Vertical baffles for the capture of floatables in sewer channels

Les cloisons verticales pour la capture des flottants dans les réseaux d'assainissement

Alberto Campisano

Department of Civil and Environmental Engineering
University of Catania
Viale Andrea Doria, 6, 95125 Catania, Italy
Email: acampisa@dica.unict.it

RÉSUMÉ

Les cloisons verticales représentent une solution efficace et économique pour la capture des flottants dans les réseaux d'assainissement. Les études expérimentales et les procédures analytiques sur l'évaluation de leurs performances ont été exécutées par plusieurs auteurs dans la décennie dernière; néanmoins les études disponibles ne fournissent pas les indications générales valides pour toutes les conditions hydrauliques de fonctionnement des dispositifs.

Cet article présente les résultats d'une recherche expérimentale qui a permis d'obtenir d'autres indications sur les performances des cloisons verticales dans les chenaux d'assainissement. Les expérimentations ont été exécutées en laboratoire sur modèle réduit en utilisant une simple cloison verticale et plusieurs sortes de flottants. La condition de seuil d'équilibre derrière la cloison et sa capacité de capture permanente ont été étudiées en dérivant des relations adimensionnelles utiles pour le projet de cloisons dans les réseaux d'assainissement.

ABSTRACT

Baffles have proven to be a cost-effective solution for the capture of floatables in sewer systems. Experimental investigations and analytical procedures concerning the evaluation of their capturing performances have been carried out by various authors in the last decades, but the available studies do not provide general indications valid for all the hydraulic operating conditions of the devices.

In this paper the results of an experimental investigation aimed at deriving further indications on the baffle capturing performances in sewer channels are presented. The experiments were performed in a laboratory flume using a simple vertical baffle and different types of floatables. The limit equilibrium condition of floatables upstream of the baffle and the permanent capturing capacity of the device were investigated deriving dimensionless relationships useful for the baffle design in sewer channels.

KEYWORDS

Experimental investigation, Floatables, Sewer channels, Vertical baffles

1 INTRODUCTION

During the last decade increasing efforts have been devoted to the control of floatables in combined sewer systems.

Origins and characteristics of floatables in sewers, in combined sewer overflows (CSOs) and in open waters have been investigated by several researchers (St. John et al., 1994; Turner, 1995; Paradis et al., 1996; Lippner et al., 2001). All studies indicate highly variable compositions of the material types, depending on the catchment characteristics, the rain patterns and the maintenance operations.

Other studies have concerned methods and devices for the capture and removal of floatables from sewer systems (Fischer and Turner, 2002; Lippner et al., 2004). In particular baffles have been proven to be a cost-effective solution among the existing devices (Heath et al., 1996; Walker et al., 1998a); commonly these devices consist of vertical (steel or plastic) plates which can be installed at selected points of the sewer system upstream of the CSO structures, preventing the floatable discharge into the receiving waters. During wet weather flows, baffles typically determine under-head outflow conditions with increased upstream water levels allowing the interception of floatables. Then, captured floatables can be removed locally (in correspondence to the site of the installation), or detained upstream of the baffle until the water level recedes, being then conveyed to the treatment facility.

The capturing efficiency of baffles has been experimentally investigated by various authors. Experiments were performed on a scaled model of an overflow chamber considering specific flow rate values and selected floatables found in real CSOs (White and Larsen, 1997, Walker et al., 1998b); the experiments indicated that the capture of the floatable elements depends on flow conditions and that an increased efficiency can be obtained with multiple-baffle configurations. A more recent experimental investigation was performed in a laboratory flume using a simple underflow baffle (Cigana and Couture 2005); the capturing efficiency of the device was evaluated under submerged flow conditions for some values of the baffle bottom opening and of the flow velocity. The experimental results have shown that the capturing efficiency quickly decreases as flow velocity increases, regardless of the depth of the baffle within the flow.

