In situ measurements of shear stresses of a flushing wave in a circular sewer using ultrasound

P. Staufer and J. Pinnekamp

ABSTRACT

Deposits build up in sewer networks during both spells of dry weather and in connection with storm water events. In order to reduce the negative effects of deposit on the environment, different cleaning technologies and strategies are applied to remove the deposits. Jet cleaning represents the most widely used method to clean sewers. Another alternative cleaning procedure is flushing. On account of new developments in measurement and control panels, the flushing method is becoming more important. Therefore, in the last few years a number of new flushing devices have been constructed for application in basins, main sewers and initial reaches. Today, automatic flushing gates are able to accomplish cleaning procedures under economical and ecological conditions.

The properties of flushing waves for cleaning sewers have been determined by several mathematical-numerical studies. These various investigations use altering numerical schemes, are based on different sets of physical equations and take one- or more dimensional aspects into account. Considering that bottom shear stress is the key value to evaluate the beginning of motion of any deposit, one may use this value that has to be determined by measurements. This paper deals with shear stresses caused by flushing waves which have been measured by an ultrasonic device that can determine the velocity in different depths of flow. Thus, it is possible, within certain limits, to calculate bottom shear stresses based on the log-wall law. Further discussion will deal with the requirements of measurements, its uncertainty and aspects in respect to the application of simulation of flushing waves.

Key words | flushing, sewer cleaning, shear stress, ultrasonic measurement, urban drainage

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INTRODUCTION

Deposits that built up during both spells of dry weather and storm water events have a great impact on water quality of receiving water bodies. Since emissions have been understood as the total load entering a receiving water body, consequently, integrated approaches have been followed. They have shown that any optimization strategy has to include waste water treatment as well as the sewer system (e.g. Schütze *et al.* 1999; Seggelke *et al.* 2005). With regard to sewer operation, deposits have been determined as a main source of emissions as they contribute greatly to the effect known as first flush (Verbanck 1990; Ashley *et al.* 1993; Huismann *et al.* 2000). Along with other restraints caused by sediments, such as the risk of blocking or H_2S degradation of concrete pipes, operators of sewer systems encounter sedimentation more often. Within the past few years, more and more flushing devices have become available because they offer the possibility of cleaning sewers often economically. Several international studies have proved this on laboratory scale (e.g. Campisano & Modica 2003; Campisano *et al.* 2005; Campisano *et al.* 2006) or full scale (e.g. Laplace *et al.* 2003; Bertrand-Krajewski *et al.* 2006; Dettmar 2006)

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The cleaning process of a flushing wave relies on the highly unsteady flow that exceeds the dry weather peak flow. Shear stresses may be used in order to evaluate the cleaning performance of a flushing wave and thus of a certain flushing device (Ristenpart 1995; Bonkadari & Larrarte 2006; Freni *et al.* 2006; Guman *et al.* 2007). Furthermore, measurements of shear stress are necessary to enhance the modeling of flushing waves. Both simple models as well as advanced three-dimensional models with elaborate turbulence modeling need data to verify the calculation. Therefore, shear stress needs to be analyzed more closely as it is the key parameter for any sediment transport of a flushing wave.

OBJECTIVE

The main objective of the study was to determine the performance of a flushing device within a real sewer by calculating shear stress. Since most highly accurate measurement devices such as particle image velocimetry (PIV) or laser based velocimetry cannot be operated in sewers yet, ultrasonic measurement device (UMD) has been used. Consequently, this paper will discuss uncertainties of the measurements. Finally, measurement data will be compared to simulation results of a calibrated one-dimensional model.

METHODS

Local circumstances and flushing device

The measurements were taken in a sewer with storage capacity and combined sewer overflow. A detailed description of the sewer and the flushing device is available in Dettmar & Staufer (2005).

The sewer of interest consists of a circular cross-section with diameters ranging from 2,500 mm to 3,400 mm. The measurement presented has been carried through in the upper part of the sewer section having a distance to the flushing device of 54 m. The storage length (L) is 104 m. Figure 1 illustrates the local circumstances of the sewer.

Properties and restrictions of the measurement device

The measurement device was placed within the flow at the bottom of a pipe. The principle of its measurement bases on the correlation of ultrasonic signals (1 MHz) reflected off particles within the flow. The velocities of different layers of the flow can be determined by assessing the movement of various particles. From velocities in various layers of a flow velocity profiles can be established (e.g. Bardiaux *et al.* 2006).

