Bed roughness experiments in supply limited conditions

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ABSTRACT: Reliable roughness models are of great importance, for example, when predicting water levels in rivers. The currently available roughness models are based on fully mobile bed conditions. However, in rivers where widely graded sediments are present more or less permanent armour layers can develop which limit local entrainment of sediment for bedform formation (supply-limitation). We conducted new experiments to study the effects of supply-limitation on the bed roughness. In these experiments the supply-limitation was systematically varied and the bed roughness was measured. The experiments show that the roughness of a partial mobile sand-gravel bed is strongly influenced by the volume of available mobile sand per unit area, or in other words, the average active layer thickness. For small layer thickness, the sand fills in the pores of the coarse layer and the bed roughness decreases for increasing sand volume. For large thickness, dunes develop and dune dimensions and bed roughness increase with increasing sand volume. An improved understanding of dune dimension under supply limited conditions can possibly help to improve the roughness prediction.

1 INTRODUCTION

When predicting water levels in rivers, a reliable prediction of the roughness-coefficient of the river bed is essential. Through the years many authors contributed to the understanding of roughness predictions of riverbeds. Some of the most successful methods are these proposed by Engelund & Hansen (1967), White et al. (1979) and Van Rijn (1984). Their roughness models are widely applied, for example in morphological models and 2D/3D flow models. In this paper, the roughness models proposed by these authors are referred to as the current roughness models.

The bed roughness-coefficient expresses the resistance the flow experiences from the riverbed. Flow resistance is often attributed to, on one hand, the roughness of surface grains and, on the other hand, the form drag due to irregularities of the bed (bedforms). For example, steeper or higher dunes cause larger form drag.

Under alluvial or full mobility condition the flow is capable of transporting all present grain sizes. It is relatively well understood what type of bedforms develop in relation to the flow velocity (e.g. Southard & Bochuwal, 1990). Also, equations have been proposed to estimate the bedform dimensions as a function of shear stress (e.g. Van Rijn 1984).

However, in rivers where widely graded sediments are present more or less permanent armour layers can develop which limit local entrainment of sediment for bedform formation. In such a case the shear stress near the bed is large enough to mobilize the finest size fractions, but is too small to exceed the critical shear stress for the coarse grain size fractions. This is called partial transport (Wilcock & McArdell 1997, Kleinhans et al. 2002). Under these conditions the bedform formation depends on the presence of an upstream sediment supply. As a result, dunes do not develop or stay smaller compared to alluvial conditions. Because the current roughness models are based on measurements in alluvial bedform conditions, they will generally give erroneous roughness predictions in supply limited conditions.

Earlier experiments (Van der Zwaard, 1974) showed that bed roughness under supply limited conditions is related to the (supply limited) sediment transport rate. Van der Zwaard developed a model to describe the roughness observations as a function of the sediment transport rate. To our knowledge, this is the only attempt to model the effects of supply limitation on the bed roughness.

We conducted a new series of flume experiments where the supply-limitation was systematically varied and the bed roughness was measured. In this paper the results of these experiments are discussed.

2 EXPERIMENTS

2.1 *Procedure and imposed conditions*

The experiments were carried out in a straight flume (length = 7 m and width = 0.3 m) at the Leichtweiss-Institute for Hydraulic Engineering at the University of Braunschweig, Germany. To simulate supply-limitation, the amount of available mobile sand over an immobile coarse layer was varied. First, a coarse gravel layer was installed on the flume bottom. The slope of the flume was not adjustable. Therefore, the coarse layer was manually installed under a predefined slope. The coarse layer was completely immobile under the imposed constant flow discharge, while the bed shear stress exceeded the critical shear stress of sand. Only under strong supply limitation, the critical shear stress of the sand was higher due to hiding in the pockets of the gravel.

Between flume runs sand was added to the flume. It was evenly distributed over the length of the flume. During an experiment, the transported sediment was circulated regularly by hand. Uniform flow was maintained by adjusting the downstream weir. Next, measurements were carried out to establish the roughness and bedform characteristics. This procedure was repeated until the coarse layer was no longer visible in dune troughs and the conditions were deemed alluvial.

