Analysis of Unsteady Free-Surface Sewer Flow over Sediment Deposits using Ultrasonic Doppler Method

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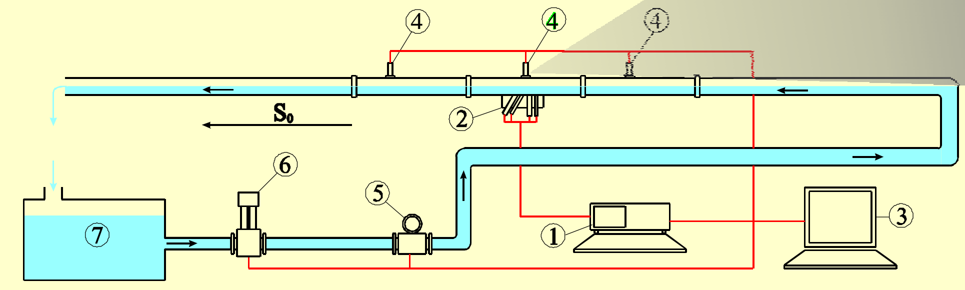
Abstract

Unsteady open-channel turbulent flow properties were theoretically and experimentally studied in circular cross section channel with fixed sediment bed. Hydrographs under investigation were generated as complete dynamic waves. Firstly, the vertical distribution of the horizontal and the vertical velocities was analysed. Secondly, fitting the horizontal velocity data in the inner region of turbulent layer temporal variation of local friction velocity was estimated. Finally, based on de Saint Venant equations, the friction velocity time behaviour was studied using both, the kinematic and the dynamic flow principles. Results validated the ability of the mentioned aproaches to appropriately describe given unsteady flow characteristics.

Methodology

! flume with circular cross section made of plexiglass (Fig. 1).
! flume length $L = 17\,m$; inner diameter $D = 0.29\,m$; bottom slope $S_0 = 0.1\,\%$.
! sediment height $h_s = 52\,mm$, grain size $d_{50} = 12\,mm$.
! measuring devices connected to data acquisition system
! hydrographs generated as dynamic waves with high level of unsteadiness(Fig. 3, Tab.1).
! instantaneous velocity profiles $u(y,t)$, $v(y,t)$ measured using *UVP (Ultrasonic Velocity Profile) Monitor.*
! 2 independent UVP transducers placed out of the flow field (Fig.2)
! time-average values obtained by FFT (Fast Fourier Transform) and IIR (Infinite Impulse Response) Butterworth filter.



LEGEND: 1 - UVP Monitor; 2 - UVP transducers; 3 - Data acquisition system; 4 -Ultrasonic water level gauges; 5 - MID flowmeter; 6 - Valve; 7 - Tank

Fig. 1 - Layout of experimental setup

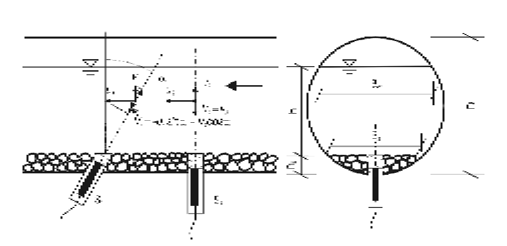


Fig. 2 - UVP transducers setup and velocity components decomposition

Models of the friction velocity

Time-varied friction velocity, as a fundamental parameter in the hydraulics of open-channel flow, was estimated as follows:

(1) de Saint Venant equation of motion using kinematic u_{*KIN} and dynamic u_{*DYN} flow principle
(2) applying the law of the wall on measured velocity distribution in the inner region of turbulent layer - u_{*LOG}
(3) steady flow formula - $u_{*ST} = (gRS_0)^{0.5}$

Results

! temporal variation of time-average horizontal or vertical velocity components $u(y,t)$, $v(y,t)$ and flow depth $h(t)$ are shown in the Fig. 4 i.e. the Fig. 5.
! applying above mentioned models on measured flow velocity and depth data one can estimate the temporal variation of the friction velocity u_* i.e. the bottom shear stress τ_0.
! dynamic values of $u_{*LOG,DYN,KIN}$ significantly exceed those values of steady flow (u_{*ST}) with equal depth h (Fig. 6). However, there are slightly lower dynamic values in the falling branch of the hydrograph.
! comparison of both the kinematic and the dynamic flow principle shows a goodness of fit in the rising branch of the hydrograph. On the other side, the values of u_{*KIN} are completely underestimated in the falling branch of the hydrograph (Fig. 6).
! moreover, the significant difference between local values u_{*LOG}, τ_{0LOG} and those averaged over wetted perimeter P ($u_{*DYN,KIN}$) was observed (Fig. 6).
! substituting the average velocity in a cross section V, the hydraulic depth H and the hydraulic radius R with the depth-average velocity U and the flow depth h one can solve the governing equations (1) for 2D flow in the plane of the pipe symmetry (Fig. 7).