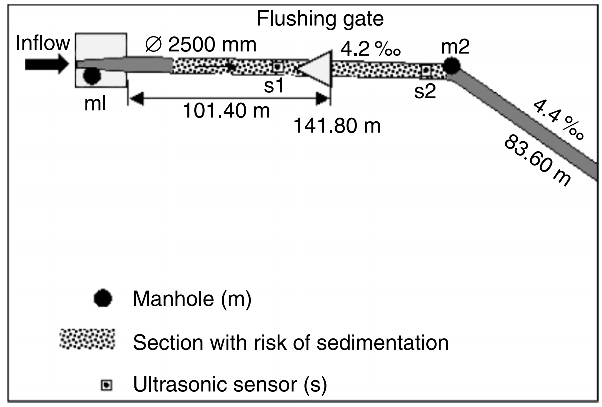

Figure 1 | Local circumstances of the flushing wave (Dettmar & Staufer 2005; modified).

The minimum flow depth is about 4 cm. With respect to the reaction time, which influences the stability of the measurement, and the minimal flow depth, the device will be able to determine the velocities and flow depths. Thus, shear stress of the main part of the wave can be determined afterwards. The measurement error is stated to be ± 1% of the value of the velocity and ± 2 mm regarding flow depths. It depends on the flow regime and rises if turbulence increases. Within the head of the flushing wave that is dominated by turbulent flow condition and great air intake, both the calculation and flow conditions will probably underestimate the shear stress. The values are saved after intervals of 5 s.

Calculation of shear stress

The calculation of shear stress bases on the wall law as stated in Schlichting & Gersten (2003).

$$\tau_0 = \rho \cdot \kappa^2 \cdot \left(\frac{\mathrm{d}v_x}{\mathrm{d}\ln y}\right)^2 \tag{1}$$

where

τ_0 [N/m^2] shear stress
ρ [kg/m^3] specific weight,

κ [m] Karman constant,
ν_x [m/s] horizontal velocity, and
y [m] vertical level.

The bottom shear stress has been calculated using the velocity of the first layer, and the common assumption that the velocity very close to the boundary is close to zero. Since the vertical level is logarithmized, deterministic errors resulting from the determination of flow depth are minor to the possible errors of the measurement of velocity.

NUMERICAL MODELING

Fluvius 1Di is a one-dimensional transient mathematical-numerical model developed by the Institute of Hydraulic Engineering and Water Recourses Management at the RWTH Aachen (Schramm 2002). It solves the full dynamic De-Saint-Venant equations with the method of finite volumes. It has been designed to analyse transient flows in complex geometric environments and steep slopes. It resolves discontinuities by applying the conservative method of Godunov with a first order approach.

The averaged bottom shear stress τ_0 is calculated using the gradient of energy level:

$$\tau_0 = \rho g r_{\mathrm{hyd}} I_{\mathrm{E}} \tag{2}$$

where

ρ [g/m^3] specific weight,
r_{hyd} [m] hydraulic radius and
I_{E} [-] gradient of energy level.

Equation 2 is valid for turbulent steady flow. Considering the properties of the De-Saint-Venant Equations (SVE) large-scale errors will occur if the dynamic approach is simplified (Barês *et al.* 2006). The dynamic approach may lead to errors if the slope of the water level is very steep. Fluvius 1Di is able to take the transition from dry surface to an approaching flushing wave into account, achieving reasonable results concerning water level and discharge (Schramm 2002; Dettmar & Staufer 2005).

The numerical model has been calibrated with six measurements along the flushing line. The bottom boundary conditions have been determined by measurement.

RESULTS

In situ measurements

The ultrasonic measurement device determines flow depths and flow velocities so that bottom shear stress can be evaluated. Figure 2 shows the results of a measurement of a flushing wave having a storage height of $H = 1.02$ m. The measurement of flow depth is consistent with other measurements stated in Dettmar & Staufer (2005).

Presenting the calculated values of bottom shear stress, the graph increases only slightly up to 6.0 N/m^2 during the first 25 s of the measurement. The slow rise is probably due to uncertain measurements that are caused by highly turbulent flow conditions within the flushing head. When the main body of the flushing wave arrives, this is indicated by the second increase of flow depth, bottom shear stress growth steadily up to the maximum of 29 N/m^2. This almost linear increase is most likely caused by the damping effect of the reaction time of the measurement. Thus these results would represent the lower limit of shear stresses that have to be expected. After the maximum has been reached the bottom shear stress declined generally. However the graph shows two minor increases at $t = 75$ s and $t = 110$ s. Both times the bottom shear stress goes up by approximately 0.5 N/m^2. Finally, the values level out at about 2 N/m^2. Both bottom shear stress and flow depth do not cease because of the dry weather flow which runs through the open flushing gate and follows a flushing wave.

