DEVELOPMENT AND TESTING OF A DEVICE FOR DIRECT BED SHEAR STRESS MEASUREMENT

Philipp Gmeiner[1], Marcel Liedermann[1], Michael Tritthart[1], Helmut Habersack[1]

[1]Christian Doppler Laboratory for Advanced Methods in River Monitoring, Modeling and Engineering
Institute of Water Management, Hydrology and Hydraulic Engineering
Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences
Austria, 1190 Vienna Muthgasse 107
E-mail: philipp.gmeiner@boku.ac.at

Abstract

The forces occurring in a river bed are subject to temporal and spatial fluctuations, which are closely linked to the characteristics of turbulent flows. In fact the random nature of turbulent flows suggests that statistical methods are required when dealing with sediment transport, hence measurements of the instantaneous bed shear stress seem to be inevitable. Bed shear stress represents an important link between turbulent flow conditions and sediment transport, and is thus a fundamental parameter to describe and predict morphodynamic processes. Though indirect methods to evaluate bed shear stress are widely applied, these techniques are only capable of estimating mean values of bed shear stress. In contrast the advantage of direct measurement techniques is the acquisition of temporal bed shear stress variations.

Therefore a device for direct measurements of the fluctuating bed shear stress in a gravel bedded river was designed and tested. In laboratory flume tests a static calibration was performed to determine the inherent frictional losses of the measurement system, resulting in a linear relationship between applied and measured forces. The functioning of the streamlined shape was confirmed and the comparison of directly measured bed shear stress was in good agreement with calculated and modeled independent data sets. Beside that a resonance frequency analysis as well as statistical analyses of the directly measured bed shear stress were performed.

After design, construction and laboratory measurements a prototype device is available for direct measurements of bed shear stress in gravel bed rivers. Future work aims at testing the functional capability of the device for field measurements.

Introduction

Though literature is rich in the descriptions of various indirect methods dealing with the evaluation of bed shear stress and shear velocity by measuring flow velocity or turbulence it is, however, difficult to estimate these variables accurately, particularly in large rivers such as the Danube. Furthermore there is a discrepancy among the calculated values due to different methods.

Indirect techniques to estimate bed shear stress and shear velocity are based upon assumptions of flow conditions. The commonly applied indirect methods are: (1) reach average method, (2) vertical velocity profile (law of wall), (3) drag estimate (quadratic stress law), (4) near bed Reynolds stress method and (5) turbulent kinetic energy (TKE) Method (Kim et al., 2000). Potential problems of (1), (2) and (3) are to define where the actual riverbed lies, to measure the water surface slope accurately or to define a representative roughness parameter (Smart, 1999). Potential error sources of the Reynolds stress method are tilting of the sensor or contamination by secondary flows, whereas the TKE method requires the finding or confirming of universal coefficients C1 or C2 (Kim et al., 2000). In addition these indirect techniques are only capable of estimating time-averaged values of bed shear stress and shear velocity. Hence they do not account for bed shear stress fluctuations and therefore are not sufficient to describe sediment transport at incipient motion conditions (Fig. 1 – case 2) or the influence of varying turbulence intensities on sediment transport rates (e.g. Nelson et al., 1995; Sumer et al., 2003; Hofland and Battjes, 2006).

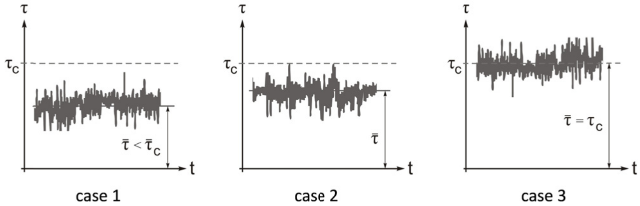

Figure 1: Interaction between bed shear stress (τ) and grain resistance (τ_{crit}): case 1 – no sediment motion; case 2 - destabilization and transport of sediment particles starts; case 3 – 50 % of the sediment particles are in motion (directly measured bed shear stress IWHW/BOKU, after Günter, 1971)

As depicted in Fig. 1 the apparent randomness of the forces acting on the particles of a river bed suggests that statistical methods are required, when dealing with sediment transport. These statistical models (Fig. 2) represent the destabilizing fluid forces and the threshold shear stress as distributions rather than as single values, thus providing a probabilistic model of sediment entrainment (McEwan and Heald, 2001).

