Storm Water Best Management Practice: Development of Debris Filtering Structure for Supercritical Flow

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Abstract

A simple, but effective, debris removal structure was developed for supercritical flow in urban storm water channels. This structure was designed as a best management practice in response to the National Pollution Discharge Elimination System. The Drop Flow Debris Filter (DFDF) structure consists of two slightly sloped plates, one placed above the other to form a debris basin. The DFDF structure translates supercritical flow of the storm water channel into subcritical flow in the debris basin. This system creates flow paths that only allow water in the bottom of the basin to pass through while debris is retained in the upper part of the basin. To investigate the hydraulic performance of the DFDF structure, a 1:3 scale undistorted physical model was constructed in a 0.91 m wide plexiglass flume. This model was also created in a three-dimensional computational fluid dynamics program. Three different density spheres were used in this model study to reproduce different buoyant storm water debris. Six different DFDF designs were developed and tested, and the modified curved plates design was recommended for the best performing DFDF structure.

Introduction

This paper describes a hydraulic modeling study for the development of a storm water debris removal structure for supercritical flow in urban storm water channels. A scaled physical model test and a three-dimensional numerical model simulation were conducted to investigate the hydraulic performance of the structure. This structure was designed to remove debris from the “first flush” in order to meet the storm water quality requirements of the National Pollution Discharge Elimination System (NPDES) to comply with Stormwater Best Management Practices (BMPs). According to NPDES regulation, cities must come up with a program to reduce the discharge of pollutants to the maximum extent practicable using management practices, control techniques, and system, design and engineering methods, and other such provisions. Widely used BMPs in cities and towns are street sweeping, storm drain system maintenance, public education, hazardous waste collection centers, recycling, and an increased number of trash receptacles. Armitage et. al. (2000) recommended that reducing the quantities of litter being deposited in catchments and preventing deposited litter from entering drainage system wherever possible should be the focus for effective storm water BMPs.

In the city of Albuquerque, New Mexico, various types of debris removal structures in storm water drainage channels has been constructed. With support from the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA), the open channel hydraulics laboratory at the University of New Mexico has developed urban storm water quality structures and conducted modeling studies to assess design hydraulic performances. In this study, the Drop Flow Debris Filter (DFDF), a space efficient and cost effective storm water quality structure was developed and tested, and shown capable of being installed in existing storm water drainage channels.

Drop Flow Debris Filter

The DFDF structure consists of two almost horizontal plates, one above the other, with a debris basin as shown in Figure 1. The 106.7 cm long upper plate is angled down 8.2°, while the 50.8 cm long down plate is angled up 20.5°, connected with a 76.2 cm long horizontal plate. The DFDF model was built using clear plexiglass.