Table 1 lists the conditions of two separate experiments; Exp2 and Exp3. A gravel layer with an average grain diameter of D_{gr} = 6.5 mm (range of 5 mm to 8 mm) was used for Exp2. For Exp3 the gravel layer was coarser with an average grain size of D_{gr} = 13.4 mm (range of 11.2 mm to 16 mm). In both experiments the same uniform sand ($D_{s,50}$ = 0.83 mm) was used for the transport material. The discharge Q and the gravel layer slope I_{gr} were chosen in such way that the resulting bed shear stress (τ_b) was large enough for dune development under alluvial conditions. In Exp3 a milder slope was installed in order to have a larger water depth (h) under uniform flow.

Table 1. Imposed conditions

	Q [Ls^{-1}]	I_{gr} [-]	D_{gr} [mm]	$D_{s,50}$ [mm]	h [cm]	τ_b [Nm^{-2}]
Exp2	10.35	0.0029	6.5	0.83	6-7	1.5-1.7
Exp3	20.05	0.0017	13.4	0.83	12-14	1.6-2.1

2.2 *Measurements*

The sediment discharge was collected in a box at the downstream end of the flume. The sediment transport rate (s) was derived by measuring the submerged weight andvolume of the collected sediment sample. When the bed is fully covered by sand sediment transport reaches its maximum value, which is indicated here as the alluvial transport capacity (s_0). The relative sediment transport rate is defined as:

$$s^* = s / s_0 \tag{1}$$

For 0 < s^* < 1 there is a limited amount of sand transport (supply limitation). The water levels and water slope were measured frequently with the use of static tubes which were located every 0.5-1 m.

The flume was drained and a bed level profile was obtained with the use of a laser-system. Bed levels were measured along the longitudinal centerline of the flume. From the bed level profiles, average dune dimensions, an average bed slope and an average bed level as present in the measurement section were derived. The volume of mobile sand per unit area on top of the coarse layer, or the average active layer thickness (δ), was measured by subtracting the initial coarse bed level profile from the bed level profile were sand was present. The relative thickness (δ_*) is defined as:

$$\delta^* = \delta / \delta_0 \tag{2}$$

δ_0 is the minimum average layer thickness needed for an alluvial bed. There is a limited availability of mobile sand for $0 < \delta^* < 1$ (supply limitation).

The area of sand covering the surface relative to the total surface (p_*) was derived from photos from the surface of the bed. The value of p_* is between 0 (only gravel) and 1 (only sand).

The level where the bed was fully covered with sand (p^* = 1) was decisive to determine whether the bed had reached alluvial conditions. The measured sediment transport rate and layer thickness where p^* = 1 were used to determine the value of s_0 and δ_0, and subsequently s^* and δ^* for every level of supply limitation.

The hydraulic roughness is expressed by the Chézy-coefficient (C). The Chézy-coefficient can be determined with the measurements of the water depth, flow discharge and the energy slope (i_e) using the Chézy-equation:

$$\bar{u} = \frac{Q}{Bh} = C\sqrt{Ri_e} \tag{3}$$

Where B is the flume width and $R = hB / (2h+B)$ is the hydraulic radius. The energy slope is used here since the flow was not always perfectly uniform. The Chézy-coefficient is corrected for sidewall effects. From separate measurements it was derived that the Nikuradse roughness height of the wall is $k_{s,w}$ = 0.00015 m. The bed related Chézy-coefficient (C_b) can be calculated if it is assumed that the mean flow velocity is equal in the wall parts and the bed parts of the flume cross-section (Einstein, 1942). This method gave similar results as other sidewall correction methods, such as the method proposed by Vanoni and Brook (1957). The Nikuradse roughness height k_s is calculated with:

$$k_s = \frac{12R}{10^{C_b/18}} \frac{C^2}{C_b^2} \tag{4}$$

Table 2. Experimental data. R_b is the hydraulic radius related to the bed.

