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Václav Matoušek

FLOW ROUGHNESS EVALUATION OF MOBILE-BED STREAMS

Summary

Recent field measurements of mobile-bed roughness in selected streams in Czech Republic are described. The results are collected in a database organized to a www catalogue. The field results of the bed roughness in two gravel-bed streams under flash flood conditions are discussed. A methodology is suggested for evaluation of the bed roughness of straight channels transporting sediments. A prediction of the bed roughness under the condition of intense sediment transport in the upper plane bed regime is demonstrated on the results of laboratory pressurized-pipe tests. An application to flood conditions in a steep mountain creek is shown in a case study.

Key words: Bed load, sediment transport, flood flow, slurry pipe, upper plane bed

INTRODUCTION

The hydraulic roughness of a mobile-bed stream has a profound effect on flow resistance and hence on the relation between the flow discharge and the water stage in a channel reach. This relation affects the channel capacity, i.e., the capability of the channel to convey certain discharges without spilling over banks. A successful prediction of the hydraulic roughness plays a vital role in flood control planning.

Web Catalogue of Hydraulic Roughness of Mobile-Bed Streams in Czech Republic

Currently, a stream-roughness project is in progress at the Czech Technical University in Prague with two major goals. One is to develop a database of values of the hydraulic roughness (in the form of the Manning's roughness coefficient *n*) of the selected reaches of natural and artificial open channels with mobile beds in the Czech Republic. Reaches are selected so that the reaches of very different conditions are represented in the database. Furthermore, the attention is paid to the effect of different discharges on the Manning's *n* value in one particular reach. The other major goal of the project is to develop a methodology for the determination of the hydraulic roughness from field measurements. This will enable to fill the database with data acquired using a unified procedure so that a very similar validity will be ensured for all database inputs. Both the database and the methodology are supposed to serve water engineers in practice as the tools that provide a more qualified estimation of the relation between the discharge and the water stage for different types of river/creek reaches and different discharges (from low discharges to flood discharges).

The database in a form of a www catalogue of the hydraulic roughness of selected open channels in the Czech Republic was established in 2007. At present, it contains data from 39 different reaches from different locations in the Czech Republic. In 2009, field measurements were carried out at two reaches of the semi-natural gravel-bed rivers in the region of the north Moravia after disastrous floods in June 2009 (see Section *Example of field determination* … below). The main objective of the catalogue is to list the values of the Manning’s roughness coefficient, *n*, for different types of open channels and floodplains typical for natural conditions in the Czech Republic.

Field data collection for catalogue

A value of Manning's *n* is sensitive to a large number of quantities associated with the properties of a reach and the flow through the reach. Field data are a necessary basis for determination of the *n*-value in a selected channel reach. It is necessary to collect as many as possible data of parameters that influence the roughness value. The data include geometrical parameters of the reach and its floodplain, hydrological parameters, grain size distribution of the reach bed, and the basic parameters of the catchment.

The process of field data collection must include the following procedures:

– selection of an appropriate reach,

– determination of the hydraulic parameters of the channel,

– determination of the longitudinal profile of water surface in the reach,

– determination of the discharge and the average cross-sectional velocities corresponding with the water-surface profile.

For the purposes of the developed methodology, the criteria have been set for an appropriate selection of the channel reach and for the measurements of cross sections along the length of the selected reach.

The collected hydrological data include the actual discharge during the field measurements, the average annual discharge, the *N*-year discharge, and the bankfull discharge. The grain size distribution of the channel bed is determined from a collected sample using an appropriate standard method.

Data processing for roughness determination

The data collected in the field were digitalized and further processed in the hydraulic software HEC-RAS for one-dimensional open-channel flows. Each reach and each *n*-value added to the catalogue were processed using the method for a steady non-uniform flow in the freeware HEC-RAS. For each measured case, the mathematical model was set up in HEC-RAS with the water surface at the outlet and the discharge as the boundary conditions. The longitudinal profile of the water surface predicted by the mathematical model was tuned up by changes in the *n*-value so that the predicted profile matched finally the profile measured in field as close as possible along the entire length of the reach. The best match gave the resulting *n*-value for the reach at the particular discharge. The method of the least squares for a mutual deviation of the two profiles was chosen as a criterion for the best match.