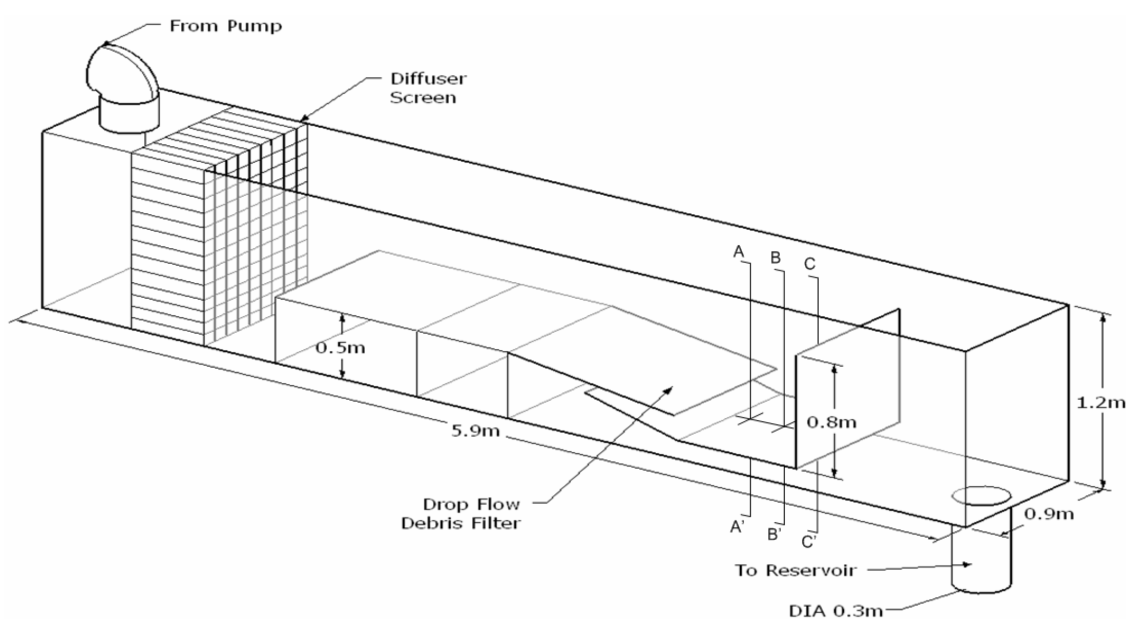
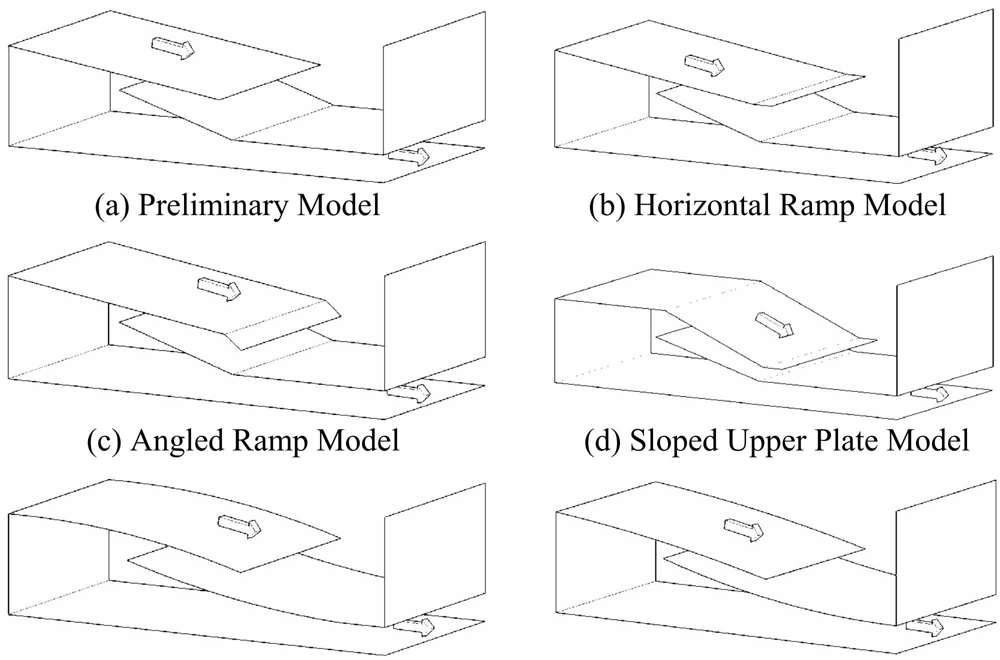


