Instantaneous ultrasonic velocity profiling using in-situ sensor in real sewer flow

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The knowledge of flow and turbulence characteristics in open-channel flow is relevant for number of transport and transformation processes. Sewer flow hydrodynamics is relevant for assessment of transport of solute constituents and solid phase in both dry and wet weather flows. Surface runoff produces hydrographs in combined sewers with significant degree of flow dynamics and unsteadiness directly influencing solids transport. These processes may have significant environmental impacts on surface water quality and are of special interests. However, in-situ observations are rare because of missing measuring techniques and other constraints related to sewer environment. In this paper we present our first results from in-sewer flow and turbulence measurements using a multi-frequency acoustic Doppler velocity profiler, the UB-Flow sensor (Fa. Ubertone, France). The campaign is carried out in a trunk sewer of Dübendorf, Switzerland. We test the capabilities of UB-Flow sensor for short and long time measurements of velocity distribution and turbulence measurements with sampling frequencies from 50 to 100 Hz. We show the capabilities of the sensor to describe sewer flow hydrodynamics under different field conditions.

Keywords: in-situ measurement, rainfall-runoff, Reynolds stress distribution, sewer flow, ultrasonic velocity profiling

1. Introduction

The discharge in the sewer can be considered most of time as steady or quasi-steady, even though diurnal, weekly and seasonal patterns can be observed [1]. However, during intense rain events, the discharge in combined sewers is characterized as unsteady. Combined sewers are hydraulically overdesigned for the purpose of removing both types of wastewater, foul sewage and surface runoff during rain events. Due to the design capacity of sewer channels, the flow can be considered as unsteady, gradually varied with free surface.

The variation of water velocities has different impact on sediment located in the sewer network. During low velocities, transported pollution tends to settle. On the contrary, during rain events, more polluted particles enter the sewer system from the surface. Due to increased bottom shear stress, bed load sediment is mobilized again and transported. In the worst case with combined sewer overflow which caused serious environmental problems in the receiving water bodies.

Key parameter for transport processes in unsteady turbulent flow is friction velocity (or bottom shear stress). The dynamic of this parameter and other turbulence parameters in unsteady flow have been studied in several experiments [2-4]. However, these experiments were conducted under laboratory conditions. With a development of measuring devices, new experiments focused on unsteady turbulent flow are recently available.

The aim of this study is a hydrodynamic analysis of in-sewer flow velocities and turbulence patterns during different weather conditions. In particular, we focus on the employment of in-situ two-component velocity profiler with asymmetric probe geometry for the evaluation of velocity profile and Reynolds stress distribution in varying sewer flow conditions.

2. Theoretical background

Friction velocity is the essential parameter in the open channel hydraulics. Therefore, accurate evaluation of the friction velocity is required to detailed investigation of turbulent structures. It is commonly used for evaluation of dimensionless velocity, turbulence intensities and Reynolds shear stresses. The friction velocity in flows around hydraulically rough boundary may be evaluated by several different methods [5]: *i)* using slope of energy gradeline, *ii)* interpolating measured velocity profile in the inner region of the boundary layer or *iii)* by direct measurements of vertical distribution of Reynolds stress in water column and fitting the data by linear model as follows:

$$u_*{}^2 = \frac{\tau_0}{\rho} = -\overline{u'v'} \; (y \to 0) \tag{1}$$

Where u_* is the friction velocity, τ_0 is the bottom shear stress, ρ is the fluid density and u' and v' are velocity fluctuation components in streamwise and vertical direction. This method is known as most reliable estimation of bottom shear stress in turbulent flows around rough boundary. Estimated bottom shear stress (or friction velocity) is required input parameter for sediment transport modelling in both suspension and bedload mode.

3. Material and methods

3.1 Experimental site

The experiment was conducted in trunk sewer of combined system in Dübendorf, Switzerland. The sewer pipe has a diameter of 1 m. The approximate flow depth during dry weather conditions is about *h/D* = 0.25, velocity range varies from 0.6 to 1.3 m/s. At the test location we have installed to devices. As reference we have used ultrasonic flowmeter NIVUS working on cross-correlation principle which is developed mainly for long-term flowrate monitoring in sewer conduits, however it can provide vertical profile of streamwise velocity. NIVUS probe was install upstream the manhole (Figure 2). Downstream the manhole we have installed UB-Flow (UBERTONE) probe working on pulse-to-pulse coherent Doppler method with two incorporated ultrasonic transducers.