Example of field determination of Manning's n for flash flood conditions in gravel-bed streams

In 2009, the web catalogue was extended with the roughness coefficient values for two reaches in two semi-natural gravel-bed streams - the Bělá river and the creek of Javornický potok. Both streams are located in the region of the town of Javorník in the north Moravia. The region was hit by severe flooding (flash floods) in June 24th-27th. Our field tests were carried out on the 22nd of July 2009. The marks of the maximum water stage were still clear on the banks of the both selected reaches.

The presence of a flow gauging station or an object for which the flood peak discharge could be calculated was one of the most important criteria for selection of a reach. The selected reach had to be straight, regular, with no obstacles in bed and banks. The water stage marks of the culminating flow had to be clearly distinguishable on both banks of the channel. For each stream, one representative reach was selected that was straight, relatively flow-uniform and flat-bed. The grain size distribution was very similar in both reaches. The flood peak discharge was very similar to the bankfull discharge, i.e., water did not spill out onto a floodplain.

The peak discharge for the reach of the river Bělá was determined from the recordings of the water flow gauging station located not far above the selected reach. (The station of Mikulovice operated by the Czech Hydrometeorological Institute, CHI). An alternative value of the peak discharge was available from the river managing company Povodí Odry (POd). The peak discharge on the creek Javornický potok was calculated from the water levels corresponding with the peak discharge on the bed drop object located just tens of meters above the reach. The values of the discharges and the additional parameters measured in the reaches (the channel cross sections, the longitudinal profile of the bed and water surface etc.) led to the computation of the appropriate values of the Manning coefficient using the HEC-RAS software.

River Bělá

The field measurements were carried out in the straight reach of the river in the town of Mikulovice just below the bridge over which the state road No. 457 crosses the river. The reach was 96 meter long, and the channel was relatively regular over the entire distance of the reach. The gravel-bed surface was composed of grains of different sizes of the order of centimeters to tens of centimeters. The largest individual stones were almost one meter big. The cross section of the channel had a shape of a compound trapezoid; the banks were composed of stones and grass. The longitudinal slope of the bed was determined by the measurements, the value was 0.5%. The peak water stage marks suggested that the maximum water depth was of about 3 meter. The peak discharge during the flood was 150 m^3/s according to CHI, or 183 m^3/s according to POd. The water stage marks suggested that the peak discharge was roughly equal to the full-bank discharge. The temporary discharge during the field test was 4.3 m^3/s and the average water depth 0.65 m.

The Manning's coefficient was determined for both water stages:

– for the discharge Q = 4.3 m^3/s, the mean value of the coefficient $n = 0.066$;

– for the discharge Q = 150 m^3/s (CHI), the mean value of the coefficient $n = 0.053$ (for Q = 183 m^3/s, n = 0.041).

For the observed reach, the value of Manning's n is smaller for the bankfull discharge than for the actual discharge at a low water stage.

Creek Javornický potok

The selected reach was located along the road No. II/457 above the town of Javorník. The area of the CRANP-KOVO company is located just across the road along the reach. The reach was 113 meter long. It was necessary to split the reach to three parts with different slopes and channel conditions. The first part upstream was processed. It was 26-meter long and the longitudinal slope of bed was 1%. The trapezoidal channel has grass banks with bushes in the highest elevations of the right bank. The gravel bed was regular and the largest stones distributed relatively uniformly over the bed surface. The peak discharge was roughly equal to the bankfull discharge. The average flow depth at the peak discharge was 2.5 m. The peak discharge calculated from the bed drop flow was approximately 34 m^3/s. The instantaneous discharge was not measured because of very low water stage in the reach.

The Manning's coefficient was determined for the maximum water stage:

– for the discharge Q = 34 m^3/s, the mean value of the coefficient $n = 0.054$.

The measurements were processed using the method of non-uniform flow in the HEC-RAS software. Information and experience gained during field tests have been implemented to the methodology that is developed for the determination of the hydraulic roughness from field measurements.