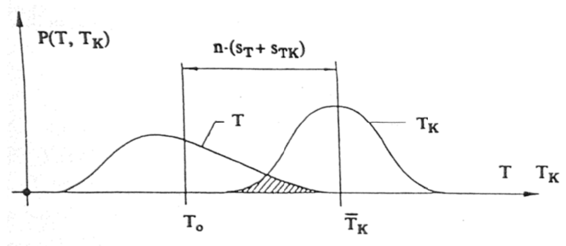

Figure 2: Probability density function of the critical shear stress T_k and bed shear stress T (Grass, 1970)

A convolution of the two distributions then yields the fraction of time in which the critical shear stress is surpassed by the instantaneous shear stress (Hofland and Battjes, 2006).

However, owing to the complexity of flow around roughness elements, there is limited information available about the probabilistic nature of the hydrodynamic forces occurring. Thus it is worthwhile to measure the fluctuating bed shear stress, in order to obtain not only mean values, but also variability, minima and maxima of this parameter, to draw conclusions in terms of critical shear stress and the initiation of motion, respectively.

Compared to indirect shear stress estimations the main advantage of direct measurement techniques is the acquisition of temporal bed shear stress variations. In flume studies Prandtl-Pitot Tubes, thermal techniques such as hot film anemometry or shear plates are sometimes used. However, due to their complexity and the requirement of careful calibration direct techniques are rarely applied. So far there have been no reported successful attempts to apply direct bed shear stress measurements using a shear plate in gravel bed rivers, though they could give substantial progress in process understanding concerning sediment transport, turbulent flow conditions and the statistical characteristics of bed shear stress. Therefore it was aimed to design, construct and test the functionality of a device for direct measurements of the instantaneous bed shear stress which can be used at the Danube.

Methods

Measurement technique

The principle of the adopted measurement technique is to allow a shear plate covered with roughness elements to move freely in horizontal directions under the forces exerted by the flowing water and to measure shear stress acting on the plate.

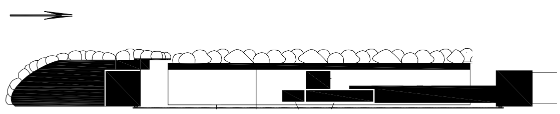

Figure 3: Sectional drawing of the measurement device

The shear plate covered with roughness elements is 0.5 m long, 0.5 m wide and mounted by means of a self-constructed roller bearing in a steel frame, which acts as a carrier for the whole measurement system (Fig. 3). The deployment area in the Danube, with flow velocities up to 3 ms^{-1} and water depths between 5 and 10 m, requires a robust construction with enough weight to ensure a secure lowering to the river bed, and beyond that to avoid a change in position during measurements. Therefore the steel frame is constructed with solid matter to gain enough weight and is provided with a three point suspension to achieve the required stability behaviour while lowering the device to the river bed. As the device is lowered to the ground by means of a cable winch, it protrudes about 12 cm above it. Hence a streamlined shape covered with roughness elements surrounds the shear device, which is required to minimize energy dissipation owing to flow separation. The profile of the streamlined shape is designed according to the shapes of NACA-profiles, which were originally developed to design wing air foils. The forces occurring are measured with two strain stress transducers, which are oriented perpendicular to each other, in order to measure the forces acting on the shear plate in and lateral to the flow direction. They are mounted underneath the shear plate and are fixed to a load transmission, which is aligned in the center of the shear plate, and to the carrier of the measurement frame. The shear device is able to measure the instantaneous bed shear stress up to about 100 Nm^{-2}.

Flume tests

After design and construction of the device, laboratory flume tests were conducted to test its functionality. The tests took place at the Austrian Institute for Hydraulic Engineering and Calibration of Hydrometrical Current Meters in an 18 m long and 1 m wide flume. Additional tests were performed in the laboratory of the Institute of Water Management, Hydrology and Hydraulic Engineering of BOKU. To meet the requirements of a fully rough turbulent boundary layer, the flumes were covered with bed material, similar to the one in the Danube East of Vienna. The objectives of these tests were the static calibration, the test of the streamlined shape, a comparison of directly measured with estimated and modeled bed shear stress and a resonance frequency analysis.

The 3-dimensional flow velocities were measured in several verticals using a Nortek Lab-ADV at the maximum sampling rate of 25 Hz and with a Nortek Field-ADV at the maximum sampling rate of 64 Hz. Velocity samples with a signal correlation < 80 % and a signal to noise ratio < 30 dB were disregarded. Existing despiking routines (Goring and Nikora, 2002; Cea et al., 2007) were adapted to detect and remove spikes, as well as to replace the eliminated spikes in the flow velocity measurements. The velocity and turbulence data were used to estimate bed shear stress, to test the streamlined shape of the device and to calibrate and validate the 3D numerical simulation model RSim-3D.