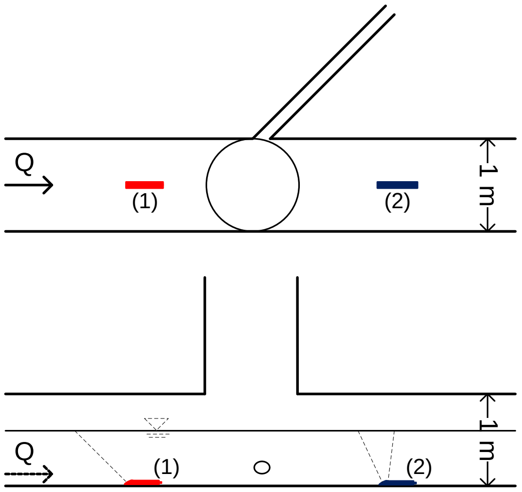

Figure 2: Installation of velocity probes in sewer section in Duebendorf, Switzerland. Upstream (1) NIVUS probe, downstream (2) UB-Flow

The experiments were conducted during both dry and wet weather flows during February 2016. At Figure 3 one can see flow depth hydrograph in main trunk sewer with dry weather flow in the morning and rainfall-runoff in late afternoon February 23rd 2016.

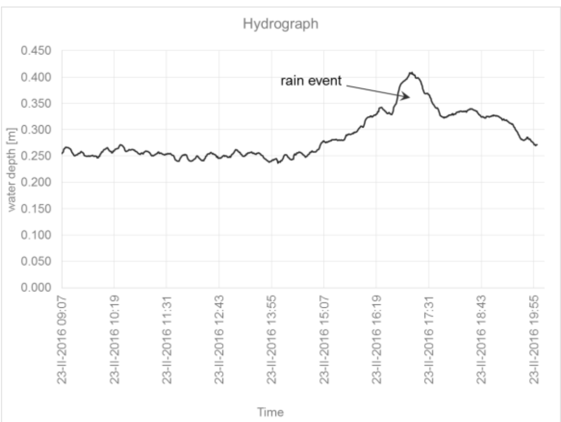

Figure 3: Hydrograph of sewer flow during 23rd of February 2016.

3.2 Sensor

The UB-Flow profiler is a multi-frequency ultrasonic measurement device, which can be used in industrial and environmental flows. This device can be installed in a conduit or in a channel of a different size and geometry [6]. The UB-Flow profiler is able to measure velocity profiles using pulse-to-pulse coherent Doppler method [7]. UB-Flow device employs two ultrasonic transducers, which are hidden in waterproof shell, which is submerged in the medium, which is being measured [6]. The probe is connected with a cable to power supply Power over Ethernet (PoE)

Each of the ultrasonic transducers has different band of working frequencies and both of them are multi-frequency with the possibility to change the emitting frequency during the experiment.

3.3 Velocity measurements

Altogether, 4 different configurations were used to obtain two dimensional velocity profile and turbulence characteristics. The first two configurations (Table 1) were used as a configuration, which should be able to measure velocity profile until 30 centimeters of water depth (i.e. in dry weather flows). The last two configurations were adjusted to use in conditions, where a higher depth of flow is expected (wet weather).

This increase was based on extension of volume size, inter-cell distance parameter and decreasing pulse repetition frequency value. The sampling rate was from 40 to 48 Hz.

Configurations 1 and 2 were assumed to be valid for dry weather condition and configurations 3 and 4 for wet weather condition.

Table 1: UB-Flow profiler transducers configuration for experiment February 23rd 2016

Date and time:	23. 02. 2016: 08:50 - 19:22			
Configuration	1	2	3	4
Emission frequency [MHz]	1.7	3.4	3.4	1.7
Choice of transducer	1	3	3	1
PRF [Hz]	1200	1200	1100	1000
Sample number	25	25	25	25
Supposed V_{min} [m/s]	0.100	-0.128	-0.118	0.200
Position of the first cell [mm]	27	27	27	28
Inter-cell distance [mm]	3.5	3.5	5.0	5.4
Cell number	96	98	116	126
Cell size along beam [mm]	3.4	3.0	5.1	5.5
Profiles per bloc	500	500	500	500

3.4 Velocity decomposition

UB-Flow profiler exploits transducer T1 and T3 to measure instantaneous axial velocities V1 and V3 (Figure 4)

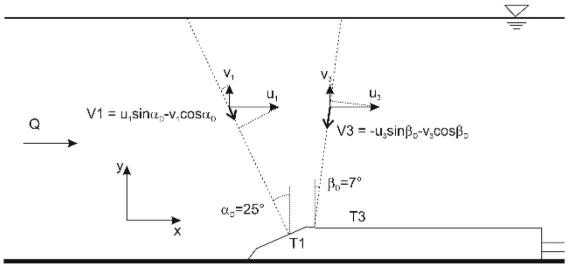

Figure 4. Installation of UB-Flow profiler at the sewer bed and velocity decomposition.

