Spatial-temporal Variation of Turbulence Characteristics in Sewer Flow

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Presented study deals with theoretical and experimental investigation of the steady uniform and transient flows with a free surface in channels with a circular cross section with smooth walls as well as with rough sediment deposits. The aim of the study is to define the relationship between the flow unsteadiness and selected flow/turbulence characteristics in circular tube running partially full. Furthermore, the influence of the sediment bed on spatial distribution on given characteristics is studied. The results show strong influence of the cross section geometry on the local values of friction velocity above the sediment bed and, interestingly, decreasing its relative value with increasing relative flow depth. The temporal/spatial turbulence intensities and Reynolds stress distribution in the mid-vertical of the pipe were identified. Generally, the values of turbulent characteristics are larger in the rising branch of the hydrograph. Finally, the individual terms of the bottom shear stress were identified. The omittance of any flow property leads to clear misinterpretation of the calculated bottom shear stress.

Keywords: circular tube, Reynolds stress, sewer, sediment deposits, unsteady flow, velocity profile,

1 INTRODUCTION

Both combined and storm sewer flows are characterized by a strong unsteadiness coming from rain events as well as from artificial factors. Field and laboratory studies have shown that during the passage of the flood hydrographs, the bed-load movement, suspended-load distribution, as well as sewer flow processes are different from those in the steady flow. In order to parameterize the above-mentioned processes, a knowledge of unsteady sewer flow and turbulence characteristics is needed.

In the past decade there have been published numerous field studies describing transport and transformation processes in transient sewer flows. These works often neglected a detailed analysis of the hydraulic and turbulence characteristics which leads to clear misinterpretation of their results. Beside that, the omitting of the hydrodynamic processes in unsteady sewer flow by engineering society can leads to cost-ineffective design.

Several previous laboratory experiments have dealt with unsteady open-channel flow over rough bed, in rectangular flumes. Tu and Graf (1993) estimated friction velocity as well as shear stress distribution using the kinematic wave theory and flow measurements using micro-propeller current meters. A two-dimensional velocity and turbulence analysis using Acoustic Doppler Velocity Profiler (ADVP) or Laser Doppler Anemometer (LDA), respectively was presented by Song and Graf (1996) and Nezu et al. (1997). Unsteady open-channel flows in a semicircular cross section flume were studied by De Sutter (2001) who used generally the same approach as Tu and Graf (1993). However, that investigation [4] was mainly concerned with the unsteady sediment transport phenomena.

Therefore, the properties of unsteady open-channel turbulent flow were investigated in a channel with a circular cross section with smooth walls as well as with rough fixed sediment deposits. The aim of the study is to define the relationship between the flow unsteadiness and selected flow/turbulence characteristics in circular tube running partially full. Furthermore, the influence of the sediment bed on spatial distribution on given characteristics is studied. The information obtained should help to better understand unsteady flow transport and transformation processes in urban drainage systems.

2 METHODS

2.1 Experimental setup

An experimental flume of plexiglass pipe (inner diameter D = 0.29 m) was constructed with a constant bottom slope S_0 = 0.1% to investigate different uniform flow conditions and triangular-shaped hydrographs (Fig. 1). The sediment bed consisted of gravel material with nearly uniform grain size d_S = 12 mm. An electromagnetic flowmeter was installed for continuous discharge measurements $Q_{MID}(t)$ in the supply conduit of the plexiglass flume. Three ultrasonic (US) water level transducers with extended temperature probes were installed on the top of the conduit at distances X [m] = 5.10, 6.94, 9.31. Measured quantities (flow depth $h(x,t)$, discharge $Q(t)$, temperature T) were digitized and recorded through a data acquisition system and synchronized with the velocity measurements.

Total of 72 reference steady flow experiments and 36 unsteady flow experiments were performed in flows over smooth pipe as well as rough sediment deposits.

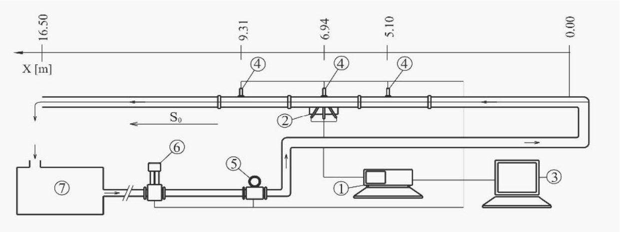

Figure 1: Experimental setup (1. UVP unit; 2. ultrasonic transducers; 3. data acquisition system; 4. ultrasonic water level gauges; 5. MID flowmeter; 6. electronically controlled valve; 7. recirculation tank).

