UNSTEADY FREE-SURFACE FLOW ANALYSIS IN CIRCULAR TUBE USING ULTRASONIC DOPPLER METHOD

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ABSTRACT

Turbulence measurements over the smooth wall in both steady and unsteady free-surface pipe flows were done by Ultrasonic Velocity Profile Monitor (UVP) and ultrasonic water-level gauges.

Vertical distribution of longitudinal and vertical velocity (u,v) was measured for 5 different hydrographs. The deviation of the velocity profile from the steady state was confirmed for both rising and falling branches. The friction velocity was determined using the motion equation and the Clauser method for velocity profile in the inner region of turbulent layer. It is shown that the friction velocity (wall shear stress) is higher for rising branch.

1. INTRODUCTION

Waste water in urban drainage systems is governed by many specific factors. That water includes high amount of suspended solid particles and both, cross-section area and pipe material are very often varying. The stationary flow prevails in dry weather periods, while during rain events flow changes to unsteady and can consider effects on hydraulic characteristics and impacts to transport of sewer solids both deposited and suspended.

For the evaluation of sediment transport in drainage systems and for design of longitudinal bottom slope of sewers a criterion of critical bottom shear stress is often used. According to Czech Standard 75 6101 its value should be $\tau_0 = \rho g R i_0 = 4\,Pa$. The value should be reached at least five times per year. However, we can observe the significant deposits in sewer systems. The question is how to set functional criteria.

Many authors (e.g. Cardoso et al, 1989, Kirgoz et al. 1989 and others) evaluated friction velocity or bottom shear stress in steady uniform open-channel flow by different methods and the results showed good applicability above mentioned relation. However, it was shown that there are some differences in free surface pipe flow due to the cross section shape effect (Knight and Sterling, 2000).

Some experimental studies made in last decade were focused on unsteady open-channel flow in rectangular shape flumes (Tu and Graf, 1993, Kabir, 1993, Nezu and Nakagawa, 1995). The authors found out significant differences between bottom shear stress in steady and unsteady state. This study is focused on circular shape channels.

The main goals of the study were experimentally to determinate hydraulic characteristics of steady and unsteady, smooth turbulent free-surface flow in circular tube and to check the suitability of UVP method for determining hydraulic characteristics in above mentioned conditions.

2. METHODS

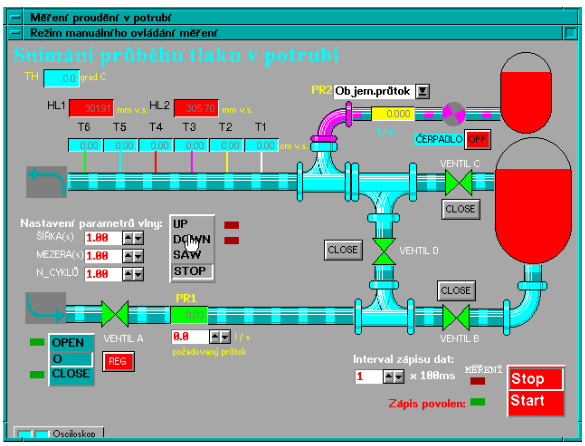
Experiment was carried out in circular pipe. The pipe was made of plexiglass, with diameter DN 290 mm, length 17 m and bottom longitudinal slope $i_0 = 0.175\ \%$.

The discharge measurements were made on inlet pipe by a flowmeter DN 150 and by a triangular measuring weir. Ultrasonic transducers Pepperl&Fuchs have been used for water level measurements. Maximum water level in both pipes was half of the pipe diameter, i.e. $H/D \leq 0.55$. Measured discharge from 2 to 35 litres per second corresponds with relative water depth H/D from 0,15 to 0,55. At the inlet of the track was automatically added suspension of PVC microparticles and water. Solids had the specific gravity $\rho = 1350\ kg.m^{-3}$ and $d_{50} = 0.15\ mm$.

The steady and unsteady turbulent, smooth free surface flows were observed in the experiment. Different shapes of flood hydrographs were simulated. PC Control Panel (Figure 2) controlled the shape of hydrographs as well as other conditions (discharge, water depth, temperature).

2.1 Velocity measurement

The velocity and turbulence information has been obtained by UVP Monitor (Ultrasonic Velocity Profile Monitor), Met-Flow S.A.. Transducers, with basic frequency $f_{01} = 2\ MHz$ and $f_{02} = 4\ MHz$, were placed outside of the pipe wall in small iron boxes in the axis plane of the circular tube. The space ahead of each transducer was filled in by the ultrasonic gel and was covered with film.



