Critical velocity of floatables in Combined Sewer Overflow (CSO) chambers

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Water Science and Technology **Vol 44 No 2–3 pp 287–294** © IWA Publishing 2001

Abstract Although the efficiency of underflow baffles has never been clearly proven, these underflow baffles have gained in popularity over the last few years as a viable means to intercept floatables in Combined Sewer Overflows (CSOs). These pilot scale essays, performed in a 17.0 metres basin at various flowrates, show that a critical horizontal velocity (V_{CR}) may develop in the overflow chamber. Whenever this critical velocity is exceeded, floatables that would normally rise to the surface are kept within the flow and never intercepted, thus rendering the underflow baffle ineffective. The equation relating the critical horizontal velocity to the vertical velocity is found to be: $V_{CR} = 16\ w\ R_H{}^{1/6}$.

Keywords Baffles; critical velocity; CSOs; efficiency; floatables

Introduction

Floatables emanating from combined sewer overflows (CSOs) are an aesthetic source of pollution. As part of a long term watershed plan, these pollutants will have to be eliminated. Indeed, removal of floatables is one of the Nine Minimum Controls required under the April, 1994 EPA CSO Control Policy (US EPA, 1994).

Utilisation of underflow baffles in front of overflow weirs for control of floatables in CSOs is one of the many technologies considered by the US EPA (United States Environmental Protection Agency). Recommended as a short-term best management practice (BMP) and as part of long-term solutions, this technology has attracted much interest from consulting engineers and municipalities due to its apparent simplicity, low operation and maintenance (O&M) costs. All this took place although the actual efficiency of the underflow baffles has never been clearly demonstrated. In this context, the study of floatables in CSOs has been actively pursued. The objective of this article is to present the methodology and hydraulic data leading to a critical velocity in the overflow chamber.

General definitions

Turbulent flow can be defined as the random instantaneous variation of velocity and direction in the flow, by opposition to a laminar flow where the instantaneous velocity is equal in direction and value to the average velocity (Munson *et al.* 1990). Suspension occurs when a material reaches an equilibrium state between gravity and buoyancy forces and is not in contact with the free surface or the bottom of the channel.

Suspended materials in CSOs can be divided into two categories:

a) *Settleable solids* are heavier than water (ρ_{SOLID}>1,000 kg/m^3). In favourable circumstances they tend to settle on the bottom of the basins and/or receiving rivers. The settling characteristics of solids in CSOs has become of some concern and has been extensively studied (Dalrymple *et al.*, 1975, Chebbo *et al.*, 1995, Aiguier *et al.*, 1995, O'Connor *et al.*, 1999).

b) *Floatables* are lighter than water (ρ_{SOLID}<1,000 kg/m^3). In favourable circumstances they tend to rise to the surface of the flow. Floatables are divided into two categories according to their state in the flow. If floatables are suspended within the flow, by the action of turbulence, they are called swimming solids ($\rho_{SOLID} \cong 1{,}000$ kg/m^3). If floatables reach the free surface, they are called floating solids.

It should be noted that some suspended solids that initially behave as floatables, would turn to settable solids after becoming saturated with water. Furthermore, a floatable at a given time may be either swimming or floating, depending upon hydraulic conditions of the flow.

The critical velocity concept

The transport of floatable solids in a suspended state (swimming) is due to the turbulence of the flow. Although the instantaneous value and direction of the turbulence varies all the time, it is generally accepted that the turbulence lifts upward the settled solids from the bottom and drags downward floating solids from the surface. In laminar flow, all solids with sufficient density would gather at the bottom of the channel and all light solids would float at the surface of the flow, as is the case in a stagnant body of water.

Previous work done on dual-density flows, oil-water separators in particular, have shown that a critical velocity (V_{cr}) of oil globules exists in the flow. Researchers at the American Petroleum Institute (API) have found that a horizontal velocity of 15 times the vertical velocity will stop the oil globules from reaching the surface, keeping them in the flow (API, 1990).

$$V_{cr} \cong 15w \tag{1}$$

where: V_{cr} = Critical velocity of the oil globule in the oil-water separator, in (m/s);
w = Vertical velocity of the design oil globule in still water, in (m/s);

Can this same phenomenon be applied to floatables encountered in CSOs? If this were the case, the evidence of a critical velocity (V_{cr}) would largely modify the optimal design of an underflow baffle. The transition from the floating phenomena to the suspension phenomena is delimited by this critical velocity. If the average horizontal velocity of the flow in an overflow chamber is less than the hypothesised critical horizontal velocity, the swimming floatable will rise towards the surface without dropping back by the action of the turbulence. On the other hand, if the average horizontal velocity of the flow is greater than the critical horizontal velocity, the suspended floatables will remain imprisoned in the flow and will not be intercepted by the baffle.