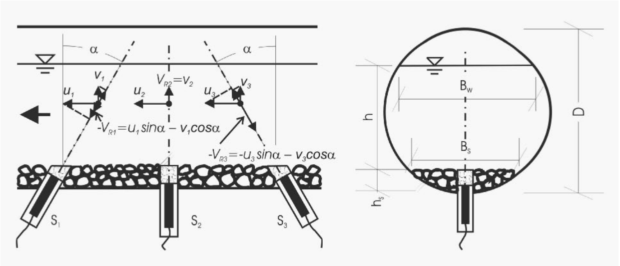

Figure 2: Geometry of UVP transducers and velocity components decomposition.

Velocity and turbulence measurements

The instantaneous information regarding velocity and turbulence distribution was obtained using two independent UVP units (Met-Flow, S.A.) connected to the couple of US velocity transducers; either S_1, S_2 or S_1, S_3 (Figure 1). The UVP Monitor operates on the principle of the Doppler shift and the details of this method have been presented by Takeda (1999). Mentioned setup allows receiving the time-averaged information about the vertical distribution of longitudinal $\overline{u}(y)$ and vertical $\overline{v}(y)$ velocity, longitudinal $\sqrt{\overline{u'^2}}(y)$ and vertical $\sqrt{\overline{v'^2}}(y)$ turbulence intensity and Reynolds stress $-\overline{u'v'}(y)$ [6], making it possible to minimize the error originating from the repeatability of hydrographs. US velocity transducers were placed in closed movable boxes under the channel bottom to prevent a disturbance of the flow (Fig. 2) and to move out the near field of the US signal [7].

Data treatment

An accurate definition of temporal mean values from measured quantities is one of the most difficult aspects of unsteady flow experiments. Therefore, the Butterworth infinite impulse response filter of the 6^{th} order was applied in both time series directions [8]. This approach was found to be preferable to the fast Fourier transform (FFT) used by the others [2-4], particularly in outlying sections of the filtered signal. However, our results showed that the application of FFT on mirrored coupled array can provide comparable results.

3 RESULTS

Steady uniform flow

In flows over the rough sediment bed the turbulence intensities and the Reynolds stress distribution was analyzed (Fig. 3 - 5). It was found that the vertical distribution of turbulence intensities can be described by theoretical equations proposed in literature [9-10]. It was confirmed as well that the Reynolds stress distribution takes a linear distribution under steady uniform flow conditions. However, it is clearly seen, that the data dispersion in case of horizontal turbulence intensity (Fig. 3) and Reynolds stress (Fig. 5) is significantly higher. It can be explained by two factors: *i)* both characteristics are analyzed at least by two US transducer. *ii)* both characteristics are more sensitive to propagation of the error coming from wrong setting of flow uniformity. Also, the mixing length distribution was found to be in good agreement with Prandtl's hypothesis.

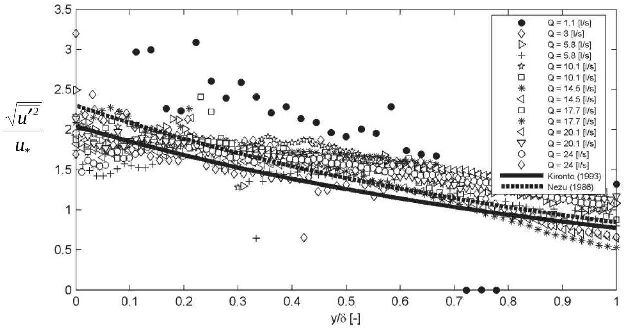

Figure 3: Dimensionless distribution of horizontal turbulence intensity $\sqrt{\overline{u'^2}}/u_*(y)$ for different flow conditions.

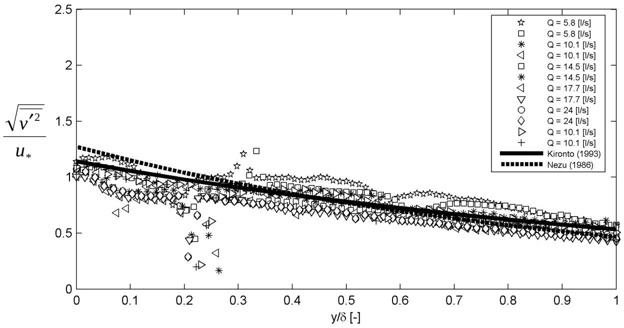

Figure 4: Dimensionless distribution of horizontal turbulence intensity $\sqrt{\overline{v'^2}}/u_*(y)$ for different flow conditions.