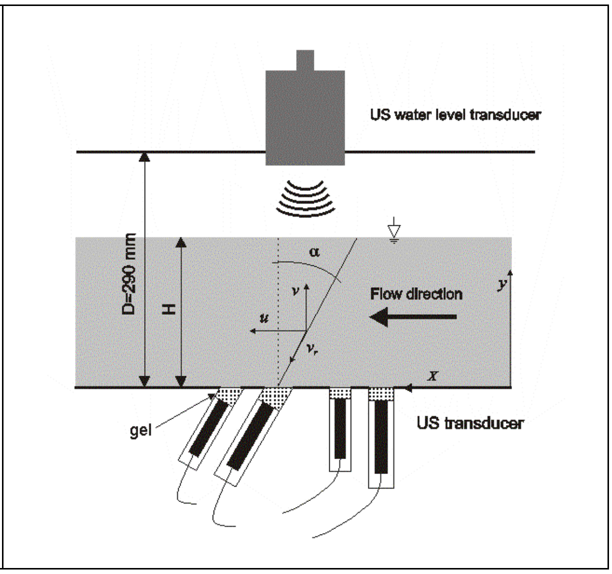


Figure 1 Hydraulic system chart **Figure 2 Transducers position**

One pair of transducers was perpendicular to pipe bottom and the second one was turned at angle α = 30° against flow direction (Figure 2). Microroparticles of PVC - NERALIT were added to the flowing water due to high quality echo.

3. RESULTS AND ANALYSIS

3.1 Steady flow

3.1.1 Velocity distribution

For description of velocity profiles in fully developed turbulent flow with free surface, generally valid semi-empirical models are used.

Inside inner region of turbulent layer the velocity distribution as a function of height is described by the relation derived by von Kármán (1930) and Prandtl (1932), called logarithmic velocity distribution law. This is expressed as:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{u_* y}{\upsilon} + B \qquad (1)$$

Nikuradse (1932) on base of his experiments has found values of $1/\kappa$ and B to be $1/\kappa = 2.5$ and $B = 5.5$ for hydraulically smooth pressure flow in circular pipe. Moreover, also Keulegan (1938) has confirmed the same values for flow with free surface as well. Nevertheless, different values B were found by other authors, in the range between 4,9 (Klebanoff, 1954) and 7 (Townsend, 1956).

The regression analysis has been used to establish B values. The Value B has been found to be in the range from *4* to *6*.

Coles (1956) has introduced the modified logarithmic “law of wake”, which describes shape of velocity profile in the outer region of turbulent layer for hydraulically smooth mode of flow, in a form:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{u_* y}{\upsilon} + B + \frac{2\Pi}{\kappa} \sin^2\left(\frac{\pi z}{2\delta}\right) \qquad (2)$$

Coles (1956) has also shown that values for $\kappa = 0.4$, $B = 5.1$, and $\Pi = 0.55$ are in agreement with experimental measurements. Different value of Coles parameter $\Pi = 0.2$ were assessed by Nezu and Rodi (1986), and Krikgoz (1989) gives value $\Pi = 0.1$. These are significantly lower values than that of $\Pi = 0.55$ given by Coles.

Values of Coles parameter $\Pi = 0.3$ and constant $B = 4.7$ were found by regression analysis. The velocity distribution is shown in Figure 3.

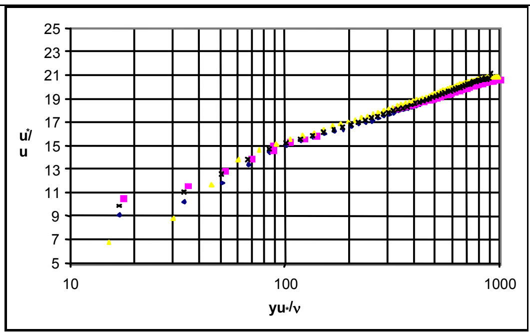


Figure 3 Velocity profiles; steady uniform flow

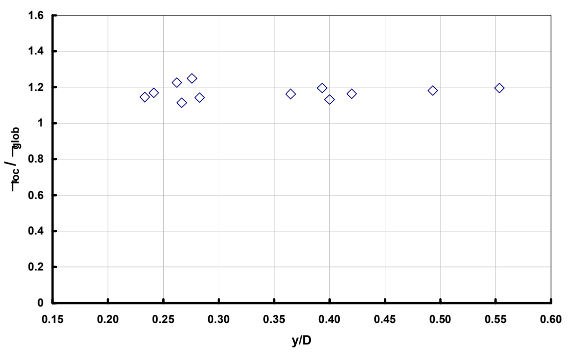


Figure 4 Ratio between $\tau_{0\ loc}$ and $\tau_{0\ glob}$

3.1.2 Friction velocity estimation

The friction velocity is being evaluated by different indirect methods. In our experiment the friction velocity u_* were estimated a) from the channel slope i_0 and hydraulic radius $R - u_{*glob}$ and b) from the inner region data by Clauser method (Nezu and Nakagawa, 1993) – $u_{*loc.}$

The ratio of evaluated bottom shear stress values $\tau_{0loc/}\ \tau_{0glob}$ fluctuated in the range 1.1 – 1.3 (Figure 4), which corresponds well with Knight and Sterling (2000) data.

