Flow velocities and shear stresses during flushing operations in sewer collectors

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Abstract Many relevant problems of drainage systems such as first flush pollution, flow capacity reduction and consequent risks of surcharges are worsened by sediment accumulation in sewer collectors. For the solution of these problems several sediment cleansing methods and techniques, e.g. mechanical methods, traps and flushing devices, have been developed and applied in the last decades. In particular, simulation studies and experimental campaigns have shown the effectiveness of flushing methods as preventive cleansing strategy in sewer collectors.

In this paper the results of a numerical investigation for determining flushing waves characteristics both in terms of duration and flow rate are presented. The collector section lengths where flow velocities and average shear stresses determined by flushing waves exceed minimum threshold values are evaluated using a dimensionless approach. The results, related to the operative ranges of the practical applications, are exposed by means of graphs and regressive equations.

Keywords Flushing; sediment; sewer cleansing

Introduction

The re-suspension of the deposited solids during rain events has been recognised as one of the main causes for first flush pollution in sewer systems. Further, the sediment accumulation in sewer collectors can produce also significant hydraulic restrictions reducing the design flow capacity and increasing the risks of surcharges during wet weather flows.

In order to solve these problems, during the last decades, the origins and the characteristics of solids deposited in combined and in separate sewer networks have been studied and several methods and techniques for cleansing sediments have been developed. In particular several studies on modelling of sediment production, build-up and wash-off over the urban catchment surfaces have been carried out (Ashley and Crabtree, 1992; Bertrand-Krajewski et al., 1993; Gent et al., 1996).

Other studies have focused on the nature and behaviour of sediments (Michelbach, 1995), on mechanics of sewer sediment erosion and transport (Ashley and Verbank, 1996; Arthur and Ashley, 1997; Fraser and Ashley, 1999) and on the influence of cohesion on sediment erosion (Berlamont and Torfs, 1996; Tait et al., 1998).

Different sewer self-cleansing criteria have also been proposed. Older studies carried out in the first half of the last century have fixed minimum self-cleansing velocities of about 0.5–0.6 m/s for the maximum daily foul flow (Imhoff, 1928; Davis, 1952). More recent results, summarised in Nalluri and Ab-Ghani (1996) suggest minimum values of velocity and shear stress for different sewer type and different pipe filling conditions. In particular reported velocity values range from 0.6 to 1.5 m/s whereas shear stress values range from 1.0 to 6.2 N/m². Similar minimum values of velocity for non-cohesive sediments are presented in May et al. (1996) while indications on the minimum shear stress for the erosion of accumulated cohesive sediment beds are reported in Nalluri and Alvarez (1992) ranging from 2.5 to 7.0 N/m². Generally these studies lead to recognise that a single value of minimum flow velocity or minimum shear stress could not adequately describe the...
self-cleansing conditions in all pipes of different size, roughness and gradient for a range of sediment characteristics and flow conditions (Pisano et al., 1998).

At the same time several methods and techniques for cleansing sediments have been developed and applied with various success to different sewer systems (Pisano et al., 1998). In particular mechanical methods, traps and flushing devices have been used over the years and considerable experience and large number of results have been gained by many research groups.

Recently, some simulation studies and experimental campaigns have been specifically carried out in order to determine the cleansing effects of high speed flushing waves in sewer collectors (Gatke and Borcherding, 1996; Lorenzen et al., 1996; Chebbo et al. 1996; Ristenpart, 1998). These studies show the effectiveness of the flushing methods as preventive strategy for sewer cleansing, allowing only for the accumulation of small amounts of sediments (Lorenzen et al., 2001). Besides, Carravetta et al. (2000) tested an old Italian formula for flushing devices and suggested a design criteria for pipe diameter values of 0.3 m and 0.5 m and for a few slope values.

In short it seems still useful to develop general criteria for the determination of the flushing waves characteristics (flow rate and duration).

In this paper a numerical investigation on flushing in sewer collectors is presented in order to obtain indications on sewer cleansing effects in relation to the pipe and sediment characteristics. The collector section lengths where flow velocities and average boundary shear stresses determined by flushing waves exceed minimum threshold values are evaluated using a dimensionless approach. The obtained results, relative to the operative ranges of the practical applications, are presented by means of graphs and equations.