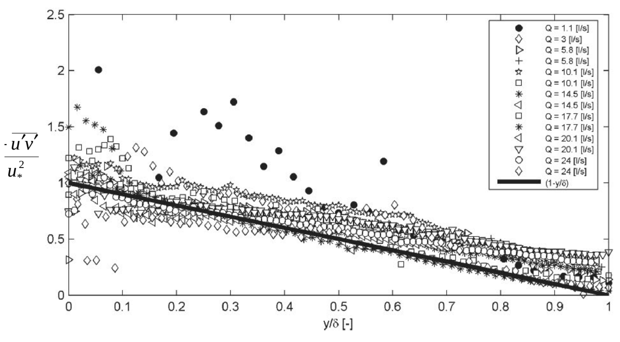

Figure 5: Dimensionless distribution of Reynolds stress $-\overline{u'v'}/u_*^2(y)$ for different flow conditions.

The influence of the cross section geometry and relative flow depth (h+h_S)/D on local values of the friction velocity u* was studied as well. The local values of u_* were independently experimentally analyzed by the Clauser method (applying the log-law for measured velocity distribution in inner region of boundary layer) given as:

$$\bar{u} = \frac{u_*}{k}\ln\left(\frac{y'}{k_S}\right) + B_R \cdot u_* \tag{1}$$

where k_S is the sediment roughness and B_R is the constant of integration. Further, direct measurement of Reynolds stress was used as:

$$u_*^2 = \frac{t_0}{r} = -\overline{u'v'}(y \to 0) \tag{2}$$

where t_0 is the bottom shear stress. In literature, the method of Clauser is often criticized because of its instability especially in flows over rough bed. However, our results proposed a close correlation between both methods.

Further, values of u_* related to the wetted perimeter *P* were calculated using a simplified Saint Venant equations. The results show strong influence of the cross section geometry on the local values of u_* above the sediment bed (factor 1.2 ÷ 1.5) (Fig. 6). Those values are significantly higher than other researchers pronounced [11-12].

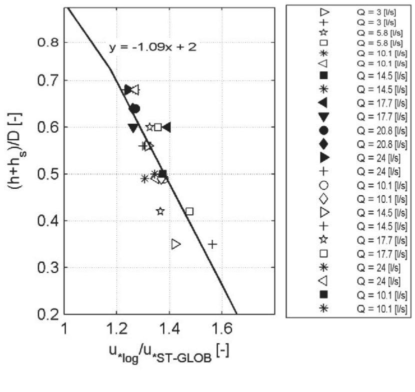

Figure 6: Relation between ratio of local (u_{*log}) and global ($u_{*ST\text{-}GLOB}$) values of friction velocity and relative pipe filling (h+h_S)/D.

It can be explained by higher ratio between roughness of the bed and walls in our study. Interestingly, the relative values of u_* decreased with increasing (h+h_S)/D. On the other side, in flows without the sediment bed (i.e. over smooth wall) was averaged value of the ratio defined by 1.04. However, the slight decreasing tendency of normalized local value of friction velocity with relative flow depth h/D was observed as well.

4 Unsteady flows

36 unsteady flow experiments have been carried out in flows over rough sediment bed. Triangular hydrographs with different degrees of the unsteadiness were generated in the experimental flume. One of the hydrograph was repeated 14 times to prove the experimental repeatability and to evaluate the resulting error in the estimated friction velocity u_*.

The hydrograph analysis revealed a dynamic wave behaviour, where the time lags of friction velocity $u_*(t)$, mean cross section velocity $V(t)$, discharge $Q(t)$ and flow depth $h(t)$ were all evident. In agreement with the theoretical assumptions for a complete dynamic wave, the friction velocity u_* reached the maximum value first, followed in chronological order by the mean cross section velocity V, the discharge Q and the flow depth h.

The temporal/spatial turbulence intensities and Reynolds stress distribution (Fig. 7) in the mid-vertical of the pipe were identified. Generally, the values of turbulent characteristics are larger in the rising branch of the hydrograph. With regard to the vertical distribution, theoretical equations proposed in literature [2-3] were found to be adequate.

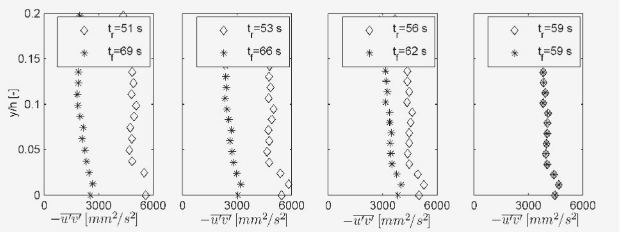

Figure 7: Measured Reynolds stress distribution for the equal flow depths h in the rising (t_r [sec]) and in the falling (t_f [sec]) branch of the hydrograph HYDR_13.

