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Unsteady open channel flow registrations in a test flume with circular cross-section

R. De Sutter, M. Huygens and R. Verhoeven
Hydraulics Laboratory, University of Gent
Sint-Pietersnieuwstraat 41
Gent, Belgium.
e-mail Renaat.Desutter@rug.ac.be

Abstract

In the framework of a research project 1996-1998 "Time dependent erosional behaviour of natural sediments in unsteady flow" the equipment of a test flume with circular cross-section was extended to perform measurements under unsteady flow conditions. The experimental setup creates the possibility to gather the necessary information concerning the time evolution of flow and friction characteristics during unsteady flow. A series of triangular hydrographs were passed through the circular flume with a fixed bottom, in course of preparation for sediment transport measurements. The obtained flow and friction parameters are evaluated and compared with both laboratory data in literature obtained for similar test flumes with rectangular section and analytic elaborations. The influence of storage, reflection and deformation in the circular flume is quantified.

1. Introduction

A period of extreme rainfall can cause a sewage overflow on the surface water. These overflows with their associated sediment transport volumes may drastically diminish the quality of the receiving surface water. Indeed, the transported fine sediments in the overflow water can be heavily polluted. By that, the extent of the damage to the receiving water body is strongly influenced by the flow parameters inside the sewer system. The flow parameters and consequently also the sediment transport will have a strong non-uniform unsteady character. Hence, these

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parameters play an important role in assessing the pollution effect of sewage overflows [1].

A lot of rivers carry high concentrations of heavy metal pollutants adsorbed on cohesive sediment particles. PLATE states that research of sediment transport in unsteady flow is needed because of the lack of agreement between sediment transport formulas for steady flow and field measurements [5].

This is why the Hydraulics Laboratories of the universities of Gent and Leuven decided to start a research project "Time dependent erosional behaviour of natural sediments in unsteady flow". As preliminar part in this research project the investigation and quantification of the transient regime in a laboratory flume with a circular cross-section has been worked out at the Hydraulics Laboratory of Gent.

2. Experimental setup

2.1. Tilting flume with circular cross-section

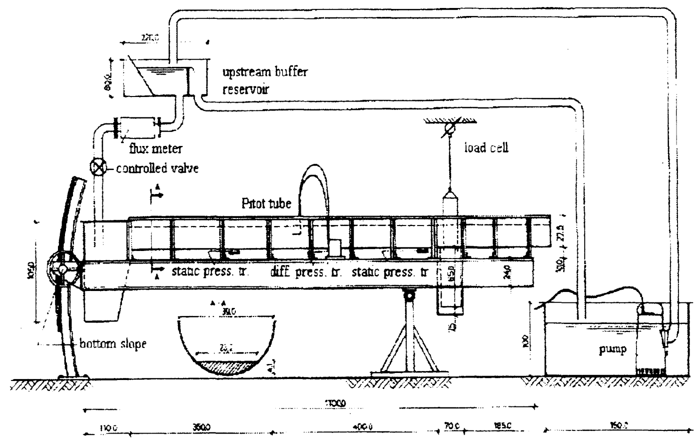

Figure 1: Experimental setup Hydraulics Laboratory Gent

The experiments are conducted in a 11 m. long tilting flume that is integrated in a closed conduit system. The closed system consists of an upstream storage reservoir connected to a downstream reservoir by the tilting flume. Water is constantly pumped from the downstream reservoir into the upstream storage reservoir with a maximum capacity of 50 l/s. This storage reservoir has a built in weir that ensures a constant water pressure for the discharge in the test flume.

The tilting flume has a semi circular cross-section with an internal diameter of 0.39 m. The flume is covered at the inner side with abrasive paper to establish a roughness which is comparable to real sewer pipes. The roughness coefficient k_w of the flume wall is estimated at 0.54 mm. This value was obtained as the average value of measurements under steady flow for a wide range of discharges and bed slopes. The bed slope of the tilting flume can range from a negative value to several percent.

The actual measuring section of the flume has a central position and a length of 4 m. For measurements without sediment transport a fixed bottom with a central height of 41 mm. is installed into the measuring section and also covered with abrasive paper.