Material and methods

Hydraulic tests were conducted in a channel 1.0 m wide and 17.0 m long at the Hydraulics Laboratory of the École Polytechnique of Montreal. The objective of these studies was to research the existence of a critical flow velocity (V_{cr}) for floatables. This V_{cr} would then have to be related to the vertical velocities of the floatables as in the API studies. The critical velocity will be expressed as $V_{CR\ \%,D}$, the critical velocity not to exceed to reach a given percentage (%) of removal of floatables for a given length of chamber D. The floatables used in these tests correspond to those sampled in the Greater Montreal area as described in Paradis *et al.* (1996) and Cigana *et al.* (1998). The principal representative of floatables in CSOs are: preservatives, oak leaves, sanitary applicators, cigarette butts, popsicle sticks, Zip-Lock bags, cigarette packs, plastic coffee stirrers and Q-Tips. The vertical velocities in still water (w) were measured in a previous study (Cigana *et al.*, 1998).

A complete test consists of the release of the floatables, in the flow, at a given proportion of the depth of the channel as shown in Figure 1. The release depth ranged from 20% to 50% of the total water depth (H). For each essay two pieces of information are retrieved: the horizontal distance travelled to reach the surface (D) and the elapsed time (t) for the floatable to reach the surface.

Whenever a floatable does not reach the surface, its elapsed time to reach the surface is infinite ($t = \infty$) and therefore its vertical velocity is considered nil ($V = 0$). Ten repetitions of the release for each of the floatables were done to obtain a significative average and median. The horizontal water velocity in these experiments ranged from 0.2 to 1.4 m/s. Twelve categories of CSOs were used in 8 sampling campaigns for this study. Vertical rising velocities for a particular floatable were ranked in descending order for a series of 10 essays. The vertical velocity of the eighth element of the ten tests represents the minimal velocity ($w'_{8/10}$) to obtain an efficiency of 80%.

Adimensional parameters of analysis

As is sometimes the case in the study of hydraulic tests, adimensional numbers are used to facilitate the analysis (Munson *et al.*, 1990). The adimensional Rouse number (Z), cited by Simons and Senturk (1977), is used to relate the vertical velocity of a floatable to the turbulent component of the horizontal velocity.

The proportions K_1 and K_2 are also introduced to study the flow. The proportion K_1 relates the horizontal velocity of the floatables to the average horizontal velocity of the flow, whereas the proportion K_2 is aimed to study the ratio of the vertical velocities of the floatables in the flow with that of the same floatable in still water.

Rouse number (Z). The Rouse number is defined as:

$$Z = \frac{w}{\kappa U^*} \qquad (2)$$

where k = Van Karman constant = 0.4

w = Vertical velocity of a floatable in still water (m/s)

$$U^* = \text{Root-Mean Square turbulent velocity component} = Vn\sqrt{\frac{g}{R_h^{1/3}}} \qquad (3)$$

and

V = Horizontal velocity of the flow

n = Manning coefficient = 0.017 for our concrete basin

g = Gravity acceleration = 9.8 m/s^2

R_h = Hydraulic radius of the cross-section of the basin, in (m)

K_1 parameter. The parameter K_1 measures the ratio of horizontal velocities of the floatables in the flow. This parameter is defined as:

$$K_1 = \frac{V'}{V} \qquad (4)$$

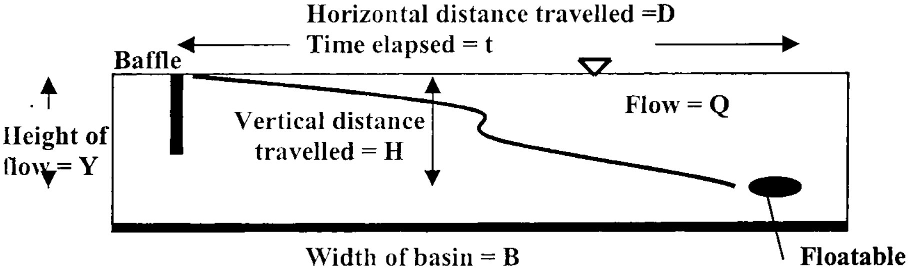

Figure 1 Schematic view of a channel used for the vertical velocity essays

where V = Average horizontal velocity of flow in basin $= \frac{Q}{YB}$, in (m/s)

V' = Horizontal velocity of floatable in flow $= \frac{D}{t}$, in (m/s)

K_2 parameter. On the other hand, the rise of floatables is studied through the relation K_2 defined as:

$$K_2 = \frac{w'}{w} \tag{5}$$

w' = Vertical velocity of a floatable in a flow $= \frac{H}{t}$, in (m/s)
w = Vertical velocity of a floatable in a *still* flow, in (m/s)

Results and discussion

Horizontal velocity of floatables, K_1

Results show that the horizontal velocity of the floatables is roughly stable throughout the flow. The ratio K_1 is not greatly affected by the turbulent flow and corresponds to the average horizontal velocity of the flow. The numerical value of K_1, for all practical purposes, is therefore 1.0. This means that we can correctly hypothesise that the average velocity of the turbulent flow is equal to the horizontal velocity of the floatable.

