Czech Technical University in Prague
Faculty of Civil Engineering
Department of Sanitary and Ecological Engineering

Doctoral Degree Program: **Civil Engineering**
Branch of study: **WATER ENGINEERING AND WATER MANAGEMENT**

Ing. Vojtěch Bareš

ANALÝZA NEUSTÁLENÉHO PROUDĚNÍ S VOLNOU HLADINOU V KRUHOVÉM POTRUBÍ

UNSTEADY FREE-SURFACE FLOW ANALYSIS IN CIRCULAR PIPE

<u>PhD Thesis - Abstract</u>

Supervisor: **Prof. Ing. Jaroslav Pollert, DrSc.**

Prague, October 2005

ABSTRACT

Both combined and storm sewer flows are characterised 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 required. Therefore, the properties of unsteady open-channel turbulent flow were investigated theoretically and experimentally 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.

Methodology (chapter 2 and 3)

The theoretical equations for mean longitudinal velocity, friction velocity and bottom shear stress were reviewed. Their definition is based on the theory of turbulent boundary layer flow and basic equations, particularly the Reynolds equations of motion, the Saint Venant equation of motion and the equation of continuity. Sediment transport theory has been discussed with respect to specific sewer flow characteristics.

An experimental flume of plexiglass pipe was constructed with a constant bottom slope to investigate different uniform flow conditions and triangular-shaped hydrographs. The sediment bed consisted of gravel material with nearly uniform grain size. Velocity and turbulence distribution data were obtained using an Ultrasonic Velocity Profiler. This experimental setup in combination with extensive data analysis allowed to obtain complex information about flow and turbulent characteristics, such as a flow depth, mean velocities and turbulence intensities. As the accurate definition of temporal mean values from measured quantities is one of the most difficult aspects of unsteady flow experiments, the Butterworth infinite impulse response filter was applied in both time series directions. It was found that this approach is superior to the fast Fourier transform, particularly on boundaries of the filtered signal.

Steady free-surface flow in circular pipe (chapter 4)

Total of 72 reference steady flow experiments were performed in flows over smooth pipe as well as rough sediment deposits. The relation between depth-integrated velocity U and average velocity in a cross section V was established. The test of the flow dimensionality shows that the velocity profiles in the conduit centre has the same properties as those for 2D flows for runs with relative flow depth h/D < 0.5. The velocity distribution can be satisfactory described using the log-law in the inner region, and Coles law in the outer region of the turbulent layer. The values of the constants of integration B_s, B_R

and Coles parameter P are determined. The friction relations for both smooth wall and rough sediment bed are established and verified.

In flows over the rough sediment bed the turbulence intensities and the Reynolds stress distribution was analysed. It was found that the vertical distribution of turbulence intensities can be described by theoretical equations proposed in literature. It was confirmed that the Reynolds stress distribution takes a linear distribution under steady uniform flow conditions. Also, the mixing length distribution is in good agreement with Prandtl's hypothesis.

The influence of the cross section geometry and relative flow depth h/D on local values of the friction velocity u_* was studied. The local values of u_* were independently experimentally analysed by i) the Clauser method, and ii) direct measurement of Reynolds stress. The obtained results show a close correlation between both methods. Furthermore, values of u_* related to the wetted perimeter O 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. In addition, the distribution of u_* along O proved to be nearly uniform for the experiments with smooth wall. Interestingly, the relative values of u_* decreased with increasing h/D.

Unsteady free-surface flow in circular pipe (chapter 4 and 5)

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 that was equipped with a sophisticated data acquisition system which allowed for very low temporal resolution to control all measured quantities synchronized. 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_*. It was found that the relative standard deviation of u_* is approximately 5.0 % when the Clauser method is applied. Furthermore, it was found that unsteady flow can be characterized by the global unsteadiness parameter Ω, or particularly by the pressure gradient b_{un}.

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. This leads to the well-known looping rating curve.

The velocity distribution analysis showed that the horizontal velocity components near the bottom rise to maximum values later than those close to the water surface. Further, the values in the rising limb of the hydrograph are generally larger than those in the falling limb. The velocity distribution in the inner region can be described by the law of the wall whereas Coles law of the wake describes the velocity in the outer region. As was suspected, it was found that the Coles parameter P is affected by flow unsteadiness. A model that described the empirical relation between P and b_{un} was developed in this thesis.

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. With regard to the vertical distribution, theoretical equations proposed in literature were found to be adequate. Furthermore, the results suggests that the turbulence intensity distribution parameters depend on flow parameter b_{un}. Interestingly, the experiments show that the vertical distribution of the mixing length is not affected by the flow unsteadiness.

Different experimental methods were used and evaluated 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. All terms in the Saint Venant equations are individually calculated from the instantaneous measured variables $V(t)$, $h(x,t)$ using both the dynamic and the kinematic flow principle. The spatial variation of the flow depth $\partial h/\partial x$ is the most significant term for the correct determination of the friction characteristics. Because the shape effect of cross section geometry, solving the Saint Venant equations the using dynamic flow principle underestimates the local values of u_* in comparison to the above methods. The influence of the cross section geometry on non-uniform distribution of u_* along wetted perimeter O is clearly demonstrated. The strong hysteresis is observed in the relationship between flow depth h and "real" dynamic values of the friction velocity u_*.

The individual terms of the bottom shear stress were identified. The contributions of i) the bottom slope, ii) non-uniformity, iii) unsteadiness and iv) cross section geometry was evaluated. 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 described by the steady flow approach. Nevertheless, the substitution of the slope of energy ie with the free-surface slope iw leads to comparable results. Due to the results of this thesis, those modelling approaches for sediment transport which are based on bottom shear stress, must consider therefore the specific attributes of the flow.

The effect of the flow unsteadiness on friction relations was studied. The relation between the flow equilibrium parameter b_{un} and the additive constant $\overline{B_R}$ was defined in presented study. For the high flow depth, the friction relation of unsteady flows inclines to be below that for steady flows.

In addition, the influence of unsteady sewer flow characteristics on sewer flow rate measurements (methodology) as well as on the bed-load transport modelling has been demonstrated. Measured sewage discharge is related to the ratio between average cross section velocity V and maximal velocity in cross section u_{max} in the majority of the sewer flow measurement devices. The relationship between V/u_{max} and the relative flow depth h/D was defined in steady flow experiments. Moreover, the empirical relation between V/u_{max} and flow equilibrium parameter b_{un} is presented. The propagation of the time behaviour of the bottom shear stress through bed-load transport models is clearly interpreted. The use of bed-load transport models derived under steady flow conditions leads to large errors in the calculated sediment transport rate.

The influence of unsteady open-channel flow characteristics on various flow variables has been clearly demonstrated. The novel methodology described in this thesis allows to study highly dynamic processes in mentioned types of flow. With regard to sewer applications, the generalized results support various tasks related to the description of dynamic sewer transport and transformation processes.