Modelling the flushing of sediments in a combined sewer

Modélisation de la chasse hydraulique des sédiments dans un collecteur unitaire

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RESUME

L’accumulation des sédiments dans les réseaux d’assainissement est la source de nombreux problèmes hydrauliques et environnementaux. Parmi les nombreux moyens de curage disponibles, les vannes de chasse hydraulique représentent une solution efficace et économique pour le curage des sédiments.

L’article présente les résultats d’une modélisation numérique de la chasse hydraulique des sédiments dans un collecteur unitaire. Les simulations ont été effectuées en résolvant les équations de Saint Venant-Exner avec un schéma numérique de type TVD MacCormack.

Le modèle, préalablement validé avec des données expérimentales de laboratoire, a été appliqué au cas d’une campagne expérimentale effectuée dans le collecteur Lacassagne à Lyon (France), où une vanne de chasse hydraulique Hydrass a été utilisée en 2003 pour le curage de sédiments accumulés depuis 3 ans. Le modèle permet de reproduire correctement l’évolution générale des profits de sédiments en fonction du nombre de chasses.

ABSTRACT

The accumulation of sediments in sewers is responsible for various hydraulic and environmental problems. Among the existing cleansing devices, flushing gates have recently proven to be a valid cost-effective solution for the cleansing of sediments.

This paper reports the results of the numerical modelling of sediment flushing in a combined sewer reach. Simulations were performed using a numerical model based on the solution of the De Saint Venant-Exner equations by the TVD MacCormack scheme.

The model, which had been initially validated against data derived from several laboratory experiments, was compared with the results of the field experimental campaign carried out in the Lacassagne trunk sewer in Lyon (France), where a Hydrass flushing gate had been put into operation in 2003 to remove sediments accumulated during 3 years. The model is able to reproduce correctly the global evolution of the sediment profiles as they change with the number of flushes.

KEYWORDS

Flushing, combined sewer, sediment transport, sewer cleansing, unsteady flow modelling.
1 INTRODUCTION

In the last decades, the management of sewer solids has become an important scientific and operational research subject due to the related hydraulic and environmental problems (Ashley et al., 2004). Sediments are in fact responsible for blockages in sewers, as well as for environmental problems due to the re-suspension and discharge of solids and associated pollutants through CSO devices into water bodies during rain events (Fan et al., 2003). Among the existing cleansing devices used in sewers, flushing gates have proven to be a valid cost-effective solution for the removal of sediments (Dettmar and Stauffer, 2005). These devices are generally inserted in-line in sewers and are designed in order to produce consecutive flushing waves, able to re-suspend deposited sediments and to transport them towards trunks with higher solid transport capacity or appropriate interception devices.

Flushing gates are the subject of a research program being developed in collaboration by the INSA de Lyon and the University of Catania. In 2001, a first experimental campaign with a Hydrass flushing gate (Sikora, 1989) was carried out in the 1.8 m x 1.1 m egg-shaped Pompidou trunk sewer in Lyon, France (Bertrand-Krajewski et al., 2003). During the experiments, flow rates and water levels upstream and downstream of the Hydrass gate were measured in order to analyse both the outflow process through the device and the downstream flushing wave propagation. In particular, hydraulic investigations allowed the derivation of an empirical outflow relation valid for the adopted gate and the analysed site.

Bertrand-Krajewski et al. (2005) performed an experimental analysis of the hydraulic behaviour of a Hydrass gate at the laboratory of Hydraulics of the University of Catania. Physically based outflow relations were derived from experimental measurements carried out under steady flow conditions using a scale model of the Hydrass gate used in Lyon. The proposed gate outflow relations were then implemented into a numerical flow routing model specifically developed for flushing simulations and validated under unsteady flow conditions by comparing the results of the model with the experimental data relative to real flushes in Lyon. A further validation of the gate outflow relations was carried out by Campisano et al. (2006) by numerical simulations dealing with laboratory flushing experiments under unsteady flow conditions.

In 2003, a second experimental field campaign was performed in the 1.8 m x 1.1 m egg-shaped Lacassagne trunk sewer in Lyon, France (Bardin et al., 2005), in order to analyse the effectiveness of flushing waves in the removal of deposited sediments. For this purpose, a Hydrass gate identical to the one used in the first campaign was installed and put into operation in the upstream part of the Lacassagne sewer, in order to flush sediments previously accumulated during 36 months. Experiments provided data relative to sediment profile evolution in the Lacassagne trunk sewer and to water levels upstream of the gate during about 12000 consecutive flushes.

This paper concerns the numerical modelling of the flushing of sediments in the Lacassagne sewer. In particular, firstly the numerical model adopted for the simulations is presented; then, the experimental site is described; finally, the comparison between numerical results and experimental data is reported.