Bed shear stress estimation

For the comparison with the directly measured bed shear stress three different indirect methods were used to estimate bed shear stress from velocity and turbulence data.

In the overlap between the inner and outer region of a turbulent boundary layer the vertical velocity distribution can be related to the logarithm of height. One expression of the 'law of the wall' is given by

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z+d}{k_s}\right) + B \qquad (1)$$

where u is the mean velocity at height z above the bed, u_* the shear velocity ($u_* = (\tau/\rho)^{0.5}$); k_s is the equivalent sand grain roughness (represented here by d_{90}), B the constant of integration (8.5 for fully rough turbulent boundary layers), d the zero plane displacement and κ denotes the von Kármán constant (0.41). Provided that the data is linearly distributed in the semilog domain, a regression of u against $ln((z+d)/k_s)$ then allows a calculation of u_*. The maximum correlation coefficient was found through incrementing or decrementing d, thus resulting in the origin of the logarithmic velocity profile.

By means of turbulence measurements bed shear stress was determined from Reynolds stress. As the value of bed shear stress can be assumed to be close to that of near-bed Reynolds stress (Kim et al., 2000)

$$\tau = -\varrho\left(\overline{u'w'}\right) \qquad (2)$$

where u' and w' are the fluctuations of the streamwise and vertical velocity component.

Assuming a linear relation between bed shear stress and the turbulent kinetic energy (Kim et al., 2000), bed shear stress can be estimated through

$$\tau = C_I\left[0.5\ \varrho\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right)\right] \qquad (3)$$

where u', v', and w' are the fluctuations of the three velocity components and C_I the proportionality constant with a value of 0.19.

Hydrodynamic numerical modeling

Additional bed shear stresses were obtained from the 3D numerical simulation model RSim-3D, to obtain bed shear stress values beside the ones estimated from velocity data.

RSim-3D applies the Finite Volume Method to solve the three-dimensional Reynolds averaged Navier Stokes equations. Turbulence is modeled by means of the standard two equation k-ε turbulence closure. (Tritthart et al., 2009)

Results

Static Calibration

Though the strain stress transducers are calibrated it is necessary to perform a static calibration for the whole measurement system, due to inherent frictional losses. The static calibration procedure was executed using a spring balance to apply known forces. The relationship between the applied and the measured forces is linear (Fig. 4) and the inherent frictional losses are at the order of approximately 20 %.

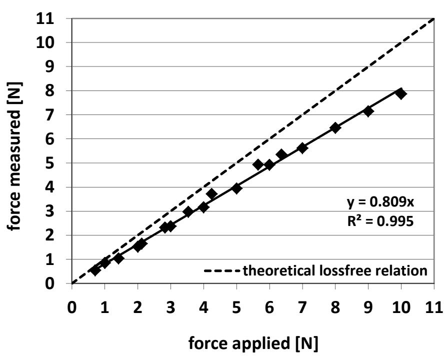

Figure 4: Static calibration – relationship between applied and measured forces

Test of the streamlined shape

Two experimental setups were employed to test the streamlined shape: In a first test the device was protruding to meet the measurement situation in the Danube, in a second test it was buried behind a long flat ramp. Vertical velocity profiles, the turbulent kinetic energy, flow visualization with $KMnO_4$ (potassium permanganate) and directly measured bed shear stresses served as parameters for comparison.

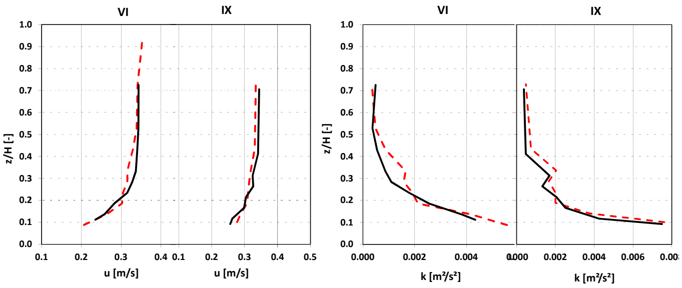

Figure 5: Comparison of flow velocity and turbulent kinetic energy in two measurement positions VI and IX– dashed line: device protruding; solid line: device behind the ramp

The analysis of the vertical velocity profiles and the turbulent kinetic energy distribution over the flow depth, exhibits no significant differences between the two experimental configurations (Fig. 5). Equal results are received for the comparison of directly measured bed shear stresses (Fig. 6) and the visualization with $KMnO_4$.