2.2. Measuring devices

An electromagnetic flux meter is fit onto a horizontal tube between the storage reservoir and the tilting flume. Discharge under the form of a current signal is registered by the computer. The flux meter is calibrated through comparison with a volumetric discharge measurement and with another previously calibrated electromagnetic flowmeter. The maximal relative error is 0.5 % of the reading.

Two hydrostatic pressure transducers measure the upstream and downstream water height. The upstream transducer is placed 1 m before the measuring section in the flume bottom. A distance of 1 m was taken out of precaution to avoid direct influence from the little waterjump at the 41 mm treshold of the fixed bottom at the beginning of the measuring section. The downstream transducer is installed 0.5 m behind the measuring section in the flume wall. The transducer is positioned in the flume wall because of the possible presence of sediment particles at this point inhibiting accurate measurements. The two transducers are calibrated in two steps. First the slope of the linear calibration curve has been determined using a calibration column. Secondly the offset is determined in situ through comparison with a level gauge with an accuracy of 0.1 mm. Relative sensitivity of the transducer itself is 0.5 % of the reading. This results in a water height measurement with a standard error of 1 mm.

A Pitot tube connected to a differential pressure transducer assures an accurate measurement of point velocities. The Pitot tube, with an internal diameter of 3 mm. and an external diameter of 6 mm, is connected to the transducer by means of two plastic tubes with minimal length. It is put forward in literature that this combination should not be used in unsteady flow because of the inertion of the pressure transfer [9]. The use of a micropropeller was suggested. This is contradicted by thorough investigation of the sequence of velocity and discharge values. A micropropeller has been tested but delivers inaccurate values due to the larger relative dimensions (22 mm.) of this device which make that an

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area averaged velocity is measured. The Pitot tube is located in the middle of the measuring section and is placed on a frame with a level gauge. This frame forms an accurate lateral and vertical positioning system. Relative maximum error of the pressure transducer is determined on 0.8 % of the maximum value. Both velocity and waterheight data are recorded by the computer with a maximum sampling frequency of 220 Hz. During experiments, all recordings can be observed on screen.

An accurate and reliable discharge control is the essential point in the investigation of the transient regime. This control is realized by electronic adjustment of the opening angle of a butterfly valve. This valve is installed in a horizontal tube next to the discharge meter.

3. Hydrographs

A series of triangular hydrographs were passed in the circular flume to evaluate the flow and friction characteristics. Each hydrograph consists of an start period T_i at base flow Q_b, an ascending branch with duration T_s starting at base flow Q_b and ending at peak flow Q_m, a descending branch with duration T_d ending at the same base flow Q_b and an outlet period T_u at base flow Q_b.

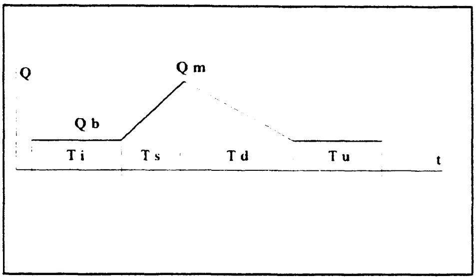

Figure 2: Parameters of a hydrograph

The start period T_i and the outlet period T_u should have a duration of 60 s. to establish and attain a steady flow.

The duration of the ascending branch T_s and descending branch T_d is chosen taking into account two factors. First, if the duration is too long, the regime will be quasi-permanent. Secondly, T_d is always equal or larger than T_s for a real hydrograph. Therefore, after consulting literature, T_s is set on 40 s and 80 s, T_d is set on 80 s and 120 s [3,6,9].

The waterheight at base flow Q_b must provide a minimum water height of approximately 5 cm to enable the measurement of a velocity profile with a Pitot tube. Q_b is taken 5 l/s and 10 l/s, in relation with the bottom slope of 0.3%.

Q_m is limited by the pump capacity and the flume dimensions and is set on 25 l/s and 35 l/s.