2 NUMERICAL MODEL

The numerical model used for the simulations of sediment flushing in the Lacassagne sewer is based on the solution of the De Saint-Venant-Exner equations written in the following vectorial conservation law form (Bhallamudi and Chaudhry, 1991):

\[
\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} = \mathbf{D}(\mathbf{U})
\]

(1)
with the vectors $\mathbf{U}$, $\mathbf{F}$ and $\mathbf{D}$ given by:

$$
\mathbf{U} = \begin{bmatrix}
A \\
Q \\
A_s
\end{bmatrix},
\mathbf{F}(\mathbf{U}) = \begin{bmatrix}
0 \\
Q - V \cdot Q + \frac{F_h}{\rho} \\
1 - p \cdot Q_s
\end{bmatrix},
\mathbf{D}(\mathbf{U}) = \begin{bmatrix}
0 \\
g \cdot A \cdot (i - J)
\end{bmatrix}
$$

(2)

where $x$ [m] and $t$ [s] are the spatial and temporal independent variables respectively, $A$ [m$^2$] is the wetted area, $Q$ [m$^3$/s] and $V$ [m/s] are the water discharge and flow velocity respectively, $F_h$ [N] is the hydrostatic force over the cross section, $\rho$ [kg/m$^3$] is the water density, $g$ [m/s$^2$] is the gravity acceleration, $i$ is the channel bottom slope and $J$ is the energy friction slope. Moreover, $p$ is the sediment porosity, $A_s$ [m$^2$] is the sediment cross sectional area and $Q_s$ [m$^3$/s] is the sediment discharge.

The friction slope $J$ is evaluated by the Manning-Strickler equation:

$$
J = \frac{Q^2}{K_c^2 A^2 R^{4/3}},
$$

(3)

with $R$ [m] and $K_c$ [m$^{1/3}$/s] being the hydraulic radius and the Strickler composite roughness coefficient, respectively. This coefficient is evaluated by the Einstein relation (Einstein and Banks, 1950), taking into account various roughness values $k_i$ on various parts $P_i$ of the wetted perimeter $P$:

$$
k_c = \left( \frac{P}{P_w + P_D} \right)^{2/3},
$$

(4)

where the subscripts $w$ and $b$ are related to the channel side walls and bottom, respectively. In the case of bed sediments, $K_c$ can be evaluated as a function of the sediment characteristic grain size by the well known Strickler formula.

The solution of Equation 1 requires the use of a sediment transport formula for the estimation of the sediment discharge $Q_s$ as a function of flow and sediment characteristics. The Meyer-Peter and Müller formula (Meyer-Peter and Müller, 1948) was used in the elaborations of this paper; this formula can be written as follows:

$$
Q_s = C_{MPM} B \left[ \frac{\rho_s - \rho}{\rho} \right] \left[ \frac{\tau}{\left( \frac{\rho_s - \rho}{\rho} \right) g d_{50}^2} \right]^{3/2},
$$

(5)

where $B$ [m] is the channel width, $\rho_s$ [kg/m$^3$] is the sediment density, $d_{50}$ [m] is the mean diameter, $\tau$ [N/m$^2$] is the shear stress on the sediment bed [N/m$^2$] and $\theta_c$ is the entrainment factor (dimensionless critical shear stress), to be fixed equal to 0.047 for granular sediments. The coefficient $C_{MPM}$ is generally assumed equal to 12 under high shear stress conditions (Nielsen, 1992), as during flushing operations. Equation 5 with $C_{MPM} = 12$ takes both bed-load and suspended-load transport into account.

The finite difference predictor-corrector MacCormack scheme is used for the numerical integration of equation (1) (Campisano et al., 2004). The scheme has a second order accuracy and is shock capturing, i.e. able to reproduce the propagation of internal discontinuities such as hydraulic jumps and shock waves. A step based on the Total Variation Diminishing (TVD) theory is applied in order to reduce the numerical oscillations corresponding to high gradients in the water flow variables.
3 THE EXPERIMENTAL SITE

The Lacassagne trunk sewer reach (Bardin et al., 2005) in Lyon (France) is almost 400 m long and has a 1.8 m high and 1.1 m wide egg-shaped cross section. It has a very irregular invert with hollows, humps and counter-slopes (Figure 1). It terminates in a confluence with the Paul Bert trunk sewer.

![Figure 1. Elevations of the bottom of the Lacassagne sewer reach with reference to the lowest section.](image)

The average dry-weather flow in the reach is about 0.04 m$^3$/s.

Deposited sediments have median grain size, density and porosity close to 270 μm, 1800 kg/m$^3$ and 0.285 respectively.

In 2003, a Hydrass gate was put into operation in the Lacassagne trunk sewer to scour sediments which had previously accumulated during 36 months (Bertrand-Krajewski et al., 2006).