Transducer T1 has degree of α = 65° which is given by the probe geometry. The angle of transducer T3 is β = 97°. Therefore, by using geometric relations, the components of the instantaneous axial velocities can be written as:

$$V1 = u_1 \times \sin \alpha_D - v_1 \times \cos \alpha_D \quad (2)$$

$$V3 = -u_3 \times \sin \beta_D - v_3 \times \cos \beta_D \quad (3)$$

Using Reynolds decomposition we can write for the mean velocities in radial directions of T1 and T3:

$$\overline{V_1} = \overline{u_1} \times \sin \alpha_D - \overline{v_1} \times \cos \alpha_D \quad (4)$$

$$\overline{V_3} = -\overline{u_3} \times \sin \beta_D - \overline{v_3} \times \cos \beta_D \quad (5)$$

And similarly for velocity fluctuations

$$V_1{}' = u_1{}' \times \sin \alpha_D - v_1{}' \times \cos \alpha_D \quad (6)$$

$$V_3{}' = -u_3{}' \times \sin \beta_D - v_3{}' \times \cos \beta_D \quad (7)$$

In case of negligible distance between T1 and T3 the statistical hydraulic parameters (the mean velocities, the turbulence intensities and the Reynolds shear stress) at the same vertical position, but at different longitudinal sections, can be assume same in both steady and unsteady flows [3]. Therefore, it can be written:

$$\overline{u_j} \equiv \bar{u};\ \overline{v_j} \equiv \bar{v};\ \overline{u_j{}'v_j{}'} \equiv \overline{u'v'} \quad (8)$$

where j indicates position of measuring volumes in streamwise direction (here 1 and 3). The mean vertical and horizontal velocity and the covariance can be transformed into:

$$\bar{u} = \frac{\overline{V_1} \times \cos \beta_D - \overline{V_3} \times \cos \alpha_D}{\sin(\alpha_D + \beta_D)} \quad (9)$$

$$\bar{v} = -\frac{\overline{V_1} \times \sin \beta_D + \overline{V_3} \times \sin \alpha_D}{\sin(\alpha_D + \beta_D)} \quad (10)$$

$$-\overline{u'v'} = \frac{\overline{V_1'^2} \times \sin^2 \beta_D - \overline{V_3'^2} \times \sin^2 \alpha_D}{\sin 2\alpha_D \times \sin^2 \beta_D + \sin 2\beta_D \times \sin^2 \alpha_D} + \frac{\overline{v'^2} \times (\cos^2 \alpha_D \times \sin^2 \beta_D - \cos^2 \beta_D \times \sin^2 \alpha_D)}{\sin 2\alpha_D \times \sin^2 \beta_D + \sin 2\beta_D \times \sin^2 \alpha_D} \quad (11)$$

Where $\bar{u}$ is mean horizontal velocity, $\bar{v}$ is mean vertical velocity and $-\overline{u'v'}$ is Reynolds shear stress.

Non-symmetric geometry of the transducers of the UB-Flow complicates equation (11) by evaluating the Reynolds shear stress from the equation. The variance element of $\overline{v'^2}$ could not be identify directly. Therefore, a following simplification was made. It was assumed, that the instantaneous data from the transducer 3 could be used as an instantaneous vertical measurement, due to geometry of the UB-Flow profiler. This step was chosen as a step, which produce the smallest error in Reynolds shear stress evaluation, due to the fact, that cos 7°≅1. This simplification solved our problem with variances in vertical direction.

Estimated Reynolds shear stress profiles were fitted by straight line to estimate the bottom shear stress at the sewer invert neglecting the near-bed region. These values were compared with values from the other probe, which is installed on the same place in the sewer conduit.

5. Results

5.1 Dry-weather flow conditions

Firstly, we take a look at Reynolds shear stress and velocity distribution results during dry weather conditions. Even though the change in hydraulic conditions is slow and small, the *Butterworth* filter was applied to extract the mean flow characteristics. Two components horizontal velocity distribution was evaluated by using equation (9-10), while the Reynolds shear stress distribution was evaluated by using (11). Figure 4 displays the velocity and Reynolds shear stress profiles with linear approximation of Reynolds stress distribution.

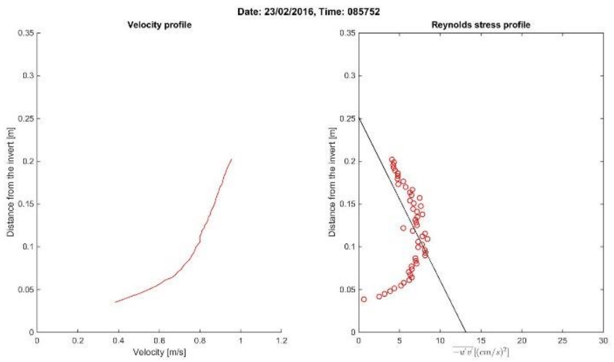

Figure 5: Mean velocity and Reynolds shear stress distribution for the configuration 1.