3.2 Unsteady flow

5 different hydrographs with varied surface slope and length were simulated. The instantaneous velocity profiles were smoothed by moving time average method.

3.2.1 Velocity distribution

The evolution of the mean velocity with the time and water height has shown that the point velocity near the water surface arrives the maximum earlier than those near the bottom.

The velocity profiles in the rising branch were found generally larger than in the falling branch for equal water depth (Figure 5).

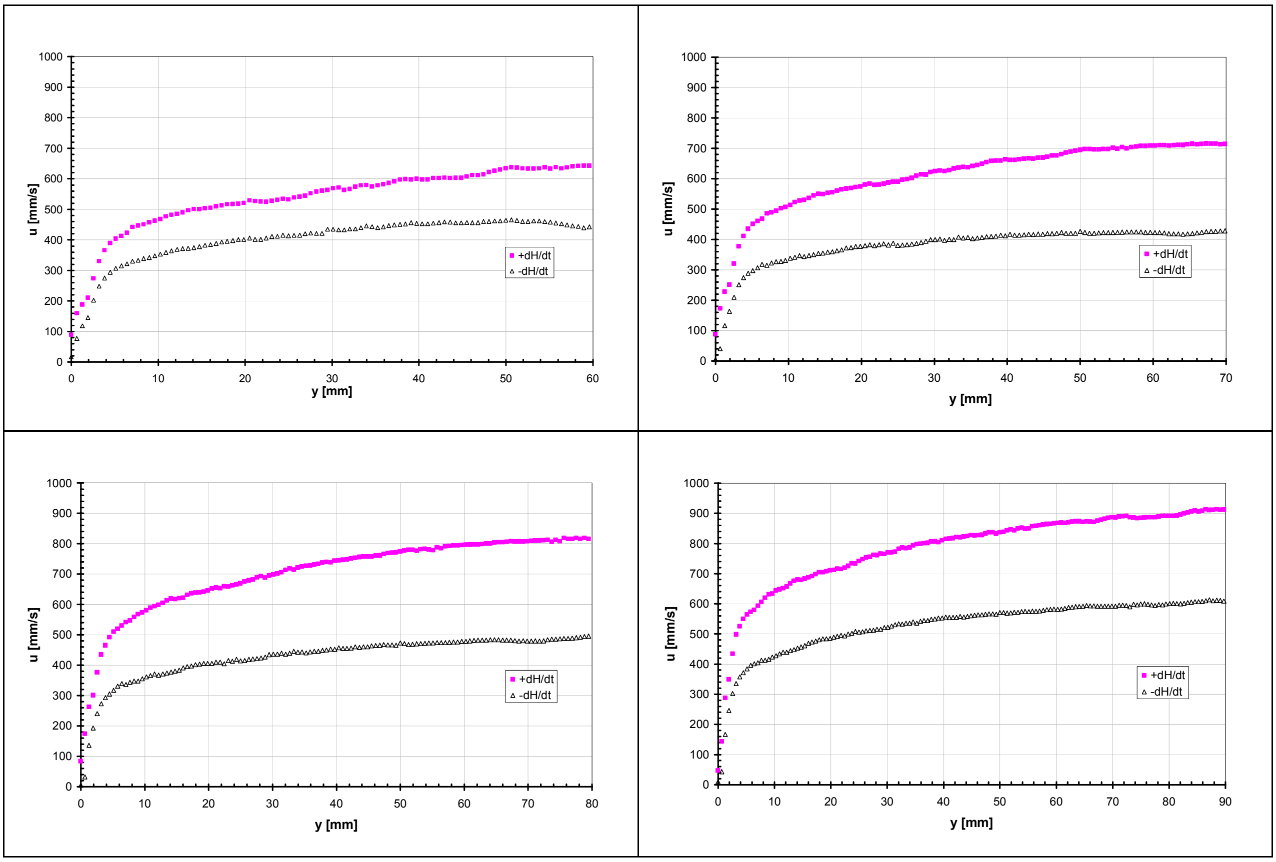


Figure 5 Vertical velocity profiles in the rising and falling branches for given hydrograph and water depths 60, 70, 80 and 90 mm