Analytical approaches for the design of baffles and the assessment of their capturing efficiency were also proposed by several authors (Dalkir et al., 1996; Cigana et al. 1998, 1999; Newman, 2001). These approaches are mainly based on the evaluation of the rise trajectories of floatable elements in the flow and on the baffle capability of intercepting these trajectories.

Since the available studies do not allow an exhaustive evaluation of the baffle performances under various hydraulic operating conditions, an experimental investigation aimed at deriving further indications on the baffle capturing performances was recently carried out at the Laboratory of Hydraulics of the University of Catania. The results of this investigation are presented in this paper.

2 BASICS AND DIMENSIONAL ANALYSIS

As it is well known, the under-head outflow conditions determined by the baffle are characterised by modifications of the flow streamlines and by the presence of vorticity fields which can significantly affect the capture of floatables upstream of the device; in particular, depending on the characteristics of the flow, the intercepted floatables can be permanently captured upstream of the baffle or released into the main flow and transported downstream (Cigana and Couture, 2005).

Following a simplified schematization of the process, the generic floatable element intercepted upstream of the baffle is subject to its submerged weight and to the hydrodynamic force due to the flow (dipping the element downwards to the baffle bottom opening). Then, from the balance of forces, a limit equilibrium condition for the floatable elements upstream of the baffle can be defined; in particular, a threshold value of the upstream flow velocity V_t can be determined, this value corresponding to the limit condition beyond which the floatables start to escape the baffle.

The following functional relationship among V_t and characteristics of the flow, of the baffle and of the intercepted floatables can be assumed:

$$f_1(V_t, h-a, d, \rho, \mu, \gamma-\gamma_f) = 0 \tag{1}$$

with V_t [m/s] being the threshold flow velocity upstream of the baffle; h [m] the water level upstream of the baffle; a [m] the baffle bottom opening; d [m] the floatable size, ρ [kg/m^3] the water density; μ [kg/m/s] the water viscosity; γ [N/m^3] and γ_f [N/m^3] the specific weights of the water and of the floating solid, respectively.

The application of the well known Π-theorem allows to express equation (1) in dimensionless form; in particular, choosing V_t, d and ρ as reference variables, the three following dimensionless groups are obtained:

$$\Pi_1 = \frac{\rho V_t^2}{(\gamma-\gamma_f)d} \qquad \Pi_2 = \frac{\rho V_t d}{\mu} \qquad \Pi_3 = \frac{h-a}{d} \tag{2}$$

The group Π_1 relates to the ratio between the forces acting over the floatable element (hydrodynamic force, buoyancy and weight of the element); the group Π_2 corresponds to the Reynolds number of the floatable; the group Π_3 is proportional to the distance *h-a* that the floatable should run to pass through the baffle bottom opening.

According to these results, equation (1) can be expressed in explicit form as:

$$\frac{\rho V_t^2}{(\gamma-\gamma_f)d} = f\left(\frac{\rho V_t d}{\mu}, \frac{h-a}{d}\right) \tag{3}$$

Neglecting the influence of the Reynolds number Π_2 and applying the hypothesis of self-similarity derived by the dimensional analysis (Barenblatt, 1987; Ferro, 1997; 2002) the following form for the equation (3) is obtained:

$$\frac{\rho V_t^2}{(\gamma-\gamma_f)d} = \alpha_1 \cdot \left(\frac{h-a}{d}\right)^{\alpha_2} \tag{4}$$

with α_1 and α_2 being two numerical parameters to be determined experimentally. Once calibrated, equation (4) allows to evaluate the threshold flow velocity for the generic floatable element upstream of the baffle.