For steady flow measurements provisions are present at the upstream end of the flume to establish a perfect steady regime. These provisions consist of a grill of plastic tubes. In transient regime it is observed that these provisions cause reflection, storage and deformation phenomena in the little reservoir at the upstream end of the flume. These phenomena result in a second peak for the upstream and downstream water height even bigger than the first peak. Removal

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of these provisions causes no obvious secondary flow patterns in the circular flume. Only slight oscillatory flow could be observed on the water surface and at high discharge a water jump at the entrance of the flume due to the change in section.

4. Results

4.1. Repeatibility

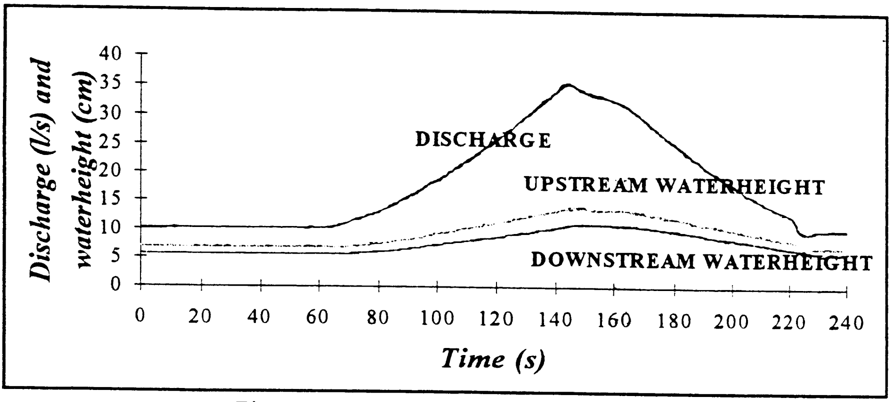

Figure 3: Repeatibility of a hydrograph

Each hydrograph is repeated at least 30 times to measure point velocities at different lateral positions and different depths. Hence the importance of a perfect repeatibility is obvious. This can be shown on the basis of the discharge and waterheight measurements. Figure 3 shows the results of seven similar test runs. This leads to the conclusion that variations of the opening angle of the butterfly valve, variation of the waterheight in the upstream buffer reservoir and deformation of the flow pattern are minimal.

A dynamic hydrograph shows hysteresis effects. This means that, for the same discharge value, a higher waterheight will be obtained in the falling branch than in the rising branch. As a result there has to be steered to a lower discharge value for a small period immediately after passing of the hydrograph to reach base flow. This causes a small dip in the discharge graph (figure 3).

After maximum flow a small inflection in the discharge hydrograph is always observed. This is the result of inversing the direction of movement of the butterfly valve, going from opening to closing sequence.

For velocity measurements in unsteady flow, the most difficult aspect is to reasonably define the mean velocity and the turbulence intensity. Methods available in literature are the phase averaging method, mathematical smoothing and Fourier transformation [3,4,6]. The phase averaging method consists of repeating the same experiment as many times as possible. This time-consuming method is not practically realizable. Mathematical smoothing is in fact replacing

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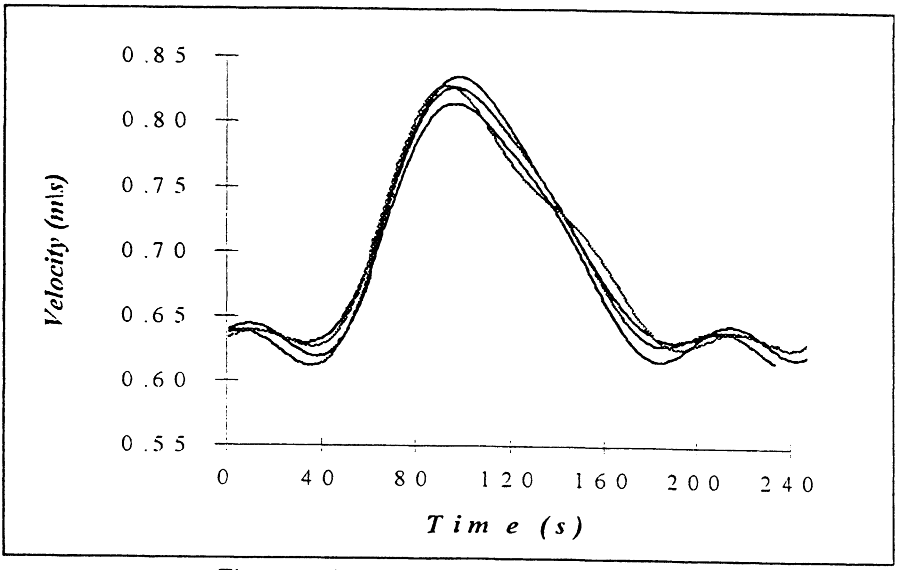