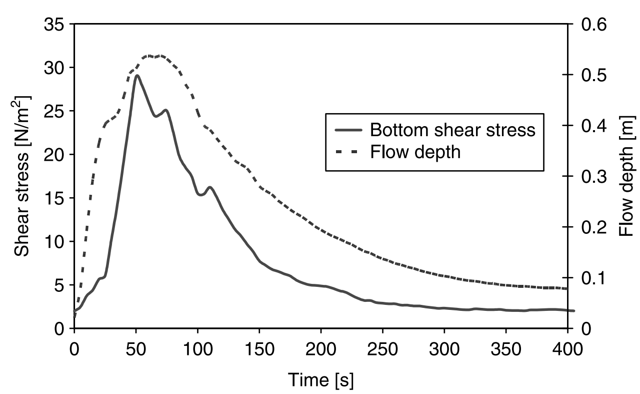

Figure 2 | Measurement of shear stress and flow depth of a flushing wave ($H = 1{,}02$ m; $\Delta s = 54$ m).

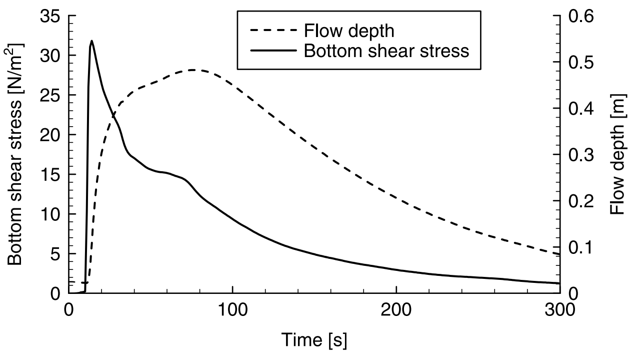

Figure 3 | Simulation results of bottom shear stress and flow depth of a flushing wave ($H = 1.02$ m; $\Delta s = 54$ m).

Numerical results

In order to evaluate the measurements generally, they will be compared with values from a numerical model. The results of the simulation are presented in Figure 3. The peak value rises very quickly up to 32 N/m^2. The value is due to the high energy gradient I_e of the flushing head. After approximately 50 s the decrease of bottom shear stress slows down and picks up again as soon as the maximum flow depth is reached. Finally, the graph peters out.

DISCUSSION

The measurement by ultrasound has a considerably reaction time that leads to a dampening effect and a retention of the peak value. This and the high turbulent flow regime may be the reasons that the measurement shows a late maximum of bottom shear stress. When comparing the peak values of the numerical investigation to the measurement a difference of 5 N/m^2 becomes evident. The comparison of a one dimensional model (Fluvius 1Di) with a three dimensional model (SSIMM) by Staufer *et al.* (2007) suggests a overestimation of bottom shear stress at the beginning of a flushing wave if the stationary approach using the gradient of energy level is used. However, if the measured values represent the lower limit, the error will be less than the difference of the peak values of 5 N/m^2. Therefore the maximum relative error of the peak value of the simulation calculates to 16%.

The peak is followed by another two relative maxima that may be a result of following waves. Briechle & Köngeter (2002) reported findings about a secondary wave. The laboratory study of dike-break waves show similarities to the two waves that are inherent in the dam-break wave (Laubner 1997). Furthermore, Briechle & Köngeter (2002) have presented the velocity of the wave front with respect to the distance of the flap gate. They found that the propagation of the wave front decelerates and accelerates afterwards along the flume. The consequently rising and falling velocities support the findings of the two relative maxima of bottom shear stress.

The appearance of a second wave has also been described by Schaffner (2007). He concludes from three-dimensional simulation that the secondary wave results from the sunk wave which is caused by the rapidly breaking storage volume. The occurrence of a second wave can easily be observed by the measurement and the simulation of flow depth. However, a third wave that could be responsible for the second local maximum is not noticeable on the graph of the flow depth. This may be due to the resolution of the measurement of water level.

The length of the storage volume of the full scale study is over a 100 m and the ratio of storage height to storage length is very small compared to laboratory studies. This may be the reason why no further waves have been reported from laboratory studies because the flume has been too short that a third wave can form.

CONCLUSIONS AND PERSPECTIVE

The measurements of bottom shear stress in a large scale experiment show the following findings.

- The measurement of velocity profiles of a flushing wave by ultrasound gives a good lower boundary of bottom shear stress. The reaction time and the intake of air that are both strongest within the flushing head dominate the uncertainties and errors.
- Knowing the lower boundary of bottom shear stress further optimization of the construction of flushing gates is possible
- The occurrence of a second wave can be observed by the measurement of bottom shear stress. Although dampened, the shear stress increases by approximately 0.5 N/m^2.

- The results of a numerical model demonstrate that the peak value of bottom shear stress is reached while the flushing head is passing. This is probably due to the high energy gradient of the flow. Though dampened, the measurement suggests that the maximum shear stress is attained later when the water level picks up as well.

Further research is needed to describe the turbulence mechanisms of the flushing head. Especially the intake of air that influences the specific weight has to be considered. Furthermore, laboratory studies to investigate the boundary layer of a flushing wave with highly resolving measurement techniques will be useful to minimize the uncertainties and deterministic errors of the determination of the flushing wave. However, there are scaling problems to overcome if the proportions get very small.

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