The Hydrass gate (Figure 2) is an in-line flushing device, whose hydraulic behaviour can be summarized in two consecutive phases (Bertrand-Krajewski et al., 2005). In the first the gate is closed in the vertical position and allows the upstream in-line storage of water. In the second, after the gate tips around its horizontal hinge, the stored water volume is quickly discharged by the outflow process through both the upper and the lower parts of the device generating the flushing wave. The second phase ends when the gate tips back to the vertical position for a new storage process.

About 12000 consecutive flushing operations were performed in the Lacassagne trunk sewer over 5 months, from 16/05/2003 up to 28/10/2003 (Bardin et al., 2005).

The evolution of sediment profiles along the sewer was monitored by measuring manually sediment heights with a 5 m step over the 385 m length downstream of the Hydrass gate. Globally, 15 profiles were measured during the whole campaign.

A selected number of flushing operations was considered for the elaborations of this paper. In particular, the period between 18/06/2003 and 24/06/2003 (3095 flushing operations) was chosen, during which accurate measurements of the water level upstream of the gate were performed. In particular, water level measurements were carried out 3.0 upstream of the gate with a 5 s time step from 18/06/2003 to 20/06/2003 (1087 flushing operations) and with a 10 s time step from 20/06/2003 to 24/06/2003 (2008 flushing operations).
4 NUMERICAL SIMULATIONS

The numerical model described above was used to simulate the 3095 flushing operations performed in the Lacassagne trunk sewer in the period between 18/06/2003 and 24/06/2003. In particular, numerical simulations were performed adopting a spatial step $\Delta x = 0.5 \text{ m}$; the temporal step $\Delta t$ was fixed by imposing the Courant stability condition in the whole domain (Courant number $C_r = 0.8$).

As hydraulic upstream boundary condition, two hydrographs $Q(t)$ were considered, the first for flushes 0-1087 and the second for flushes 1088-3095; these hydrographs were obtained from the average water levels upstream of the gate during the flushes by the Hydrass gate outflow relation (Bertrand-Krajewski et al., 2005). For what concerns sediments, the discharge $Q_0(t) = 0$ was prescribed at the upstream end because sediment inputs were assumed to be negligible during the experiments.

A specific hydraulic condition was imposed at the downstream boundary; in particular, following experimental observations relative to dry weather flow conditions in the confluence of Lacassagne sewer with Paul Bert sewer, the downstream water level was fixed equal to 0.25 m.

The sediment profile along the Lacassagne sewer on 18/06/2003 (Figure 3) was adopted as initial condition of the bed for the numerical simulations.
Figure 3. Initial sediment profile along the Lacassagne sewer on 18/06/2003.

The results of the numerical simulation of sediment flushing in the Lacassagne sewer were compared with the experimental data in the graphs of Figure 4, where sediment profiles after 1064 and 3095 flushes are reported.

Figure 4. Comparison between measured and simulated sediment profiles along the Lacassagne sewer ($\theta_c=0.047$).
The observation of the graphs of Figure 4 points out that numerical results are not in good agreement with experimental data; in particular, the simulated sediment profile seems to be shifted forward in comparison with the experimental one, highlighting higher erosive effects in numerical simulations than in experiments. This may be ascribed to the fact that the numerical modelling did not take into account cohesive effects, which could be rather strong in sediment beds of Lacassagne sewer, especially at the upstream extremity where sediments accumulated and consolidated during 36 months.

An attempt was then made to try and reproduce the increased resistance to erosion of cohesive sediments with respect to granular sediments. For this purpose, other simulations were performed increasing the value of $\theta_{cr}$ in Equation 5; in particular, according to Skipworth et al. (1999) and Rushforth et al. (2003), the value $\theta_{cr} = 0.20$ was considered. The comparison between experimental data and numerical results with $\theta_{cr} = 0.20$ is reported in Figure 5.

Figure 5 highlights an improved agreement between numerical results and experimental data when $\theta_{cr}$ is equal to 0.20, above all for the sediment profile after 1064 flushes.

A possible complementary approach for further numerical simulations is that $\theta_{cr}$ could be a function of sediment depth and/or age, based on the sediment accumulation data.
5 CONCLUSIONS
In 2003, an experimental field campaign was performed in the 1.8 m x 1.1 m egg-
shaped Lacassagne sewer trunk in Lyon, France in order to analyse the effectiveness
of flushing waves in the removal of sewer sediments. The modelling of this
experimental field campaign was performed with the De Saint Venant-Exner
equations solved by means of the TVD MacCormack numerical scheme. The
comparison between numerical results and experimental data was carried out in
terms of sediment profiles along the Lacassagne sewer. Firstly, a numerical
simulation was performed using the model configuration that had been validated on
the basis of flushing experiments in laboratory flumes with granular sediments.
Further numerical simulations were then carried out, considering an increase in the
entrainment factor in order to allow for the effects of cohesion, leading to an
improvement of the model predictive capacity. Rather correct results were obtained,
but further improvements are still possible by refining some hypotheses.

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