	s^* [-]	δ^* [-]	p^* [-]	h [cm]	R_b [cm]	u [ms^{-1}]	i_e 10^{-3}[-]	τ_b [Nm^{-2}]	k_s [mm]
Exp2-L00	0.00	0.00	0.00	7.3	6.0	0.45	2.51	1.48	6.4
Exp2-L01	0.00	0.04	0.13	7.0	5.8	0.49	2.72	1.54	4.8
Exp2-L02	0.00	0.03	0.30	7.1	5.8	0.49	2.64	1.49	4.3
Exp2-L03	0.03	0.11	0.40	6.8	5.6	0.51	2.81	1.53	3.7
Exp2-L04	0.10	0.20	0.55	6.6	5.4	0.52	2.90	1.54	3.2
Exp2-L05	0.30	0.39	0.81	6.3	5.0	0.55	2.90	1.42	1.7
Exp2-L06	0.54	0.52	0.84	6.0	4.8	0.57	2.98	1.39	1.2
Exp2-L07	0.65	0.57	0.89	6.2	4.9	0.56	2.91	1.39	1.5
Exp2-L08	0.73	0.70	0.93	6.2	4.9	0.56	3.03	1.46	1.7
Exp2-L09	0.87	0.81	0.97	6.1	4.9	0.56	3.20	1.55	2.0
Exp2-L10	1.00	1.00	0.99	6.0	4.8	0.58	3.35	1.58	1.7
Exp3-L00	0.00	0.00	0.00	14.0	10.4	0.51	1.84	1.87	11.4
Exp3-L01	0.00	0.00	0.15	13.3	9.9	0.50	1.84	1.79	10.2
Exp3-L03	0.01	0.01	0.52	13.1	9.5	0.51	1.73	1.61	7.1
Exp3-L04	0.08	0.03	0.68	12.7	9.5	0.52	2.01	1.87	8.8
Exp3-L05	0.18	0.08	0.81	12.5	8.9	0.54	1.84	1.62	5.2
Exp3-L06	0.32	0.19	0.76	12.2	8.3	0.55	1.62	1.31	2.4
Exp3-L07	0.64	0.24	0.86	11.7	8.1	0.57	1.89	1.51	2.7
Exp3-L08	0.96	0.37	0.92	11.4	8.1	0.58	2.11	1.68	3.2
Exp3-L09	0.82	0.49	0.91	12.0	8.9	0.56	2.18	1.90	6.4
Exp3-L10	0.83	0.55	0.93	12.3	9.4	0.54	2.32	2.14	10.4
Exp3-L12	0.85	0.77	0.97	12.6	9.7	0.53	2.40	2.28	13.4
Exp3-L13	1.00	1.00	1.00	12.5	9.7	0.53	2.46	2.35	14.2

3 RESULTS

Table 2 gives an overview of the experimental data. In Figure 1 the measured relative roughness height (k_s/h) is plotted on the vertical axis against the relative thickness (Fig. 1a), the relative sediment transport rate (Fig. 1b) and the relative sand coverage (Fig. 1c) for the two experiments. The observed bedform types are indicated with symbols and are classified as ‘no bedform’ (circles), ‘low relief bedforms’ (squares) or ‘dunes’ (triangles). The latter compromises large flow transverse bedforms with a gentle stoss-side and a steep lee-side. The low relief bedforms have a low relief compared to dunes, and do not scale with the water depth.

Figure 1a shows the variations in bedform type and relative roughness height against the relative thickness. We observed that for increasing thickness ($\delta^* < 0.5$ for Exp2 and $\delta^* < 0.2$ for Exp3) the bed developed from no bedforms towards low relief bedforms. Initially, the sand filled in the deepest pockets of the coarse layer making the bed smoother, resulting in lower roughness heights. The sand concentrated in flow parallel sand ribbons (covering the full length of the flume) for increasing layer thickness. These bedform types have a low relief and therefore induce very little form drag. For larger thickness ($\delta^* > 0.5$ for Exp2 and $\delta^* > 0.2$ for Exp3), dunes developed and the roughness height increased due to form drag of the dunes. The form drag due to dunes in Exp2 was rather low, which may be explained by the high Froude-number of Exp2. A high Froude-number indicates a transitional regime where dunes are washed out (Van Rijn, 1984). Dune height and steepness increased for increasing layer thickness and finally reached maximum dimensions for an alluvial bed. The bedform types we observed are in line with existing observations as for example mentioned by Kleinhans et al. (2002).