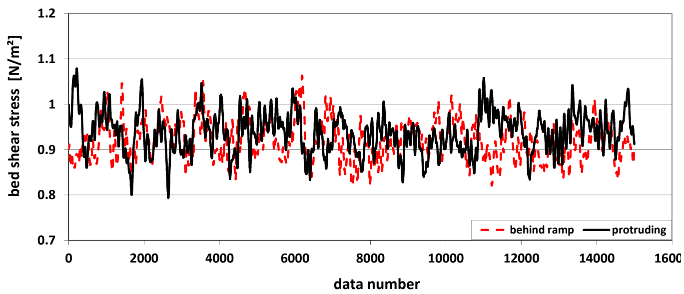

Figure 6: Comparison of directly measured bed shear stress – dashed line: device protruding; solid line: device behind a ramp

Comparison of directly measured with estimated and modeled bed shear stress

The directly measured bed shear stresses were compared with shear stress estimated from the law of wall, Reynold's stress and the turbulent kinetic energy, as well as with numerically modeled bed shear stress. For the comparison shear stress estimates at the front side and in the middle of the shear plate were used. When the depth Reynolds number is the same over the shear plate as in the remaining part of the flume, the comparison of directly measured bed shear stresses fit well with calculated and modeled datasets (Fig. 7 - rhombi) across the length of the shear plate. Else only calculated respectively modeled bed shear stresses at the front side of the shear plate are consistent with the directly measured bed shear stresses.

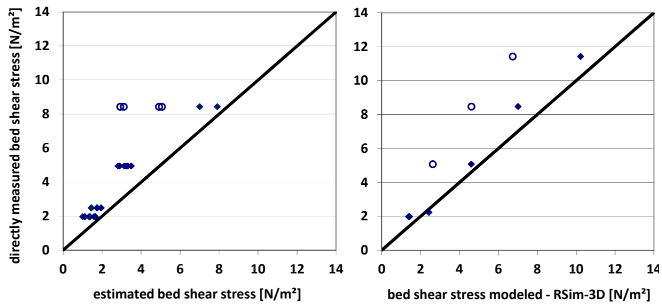

Figure 7: Comparison directly measured with estimated bed shear stress

This deviation is due to the low water depth (less than 0.30 m) over the measurement device, resulting in a strong acceleration and a substantially higher velocity head attacking at the front side, leading to an overestimation of bed shear stress for those flow situations (Fig. 7 - circles). However, by reason of much higher water depths at the Danube, flow situations with water depths smaller 0.50 m are not expected to occur during field measurements.

Resonance frequency analysis

In order to perform shear stress measurements in turbulent flows, it is necessary to characterize the frequency response respectively the natural frequency of the assembly. The excitation frequency should be lower than the natural frequency to conduct accurate correlation and spectral analysis, for an excitation frequency that is much higher than the natural frequency of the assembly leads to an amplitude reduction and a phase shift.

To identify the frequency response, time series of enforced vibrations were measured, and transformed into the frequency domain using fast Fourier transform (FFT). As shown in Fig. 8, there is a sharp peak at ~37.5 Hz, corresponding to the natural frequency of the assembly, which should be sufficient for the turbulent flow in a river. Nevertheless a slight improvement of the natural frequency, shifting it to a somewhat higher frequency appears to be worthwhile.

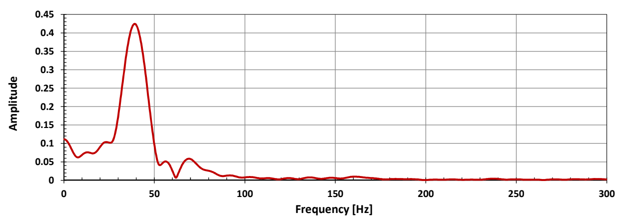

Figure 8: Frequency response of the assembly

Conclusions

After design, construction and the first successful measurements in the laboratory, a significant step towards availability of a device for direct bed shear stress measurement was made. In these tests the functionality of the streamlined shape was confirmed and the calculated and modeled independent data sets were in good agreement with the directly measured bed shear stresses, for flow situations with similar depth Reynolds numbers over the shear plate and in the remaining part of the flume. Beyond that with a value of 0.50 m a lower limit of application of the device of use regarding water depth was found. Beside a slight improvement of the resonance frequency, future work aims at testing the functional capability of the device for field measurements.

Acknowledgments

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