3.2.2 Friction velocity estimation

The friction velocity was estimated in different ways: a) with steady, uniform formula $u_{,steady} = (gHi_0)^{0.5}$, - b) from the inner region data of velocity profiles, by employing the log – law (1) and c) from the St. Venant equation of motion. By the assumption that the hydrographs are kinematics and/or non-subsiding waves the friction velocity can be obtains (Tu, Graf, 1993):

$$u_{*SV} = \sqrt{gH\left[i_o + \frac{1}{C}\frac{\partial H}{\partial t} - \frac{1}{g}\frac{\partial U}{\partial t}\left(1 - \frac{U}{C}\right)\right]} \qquad (3)$$

where

$$C = U + H\frac{\partial U}{\partial t}\bigg/\frac{\partial H}{\partial t} \qquad (4)$$

and

$$U = \frac{1}{H}\int_0^H u\,\mathrm{d}y \qquad (5)$$

The results are shown in Figure 6. The similar tendency of u_{*log} and u_{*sv} was observed. The friction velocity is higher in rising branches than in the falling branches. In comparison with steady state values the results are similar and agree well with Tu, Graf (1993).

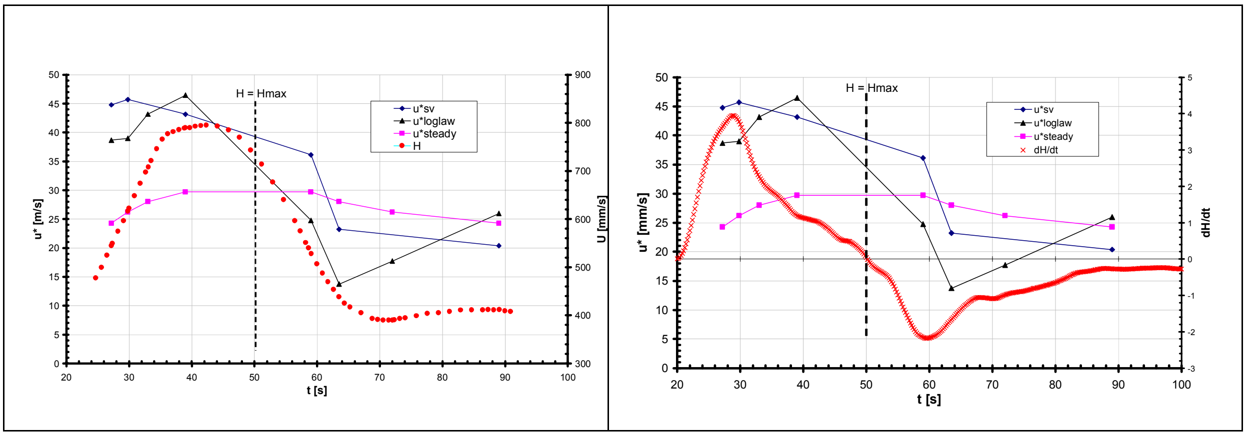


Figure 6 Comparison between the observed values of the friction velocity u_{*log}, u_{*sv} , steady state values $u_{*steady}$ and dU/dt, resp. dH/dt

4. CONCLUSIONS

Using the UVP method the turbulent steady and unsteady flow with free surface over smooth wall in circular tube were observed .

The steady flow measurements showed that a) velocity distribution in the inner region of turbulent flow has been evaluated. The value of parameter B has been found to be in the region from 4 to 6. b) The value of Coles parameter Π for outer region of turbulent layer has been established as $\Pi = 0.3$. c) the ratio $1.1 \div 1,3$ has been found between local bottom shear stress at pipe plane of symmetry, and between average value calculated on base of hydraulic radius R and longitudinal pipe bottom slope i_0.

Unsteady flow measurements showed a) point velocity near the water surface arrive the maximum values earlier than that near the wall. b) for equal water depth the point velocity are generally higher in the rising branch (Figure 5). c) for given hydrograph is the friction velocity larger in the rising branch than in the falling branch (Figure 6). d) calculated and observed friction velocity has the same tendency (Figure 6).

The UVP method provides successfully data of both steady and unsteady turbulent flow with free surface in circular tube. The applicability of this method in non-intrusive measuring mode was confirmed.

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NOTATION

Q	Discharge ($m^3.s^{-1}$)	ν	kinematic viscosity
Π	Coles parameter	i_0	longitudinal pipe bottom slope
B	integration constant	R	hydraulic radius
H	overall depth (m)	α	angle of transducer with vertical
u_*	friction velocity ($m.s^{-1}$)	v	average vertical point velocity
x,y	Cartesian co-ordinates	U	average sectional velocity
u	average longitudinal point velocity ($m.s^{-1}$)	D	pipe diameter
κ	von Karman constant	C	wave velocity