From a theoretical point of view, once that the limit equilibrium condition has been exceeded, floatables should be released downstream of the baffle at a certain rate N_{fd} (number of floatables per unit time). In this condition, the number of floatables detained upstream of the baffle clearly depends on the balance N_{fu} - N_{fd} with N_{fu} being the rate of floatable elements coming from the upstream sewer and approaching the device. In particular if $N_{fu} > N_{fd}$ the detained number of floatables tends to increase, while if $N_{fu} < N_{fd}$ the detained floatables tend to decrease down to a minimum value n_f. This value concerns the floatables which remain permanently captured upstream of the baffle due to the presence of the "dead zone" originally hypothesized by Cigana and Couture (2005) and represents the effective (permanent) capturing capacity of the baffle. Specific dimensionless relationships for determining n_f as function of the hydraulic characteristics of the flow and of the device and of the characteristics of the intercepted floatables, can be derived. In particular, focussing on the variables involved in the process, the following functional relationship can be assumed:

$$f_2(n_f, V, V_t, h-a, d, \rho, \mu, \gamma - \gamma_f, B) = 0 \quad (5)$$

being V [m/s] the flow velocity upstream of the baffle and B [m] the channel width.

In addition to the previous dimensionless groups Π_1, Π_2 and Π_3, the application of the Π-theorem yields the following further groups:

$$\Pi_4 = n_f \qquad \Pi_5 = \frac{V}{V_c} \qquad \Pi_6 = \frac{d}{B} \quad (6)$$

while the simple functional form:

$$n_f = \beta_0 \cdot \left(\frac{\rho V^2}{(\gamma - \gamma_f)d}\right)^{\beta_1} \cdot \left(\frac{h-a}{d}\right)^{\beta_2} \cdot \left(\frac{V}{V_t}\right)^{\beta_3} \cdot \left(\frac{d}{B}\right)^{\beta_4} \quad (7)$$

can be adopted for the evaluation of n_f. Also in this case, parameters β_0, β_1, β_2, β_3, β_4 have to be determined by means of specific experiments.

3 EXPERIMENTAL SET-UP

Experiments were performed in a 17.8 m long laboratory flume with a 0.40m x 0.65m rectangular cross section, plexiglass bottom and sidewalls and variable bottom slope. The flume is fed by an upstream tank and discharges into a downstream tank. The two tanks are connected by a recirculating system consisting of a pipe, a pump and a gate valve for the flow rate regulation.

A rectangular baffle made up of a 0.40 m x 0.70 m stainless steel plate was inserted into the flume 10.50 m downstream of the flume entrance. Free flow conditions through the baffle were considered for all the experiments, this condition being common in sewer channels and unfavourable for the capture of floatables.

A basket equipped with a metallic grid was introduced into the downstream tank for the interception of floatables flushed out of the flume during the experiments.

Water level measurements into the flume were carried out by mechanical gauges (error of 0.05 mm) while an electromagnetic flow-meter positioned along the recirculating pipe was used for the flow rate measurements (accuracy of 0.5%).

Two kinds of floatable elements were used for the experiments. The first kind consisted of artificial floatables made up of 4 types of selected spherical elements with various diameters and specific dry weights (table I). These elements, accurately chosen for their simple geometry, allowed to simplify the understanding of the hydraulic phenomena occurring during the experiments.

Floatable types	**Material**	**Diameter (d)** [cm]	**Specific weight (γ_f)** [N/m^3]
spheres	polystyrene	4.1	134
spheres	deal	3.1	7567
spheres	gum resin	2.0	4889
spheres	seasoned wood	1.1	7110

Table I. Characteristics of the selected artificial floatables used for the experiments.

Deal and seasoned wood elements were preventively treated on their surface by a silicone spry that allowed a constant waterproofing (and then a constant specific weight of the elements) to be maintained during the entire experimental campaign.

The second kind of floatable elements used for the experiments consisted of 3 types of real floatables selected among elements typical of CSOs (Paradis et al., 1996); the main characteristics of these elements are summarised in Table II.