Figure 1b shows the variations in bedform type and the relative roughness height against the relative sediment transport rate. The roughness height decreases for increasing sediment transport rates for $s^* < 0.3$ and bedforms developed from no bedforms toward low relief bedforms. For large values of s^* ($s^* > 0.55$) dunes developed and for increasing sediment transport rate the roughness height increased. This observation is in line with the experiments by Van der Zwaard (1974).

Figure 1c shows the variations in bedform type and the relative roughness height against the relative sand coverage. For both experiments we can see a clear decrease of roughness height up to a point where $p^* = 0.85$. For $p^* < 0.85$, there were no bedforms or low relief bedforms. Only for $p^* > 0.85$ the volume of sediment suffices for dune formation. Here the roughness quickly increases with the increase in bed coverage.

The parameters s^*, δ^* and p^* are alternatives for describing the influence of supply limitation on the bedform types and the roughness. These differences are discussed here. The parameter p^* has a wide range of values ($0 < p^* < 0.85$) to describe the roughness development for the levels with no bedforms or low relief bedforms. Changes in dune induced roughness take place over a short range in p^* ($0.85 < p^* <1$). Therefore p^* would be a very sensitive parameter for roughness prediction in the supply limited dune regime. Besides that, the sand coverage is hard to determine as dunes migrate and gravel sec-

