run was 180 seconds which was adequate to obtain time averaged steady state results and numerical stability. The total number of cells for inlet position 1 was 27,659 and for inlet position 2 was 38,619.

Plausibility check of the CFD model

As there was no experimental data available to calibrate the CFD model, the plausibility check of the CFD model was done using a simplified analytical solution. Analytical equations for shear stress, unit flow, average velocity and curve of ogee weir were calculated as reported by Aziz et al. (2013b).

Shear stress

$$\tau_{xy} = \rho g h \sin\theta \,(\text{as}\, y = 0). \tag{1}$$

Unit flow

$$q = \int_0^h u_x dy = \int_0^h \frac{\rho g}{2\mu} \sin\theta (2hy - y^2) dy = \frac{1}{3\mu} \rho g h^3 \sin\theta. \tag{2}$$

Average velocity

$$v = \frac{q}{h} = \frac{1}{3\mu} \rho g h^2 \sin\theta. \tag{3}$$

Curve surface of the ogee weir was used (US Army Corps 1970).

Curve ogee weir profile

$$X^{1.85} = 2.0 H_d^{0.85} Y. \tag{4}$$

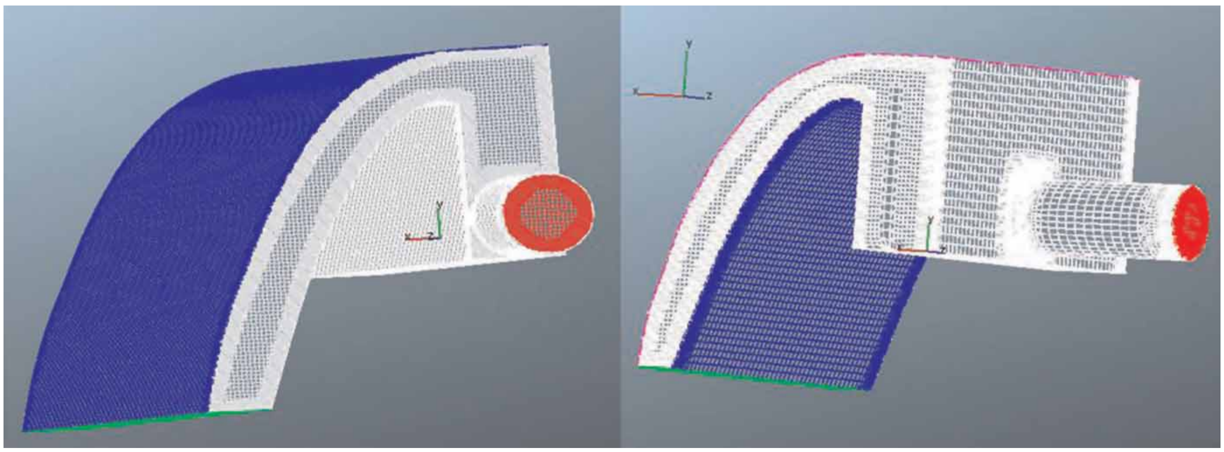

Figure 4 | Position 1 (left) is the inlet parallel and position 2 (right) is the inlet perpendicular to the weir direction.

where τ_{xy} is the shear stress, ρ is density, g is gravitational acceleration, h is uniform depth of water, q is unit flow, μ is dynamic viscosity of water, X (x) and Y (y) are directions, u_x is velocity along x-direction, θ is the inclined angle with horizontal surface, v is average velocity, and H_d is depth of water upstream of the spillway.

The (1D) analytical solution matches the trend of the 3D CFD water level and velocity reasonably well. In the absence of experimental data this provides a decent plausibility check for the numerical model, refer to Figure 5.

Explaining CFD results

The water level was determined by considering the flooding and drying concept reported by Stelling (1984), which suggests a value ≥50% of the volume fraction is considered as water level. Flow reflection is dominating over the cross-section profile of the sewer overflow device. For analysing the 3D numerical results for water level and velocities, three distinct sections across the width of the weir were selected. The selected left-, middle- and right-section data were extracted from the simulation results. The first set over the weir is 3 cm, and the second and third sets are 6 cm downstream of the ogee weir.