Floatable types	**Material**	**Size (d_1, d_2, d_3)** [cm]	**Specific weight (γ_f)** [N/m^3]
plastic caps	polyethylene	3.2, 3.2, 1.6	8237
plastic glasses	polypropylene	6.0, 3.8, 5.5	8629
corks	cork	2.0, 2.0, 4.5	1177

Table II – Characteristics of the selected real floatables used for the experiments.

4 DESCRIPTION OF THE EXPERIMENTS AND RESULTS

4.1 Evaluation of the limit equilibrium condition

After preliminary tests leading to the evaluation of the baffle outflow relationship, a set of experiments was carried out under steady flow conditions in order to determine the limit equilibrium condition of floatables upstream of the baffle. The artificial and real elements summarised in tables I and II were used for the experiments; in particular, specific experiments were performed separately for each type of floatables and for 3 different values of the bottom opening (*a* = 5.89 cm; *a* = 8.15 cm; *a* = 10.66 cm).

The experimental procedure consisted of four main steps:

- once the bottom opening was fixed, steady flow conditions characterised by high water levels and low flow velocities upstream of the baffle were determined;
- a relatively large number of floatables (200 of the same group) was introduced simultaneously into the flume checking their capture upstream of the baffle;
- slow flow rate regulations (determining successive conditions of steady flows) were operated at the gate valve providing small reductions of the water level upstream of the baffle up to the release of the first floatable element (limit equilibrium condition);
- finally, in correspondence to this condition, the flow rate and the water level (0.70 m upstream of the baffle) were measured.

The number of elements introduced for each experiment was assumed to be so large as to be representative of the condition of unlimited availability of floatables upstream of the baffle. This assumption was then verified by increasing the number of introduced elements (up to several hundreds) and by checking the invariability of the limit equilibrium condition.

The results of the experiments are reported in figure 1. The geometric diameter $d = (d_1 \cdot d_2 \cdot d_3)^{1/3}$ was used for the characterisation of the size of the real floatables. Measurements derived from the experiments allowed the calibration of equation (4) by determining the values of the two parameters α_1 and α_2. In particular, the best fit was obtained for α_1 = 0.803 and α_2 = 0.697 with R^2 = 0.93; as expected, the values obtained for the two parameters determine an increase of V_t as the specific weight γ_f decreases and as the water head *h-a* or the floatable diameter *d* increase.

Further tests were finally attempted using cigarette butts (as additional real floatables) but all the tests showed that the capture of these elements strictly depends on the experiment duration (as already found by Newman (2001)); in fact, these elements are subject to a change of their buoyancy properties being quickly soaked with water.

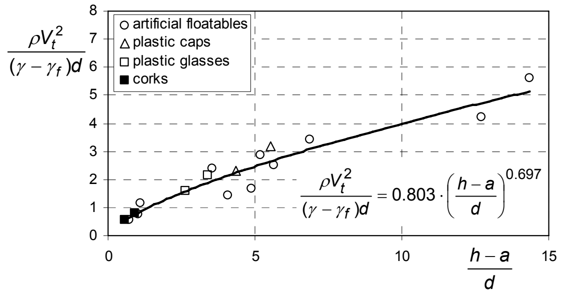

Figure 1 – Limit equilibrium condition. Experimental results with artificial and real floatables.

4.2 Evaluation of the permanent capturing capacity of the baffle

Specific experiments were performed for determining the permanent capturing capacity of the baffle. The experiments were carried out introducing floatables at the upstream entrance considering different rates N_{fu} and determining the downstream rate N_{fd} (by counting the number of elements flushed out into the basket). For all the experiments the floatable transport capacity downstream of the baffle resulted higher than N_{fu}; in fact, once the number n_f of floatables upstream of the baffle (permanent capturing capacity) was achieved, no further increase in this number was observed.

As an example, the graph of figure 2 reports the results of the experiment carried out using deal spheres for N_{fu} = 6 spheres/min (flow rate value Q = 19.7 l/s; a = 5.89 cm); the graph shows that, after about 50 minutes from the beginning of the test, a stationary condition for the floatables was achieved determining a constant number n_f of spheres permanently captured by the baffle.