Figure 1. Preliminary DFDF model in experimental flume



(a) Preliminary Model (b) Horizontal Ramp Model

(c) Angled Ramp Model (d) Sloped Upper Plate Model

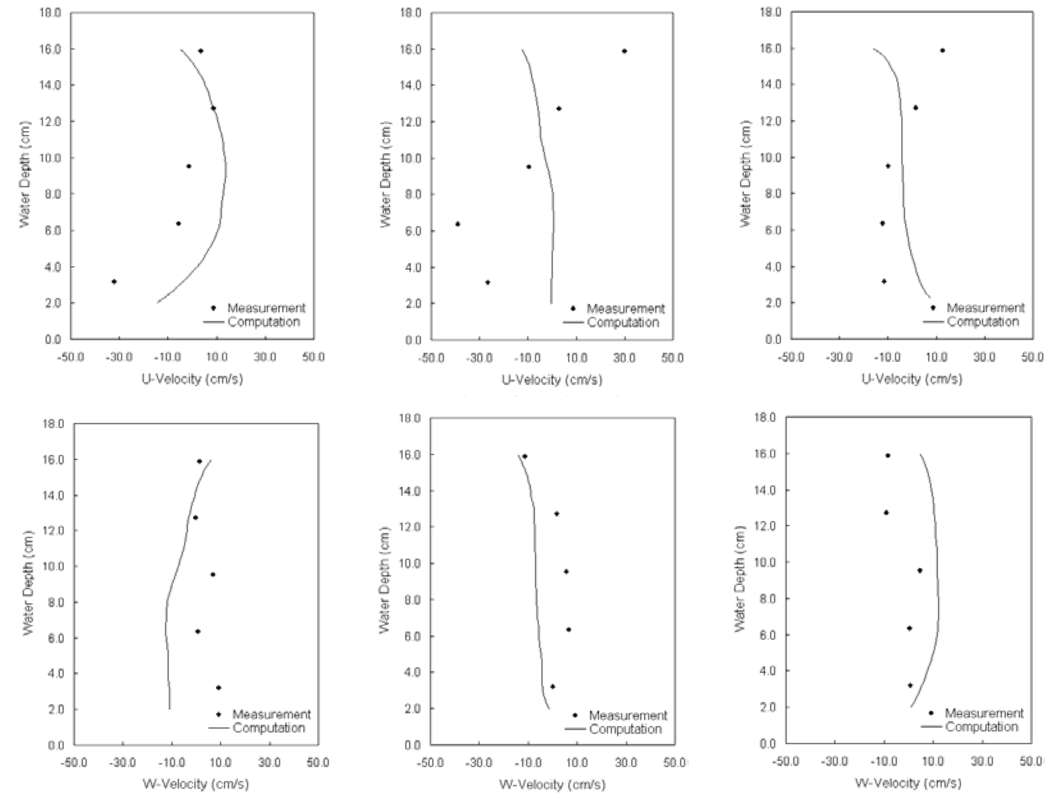
(e) Curved Plates Model (f) Modified Curved Plates Model

Figure 2. DFDF model variations for design modification

The sides of the flume were covered with 2 cm thick plexiglass, allowing the flow characteristics to be observable while providing support to the structure. The flow was provided from the upstream (left in this figure) side of the flume a by 0.13 m^3/s capacity centrifugal pump and discharged to the bottom right of the flume. This DFDF structure system creates flow paths that only allow water in the bottom of the basin to pass through while debris is retained in the upper part of the basin. The structure translates supercritical flow in the upper plate into subcritical flow through the debris basin. Low density floating debris is retained at the water surface, and high density heavy debris sinks to the bottom and rear of the debris basin, while filtered water is discharged through the exit of the debris basin.

Modeling Approach

The DFDF structure was developed to remove floating debris during storm water first flush and for the simple maintenance after a flood event. Using screen material is another method for debris removal, but due to its high debris clogging potential, was not considered in the structure design. The model was initially tested at three different flow rates: 0.019 m^3/s, 0.050 m^3/s, and 0.076 m^3/s. Approximately 3.7 cm diameter spheres of three different densities were used to model prototype debris of floatable (γ_d, specific weight = 0.5), neutrally buoyant ($\gamma_d = 1.0$), and heavy material ($\gamma_d = 1.5$). Twelve spheres of the debris model were placed at the upper deck to model the first flush effect, and the percentage of debris retained in the debris basin determined the effectiveness of the structure design. The physical model experiments were conducted under Froude number model similitude.