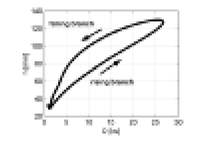


Fig. 3 - Looping rating curve (HYDR1)

Tab. 1 - Hydraulic characteristics of basic hydrographs

Hydro-gram	S_0 [%]	T_R [sec]	T_D [sec]	h [mm]	Q [l/s]	Fr [-]	Re [×10⁴]	T [°C]	u_{*LOG} [mm/s]	Ω [-]
HYDR1	0.1	30	32	30.4-129.3	1.28-27.53	0.33-0.71	1.22-15.68	19.1	15.7-66.9	12.90
HYDR2	0.1	33.2	36.0	32.4-133.6	1.29-27.65	0.30-0.68	1.22-15.52	19.2	16.1-71.3	11.12
HYDR3	0.1	43.8	56.7	31.4-141.0	1.30-27.4	0.32-0.62	1.25-15.04	19.3	15.9-68.1	8.54

Legend: S_0 = bottom slope; T_R = duration of rising branch; T_D = duration of falling branch; h = flow depth; Q = discharge; Fr = Froude number; Re = Reynolds number , T = water temperature; u_{*LOG} = friction velocity estimated from log-law (2); **W**= unsteadiness parameter (Qu, 2002); h, Q, Fr, Re, u_{*LOG} values describe those of the base flow and the peak flow

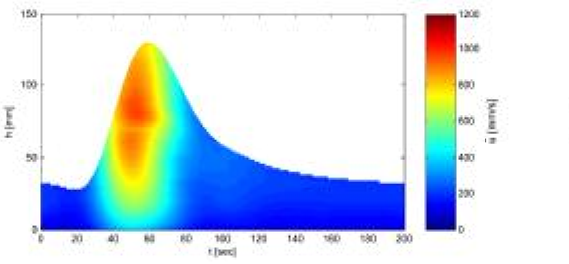


Fig. 4 - Visualization of horizontal time-average velocity components $\bar{u}(y,t)$

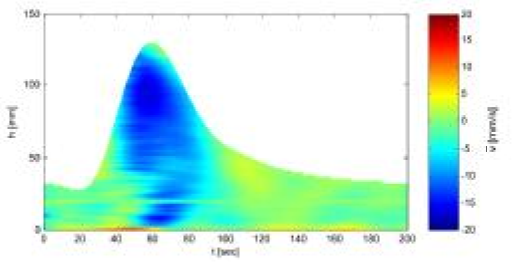


Fig. 5 - Visualization of vertical time-average velocity components $\bar{v}(y,t)$

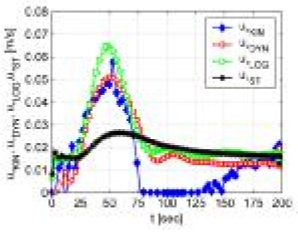


Fig. 6 - Temporal variation of u_{*KIN}, u_{*DYN}, u_{*LOG}, u_{*ST} (HYDR1)

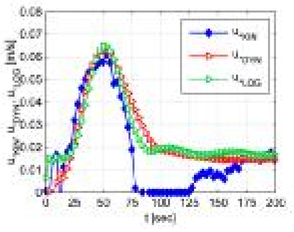


Fig. 7 - Temporal variation of u_{*KIN}, u_{*DYN}, u_{*LOG} (HYDR1) in axes of sediment bed

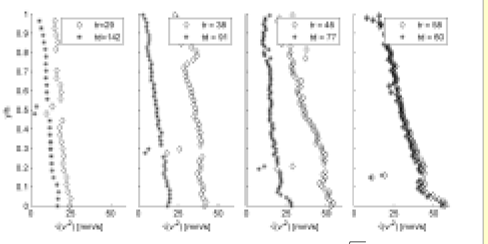


Fig. 8 - Vertical turbulent intesity distribution $\sqrt{\overline{v'^2}}(y)$ for equal depth (HYDR1); t_r = time instant at rising branch; t_d = time instant at falling branch

Conclusions

Unsteady turbulent flow characteristics have been studied using series of hydrographs with high level of unsteadiness. It can be concluded that:

! *temporal and spatial variation of the horizontal velocity $u(y,t)$ were observed in accordance with general meaning of looping rating curve.*
! *vertical velocity profiles $v(y,t)$ achieved negative values in the rising branch of hydrograph - the flows are accelerating ones.*
! *vertical turbulence intensity distribution $\sqrt{\overline{v'^2}}(y)$ is significantly higher for the rising limb of the hydrograph than the in the falling one.*
! *friction characteristics of given unsteady sewer flow can be appropriately described using the dynamic flow principle. Other solutions lead to significant errors.*
! *the shape of the cross section and presence of bottom sediments influence distribution of bottom shear stress over wetted perimeter.*
! *applicability of the UVP method in the non-intrusive measuring mode was confirmed. However, presented geometrical setup is not applicable on runs with bed-load transport.*

List of symbols

B	*water (sediment)surface width*
D	*inner diameter*
Fr	*Froude number*
g	*gravity acceleration*
h	*flow (sediment) depth*
H	*hydraulic depth*
P	*wetted perimeter*
R	*hydraulic radius*
Re	*Reynolds number*
S_0	*bottom slope*
u	*horizontal velocity component*
U	*depth-average velocity*
u_*	*friction (shear) velocity*
v	*vertical velocity component*
V	*average velocity in a cross section*
$V_{1,2}$	*radial velocity components measured using UVP transducers*
τ_0	*bottom shear stress*

References

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