Physical model study of a vortex separator overflow

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Abstract

A detailed research project is set up to validate a vortex separator overflow construction. In this vortex separator, collected sewer water enters radially from the sewer pipe in a cylindrical inner reservoir. The passage flow to the treatment plant is situated in the bottom centre, while the overflow passes a radial weir into an outer shell reservoir. In a laboratory model the removal efficiency of this overflow structure is identified for several hydrodynamic flow operation modes by recording sediment redistribution over the structure. As a result of these series of experiments on a model of a vortex separator overflow, the efficiency of this kind of construction is identified as a function of both hydrodynamic parameters and lay-out features. Doing so, the vortex separator is introduced as an alternative overflow construction to control and manage combined sewer overflow (CSO)-events, leading to a less negative operation impact of combined sewer systems on the receiving waters.

1 Introduction

In Flanders, combined sewers collect and transport both sanitary sewage and rain water to a treatment plant. During dry weather, combined pipe systems carry all sewage flows to the purification plant. During heavy rain events however, flow rates increase beyond the design capacity of the facility treatment. Regulating devices or constructions are built into the conveyance system to allow discharge of excess flow into the nearest water body. These combined sewer overflows (CSO) contain stormwater, diluted sanitary sewage and debris. Containing high levels of suspended solids with associated heavy metals, nutrients, organic compounds and other pollutants, these CSO pose risks to human health, threaten aquatic life and its habitat and impair the general use of the receiving water.
body. Therefore, a proper overflow structure should separate optimally the "clear" water from the "polluted" fraction in the sewer overflow water mass. By expanding the sewer system itself (to achieve a stable aquatic ecosystem) the impact of a single overflow event increases due to the higher vulnerability of the receiving waters. Both acute and accumulative effects of pollution on the receiving water should be taken into account to validate the overall efficiency of an overflow/separator-structure.

As a result, these overflow constructions are an essential link in the operation of the urban drainage system. Due to the important level of sewer sediment deposition in the mostly oversized sewer pipes (during dry weather periods), the release of polluted sediments with storm events is significantly high. Indeed, a first flush of sediments and sediment associated pollutants typically occurs during the initial period of storm flow with some 70 % of the total suspended load being discharged with the first 30 % of the run off volume [5]. To reduce storm flow impact on the general quality of the receiving water, two alternative approaches can be explored to reduce the overflow volume and frequency :
- increase in storage capacity of the sewer system by introducing both on-site measures such as (natural) infiltration, rain water retention,... and off-site constructions (settlement tanks, sedimentation fields)
- reduction of the pollution level of the overflow volume.

This reduction can be achieved by different maintenance and operation procedures. First, a proper cleaning of both drained surface areas and sewer pipes itself will reduce the sediment deposition during dry weather periods and by that, the sediment removal in storm flows. Secondly, an optimum separation in the overflow construction between polluted (fine) sediments and relatively clear overflow water secures a considerable amelioration in the pollution removal. In this paper, an optimum design and operation of a new overflow configuration is validated in order to control and reduce the negative impact of the overflow on the receiving water body.
2 The vortex separator

Besides the well-known high weir lateral overflow construction [3], this vortex separator overflow [4] forms an alternative structure to be placed in the sewer system. Basically, the vortex separator consists of a central, cylindrical inner reservoir where the sewer water tangentially enters [2]. The outflow of the "polluted" water fraction to the treatment plant is situated centrally in the bottom of the vortex chamber, while the overflow of the "clear" water to the receiving body is situated, as a radial weir, at the outer circumference of the vortex reservoir, passing into an outer shell to the overflow pipe.

![Diagram of the vortex separator](image)

Figure 2. The Vortex separator.

The bottom of the inner vortex chamber has a radial slope to the central outflow in order to collect and guide the deposited sediments to the treatment side. A spiral partition, placed in front of the radial overflow weir, obstructs the floating particles to pass with the clean overflow water. Due to the natural vortex flow in this separator construction (by the tangential inflow) no external centrifugal forces are needed to separate the sediments from the sewer water. As a result, less maintenance and optimum removal can be expected for a wide range of inflow discharges. In comparison with the high weir lateral overflow, the vortex separator is much more compact. The main disadvantage of this kind of construction is the relatively low position of the outflow to the treatment plant.
3 The physical model

In a full-scale laboratory model the removal efficiency of a vortex separator overflow is identified for several hydrodynamic operation modes and constructional alternatives by recording sediment redistribution over the structure [1]. The model (with a fixed vortex chamber diameter D = 1200 mm) permits an easy adaptation of both the overflow weir (length, location and height) and the inflow pipe diameter to identify constructional impact on the removal efficiency. Flow operation modes are also validated by varying the flow distribution in the vortex separator. Since the basic design requirement for an overflow structure is an optimum (polluted) sediment removal, all experiments for different test situations are evaluating the removal efficiency, defined as the ratio between the overflow pollution load to the input pollution load.