(a) **(b)** **(c)**

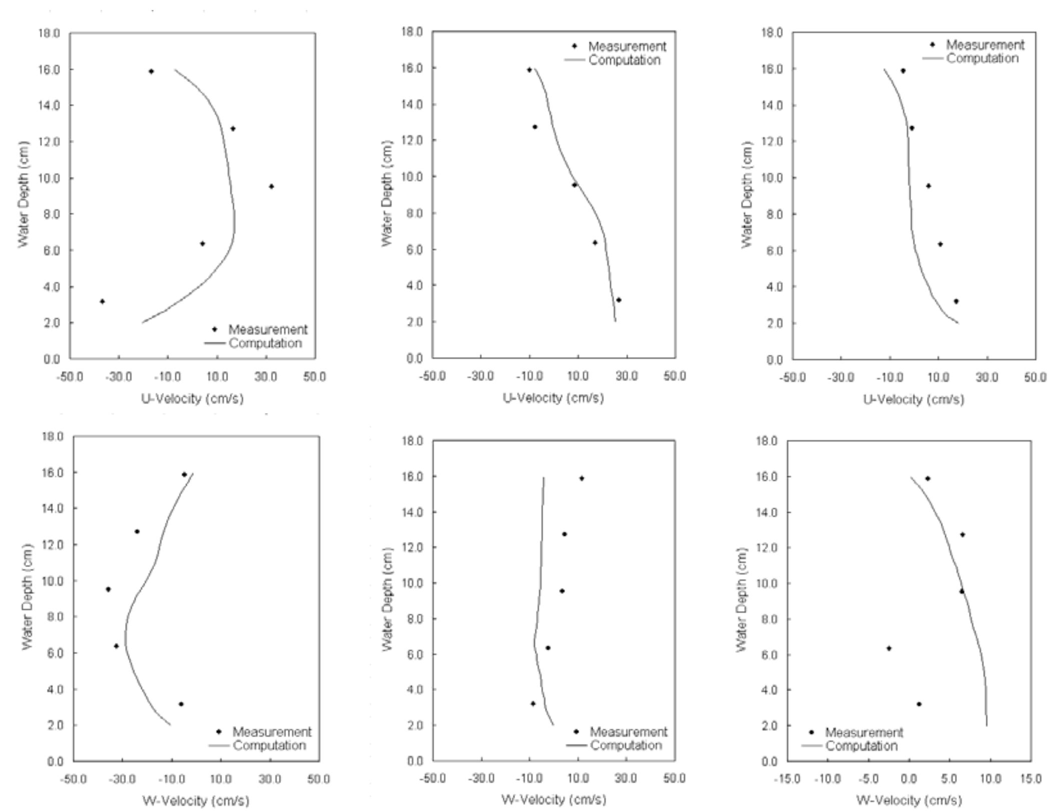
Figure 3. Comparison of velocity profiles for the preliminary model

A three-dimensional acoustic doppler velocimeter (ADV) was used to measure velocities at the approach channel, upstream of the DFDF structure, and in the debris basin. Each model was run for 60 seconds to allow time for observing the effectiveness of the system.

Six different DFDF models were designed (Figure 2). Horizontal and angled down ramp were added at the end of the top plate to generate compact circuiting inside the debris basin as shown in Figure 2 (b) and Figure 2 (c), respectively. Figure 2 (d) shows another modification to the shape of the top plate to move the subcritical flow region further back into the debris basin. The final configuration design was with slightly curved plates to obtain more streamlined flow and to increase the amount of heavy density deposition at the end of the debris basin as shown in Figure 2 (e) and (f).

Numerical Model Implementation

A commercially available Computational Fluid Dynamics (CFD) program Flow-3D (developed by Flow Sciences) was used for the numerical modeling in this study. This computer program solves the Reynolds-Averaged Navier-Stokes (RANS) equations by the finite volume formulation obtained from a staggered finite difference grid. For each cell, average values for the flow parameters, pressure and velocity, are computed at discrete times.