Figure 4: Accuracy Fourier transformation

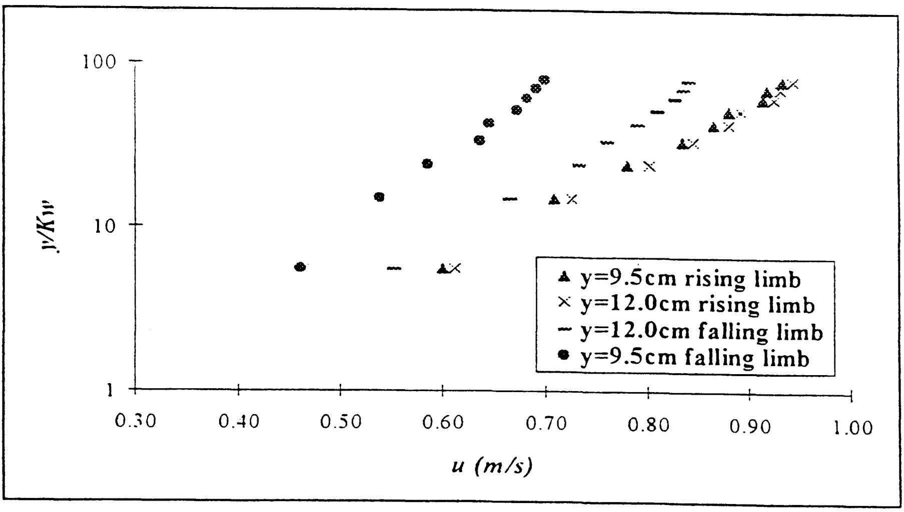

Figure 5: logaritmic velocity law

phase averaging by time averaging over a short period. An attempt has been made using an averaging period of 4 s and a data acquisition rate of 5 Hz. The results still show turbulence effects. Preference is given to a Fourier transform [4,6]. A Fourier transform splits the point velocity signal in a sum of sinus waves with

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increasing frequency. The maximum frequency retained is chosen in an appropriate way so that high frequency components indicating turbulence are filtered out. A Fast Fourier Transform (FFT) is used. The FFT consists of a variety of mathematical tricks for reducing computation time required to compute a Discrete Fourier Transform. FFT is used in many different domains and available on spreadsheet-programs as Excel. The accuracy of a Fourier transform is demonstrated in figure 4 . The maximal deviation for 5 tests is about 2 cm/s.

4.2. Velocity profiles

Velocity measurements are only made under base waterheight to prevent air from entering the Pitot tube. Therefore the point velocities at different waterheights have to fit at the logaritmic velocity law of Prandtl - von Karman, valid in the inner region (max. 20 % of the waterheight):

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{y+y_0}{k_w}\right) + Br \qquad (1)$$

The linearity of the velocity profiles in a semi-logaritmic diagram indicate the accuracy of the registration and the validity of the log-law for unsteady instant flow velocities in a test flume with circular cross-section. This confirms the results obtained in similar test flumes with rectangular section [6,9].