Evaluation of field test results

It is difficult to evaluate the obtained n values as there is no generally accepted reference with which the values could be compared. Our earlier experience learns that a value of n is affected by a flow discharge in a reach and the measurements in the river Bělá confirm it. In both streams, flood discharges were accompanied with transport of sediment and this affected the value of n as well. An analysis of this effect on n in the two reaches is described in [Matoušek and Krupička, 2010]. A methodology that should be applied in order to evaluate the effect of sediment transport on the roughness of a mobile bed is described below.

Evaluation of Sediment Transport Effect on Mobile-Bed Roughness

In the literature, the roughness of a mobile bed has been investigated extensively for flow conditions usual in open channels, i.e. for the conditions associated with low bed shear and none or weak sediment transport. Much less information is available about flows at high bed shear, i.e. flows that erode the top of the mobile bed, prevent development of bed forms (the upper-plane-bed regime), and cause intense transport of sediments. The flow in the upper-plane-bed regime is typical for e.g. slurry flows above stationary deposits in pipelines or open-channel flows of steep slopes at high discharges (flood conditions).

Methodology for determination of mobile-bed roughness

Recently, a methodology has been proposed [Matoušek, 2009a] for determination of the roughness of a mobile bed of straight reaches of channels transporting sediments. It suggests three successive steps that lead to an appropriate choice of a bed-roughness value:

A. the determination of a characteristic value of Shields number for the mobile bed,

B. the evaluation of the bed conditions based on the Shields number (bed forms, sediment transport),

C. the calculation of the bed roughness using an appropriate equation for the identified bed conditions.

A. Determination of characteristic value of Shields number

The shear stress develops at the top of the mobile bed as a result of the interaction between the bed and the flow above the bed. The dimensionless form of this bed shear stress is called Shields number and it is defined as $\theta_b = \dfrac{\tau_b}{(\rho_s - \rho)\cdot g \cdot d}$, where τ_b = bed shear stress, ρ_s = density of sediment grain, ρ = density of liquid, g = gravitational acceleration, d = characteristic diameter of sediment grain. This parameter evaluates the ability of bed grains to move. It was originally formulated as a criterion for the incipient motion of bed grains. Further investigations have revealed its usefulness also for evaluation of bed conditions at θ_b values higher than that at the incipient motion of the top of the bed (fig. 1).

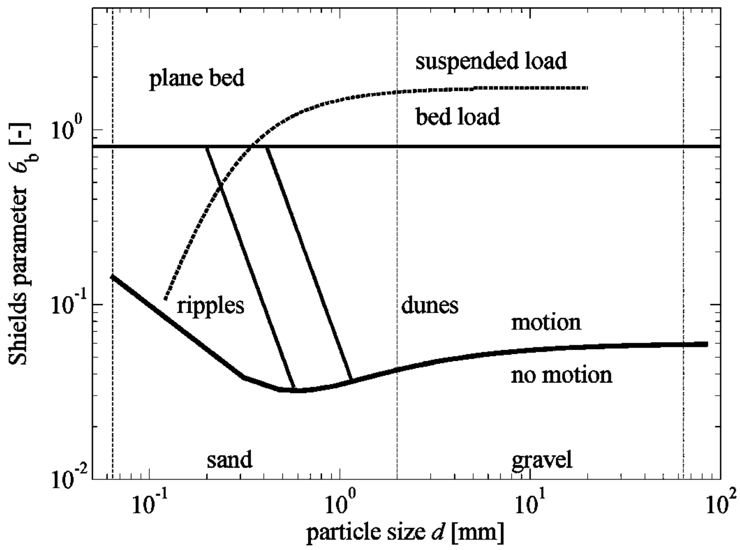

Figure 1. Extended Shields diagram

B. Evaluation of bed conditions

The extended Shields diagram in Fig. 1 estimates the types of bed forms that develop for different values of θ_b at the top of the bed composed of grains of a certain size. The thresholds for different bed conditions in Fig. 1 are rough estimates and subject to further investigation. Further, θ_b helps to determine the flow rate of sediment eroded from the top of the bed. This relation is not in Fig. 1. Instead, it is given by various transport equations proposed in the literature (e.g. the Meyer-Peter and Müller formula for bed loads or the van Rijn formula for suspended loads). Both the bed forms and the sediment transport influence considerably the roughness of a mobile bed.