At this part the performance of the sensor was verified by another ultrasonic device (Nivus). A small offset between UB-Flow data and Nivus data was observed. Nivus measured slightly higher velocities. This difference might be caused by different places of installations of each device, where Nivus is installed upstream the manhole, while UB-Flow profiler is installed downstream the manhole (see Figure 2). The second option why velocity data from two probes are mismatched could be due to different method of velocity estimation.

Measured values of $-\overline{u'v'}$ decreased with increasing water depth. The trend of Reynolds shear stress values is almost linear with maximum values near the sewer invert and minimum values at the region near the water level. Dimensionless values of $-\overline{u'v'}/u_*^2$ at the sewer invert were in the interval 0.8 to 1.2, which corresponds to the theory. However in some cases, no linear trend of $-\overline{u'v'}$ was observed and normalized values could not be estimated. Square values of friction velocity were estimated from the

Nivus water level measurement.

5.2 Wet-weather flow conditions

During wet weather conditions, a strong unsteadiness of flow was expected. A hydrograph of the rain event, which occurred on February 23rd is displayed in the Figure 3. The water depth signal was measured and stored by Nivus probe. During the wet weather condition, an increase in velocities and Reynolds shear stress was expected.

At Figure 6 we see individual velocity profiles from the different time instants of flow hydrograph (recorded from 16:17 to 17:13) with maxima at the beginning of the hydrograph and minima later, however with higher flow depths. This effect can be caused by hydrodynamic behavior eg. backwater effect.

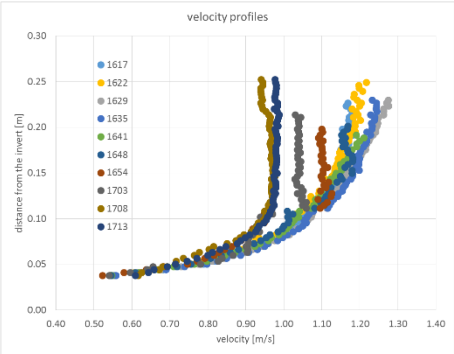

Figure 6. Velocity distribution along the flow hydrograph.

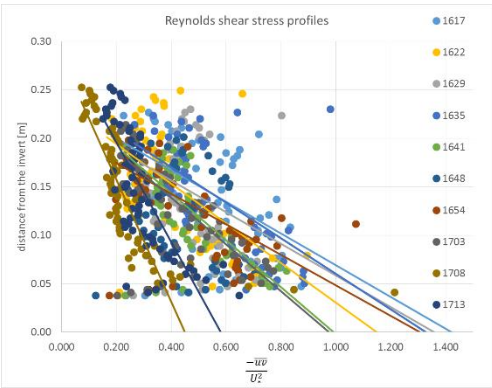

Figure 7. Normalized Reynolds stress distribution.

This corresponds to normalized Reynolds stress distribution at Figure 7. The values of Reynolds stress are normalized by friction velocity derived from channel slope which remains constant neglecting the hydrodynamic effect. Therefore, we see maxima for lower flow depths with higher velocities and vice versa.

6. Discussion

Two specific limits of the method are discussed.

First, the position of UB flow sensor at the sewer bottom influences the flow field around the sensor and thus the velocity and Reynolds stress distribution in close vicinity of the probe. However, we supposed that the results are not influenced in the upper region of the flow because the sensor height is low compare to channel depth. The linear distribution of Reynolds stress is therefore derived only from upper region. We also do not work with data from near field regions of ultrasonic sensors T1 and T3.

Second, we work in time-averaged domain, therefore we can conclude that the time-averaged flow characteristics (velocity, the turbulence intensity and the Reynolds shear stress) are equal to each other at position of T1 and T3 at the same vertical position y (8). This assumption is also valid for gradually varied flows [2,3] while the distance between T1 and T3 is small compare to the length of flood hydrograph.

7. Summary

In this contribution we investigated hydrodynamic characteristics of in-sewer flow as 2D-velocities and turbulence patterns by using ultrasonic Doppler technology. To achieve this goal a newly developed two-transducers ultrasonic profiler was used. The device is capable of measuring a two-component velocity profile with high frequency and thus turbulence patterns can be estimated . We show that device provide reliable results in both dry and wet weather flows. We can therefore conclude that applied methodology can provide required data for description of transport processes in sewer flow.

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