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Comparison of two- and three-dimensional modeling of invert trap for sewer solid management

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Abstract

In the present study, five different invert trap configurations (rectangular with and without lids on both sides; trapezoidal, trapezoidal with rectangular base and rectangular with trapezoidal base with lids on both sides) were simulated for both two-dimensional (2D) and three-dimensional (3D) flow conditions for three sediment types (sand, styrocell and plastic beads) at six flow rates (0.35, 0.70, 1.05, 1.35, 4.55 and 9.95 L/s) for each trap. Computational fluid dynamics (CFD)-based modeling using FLUENT software with Renormalization Group (RNG) k–ε model along with discrete phase model (DPM) were used in the simulations. A hexagonal/tetrahedral and map-type non-uniform grid was chosen to discretize the entire computational domain and a control volume finite difference method was used to solve the governing equations. The flow rates selected in the present study cover the entire range of flow rate expected for dry weather and monsoon. The simulation is capable of differentiating between 2D and 3D modeling of particle trajectories, the effects of flow rate and trap geometry on flow patterns developed in the trap. The sediment retention ratio for 2D is higher than that for 3D modeling for all flow conditions, particle types and model geometry due to inclusion of lateral effects in 3D modeling. The invert trap having rectangular shape with trapezoidal base is found to be the most efficient configuration in both 2D and 3D modeling.

Keywords: CFD modeling; 2D; 3D; Invert trap; Sediment trapping; Urban drainage

1. Introduction

Solids deposition in sewers constitutes a serious problem because of reduction of sewer diameter, which may cause flooding or even higher pollution due to overflow to receiving waters. The management of sediment is also vital if future systems have to operate more sustainably (Ashley, Bertrand-Krajewski, & Hvitved-Jacobsen, 2004). The principal causes of sediments in the system are hydraulic and structural discontinuities. To remove the sediments, they should either be extracted for adequate disposal or be moved downstream. The aim of sediment management in sewers is to minimise maintenance costs by reducing the sediments in combined sewer overflow (CSO) structures. Numerous devices have been developed to manage sediments including flushing systems and invert traps.

Invert trap consists of a discontinuity in the invert of the sewer in which the sediments fall. To permit cleaning, the trap can be isolated through gates and the flow diverted. The traps need regular maintenance, that is, to be emptied periodically. To allow this operation the flow can be diverted and the sediments be extracted through manholes.

Invert traps for combined sewer are mostly adopted in UK and in France (Ashley & Hopkinson, 2002). Recently, a modified invert trap with lids, has been developed in France. The traps are covered with plates with transverse open slots between them (Ashley et al., 2004). The gap between the plates is approximately 300 mm, which allows only the heaviest of the bed load solids to settle into the trap (Laplace, Bachoc, Sanchez, & Dartus, 1992). The operation of these traps is not based on the settling of bed load and suspended solids, but on the selective interception of the heavier bed load solids moving along the sewer invert (Bertrand-Krajewski, Madiec, & Moine, 1996). Modified invert traps are smaller in size with their volumes ranging from 1 to 5 m^3, and therefore can be easily cleaned with the help of vacuum suction vehicle. These traps are more efficient

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Nomenclature

b	width of channel (=0.28 m)
C_{3z}, C_{2z}, C_{1z}, C_μ	constant terms
C_D	drag coefficient
d_k	inverse effective Prandtl number
d_p	particle diameter
D_H	hydraulic diameter
E	empirical constant (=9.793)
F_D	drag force
F_x	external force
G_b	production of turbulent kinetic energy due to buoyancy
G_k	production of turbulent kinetic energy due to mean velocity gradient
k	turbulent kinetic energy
p	static pressure
R_z	additional term in dissipation rate equation
Re	Reynolds number
S_k	source term
S_m	mass added to the continuous phase
Δt^C	time that a particle on *j*th trajectory takes to pass through cell (C)
u	liquid phase velocity
u_p	particle velocity
u'	turbulence fluctuation in the liquid phase velocity u
$\bar{U}$	mean velocity of the liquid
V_C	volume of the cell
V_p	volume of the particle
y	local depth
y_v	viscous sub-layer thickness
Y_M	fluctuation dilatation

Greek symbols

δ_{ij}	Reynolds stress tensor
ε	dissipation rate
η_j	number of particles per unit time traversing the *j*th trajectory takes to pass through cell (C)
μ	viscosity
μ_{eff}	effective viscosity
ρ	liquid density
τ_w	wall shear stress
ϕ_i^M	source terms in the momentum equation, equal to the momentum added to the continuous phase due to presence of the particulate phase
$\Phi_i^M(C)$	source term in the momentum equation due to presence of the particulate phase and for each cell C

than grit chambers in intercepting the coarser particles due to the provision of lids on both the sides of the invert trap (Ashley et al., 2004).

Toward the latter part of the last decade, computational fluid dynamics (CFD) fluid flow simulation software became increasingly applied for the study of sewer and drainage systems and processes (Faram & Harwood, 2000). Schmitt, Milisic, Bertrand-Krajewski, Laplace, and Chebbo (1999) carried out simulations for various cases (centrally placed slot with both covers at same height, the slot with a raised downstream cover, the slot situated at the downstream edge of the trap and the slot situated at the upstream edge of the trap) using the density current approach in CFD modeling. They concluded that the best invert trap design is the centrally placed slot having width similar to that of the channel and the two lids covering the slot on both sides at the same level.

Buxton, Tait, Stovin, and Saul (2002) compared retention efficiencies obtained experimentally and computationally based on two-dimensional (2D) CFD modeling, for invert traps having three rectangular configurations with slots of 90, 45 and 22.5 mm. They found that CFD modeling gives slightly over predicted values of the retention efficiencies.

Harwood (1998) and Faram and Harwood (2000, 2002, 2003) applied CFD for comparative assessment of different configurations of stormwater treatment chambers including a simple catchbasin (SCB), a gravity sedimentation device (GSD), a simple vortex separator (SVS) and an advanced vortex separator (AVS) using Lagrangian particle tracking approach in FLUENT CFD software at low solid concentration. They observed fair matching between computational results and experimental data.

As none of these studies considered the effect of trap configurations on the efficiency of trapping sediments, in the present study, an attempt has been made to propose optimum configuration by performing 2D and three-dimensional (3D) CFD modeling of five different configurations of invert trap.

2. Numerical study of water and sediment turbulent flow

The commercial FLUENT 6.2 (2005) software package based on the finite volume approach was used for solving the following set of governing equations. The discretized governing equations for modeling both the continuous liquid phase and dispersed particulate phase, along with their initial and boundary conditions, were solved using the segregated solution method. A pressure-correction equation was used to ensure the conservation of momentum and mass (continuity equation). The Renormalization Group (RNG) k–ε model was used to treat turbulence phenomena in both phases. The granular theory for liquid–solid flow of the discrete phase model (DPM) was employed to predict the liquid–solid flow behavior in open channel and invert trap.

2.1. Modeling of turbulent water flow

All six flow rates considered in the present study are in turbulent flow, that is, steady, incompressible, isothermal and chemically homogeneous, as shown below.

Conservation of mass:

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_m \qquad (1)$$