Equations and numerical model

The analysis of the flushing waves needs a realistic description of the hydrodynamic flow characteristics and, for a generalisation of the results, it has to be performed by using a dimensionless approach. In order to achieve these features the present investigation has been developed by using the dimensionless fully-dynamic De Saint Venant equations obtained with the following dimensionless variables:

\[ \bar{h} = \frac{h}{h_0}; \quad \bar{B} = \frac{B}{h_0}; \quad \bar{R} = \frac{R}{h_0}; \quad \bar{A} = \frac{A}{h_0^2}; \quad \bar{V} = \frac{V}{V_0}; \quad \bar{Q} = \frac{Q}{Q_0}; \quad \bar{F}_h = \frac{F_h}{F_{h0}} \quad (1) \]

\[ \bar{R}_0 = \frac{R_0}{h_0}; \quad \bar{A}_0 = \frac{A_0}{h_0^2}; \quad \bar{F}_0 = \frac{V_0}{\sqrt{gh_0}} \quad (2) \]

\[ \bar{x} = \frac{x}{L_0}; \quad \bar{t} = \frac{t}{t_0}; \quad L_0 = \frac{h_0}{i}; \quad t_0 = \frac{L_0}{V_0} = \frac{h_0}{iV_0} \quad (3) \]

where \( h, B, R, A, V, Q, F_h \) are respectively water depth, surface width, hydraulic radius, wetted area, flow velocity, flow rate and hydrostatic force over a cross section; \( h_0, R_0, A_0, V_0, Q_0, F_{h0} = \rho gh_0^3 \) are the corresponding variables referred to the maximum entering flow rate \( Q_0 \) and evaluated considering uniform flow conditions; \( F_0 \) is the Froude number in the same flow conditions; \( \rho \) is the water density; \( g \) is the gravity acceleration; \( x, t \) are the spatial and temporal independent variables; \( L_0, t_0 \) represent respectively a characteristic collector length and a characteristic flow time, being \( i \) the average collector slope.

For a prismatic collector, neglecting the lateral flows, the dimensionless De Saint Venant equations can be written in the conservation-law form:

\[ \frac{\partial \bar{U}}{\partial \bar{t}} + \frac{\partial \bar{F}(\bar{U})}{\partial \bar{x}} = \bar{D}(\bar{U}) \quad (4) \]
The dimensionless approach shows that the values of $\bar{A}$ and $\bar{Q}$, as function of $\bar{x}$ and $\bar{t}$, depend in general on five different dimensionless parameters: three of them are related to the geometrical and hydraulic characteristics of the collector and the other two are related to the entering hydrograph. Neglecting the initial base flow rate and considering both circular cross-sections and rectangular entering hydrographs, like the hydrographs generated by many siphon flushing devices, the dimensionless parameters are reduced to three: $\bar{A}_0$, $F_0$, and $\bar{t}_f = \frac{t_f}{t_0}$

where $t_f$ is the duration of the entering flushing hydrograph.

In order to reproduce the typical phenomena connected with flushing the McCormack numerical scheme has been chosen for solving Eq. (4). This scheme is a “shock-capturing” scheme, i.e. it is able to describe rapidly varied flow discontinuities such as hydraulic jumps and shock waves propagating over initial dry beds. An additional procedure based on the theory of Total Variation Diminishing (TVD) (García-Navarro et al., 1992) is also coupled to the McCormack scheme for reducing the numerical oscillations generated in correspondence of the high flow gradients.

Boundary conditions are imposed at the upstream and downstream ends by means of the usual method of characteristics in relation to the subcritical or supercritical flow conditions.

The numerical model is then well suited for reproducing the hydraulic effects of high speed waves generated by flushing devices in sewer collectors.

Simulations and analysis of the results

In order to obtain indications on sewer cleansing effects, simulations have been run evaluating the section lengths where flow velocities and average boundary shear stresses, determined by the flushing waves, exceed minimum threshold values. Circular and straight sewer collectors with dimensionless length $\bar{L} = \frac{x_{\text{max}}}{L_0}$ in the range of values 0–30 have been considered.

The simulations have been run taking into account different values of the three considered dimensionless parameters. In particular values of $\bar{A}_0$ between 0.9 and 4.0, of $F_0$ between 0.4 and 1.4 and values of $\bar{t}_f$ between 0.5 and 5.0 have been considered. Values of $F_0$ higher than 1.4 have not been investigated considering their low occurrence in sewer collectors with deposition problems. The adopted values are summarised in detail in Table 1 and allow for considering dimensional variable values in the ranges of the practical applications.

For all the simulations a spatial step $\Delta \bar{x} = \bar{L}/750$ has been considered while time steps $\Delta \bar{t}$ have been evaluated maintaining the Courant number $C = 0.8$.

In Figure 1 the results in terms of maximum flow velocities $\bar{V}$ along the collector obtained for $F_0 = 0.8$, $\bar{t}_f = 2.0$ and for the complete range of values of $A_0$ are presented. The figure shows the decreasing trend of the curves due to the propagation effects of the waves. In particular the curves are characterised by two parts with different trends. The first part, for low values of $\bar{x}$, in which flow velocity tends to uniform conditions ($\bar{V} = 1$), represents
substantially the length covered by the flushing wave front until the emptying wave, consequent to the flushing end, has reached the front itself. The second part, for higher values of \( \bar{x} \), is related to the successive emptying phase.