Similar results were obtained with further tests carried out introducing all the available spheres simultaneously upstream of the baffle; in particular, also in these cases the same values of the permanent capturing capacities were obtained after the achievement of the stationary condition for the floatables.

All the experiments were conducted considering relatively large ranges of values of flow rates depending on the adopted bottom opening (between 15.6 l/s and 29.1 l/s for a = 5.89 cm; between 27.1 l/s and 42.2 l/s for a = 8.15 cm; between 41.5 l/s and 61.5 l/s for a = 10.66 cm).

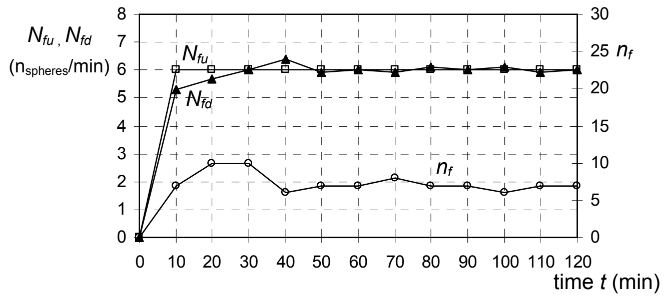

Figure 2 – Determination of the permanent capturing capacity of the baffle (N_{fu} = 6 spheres/min).

Measurements derived from the experiments were used for the calibration of equation (7). In particular, the following non linear best fit regression was found:

$$n_f = 21.81 \cdot \left(\frac{\rho V^2}{(\gamma - \gamma_f)d} \right)^{-0.70} \cdot \left(\frac{h-a}{d} \right)^{0.77} \cdot \left(\frac{V}{V_t} \right)^{-3.65} \cdot \left(\frac{d}{B} \right)^{-0.62} \text{ with } R^2 = 0.84 \quad (8)$$

In this case as well, the geometric diameter was used to characterise the size of the real floatables.

Equation (8) can be used to evaluate the number n_f of elements permanently captured by the device, when the characteristics of the flow, of the baffle and of the floatables are known.

As expected, the obtained regression shows an increase in the permanent capturing capacity of the baffle as the water head *h-a* increases and as the flow velocity *V* decreases; moreover higher capturing capacities are obtained for floatables with smaller size and lower specific weight.

The graphical comparison between observed and calculated (with equation 8) values of n_f is shown in figure 3.

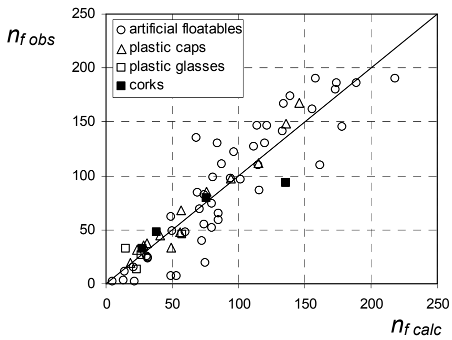

Figure 3 – Baffle capturing capacity. Comparison between observed and calculated values of n_f.

5 CONCLUSIONS

In this paper the results of an experimental investigation on the performances of baffles for the capture of floatables in sewer channels are presented.

The experiments were performed in a laboratory flume using a simple vertical baffle and different types of floatables consisting of both artificial elements with various sizes and densities and real elements typical of CSOs. In particular two different sets of experiments were carried out, the first set being addressed to determine the limit equilibrium condition beyond which the floatables start to be released by the baffle, the second aimed at evaluating the permanent capturing capacity of the baffle as function of the characteristics of floatables, of the device and of the sewer flow.

The dimensional analysis was applied in order to derive the dimensionless variables involved in the process and to determine general relationships useful for the evaluation of the baffle performances for the capture of floatables.

In order to extend the obtained results, future experiments could be aimed at evaluating how the channel width and the baffle shape could affect the device capturing performances.

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