RESULT AND DISCUSSION

Inlet parallel to ogee weir provided better self-cleansing capacity than perpendicular inlet

The CFD simulated results showed that due to wave reflection under condition 1 (inlet parallel to the weir), water level at the right-side overrode the water levels at the middle and left sections, whereas, under condition 2 (inlet perpendicular to the weir), reflected wave contributed to elevated water levels towards both the left and right sides of the device. However, towards the bottom of the inclined surface, the wave became equally distributed turbulent flow (across the width). The reflected water level in the right side reduced as the wave travelled downstream of the ogee weir (condition 1). Owing to higher water level, higher velocity was found downstream near perforations, which was a favourable condition for self-cleansing. Condition 1 can provide a better screening effect on the right side considering high water level to generate higher velocity and shear stress, refer to Figure 5.

Location of circular holes at the bottom of ogee weir were more efficient to operate

Owing to varying water levels (higher at the right than the left side), near the top of the weir surface, the self-cleansing property will not be as effective near the top region at condition 1. If screens are provided near the top of the weir surface as condition 1, only the right-hand strip will have efficient self-cleansing whereas the left-side holes are likely to be blocked by larger pollutants in the sewer water. However as the wave becomes uniform (across the width) near the bottom of the weir surface, the self-cleansing capability can be achieved. Moreover as the water flows down, its velocity and shear stress increases. Velocity of the sewer flow increases up to three times near the perforated holes from around 1 m/s at the ogee weir to 3 m/s at the perforated holes for an inlet flow of 40 L/s. Shear stress also increased substantially from around 100–300 N/m^2 close

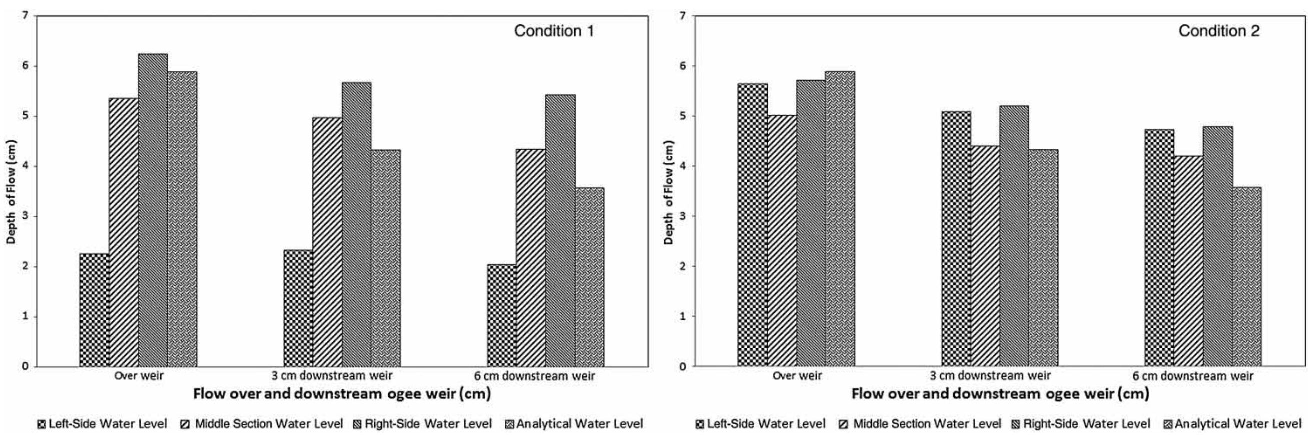

Figure 5 | Comparison of water level along the flow for conditions 1 and 2, showing water level from the top of the weir, 3 and 6 cm downstream.