Considering the decreasing trend of the curves, the graph can be used for evaluating the section lengths \( x \) where flow velocities \( V \) exceed minimum threshold values.

Similar curves have been obtained considering the dimensionless average flow shear stresses \( \bar{\tau} \) (related to the shear stresses in uniform flow conditions \( \tau_0 \)) instead of the flow velocities \( V \). These curves also present the two different trends and allow for determining the dimensionless section lengths \( x \) where shear stresses \( \bar{\tau} \) exceed minimum threshold values. The results obtained for the entire examined ranges of \( \bar{t}_f \) and \( \bar{A}_0 \) are plotted in Figure 2 for the lowest and the highest adopted values of \( F_0 \). The figure shows the high influence of the dimensionless flushing duration \( \bar{t}_f \).

In particular, as expected, increased values of \( \bar{t}_f \) produce longer flushed sections for fixed threshold shear stresses.

Globally all the simulations have shown that flushing durations \( \bar{t}_f \) equal to 0.5, 1.0, 2.0 and 5.0 lead to dimensionless shear stresses higher than about 0.10, 0.25, 0.40 and 0.80 respectively for the entire length \( L \) investigated.

Moreover the graphs show that lower values of \( \bar{A}_0 \), corresponding to higher water depths, produce longer flushed sections, while the comparison between the curves for \( F_0 = 0.4 \) and \( F_0 = 1.4 \) puts in evidence the low influence of this last parameter.

From the practical point of view the graphs of Figure 2 can be easily used in order to evaluate the flushed section lengths \( x \) once have been fixed the geometrical characteristics of the collector and of the entering hydrograph, i.e. \( \bar{A}_0 \), \( F_0 \) and \( \bar{t}_f \), and once have been determined the necessary cleansing flow shear stresses \( \bar{\tau} \) (by means of specific transport formulae).

More operatively, in order to compact the results relative to all the simulations, useful regressive equations are here proposed with reference to the shear stress variable. In particular regressive equations have been evaluated dividing the range of \( \bar{x} \) in two parts relative to the different trends found. The splitting value \( \bar{x}_s \) has been determined as function of \( \bar{t}_f \) as:

\[
\bar{x}_s = 2.569 \bar{t}_f^{0.906}
\]  

(7)
The multiple non linear regressions led to:

\[ \bar{x} = 37.380 \tau^{-7.927} A_0^{-0.215} F_0^{0.073} \tau_f^{0.253} \quad R^2 = 0.878 \quad \text{for } \bar{x} \leq \bar{x}_s \]  
\[ (8) \]

\[ \bar{x} = 6.821 \tau^{-1.219} A_0^{-0.291} F_0^{0.028} \tau_f^{0.803} \quad R^2 = 0.808 \quad \text{for } \bar{x} \geq \bar{x}_s \]  
\[ (9) \]

Alternatively, when \( \bar{x} \) is known, the corresponding \( \tau \) value can be determined as:

\[ \bar{x} = 1.848 \bar{x}^{-0.234} A_0^{-0.050} F_0^{-0.020} \tau_f^{-0.019} \quad R^2 = 0.837 \quad \text{for } \bar{x} \leq \bar{x}_s \]  
\[ (10) \]

\[ \bar{x} = 2.189 \bar{x}^{-0.555} A_0^{-0.171} F_0^{0.011} \tau_f^{-0.609} \quad R^2 = 0.964 \quad \text{for } \bar{x} \geq \bar{x}_s \]  
\[ (11) \]
Conclusions
In this paper a numerical investigation on flushing in sewer collectors is presented in order to derive indications on sewer cleansing effects. The section lengths where flow velocities and shear stresses, determined by flushing waves, exceed minimum threshold values have been evaluated. In order to obtain realistic simulations of the flushing and to generalise the results, the analysis has been performed by using the dimensionless fully-dynamic De Saint Venant equations solved by the TVD McCormack numerical scheme.

A large number of simulations have been run considering circular and straight sewer collectors and adequate ranges of values of three dimensionless parameters characterising the hydraulic of the phenomena.

Firstly the simulations have shown a rapid decreasing of the flow velocities and shear stresses values in the upstream part of the collector. Secondly an high influence of the flushing duration $t_f$ and consequently of the flushing volume has been shown in the results. In particular, considering long flushing events, appreciable flow shear stresses, close to the shear stresses produced by the flushing flow rate in uniform conditions, can be achieved in the examined range of $L$. Moreover, a lower influence of the parameter $A_0$ has been found while negligible effects have been evidenced with reference to the parameter $F_0$.

Finally, on the basis of all the simulations results, useful regressive equations have been proposed for evaluating the section lengths where shear stresses exceed minimum threshold values or, vice versa, for determining the minimum shear stress achieved in a prefixed collector section length.

Globally, the results obtained from the sensitivity analysis on the parameters concerned in the flushing operation can provide practical indications for the correct setup of flushing devices in sewer collectors.

References