![Diagram of Laboratory model of the vortex separator overflow.](image-url)
Hydrodynamics are modelled according to the traditional Froude law while sedimentologic scaling is based on the fall velocity \( w \) in order to achieve a proportional settling process in the model. Most of the experiments are done with bakelite particles \((\rho = 1400 \text{ kg/m}^3 - w = 15-30 \text{ mm/s})\) while some alternative model sediments (artificial nacre and polystyrene) are only used to verify scale effects.

Basically, the operation procedure of the experiments, all performed under permanent flow conditions, can be split up in following sequences:

- fixing test configuration of the vortex separator
- initiation of the permanent flow conditions (of pure water) by operating the main valves on in- and outflow pipes
- gradual introduction of a fixed mass of model sediments (e.g. 1 kg of bakelite particles)
- normal operation of the overflow structure during five minutes
- gradual closing of the sewer inflow
- collecting the distributed model sediments in the respective parts of the model

Following parameters are validated during the test program in a total of 16 constructional combinations:

- inflow pipe diameter \( D_{in} = 250 - 300 - 350 \text{ mm} \)
- radial overflow weir characteristics
  - height = 450 \( \rightarrow \) 750 mm above the bottom of the inlet pipe
  - length = 1/3, 1/4 or 1/6 of the total circumference of the vortex reservoir
  - location in relation to the inflow (in front, central or at the end)
- sediment type and grain fractions
  - bakelite (three fractions \( d_{50} = 430 - 600 - 850 \mu m \))
  - artificial nacre
  - polystyrene grains
- sewer inflow discharge \( Q_{in} = 17 \rightarrow 90 \text{ l/s} \)
- ratio between pass flow \( Q_{out} \) (to treatment plant) and sewer inflow \( Q_{in} \) = 10 - 15 - 20 

4 Evaluation of the experimental results

First, the reproducibility is tested by comparing a series of identical experiments. An absolute deviation of 0.8 % on the mean removal efficiency (42.6 %) has been recorded for 4 experiments. So, a qualitative comparison between all experiments can be performed; although an absolute, quantitative result remains uncertain due to systematic errors and scaling effects. The removal efficiency, as used for the evaluation, is given by:

\[
\eta = \frac{m_{out}}{m_{in}} = \frac{m_{out}}{m_{out} + m_{over}}
\]

where
- \( m_{out} \) = total mass of passing sediments to the treatment plant [kg]
- \( m_{over} \) = total mass of sediments in the overflow [kg]
- \( m_{in} \) = total mass of sediments, initially entered from the sewer [kg]

Figure 5. Example of physical model results.
Neither location nor length of the radial overflow weir have a great impact on the removal efficiency of the vortex separator, but an optimum overflow will be situated at the end of the tangential flow trajectory in the vortex chamber. As a result, only pure hydrodynamic features can control the dimensioning of the radial weir in the vortex separator.

The height of the radial weir $h$ (above the bottom of the inlet pipe) should be minimal two times $D_{in}$ to obtain an optimum removal efficiency. Some general, physically founded conclusions are revealed [6]:

- The overall efficiency of the vortex separator increases with the sediment fall velocity $w$ and decreases with the mean inflow velocity $U$.
- The separating impact is relatively high with small passing flow discharge, although the absolute efficiency increases with growing flow to the treatment plant.

Based on these limited experimental analysis, an efficiency formula is explored for this new type of vortex separator overflow. Similar to previously explored laboratory data for the high side weir overflow [3], following expression is found by multiple regression of all relevant (dimensionless) parameters:

$$\eta = 1 - \left[ 1 - \frac{Q_{out}}{Q_{in}} \right] \cdot \exp(A)$$

with

$$A = - 26.8 \frac{w}{U} \left( 1 - \exp \left( -0.7 \frac{h}{D_{in}} \right) \right) \left( 1 - \exp \left( -1.25 \frac{D}{D_{in}} \right) \right) f_2(Re)$$

where

$$f_2(Re) = 1 - \exp \left[ - \frac{162000}{(Re - 205000)} \right]$$

As already indicated before, two parameters are governing the removal efficiency of the vortex separator. The ratio between vortex chamber diameter $D$ and inflow sewer pipe diameter $D_{in}$ should be around 4, while the height of the radial weir $h$ above the bottom of the inflow should be minimal two times the inflow pipe diameter $D_{in}$. 
Figure 6. Efficiency of vortex separator overflow.

5 Conclusion

Based on a series of limited laboratory model data, an initial efficiency formulation is developed for a new type of vortex separator overflow. By identifying the most relevant design parameters of this kind of overflow structure, a first attempt to optimize both constructional and operational features has been formulated. By that, the vortex separator overflow is identified as a proper alternative to control and reduce the negative impact of combined sewer overflows on the receiving waters. Further research, both in the laboratory and under field conditions, can reveal more detailed information on this type of auxiliary construction of the urban drainage system.

6 References