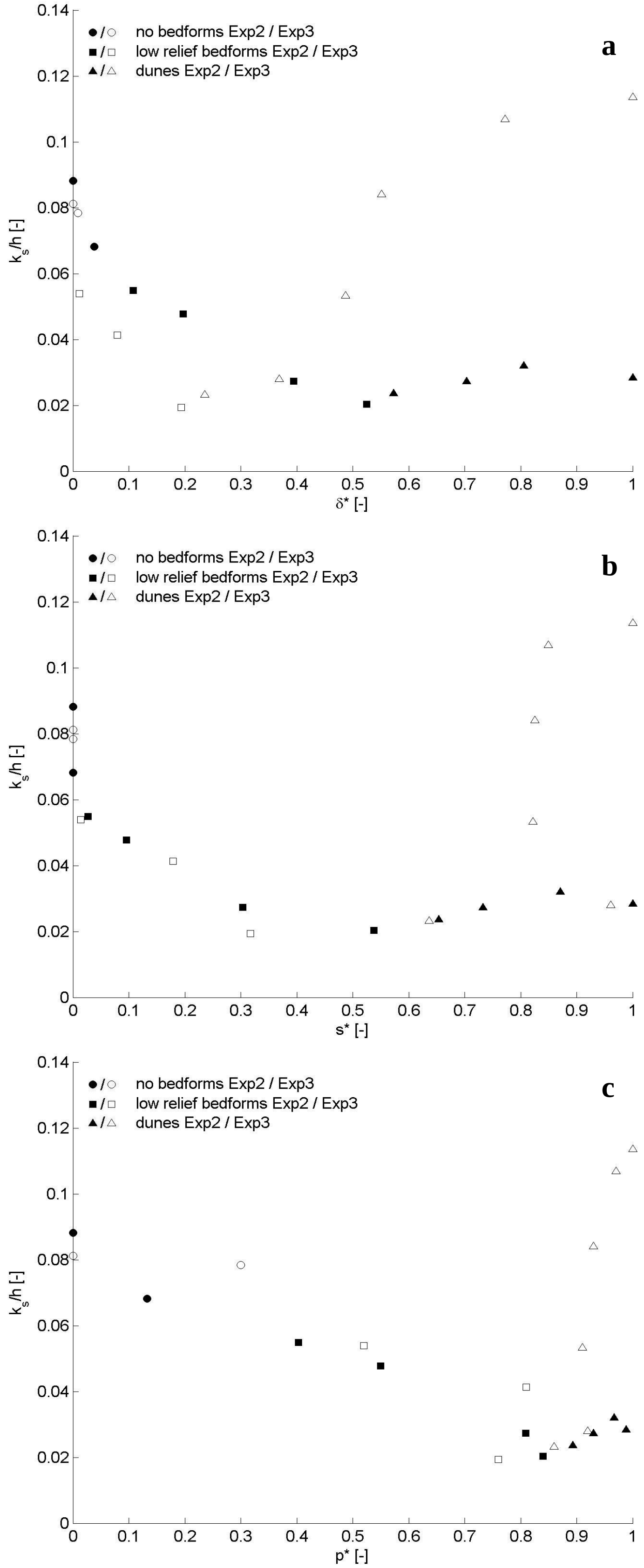

Figure 1. Observed bedform types and bed roughness height against a) the relative thickness b) the relative sediment transport rate and c) the relative sand coverage.

tions change constantly. The parameter *s** also shows shortcomings when it is used to describe the roughness variations under supply limited conditions. For values of *s** around 0.8 in Exp3, the observed variation in roughness height can not be related to the measured *s**, i.e. an equal *s** is related to different roughness heights. Furthermore, a very high *s** ($s^* = 0.96$) was measured which is related to a relative low roughness height. This measurement was done for a relative thickness of only $\delta^* < 0.37$.

The bedform dimensions are determinative for the roughness at a small supply limitation. The coverage of the coarse grains of the immobile layer is the determinative for the roughness when the supply limitation is strong. Because both processes are directly related to the present volume of sand we think δ^* is the best parameter to characterize the supply limitation.

4 DISCUSSION

In the present experiments it was not possible to do simultaneous bed level and water level measurements with the available instruments and experimental set up. The average water slope was measured during the experiment. The average bed slope was measured afterwards. Therefore uniform flow conditions were hard to obtain. Besides that, the limited length of the measurement section causes some uncertainty in the determination of the average bed slope. This results in some extra uncertainty in the bed roughness. Simultaneous bed level and water level measurements during flow and a longer flume could improve the bed roughness measurements. Nevertheless the observed trends are logical and are not obscured by random scatter.

For large layer thickness we observed that small dunes developed towards larger dunes with an increase in sand volume. The bed roughness increased accordingly. This implies a relationship between dune dimensions and bed roughness. A relationship between supply-limitation and dune dimension can possibly help to improve the roughness prediction. However, the data was not sufficient to formulate such a relationship. For this, a more elaborate set of measurements of dune dimensions under supply limited conditions is required. Our current research focuses on a more detailed relationship between supply-limitation and bedform dimensions.

5 CONCLUSIONS

The experiments show that the roughness of a partial mobile sand-gravel bed is strongly influenced by the volume of available mobile sand per unit area, or in other words, the average active layer thickness. We found that the active layer thickness correlates strongly with roughness height under supply limited conditions. For small layer thickness, the sand fills in the pores of the coarse layer and the bed roughness decreases for increasing sand volume. For large layer thickness, dunes develop and dune dimensions and bed roughness increase with increasing sand volume.

An improved understanding of dune dimension under supply limited conditions can possibly help to improve the roughness prediction.

ACKNOWLEDGEMENTS

This research project, which is part of the VICI project ROUGHWATER (project number TCB.6231), is supported by the Technology Foundation STW, applied science division of the Netherlands Organization for Scientific Research (NWO) and the technology programme of the Ministry of Economic Affairs. The laboratory experiments are funded by the Delft Cluster program ‘Natural Hazards’, work package A2 River Morphology (WP CT 043211). Furthermore the authors would like to thank A. Dittrich and the rest of the staff of the Leichtweiss-Institute for Hydraulic Engineering for their cooperation in the experiments.

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