HENRY
Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

Conference Paper, Published Version

Cooper, James R.; Aberle, Jochen; Koll, Katinka; Tait, Simon; Marion, Andrea

Different Roughness Length Scales in Water Worked Sediment Deposits and Their Effect on the Near Bed Turbulent Flow Field

Zur Verfügung gestellt in Kooperation mit/Provided in Cooperation with:
Kuratorium für Forschung im Küsteningenieurwesen (KFKI)

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/110051

Vorgeschlagene Zitierweise/Suggested citation:
Cooper, James R.; Aberle, Jochen; Koll, Katinka; Tait, Simon; Marion, Andrea (2008): Different Roughness Length Scales in Water Worked Sediment Deposits and Their Effect on the Near Bed Turbulent Flow Field. In: Wang, Sam S. Y. (Hg.): ICHE 2008. Proceedings of the 8th International Conference on Hydro-Science and Engineering, September 9-12, 2008, Nagoya, Japan. Nagoya: Nagoya Hydraulic Research Institute for River Basin Management.

Standardnutzungsbedingungen/Terms of Use:

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

Different Roughness Length Scales in Water Worked Sediment Deposits and Their Effect on the Near Bed Turbulent Flow Field

J. R. Cooper(1), J. Aberle(2) K. Koll(2), S. Tait(3), A. Marion (4)

(1) Department of Geography, University of Hull, Hull, UK
(2) Leichtweiss-Institute for Hydraulic Engineering, Braunschweig Technical University, Germany
(3)School of Engineering, Design & Technology, University of Bradford, Bradford, UK
(4) Department of Hydraulic, Maritime, Environmental and Hydraulic Engineering, University of Padova, Italy

ABSTRACT

This paper reports on two flume experiments which were designed to examine the effect of the surface organisation of water-worked gravel deposits on the near bed flow field. Two water worked gravel deposits were formed with a similar distribution of bed elevations but with different surface organisation. This was achieved by first forming a water deposit and then rotating it by 90° and measuring the near bed velocity flow field using a 3D PIV system. Detailed spatially distributed velocity measurements were made using the PIV system. Examination of the streamwise velocity profiles and distributions of turbulent and spatial velocity fluctuations show that the surface grain arrangement has an effect on the near bed flow field. The results indicate that some representative surface grain size or bed surface roughness height derived from simple statistics of bed elevations cannot accurately account for the resistance imposed by a water-water gravel bed on the flow. Examination of the near bed flow field indicates that the pattern of grain orientation needs to be taken into account to predict flow resistance.

Keywords: roughness length scale, turbulent flow, PIV, gravel deposit

1. INTRODUCTION

A key problem in river hydraulics has been the evaluation of the resistance imposed by different bed morphologies on the flow. The determination of this flow resistance is a fundamental requirement for the prediction of flow depth, and thus the calculation of channel flood capacity and bed shear stress to estimate sediment entrainment and transport. The magnitude of the resistance is known to be a function of the geometry of the bed surface. This geometry can only be fully characterised by considering the grain-size distribution, grain shape, grain orientation, bed arrangement, and concentration and geometry of features on the bed surface (Robert, 1990). Generally, in rivers, a roughness length scale has been used to account for the effects of all these features on the near-bed flow k_s, the equivalent sand roughness height. The roughness length scale is normally assumed to be related to some representative surface grain size such as D_{50} or D_{84} (Hey, 1979; Bray, 1982). But it does not take into account the spatial heterogeneity in the bed surface and how this heterogeneity imparts resistance on the flow, nor on the way in which this relationship changes with variables such as flow stage. But in reality river bed surfaces are highly irregular and their effects are known to be greater at low flows than at high flows (Griffiths, 1989). As such the roughness characteristics of a river bed are poorly described and are poorly approximated by the use of a single grain-size index, for which the underlying physical basis is unclear.

Recent studies investigating the structure of gravel beds, using statistical methods, have suggested that water-worked surfaces have systematic patterns of grain arrangement depending on whether they were created during phases of static or dynamic armouring. For static armour layers, the *a*-axis of the grains are aligned preferentially in the direction of the flow (e.g. Aberle and Nikora, 2006) whilst for dynamic armour layers, the *a*-axis of the grains are aligned preferentially in a perpendicular manner to the flow direction (Robert, 1991; Nikora *et al.*, 1998; Nikora and Walsh, 2004). It is therefore possible for deposits to have the same statistical distribution of bed surface elevations and surface grain size distributions but to have a very different surface structure, as the grains have been arranged in different streamwise and lateal roughness scales. This further suggests that the use of a single roughness scale determined from either a 'representative' surface grain size or from the distribution of bed surface elevations (e.g. standard deviation of bed surface elevations) may not contain sufficient information to determine, in detail, the influence of the bed on the characteristics of the near-bed flow field. It is the hypothesis of the writers that systematic differences in the surface topography will the affect the near bed turbulent flow field. The confirmation of this hypothesis is the objective of this study.