The flow pattern in unsteady flow is investigated by recording point velocities at eleven different lateral positions over a cross-section in the middle of the test section of the flume. A typical result is seen in figure 6. The velocity profile is very uniform in

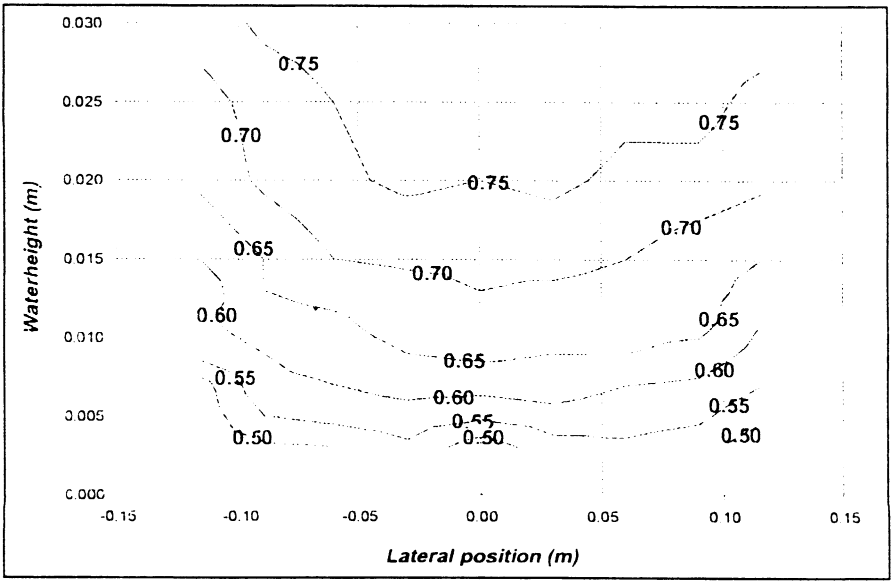

Figure 6: Isoclines

between -9 cm. and +9 cm. Above the bottom-wall intersection point (-11.6 cm. and +11.6 cm.) the isoclines or lines of equal velocity bend upwards. This confirms the findings of an investigation of velocity and shear stress profiles in steady regime as a result of a previous research project [7,8].

The figure shows symmetrical results over the whole width of the circular cross-section of the flume. This result at a fixed moment in time can be extended over the whole duration of the hydrograph. This makes us believe that the removal of the provisions to ensure steady flow conditions, mentioned in paragraph 3, doesn't cause any secondary flow patterns.

At corresponding waterheights, point velocities in the rising branch are always larger than the local velocities in the falling branch. The difference decreases as water height increases. Point velocities near the water surface arrive at their maximum values earlier than those near the bottom. These results are confirmed by TU and SONG opposite to the results of KABIR [3,6,9].

Finally, a comparison is made between the average vertical velocity V obtained by integrating the logaritmic law of Prandtl - von Karman and U being the discharge divided by the wet surface at the location of the velocity readings.

The logaritmic velocity law is only valid in the inner region of the waterdepth, which is approximately 20 % of the total waterdepth [9]. Hence integrating this law over the entire waterdepth causes a certain error. This error declines with increasing water level but leads only to a relative maximal error of a few percent.

Under transport conditions, the registrations of discharge and local water levels (and from that the U-values) are not influenced by the sediment movements. On the contrary, velocity measurements with a Pitot tube may be disturbed under sediment transport conditions. Firstly, the logaritmic velocity law is very sensitive to the determination of the reference bottom level y_0 (equation (1)). Due to sediment transport, ripples appear at the bottom of the flume. The application of the log-law to determine the mean velocity is then prohibited. Furthermore, sediment particles tend to clog the entrance of the Pitot tube.

A typical result of comparison is shown in figure 7. V tends to have a smoother profile due to the Fourier transformation. U has the same sequential behaviour of the discharge profile. This means an inflection at maximum velocity and a dip immediately after the hydrogram. A good agreement is found between V and U for all investigated hydrographs. The maximal values occur at the same moment in time. Hence no time shift occurs between V and U. This means that the time shift chosen for Q, relative to h, is well estimated. This time shift of approximative 5 s is a function of the wave velocity of the hydrogram. Maximal deviations are 5 cm/s, the average deviation lies around 2 cm/s, being the accuracy of the Fourier transformation. U therefore yields a quantitative approximation of the average velocity that can also be used in tests evaluating sediment transport.