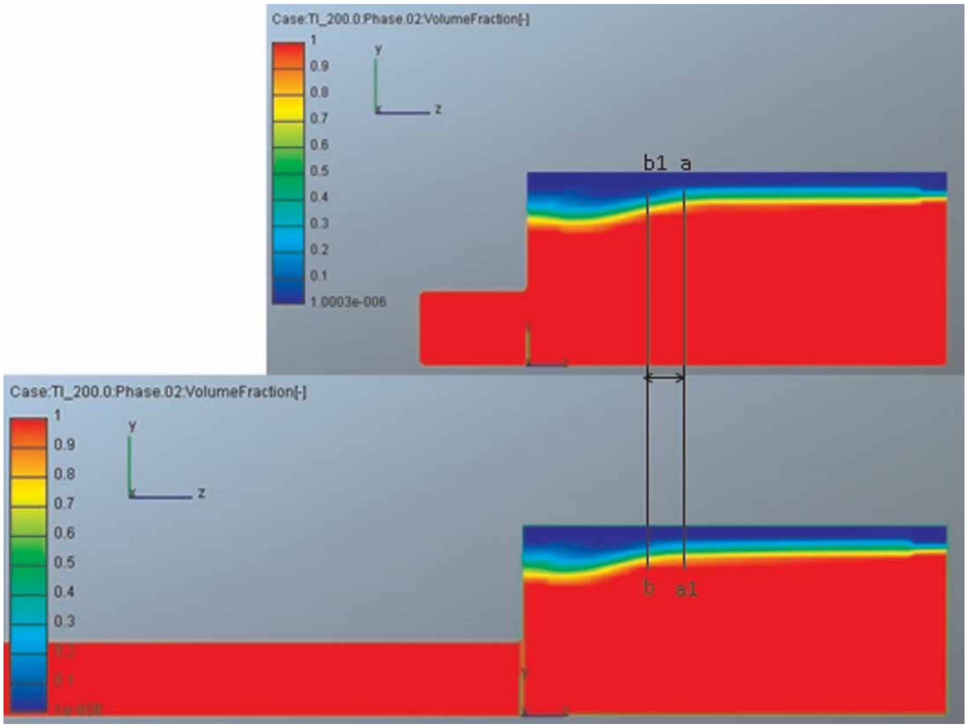

Figure 6 | Impact of device inlet position on the wave reflection with view at the back of the weir with a laterial inflow.

to perforated holes (Aziz *et al*. 2013b). Keeping this in mind, it is proposed to provide perforations (circular holes) near the bottom of the weir surface.

Increasing inlet length reduces wave reflection

A series of different inlet lengths were tested. It was found that wave reflection reduced as the inlet length increased; however, only results for minimum (0.3 m) and possible maximum lengths (1.5 m) for existing systems are reported here. At point 'a' (upper inlet) water level was equally distributed only at the 0.3 m inlet whereas at 'b' (lower inlet) water level was still equally distributed at the 1.5 m inlet. At point 'b1' (upper inlet) wave reflection was experienced whereas point 'b' (lower inlet) had no wave reflection (Figure 6). The wave reflection was reduced around 10% over the weir by increasing the inlet length from 0.3 to 1.5 m.

Standard weir orientation slope 1:3 (horizontal: vertical) at 'R' provides best screening performance

Since ogee weirs provide excellent hydraulic features, in-depth research has been carried out to determine the standard shape and size of the crest of the overflow spillway (Chow 1959). After extensive testing of physical modelling, the US Army Corps of Engineers suggested standard design parameters for the ogee weir (US Army Corps of Engineers 1970, 1990). The proposed experimental design conditions were tested using the CFD modelling technique to maximise uniform flow for better screening. Inlet conditions 'P' and 'Q' with 0H:3V and 2H:3V (H: horizontal, V: vertical) slope demonstrate a similar type of water level variation due to wave reflections from the wall (Figure 7). In fact orientation 'P' produced more wave reflection than the rest. Orientation 'S' with 3H:3V slope also demonstrated more water level variation than orientation 'R'. Inlet condition 'R' with 1H:3V slope for the rectangle with the ogee showed less wave reflection compared with the other slopes. Orientation 'R' provided the best self-cleansing effect downstream, having reasonable equally distributed water flow among all the best practice ogee inlet orientations suggested. With orientation 'R' flow became equally distributed across the weir ensuring more effective self-cleansing (Figure 7).