This paper reports on flume experiments in which the flow over two gravel bed surfaces characterized by exactly the same statistical distribution of bed elevations but with the surface grains arranged in different streamwise and transverse scales was investigated. This was achieved by rotating a water-worked bed through 90°. Detailed spatially distributed measurements of the near-bed flow field were made using Particle Image Velocimetry (PIV) to describe the temporal and spatial variability of the flow fields over each surface. These data will be used to show that the pattern of spatial variability in the near-bed flow field can be related to the pattern of grain orientation and not simply to the statistical distribution of the bed elevations. Relationships are proposed, linking key elements of the grain surface pattern with variations in the near bed flow field.

2. EXPERIMENTAL DESCRIPTION

The experiments were carried out in the Total Environment Simulator (TES) at the University of Hull, UK as part of an EU funded research program. The simulator is a 14 m long and 6 m wide tank. In the tank, an 11 m long and 1.2 m wide channel was constructed for the experiments. Water depths were measured at a number of streamwise locations on the flume centerline with piezometric pressure sensors and the discharge was adjusted through the use of a variable speed pump. All experiments were carried out with steady, uniform flow conditions. A coarse sediment mixture ($0.71 < D < 64$ mm) was used as bed material. It was placed in the channel and manually mixed and screeded to obtain a bed with an initial slope of 0.005 along the channel length. No sediment was fed into the flume during the tests, the bed material was water worked with a discharge of $Q = 0.254$ m^3/s to obtain a stable static armour layer (Bed 1). This ensured that a bed was produced in which the a-axis of the grains were aligned preferentially in the direction of the flow. The aim of the experimental program was to measure the near bed flow velocity field over two beds with the same statistical distribution of bed surface elevations and the same surface grain size distributions, but with different surface organizations. To achieve this, three 1 x 1m^2 steel trays were buried at a distance 3.5 m downstream from the inlet within the sediment deposit before the armouring of Bed 1 commenced. Once the flow velocity measurements had been completed on Bed 1, the trays were removed carefully from the channel and rotated by 90° and placed back within the channel without physical disturbance to the surface grains in order to create the second bed (Figure 1). Hence, Bed 2 simulates a water worked surface with the a-axis of the grains being aligned preferentially in a perpendicular manner to the flow direction.

Figure 1 The equipment used to rotate the water worked bed by 90° to form bed 2.

The bed surface topography was measured using a laser displacement sensor that was attached to an automated movement frame. This provided a data set of bed elevation measurements made over a 1.00m by 0.6m area that was centred on the flume centreline 5.39m from the flume inlet. The bed elevation were measured at a streamwise sampling interval of 1.0mm and 0.25mm in the lateral direction. The digital elevation maps of the two beds are shown in figure 2.

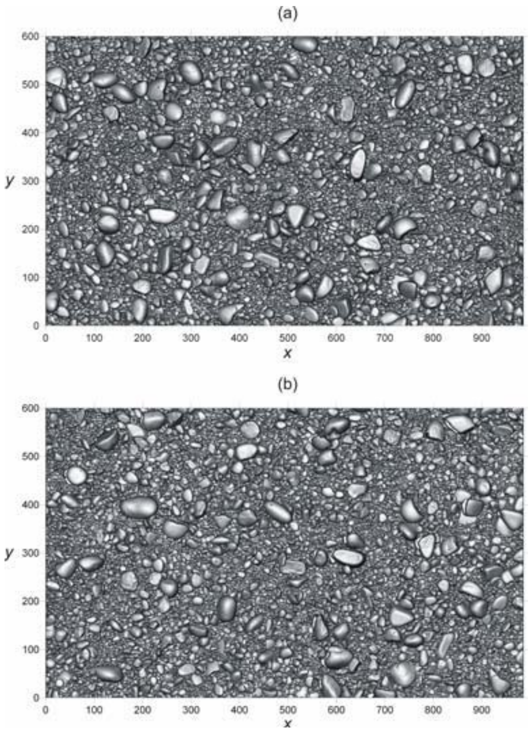

Figure 2 DEM of bed1 (a) and bed 2 (b), y =300mm is the flume centreline

A Dantec 3D Particle Image Velocimetry system was used to measure the near bed flow velocities on a vertical plane at three locations in the measurement area. The two cameras imaged an area of 279 by 252mm, providing 3534 velocity measurements at a streamwise spacing of 4.98mm and 4.13 mm in the vertical direction. The velocity data was collected at a sampling frequency of 15Hz. The velocity measurements were made on three streamwise line located at y = 300mm, 350mm and 400mm, with a starting point at x=568.7mm and ending at 847.7mm. These locations were located in the most downstream sediment tray so that after rotation at least 2.5m, equivalent to at least 11.6 water depths of the rotated bed surface was present upstream of any velocity measurement.