Above mentioned experimental methods (eq. (1-2)) were used to estimate the friction velocity u_*. The Clauser method and the direct measurements of the Reynolds stress propose quantitatively similar results of local values of u_* in the centre of sediment bed. However, the standard deviation of estimated u_* is significantly smaller for the method of Clauser. It was found that the relative standard deviation of u_* is approximately 5.0 % when the Clauser method is applied (Fig. 8).

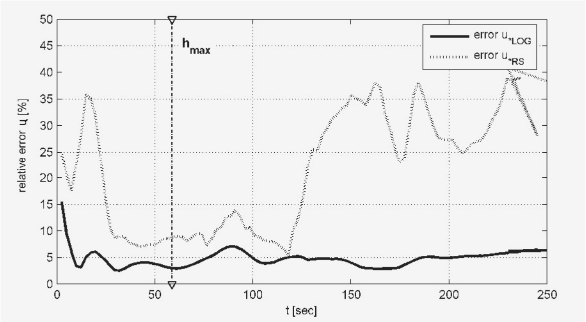

Figure 8: Relative error along the hydrograph HYDR_1 of friction velocity u_* estimated by the Clauser method u_{*LOG} and by direct measurement of the Reynolds stress u_{*RS}

With respect to broadly used 1-D flow modeling approach, the applicability of the Saint Venant equation of motion given as:

$$\frac{\partial h}{\partial x} - S_0 + \frac{1}{g}\frac{\partial U}{\partial t} + \frac{U}{g}\frac{\partial U}{\partial x} + \frac{1}{h}\frac{t_0}{rg} = 0 \tag{3}$$

where S_0 is a bottom slope, was analyzed. All terms of eq. (3) were individually calculated from the instantaneous measured variables *U(t)*, *h(x,t)* using both the dynamic and the kinematical flow principle (Fig. 9). The spatial variation of the flow depth ∂*h*/∂*x* is the most significant term for the correct determination of the friction characteristics. At the time instant of the minimal value of ∂*h*/∂*x* (*t* ≈ 80 ÷ 90 sec), the flow is most accelerating and kinematical approach is inadequate (Fig. 9).

Further, the individual terms of the bottom shear stress were identified. The contribution of *i)* the bottom slope t_{01}, *ii)* non-uniformity t_{02}, *iii)* unsteadiness t_{03} and *iv)* cross section geometry t_{04} was evaluated (Fig. 10).

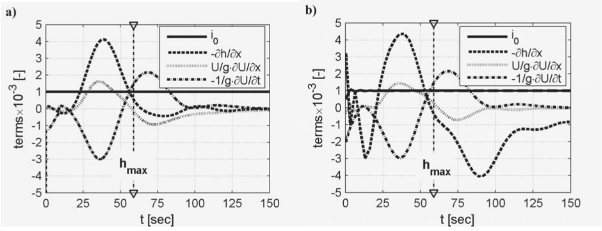

Figure 9: Time variation of individual terms of the Saint Venant equation of motion: a) the dynamic flow principle; b) the kinematic flow principle.

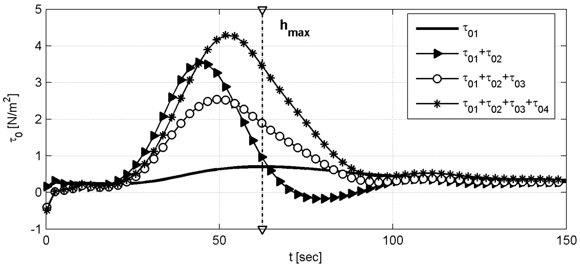

Figure 10: Contribution of the bottom slope τ_{01}, non-uniformity τ_{02}, unsteadiness τ_{03} and cross section geometry τ_{04} on the behavior of the bottom shear stress.

The omittance of any flow property leads to clear misinterpretation of the calculated bottom shear stress. This leads to the important conclusion that the bottom shear stress in unsteady sewer flow cannot be simplified by the steady flow approach. Those modeling approaches for sediment transport which are based on bottom shear stress, must consider therefore the specific attributes of the flow.

SUMMARY

The influence of unsteady sewer flow characteristics on various flow variables has been clearly demonstrated in the study. The methodology described allows studying highly dynamic processes in mentioned regime of flow without any intrusions of the observed flow. With regard to sewer applications, the generalized results support various tasks related to the description of dynamic sewer transport and transformation processes.

ACKNOWLEDGEMENT

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