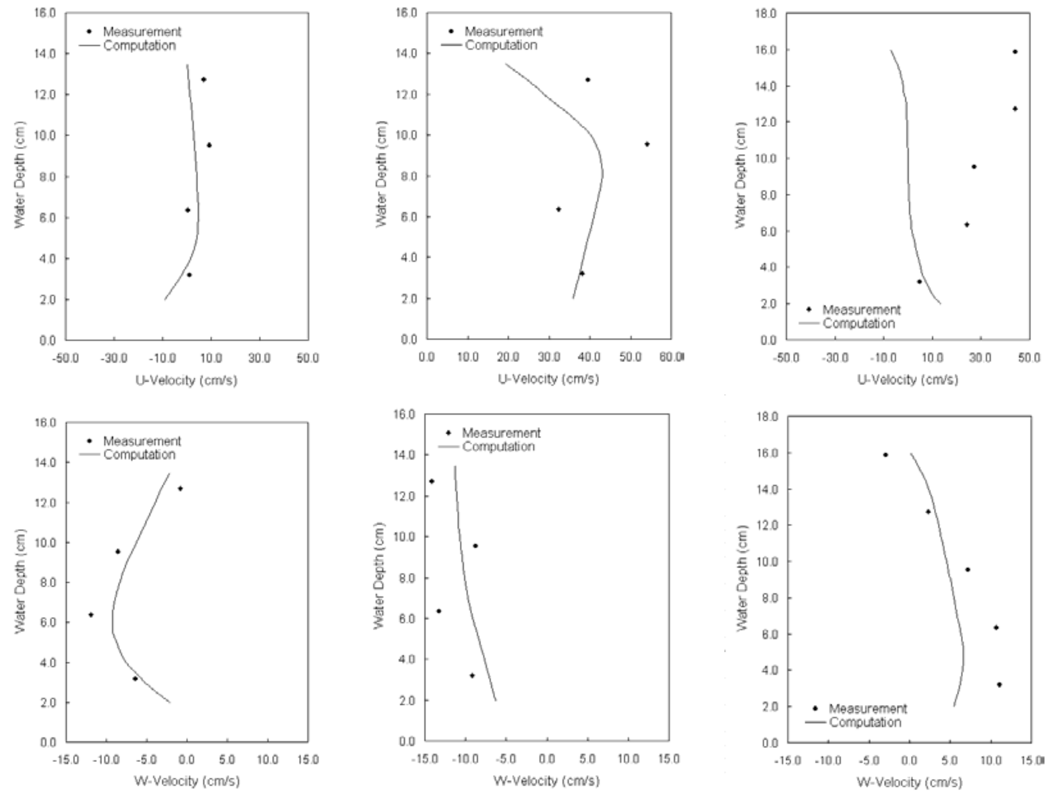


(a) (b) (c)

Figure 4. Comparison of velocity profiles for the horizontal ramp model

To solve the RANS equations, velocity in each cell is estimated from the coupled momentum and continuity equations using the initial conditions or values from the previous time step. The Volume Of Fluid (VOF) method is used for tracking the fluid interfaces. With the VOF method, grid cells are defined as empty, full, or partially filled with fluid. Cells are assigned the fluid fraction varying from zero to one depending on the quantity of fluid. Along the fraction cells, advection of fluid handling and the given boundary conditions at the free surface (zero fraction cells) maintain the sharp interface. The free surface slope of a partially filled cell is computed by free surface angle and location of the surrounding cells, and then it is defined by a series of connected chords in a two-dimensional model or by connected planes in a three-dimensional model. These fractions are embedded into all of the terms of the RANS equations. For mesh geometry on the finite control volume, the Fractional Area/Volume Obstacle Representation (FAVOR) method developed by Hirt and Sicilian (1985) is used. The FAVOR method is a porosity technique, which defines an obstacle in a cell with a porosity value between zero and one as the obstacle fills in the cell. Each obstacle within a grid is defined as a volume fraction, (porosity) to represent a solid condition.

For the upstream boundary condition, the stagnation pressure value was specified. The stagnation pressure, $P+ \rho V^2/2$, boundary condition assumes that the fluid next to the boundary is stagnant at the specified pressure value which approximates a large reservoir of fluid outside the mesh domain (Flow Science, 2003).