C. Calculation of mobile-bed roughness

The bed shear stress, τ_b, is related to the average velocity, v, of the flow through the bed friction coefficient λ_b and $\tau_b = \frac{\lambda_b}{8} \cdot \rho \cdot v^2$. The "law of the wall" of the top of the bed relates λ_b with the oughness of the bed taking into account development of the boundary layer at the interface between the flow and the bed. The bed surface is composed of cohesionless particles. On one hand it can be seen as a hydraulically rough boundary but on the other hand it does not behave as a fix boundary if subjected to erosion. The boundary condition is the simplest for $\theta_b < \theta_{b,cr}$ ($\theta_{b,cr}$ is θ_b at the incipient motion of bed particles), where particles at the top of the bed are not in motion. The boundary is clearly defined and its equivalent roughness size, k_s, can be considered as related to the size, d, of the particles covering the top of the bed. Hence, the Nikuradse formula for the hydraulically rough boundary can be modified for the top of the bed as

$$\sqrt{\frac{8}{\lambda_b}} = \frac{1}{\kappa} \cdot \ln \frac{B_s \cdot R_{hb}}{k_s} \tag{1}$$

where:

κ – Kármán constant,

B_s – constant,

R_{hb} – hydraulic radius of flow area associated with top of bed.

For $\theta_b < \theta_{b,cr}$, the value of k_s is usually related to a certain characteristic size of grains forming the top of the bed, e.g. $k_s = d_{90}$. For $\theta_{b,cr} < \theta_b < 0.8$ (approximately), the relation between k_s and d is further complicated by the presence of both the bed forms and the (weak) sediment transport at the interface between the flow and the bed. This increases bed resistance and various authors take this effect into account through multiplication of the characteristic grain size in the k_s relationship. The direct method for implementation of bed forms to the bed roughness superposes the grain roughness and the form roughness to the total roughness of the bed.

At $\theta_b > 0.8$ the bed forms are washed out by the high shear stress and the bed becomes plane again (the upper-plane-bed regime). The top of the bed is eroded and intense sediment transport takes place. The eroded part of the bed is called the shear layer. The resistance of the eroded plane bed, and hence its roughness, are affected not only by the size of grains at the top of the grain deposit but also by particles transported through the shear layer adjacent to the top of the deposit. The mechanism that governs bed friction is much less understood for this high-bed-shear flow at than for flows at lower θ_b. Our recent investigations revealed an approximately linear relationship between k_s/d and θ_b for pure sheet flows (i.e. flows in which particles are transported exclusively as the bed load through a shear layer) and a more complex relationship among k_s/d, θ_b and additional relevant parameters for flows transporting particles as combined load (a certain portion of particles is transported as suspended load and the rest as bed load).

Laboratory experience with stratified flows in pressurized pipes

Laboratory pipe loops manufactured to convey slurries are appropriate for testing phenomena related to friction at the top of a granular bed. This is because a broad range of flow conditions can be installed in the loop. Moreover, it is easy to control the conditions and to measure required quantities. Our laboratory tests were focused to eroded beds in the upper-plane bed regime, i.e. to flows with Shields number θ_b that exceeded, say, 0.6. At high shear stress, the flow erodes the top of the mobile bed and prevents development of bed forms. As a result the bed is flat and intense transport of solid particles takes place. The transported particles influence friction conditions at the top of the bed. Our tests are described in more details e.g. in [Matoušek and Krupička, 2009, 2010]. The eroded-bed roughness size k_s is determined from the measured quantities using Eq. 1 with $\kappa = 0.4$, $B_s = 14.8$ for circular-pipe flows.