CONCLUSIONS

Some of the key findings from the CFD model are summarised below.

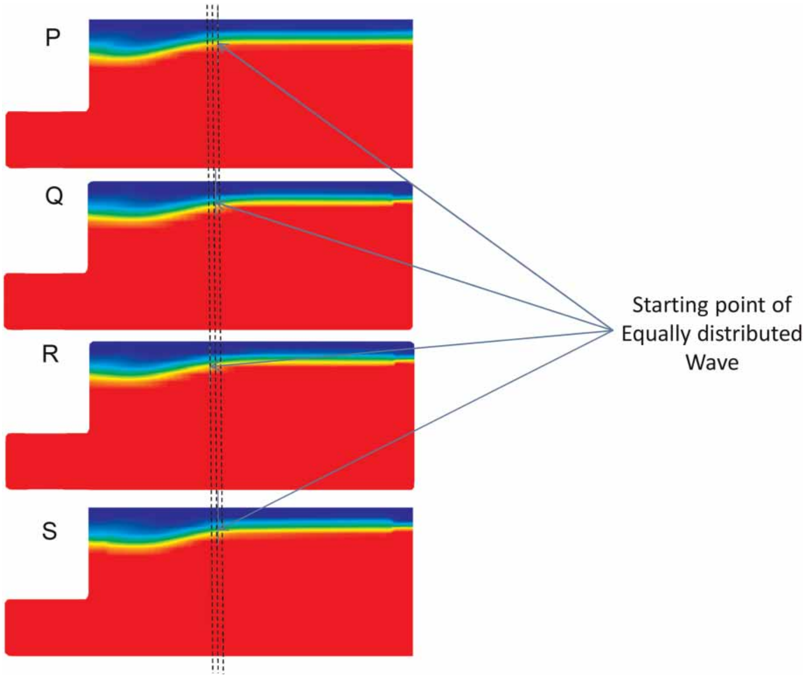

Figure 7 | CFD results with view at the back of the weir with a laterial inflow on four standard inlet orientations as suggested by US Army Corps of Engineers.

- Inlet parallel to the ogee weir (condition 1) was considered a better inlet option as water level over the ogee weir was higher due to wave reflection on the right side, which can provide higher velocity and shear stress. Therefore, condition 1 can produce a better self-cleansing mechanism due to higher velocity and shear stress near perforated holes.
- The flow became uniform near the bottom of the inclined surface with higher velocity and shear stress. This suggests that the perforations should be placed near the bottom of the inclined surface to achieve an effective self-cleansing capability for the device. Equally distributed flow towards the bottom of the inclined surface will help to remove any pollutants adhered to the perforations.
- As the sewer overflow device is small, the wave reflection effect was found to be dominant for this device. The 1.5 m long inlet of existing urban devices was suggested, which will reduce wave reflection up to 10% compared with the 0.3 m inlet.
- Four standard ogee weir orientations were analysed to reduce wave reflection and maximise uniform flow to get a better self-screening effect. Orientation 'R' with an inclined slope 1H:3V from the rectangular device to the ogee weir was found to be the most efficient based on the best practice guideline provided by the US Army Corps of Engineers.

The study provided valuable insights to designing an efficient and effective gross pollutant device. The experimental work was restricted by the physical limitations inherent in laboratory studies such as significant cost and time. CFD modelling provided an excellent opportunity to design the gross pollutant screener device. Results will maximise its functionality and effectiveness in trapping sewer solids with high efficiency both in terms of capture sewer solids and a self-cleansing mechanism.

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First received 26 February 2014; accepted in revised form 7 October 2014. Available online 27 October 2014