(a) **(b)** **(c)**

Figure 5. Comparison of velocity profiles for the modified curved plates model

In this numerical model, fluid heights of 49.3 cm, 54.3 cm, and 58.5 cm were used for the stagnation pressure of the upstream boundary conditions. On the other hand, the continuative boundary condition, which consists of zero normal derivatives at the boundary for a smooth continuation of the flow through the boundary, was adopted as the downstream boundary condition to evaluate the outflow rate at the downstream with the physical test measurement. Atmospheric pressure was set at the top of the mesh, and no slip wall condition, which is defined as having zero tangential and normal velocities, was applied at the bottom and sidewalls of the mesh.

A particle traction scheme was used to simulate the storm water debris movement in the DFDF structure. In the Flow-3D model, particles can be one of two types: constant density and variable size or constant size and variable density; marker particles can be used as species in either case (Barkhudarov, 1995). For a mass particle, drag forces are imposed when it moves in a fluid. In this study, three different specific weights of 1 cm diameter particles (γ_p = 0.5, 1.0, and 1.5) were used in the numerical model to simulate the buoyant debris materials used in the physical model tests.

Modeling Results

The computed velocities and water depths were compared and validated with the physical model measurements to assess the flow patterns of the DFDF model.

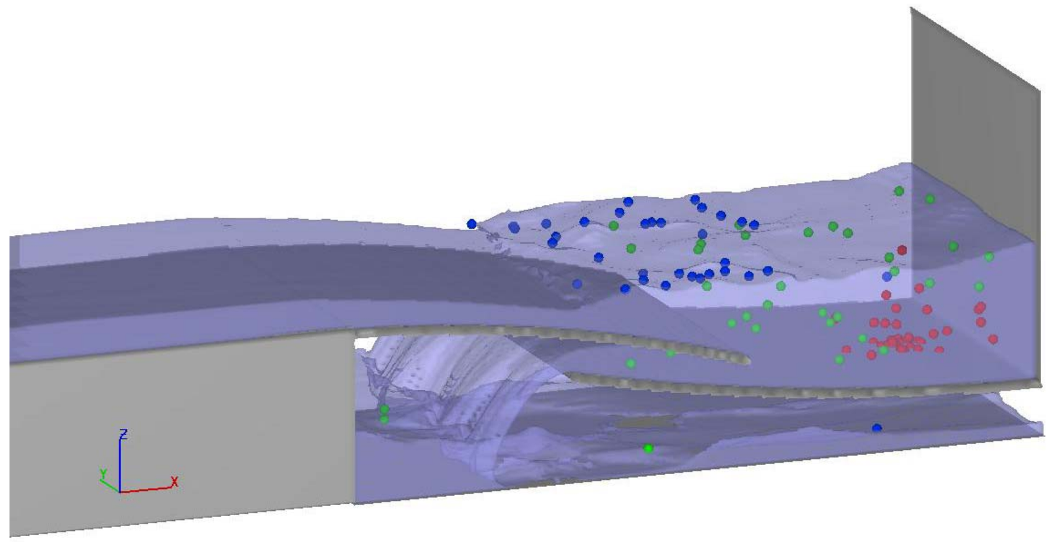


Figure 6. Various buoyancy debris movements

Figure 3, 4, and 5 show velocity profile comparisons at the latitudinal axis (u-velocity, x-component) and the longitudinal axis (w-velocity, z-component) for three different DFDF models. The velocity profiles of the preliminary model at the edge of the top plate (A-A' in Figure 1), center of the debris basin (B-B'), and the end of the debris basin (C-C') were shown in Figure 3 (a), (b), and (c), respectively. These computed velocity profiles represented the flow pattern inside the debris basin observed from the physical model. Negative value of the u-component velocity for the reverse flow direction was computed at the bottom of the exit region of the debris basin (figure 3 (a)). At the center of the debris basin, unstable u-component velocity profile was measured in contrast with the computation. In most regions, negative w-component velocity profiles (downward flow) were obtained except at the end of the basin (C-C' in Figure 1). Velocity profiles of the horizontal ramp model are shown in Figure 4. Similar velocity profiles were measured with results of the preliminary model test. However, inconstant velocity profile of the edge of the top plate (A-A' in Figure 1) was observed (Figure 4 (c)). The modified curved plates model provides high negative u-component velocities near the bottom of the debris basin exit as shown in Figure 5 (a). Although there are some magnitude and directional discrepancies, the computations show good agreement with the measurements.