Fig. 2 shows the results of the test with the slurry of a narrow graded fraction of coarse sand ($d_{18} = 1.15$ mm, $d_{50} = 1.36$ mm, $d_{84} = 1.55$ mm) in a circular pipe of the inner diameter 100 mm. At θ_b of about 0.45, k_s/d gains a value only slightly higher than 1, i.e. much lower than in the measured gravel-bed streams. However, it must be seen that the solids concentration in flow at this relatively low (from the point of view of pressurized flows) value of Shields number at the lower limit of the upper-plane-bed regime (and i.e. the upper threshold of bed undulation) was very low in the test pipe, definitely much lower than the corresponding solids concentration in discharge through the gravel-bed streams (Bělá, Javornický potok) during flood.

In the pipe, the equivalent roughness size tended to increase with Shields number (fig. 2). The solids discharge increased with Shields number as well. The relationship between k_s/d_{50} and θ_b was roughly linear and could be approximated by the Wilson's relationship proposed for sheet flows,

$$\frac{k_s}{d_{50}} = \frac{const}{C_{sh} \cdot \tan\varphi} \cdot \theta_b \approx 3.3 \cdot \theta_b \qquad (2)$$

where

C_{sh} – average volumetric concentration of solids within a shear layer,

φ – dynamic friction angle of solids.

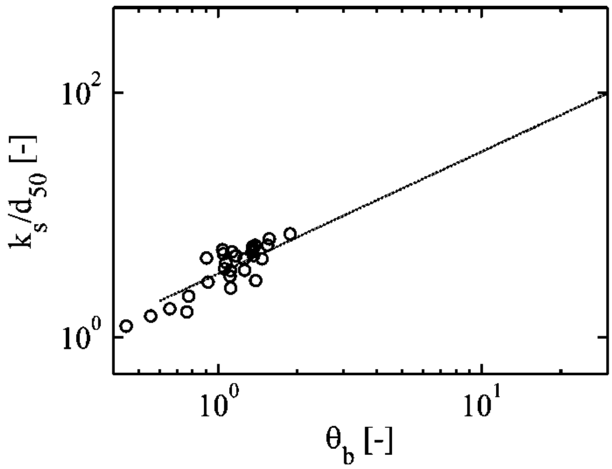

Figure 2. Roughness ratio in upper plane bed regime
(circles: 1.36-mm sand in pressurized 100-mm pipe; line: Eq. 2).

Case study: flash flood at mountain creek Dubská Bystřice in August 2002

In this case study the roughness of the mobile bed of a mountain reach of the gravel-bed stream Dubská Bystřice is evaluated for a flood condition experienced in August 2002.

A. Determination of characteristic value of Shields number

The observed reach has the longitudinal slope $i \approx i_E = 0.05$. The typical value of water depth at the peak discharge was 1.4 meter and the hydraulic radius $R_{hb} \approx 0.78$ meter. Hence, the maximum bed shear stress reached the value of about 400 Pa ($\tau_b = \rho \cdot g \cdot R_{hb} \cdot i_E \approx 9810 \cdot 0.78 \cdot 0.05 \approx 383\, Pa$). The grain size distribution of the mobile bed was $d_{16} \approx 1.3$ cm, $d_{50} \approx 5$ cm, $d_{84} \approx 18$ cm and $d_{90} \approx 22$ cm. Hence, $\theta_b \approx 0.11$ for d_{90} ($\theta_b = \frac{\tau_b}{(\rho_s - \rho) \cdot g \cdot d} \approx \frac{383}{1650 \cdot 9.81 \cdot 0.22} \approx 0.11$), $\theta_b \approx 0.47$ for d_{50}, and $\theta_b > 1.8$ for grains smaller than d_{16} (fig. 3).