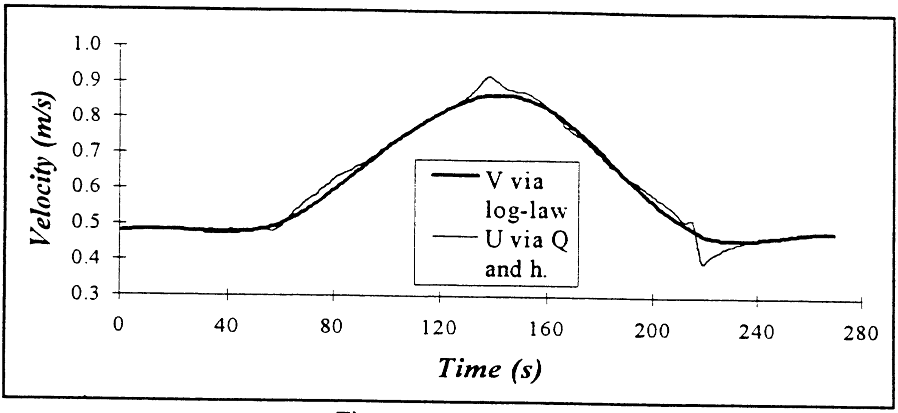

Figure 7: V versus U

The de Saint Venant equation of motion together with the kinematic flow principle can provide an expression for the friction velocity [10]:

$$u_{*SV} = \sqrt{gR\left[S_o + \frac{1}{C}\frac{\partial h}{\partial t} - \frac{1}{g}\frac{\partial V}{\partial t}\left(1 - \frac{V}{C}\right)\right]} \qquad (2)$$

An other way of estimating the friction velocity is via the theoretical Prandtl - von Karman logaritmic velocity profile gradients. A comparison of u_{*LOG} and u_{*SV} shows that u_{*SV} is larger than u_{LOG} in the rising branch while the inverse occurs in the falling branch. However, the differences do not exceed 1 cm/s and are mostly less than 5 mm/s. So the overall conclusion is a good agreement between u_{*LOG} and u_{*SV}.

The value of u_{*LOG} is very sensitive towards an exact determination of the bottom reference level y_0. In steady flow a variation of 0.5mm causes an error of 12.6% in the friction velocity u_{*LOG} [8]. This inhibites the application of u_{LOG} in measurements with sediment transport. Hence the agreement between u_{*LOG} and u_{*SV} creates the possibility to obtain a quantitative value for the friction velocity.

5. Conclusion

The velocity characteristics in transient flow have been assessed by running a series of hydrographs in a test flume with circular cross-section. Flow characteristics in unsteady flow, obtained in test flumes with rectangular section, are confirmed in the cylindrical test flume of the Hydraulics Laboratory of Gent. The influence of storage, reflection and deformation is minimal and no secondary flow patterns are induced in the current experimental setup. Real values of the average velocity can be obtained by discharge and waterheight measurements. Friction characteristics in unsteady flow can be quantified.

This series of experiments has led to a good insight in the hydraulic behaviour of the test flume in unsteady flow. The experiments are a useful even necessary step in the evolution towards the description of the sediment transport phenomena in transient regime.

6. Acknowledgement

These experiments were conducted in the framework of a project of the Fund of Collective Fundamental Research (FKFO) of the federal government of Flanders, Belgium.

Notations

A	wet surface	[m^2]	T_d	duration descending branch hydrograph	[s]
Br	integration constant log-law	[-]	T_i	enter period hydrograph	[s]
C	kinematic wave velocity	[m/s]	T_s	duration ascending branch hydrograph	[s]
h	waterheight	[m]	T_u	outlet period hydrograph	[s]
H	average waterheight	[m]	u	velocity at vertical coördinate y	[m/s]
κ	Von Karman constant (=0,4)	[-]	U	average velocity	[m/s]
k_w	roughness coëfficient wall	[m]	u_*	friction velocity	[m/s]
Q	discharge	[m^3/s]	u_{*L}	friction velocity via log-law	[m/s]
Q_b	base flow	[m^3/s]	u_{*SV}	friction velocity via de Saint Venant	[m/s]
Q_m	base flow	[m^3/s]	V	average velocity	[m/s]
R	hydraulic radius	[m]	x	lateral coördinate	[m]
S_o	bottom slope	[-]	y	vertical coördinate	[m]
S_f	friction slope	[-]	y_0	reference bottom level	[m]

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