Movement of the debris with the three different buoyancies within the modified curved plates design were simulated with the numerical model as shown in Figure 6. One hundred and twelve particles (forty balls for three density values) were generated in the numerical model. Blue, green, and red colored particles indicate the floatable, neutral, and heavy debris, respectively. The low density debris floated on the debris basin, while the heavy density debris sank to the bottom of the debris basin. The neutrally buoyant debris passed through the basin and discharged from the DFDF structure.

Debris filtering ratio of amount of debris retained to those passed was adopted to assess the various DFDF structure performance. Figure 7 shows the debris filtering ratio of each DFDF model.

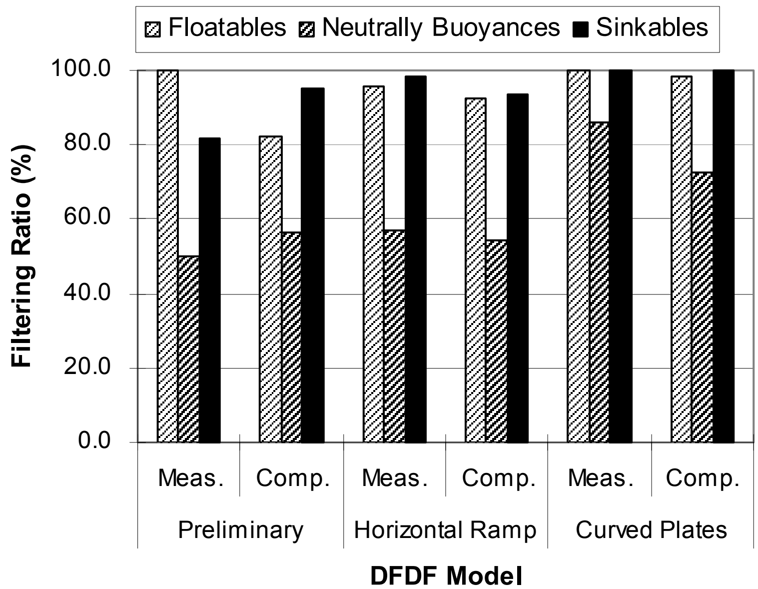


Figure 7. Debris filtering ratio of the DFDF model

The preliminary model performed adequately, but the short-circuiting at the edge of the top plate (A-A' in Figure 1) provoked passing of the most neutrally buoyant debris. Although this model was considered effective for floatable debris, several modifications were proposed.

The first modification added a short ramp at the end of the top plate to minimize debris passing from the short-circulating effect as shown in Figure 2 (b) and (c). Although, the short-circulating was not eliminated, this modification improved the debris handling characteristics. The angled down short ramp model (figure 2 (c)) performed no different that the horizontal ramp model. The slope of the top plate was increased to move the hydraulic jump further back into the debris basin, which would lead to increase debris retention as shown in Figure 2 (d). The top plate inclination was matched to the bottom plate's slope. However, the high sloped top plate model did not provide better debris filtering performance than the previous configurations. To promote streamlined flow and to increase heavy debris deposition, the top plate and the bottom plate were curved. The initial curved top and bottom plates were set at 700 cm and 900 cm radii, respectively (figure 2 (e)), and then the radii were decreased to 400 cm and 600 cm (figure 2 (f)). The modified curved plate geometry were meshed with the quadratic equations,

$$F(X,Z) = X^2 + Z^2 + 20 \cdot X + 708.7 \cdot Z - 34336.0775 \quad \text{for the top plate}$$

$$F(X,Z) = X^2 + Z^2 - 370.8 \cdot X + 1226 \cdot Z - 50142.16 \quad \text{for the bottom plate}$$

The heavy debris was retained better at all flows due to the bottom plate sloping to the debris basin wall. This design successfully removed the short-circuiting by pushing much of the debris into the back of the debris basin. Most of the floatable and neutrally buoyant debris was pushed back into the debris basin. The modified curved plates model was considered as the best performing DFDF model.