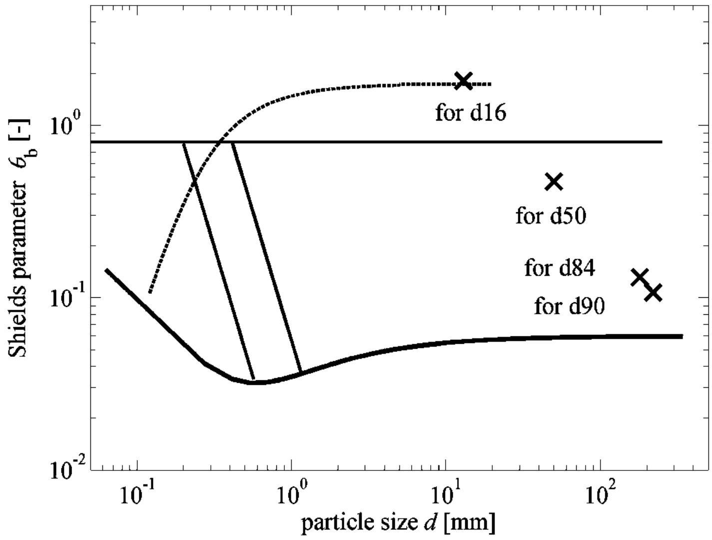

Figure 3. Extended Shields diagram applied to flood condition at Dubská Bystřice in August 2002

B. Evaluation of bed conditions

During the flood condition the critical value of θ_b for initial motion ($\theta_{b,cr} \approx 0.05$ according to the Shields diagram) was exceeded for a great majority of bed grains. The bed grains of sizes up to 0.5 m were in motion at the peak discharge. Grains smaller than say d_{16} were transported as suspended load the rest as bed load. Perhaps, intense transport of sediments and a possible forming of bed forms affected considerably bed resistance and hence the relation between the extreme discharge and the water stage.

C. Calculation of mobile-bed roughness

The evaluation of the bed conditions showed that approximately 84 per cent (per grain size) of moving grains were transported as bed load. Almost 50 per cent contributed to the upper plane bed regime. Therefore the formula for a flow with a shear layer seems to be appropriate (it was experimentally verified for $0.5 < \theta_b < 4$ by lab tests in a pressurized pipe), $\frac{k_s}{d_{90}} \approx 3.3 \cdot \theta_{b,16}$. Recalculated to the Manning coefficient using $n = \frac{\kappa \cdot R_{hb}^{1/6}}{\sqrt{g} \cdot \ln\left(\frac{B_s \cdot R_{hb}}{k_s}\right)}$, the predicted value is

n = 0.056 for $\theta_{b,16}$ = 1.8 and B_s = 14.8. If B_s = 11 (more appropriate for open channels) then n = 0.065. The use of d_{90} in the k_s/d ratio is considered here because the ratio represents the skin-friction parameter of the bed armor and d_{90} is a grain size that reasonably represents a typical armor grain. As a matter of fact, a size of even coarser grain that does not move even at the highest applied shear stress could be used. For the Shields number θ_b, however, the finest grain that still contributes to bed load (i.e. d_{16}, see Fig. 3), and hence to the shear layer, is suggested instead of d_{90}. Theoretically, k_s should be independent of the grain size in Eq. 2 for sheet flows. Nevertheless, since C_{sh} and φ could depend on d for bed load sediments of broad grain distribution the modification of Eq. 2 using a different d in θ_b than in k_s/d seems to be a plausible assumption. This assumption is supported by the finding that the constants in the solids transport formula of the Meyer-Peter and Müller type are sensitive to particle Reynolds number as reported by Matoušek [2009b]. The predicted value of n agrees well with the value corresponding with the estimated peak discharge in the evaluated reach of Dubská Bystřice during the 2002 flood event.

CONCLUSIONS

Field tests in straight reaches of mobile-bed streams provide data for a web catalogue of hydraulic roughness of selected channels in Czech Republic. The data show a profound effect of flood discharge and sediment transport on the hydraulic roughness.

A predictive formula for the equivalent roughness size of the bed in the upper plane bed regime is calibrated using data from stratified-slurry tests in a pressurized pipe. The formula can be used to predict the roughness of a steep gravel-bed stream at extreme flood discharge provided that adoptions are applied that take into account a broad grain distribution of the stream bed.

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Dr Václav Matoušek
Czech Technical University in Prague
Faculty of Civil Engineering, Dept. of Hydraulics and Hydrology
Thakurova 7, 166 29 Prague 6, Czech Republic
v.matousek@fsv.cvut.cz