Vertical velocity of floatables, K_2

Results show that vertical velocities can be enhanced or hindered according to the value of the root-mean square velocity of the turbulent flow (U^*), as shown in Figure 2. A turbulent velocity ranging between 0.015 et 0.035 m/s will, on average, ameliorate vertical velocities by a factor of up to 20% when compared to the vertical velocity measured in still water (w). Higher turbulent velocities will, on average, create adverse situations where the vertical velocity will be greatly reduced. A very high intra-essay variability was measured for each of the replicates, ranging from 25 to 50% of the mean values. These large variations are to be expected when dealing with such random events as turbulent flow. The error bars plotted on the experimental data show that for the turbulent velocity range previously discussed, 0.015 to 0.035 m/s, the vertical velocity of the floatable can range between an increase of 50% or a decrease of 30% from the average vertical velocities values. Outside this range, the vertical velocity diminishes as soon as the turbulent velocity increases, reaching as low as 20% of the vertical velocity in still water.

Critical velocity, V_{CR}, %, D

Figure 3 shows a graph of the Rouse number (Z) calculated for each of the essays as a function of the minimal vertical velocity necessary to obtain an 80% efficiency ($w'_{8/10}$) for a

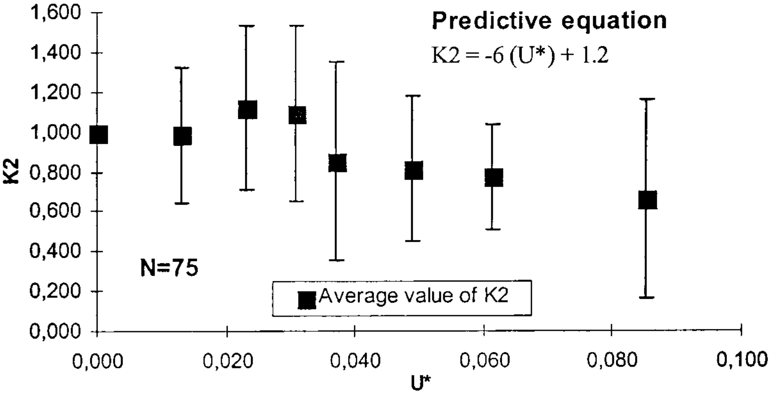

Figure 2 Graph of K_2 in function of U*

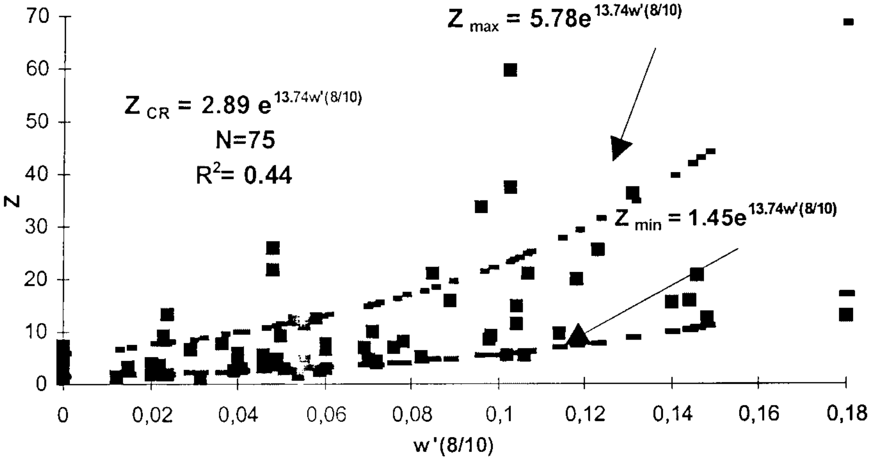

Figure 3 Graph of Rouse number (Z) in function of $w'_{8/10}$

given chamber length D. This curve shows that an exponential relationship exists between the Rouse number and the vertical velocity necessary to obtain an 80% efficiency in floatable removal. Although there is a lot of dispersion in the experimental points and a low coefficient of correlation derived from the data, the general trend of the curve is well established. Fifty of the 75 experimental data points fall between the minimal and maximal lines of influence. The critical horizontal velocity in the flow is obtained when the vertical velocity of the eighth element tested is equal to zero, i.e. when $w'_{8/10}$ is equal to zero and no floatables are intercepted. This means that the eighth floatable never reached the surface and was not intercepted by the underflow baffle. The critical Rouse number found in our data is $Z_{CR,\,80\%} = 2.89$ when $w'_{8/10} = 0$ m/s. The basic tenet of this analysis is that a floatable that doesn't reach the surface in 17 m will probably never reach the surface. In this sense, the notation $Z_{CR,\ 80\%,\ D}$ becomes $Z_{CR,\ 80\%,\ D\,=\,\infty}$. In a number of tests, some floatables released in the flow at different depths were not able to rise to the surface for the entire length of the test channel. These pilot-scale essays seem to confirm the existence of a critical velocity ($V_{cr,\,\%,\,D}$) for floatables in CSOs.

Determination of the critical velocity

It is possible to relate the critical Rouse number measured in a flow to the horizontal critical velocity ($V_{CR\ \%,D}$). By simultaneously solving for U^* in Equations 2 and 3, it becomes possible to find $V_{CR\ \%,D}$.

$$U^* = \frac{w}{\kappa Z} \qquad \text{(Eqn 6 derived from Eqn 2)}$$