Figure 8 shows computed streamlines of the preliminary model and the modified curved plates model. The streamlines vary from red for high velocity to blue for low velocity. The short-circulating occurs between the separation zone and the approach region, while the main stream flows over the separation zone and formed a long-circulating counterclockwise. The modified curved plates model generates compact short-circulation, clear separation zone, and higher approaching velocity at the approach region than the preliminary model. This flow condition keeps the debris from being swept through the structure near the approaching region. In addition, smoother streamlines were generated from the modified curved plates model.

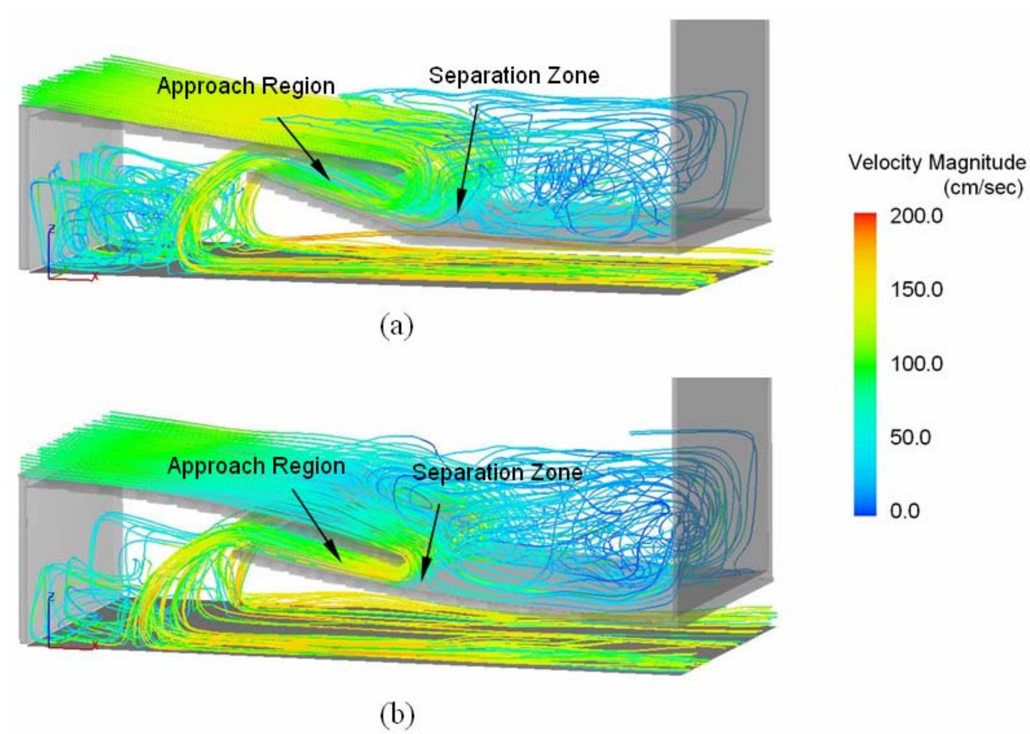


Figure 8. Computed streamlines of the DFDF model

Conclusion

The DFDF structure performed as a space effective storm water debris removal structure for supercritical flow urban flood drainage channels. Existing channels can be retrofitted with the DFDF structure, thus implementing BMPs for debris removal from storm water. A 1:3 scale physical model was tested to investigate the hydraulic performance of the DFDF structure. Velocity profile, water depth, and filtering ratio computed by a three-dimensional CFD model were compared with the physical model measurements. The numerical model shows positive agreement for the velocity profile of the debris basin with the physical model. The modified curved plates model was recommended for the best performing

DFDF structure design among six different models. This model showed the most effective debris filtering for heavy and neutrally buoyant debris. The modified curved plates model generates compact short-circulation with clear separation zone and high approaching velocity, which promote better debris retention in the debris basin. The validated numerical model provided detailed hydraulic properties and can lead to cost and time savings in future physical modeling.

Acknowledgements

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