$$U^* = Vn\sqrt{\frac{g}{R_h^{1/3}}} \qquad \text{(Eqn 3)}$$

Combining equations 6 and 3, it becomes possible to solve for the horizontal velocity, V.

$$\frac{w}{\kappa Z} = \frac{nV\sqrt{g}}{R_h^{1/6}}$$

$$V = \frac{wR_h^{1/6}}{\kappa Z n\sqrt{g}} = wR_h^{1/6}\cdot\left(\frac{1}{n\kappa Z\sqrt{g}}\right) \qquad (7)$$

If we introduce the critical Rouse number ($Z_{CR} = 2.89$) found earlier and the numerical values in the right hand terms (k = 0.4, $n = 0.017$, $g = 9.8 m/s^2$), an expression for the critical horizontal velocity (V_{CR}) of the flow can be found for a removal efficiency of 80% of the floatables in our experiments and a chamber length of 17 metres.

$$V_{CR} = \frac{wR_h^{1/6}}{\kappa Z_{CR} n\sqrt{g}} = 16wR_h^{1/6} \tag{8}$$

Length-efficiency relationship

It is important to notice that there is a relationship between chamber length *D*, removal efficiency % and vertical and horizontal velocities, *w* and *V*.

For a floatable of characteristic vertical velocity *w*, a desired interception efficiency of 80% and physical quantities *H* and *U** known, it is possible to calculate a corresponding Z_{CR}. With the curve on Figure 3, the value of Z_{CR} can be related to a necessary vertical velocity *w*'(8/10). Knowing this *w*'(8/10) value, the critical length of the chamber D_{CR} can be calculated using the following equation:

$$D_{CR} = \frac{V * H}{w'(8/10)} \tag{9}$$

Conversely, for a chamber length of *D*, with known *w*'(8/10) and *U**, the characteristic vertical velocity of the floatable w can be deduced.

Indeed, from equation 9, it follows that:

$$w'(8/10) = \frac{VH}{D}$$

This value of *w*'(8/10) can be related to a value of *Z* with the graph in Figure 3.

Release depth of floatable

Initially, the depth of release of the floatable was considered crucial in whether a floatable would reach the surface. Floatables were released from depths ranging from the bottom 20% to 50% of the total water depth. Mitigated results show that the depth of release has very little bearing on the final outcome of the floatable. Some floatables released deeply in the channel made their way back to the surface and some floatables released half-way up the channel swam their way across the basin. The initial depth of release was therefore of no real consequence in the interception of the floatable on a baffle.

Conclusions

A critical horizontal velocity ($V_{CR,\ \%,\ D}$) can develop in overflow chambers under certain hydraulic conditions. Floatables found in the flow when this critical velocity occurs will stop it from reaching the surface, rendering useless the underflow baffle. Therefore, this critical velocity greatly influences the configuration and design of the overflow chamber. Presently, this critical velocity is not taken into account in the design of underflow baffles. Although an inexpensive solution, this renders inefficient existing overflow chambers outfitted with underflow baffles. Two different approaches can be explored to correctly control floatables: stricter design rules should be provided in order to ensure a better interception efficiency of floatables or investment in more sturdy and reliable equipment installed in the overflow chamber, like bar screens or sieving, for example.

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