3. RESULTS

3.1 Bed Surface Topography

The bed elevation data was analyzed so that the statistical properties of the bed surface properties were obtained. This is reported in table 1. Examination of the statistical values for the two beds reveals that the bed rotation appears to have caused very little disturbance to the surface structure of both beds. Any difference is most likely to reflect a small difference in the placement of the tray into the original location rather than disturbance to the surface grains. The standard deviation of bed elevations can be interpreted as a characteristic vertical roughness length of a water-worked gravel beds. Table 1 indicates that this value is very similar for both the beds. Additionally, both beds have positive skewness values (*S*) of bed elevation this pattern has also been reported in other studies in which detailed measurements of water-worked armoured bed surfaces have been made (e.g. Nikora et al., 1998; Marion et al., 2003; Aberle & Nikora, 2006). The kurtosis values (*K*) reported in Table 1 are also similar to values reported in the literature (e.g., Nikora et al., 1998; Aberle & Nikora, 2006). Previous studies have suggested that the degree of surface particle organization can be assessed by using the normalized 2-D second-order structure function of the bed surface elevations (Aberle & Nikora, 2006). This function is shown for both beds in Figure 3, where the maximum spatial lags are ± 200 mm in both the streamwise and lateral direction, this value of lag has been selected as it is much larger than the maximum grain size of 64 mm.

The contour lines shown in Figure 3 are characterized by an elliptical shape. Geometrically, the elliptical shape of the contour lines reflects the levels of correlation at different streamwise and lateral lags. For Bed 1, the major axes of the elliptical contours are aligned in the direction of the flow indicating stronger correlation at longer streamwise lags, than in the lateral direction. This is a typical pattern for a static armour layer. The reverse is seen for Bed 2 and reflects the change imposed on the bed orientation by the rotation of the sediment trays.

At small spatial lags, the structure functions can be approximated by a simple power function, from which characteristic spatial scales Δx_o and Δy_o and the scaling exponents H_x and H_y, the Hurst exponents, can be estimated (Nikora et al., 1998). The values of these spatial scales and scaling exponents are given in Table 2 and show that, for each bed, the streamwise spatial scale is larger than the corresponding lateral scale. This corresponds with the shape of the contour plots shown in figure 3. Nikora et al. (1998) found that, on average, the vertical correlation length scale Δy_o is less than half the horizontal roughness length scales Δx_o for natural gravel-bed rivers. The Hurst exponents (H_x, H_y) reported in Table 1 fit within the range reported by Nikora et al. (1998), Butler et al. (2001), Nikora & Walsh (2004), and Aberle & Nikora (2006) in field and flume studies, revealing that the bed surfaces in this study have a similar surface arrangement to the surfaces investigated in these studies.

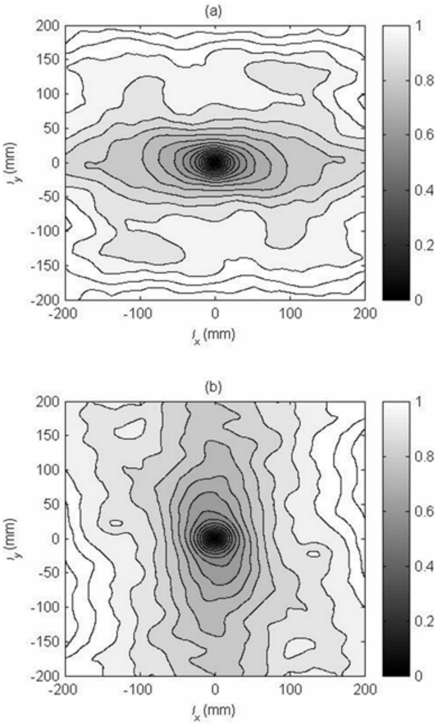

Figure 3. Contour plots of the normalised second order structure functions of the bed surface elevations for (a) Bed 1; and (b) Bed 2.

Property	Bed 1	Bed 2
k (m)	0.051	0.049
σ_b (m)	0.0071	0.0072
S	0.67	0.48
K	3.35	3.23
Δx_o	0.035	0.021
Δy_o	0.022	0.030
H_x	0.52	0.60
H_y,	0.59	0.57

Table 1 Summary of bed properties using data from de-trended bed surface elevation data, Bed 1 and Bed 2.

3.2 Hydraulic parameters

The near bed flow field was characterized using the PIV-data. The data from the three lateral locations was combined into single data sets. The heights of the measurement locations for each of the three lateral planes were nearly identical for the three planes and this allowed the velocities from each of the lateral locations to be assimilated to produce a matrix of velocity vectors over and above the bed. This assimilation resulted in a matrix of up to 168 velocity values for each vertical location

By temporarily and spatially averaging these values, the double-averaged flow parameters, including the double averaged flow streamwise velocity, and measures of the magnitude of the temporal and spatial velocity variation, were derived at given height z above the mean bed elevation. The following analysis is restricted to the examination of the double-averaged streamwise velocity distributions $< u >$ and vertical distributions of the size of the temporal (u_{rms}) and spatial velocity variations (σ_u). The normalized double-averaged streamwsie velocity profiles are shown in figure 5, where u* is the shear velocity, estimated from the depth-slope product). The figure shows that the flow retardation is higher over bed 2, indicating larger roughness effects over this bed. In order to investigate this further the roughness height (k_s) was estimated by applying the Clauser method to the logarithmic layer in the flow fitted from the upper level of the roughness layer to 20% of the water depth and, assuming κ =0.4 (Nezu and Nakgawa, 1993). This indicated that the value of k_s for bed 1 was 0.048m and bed 2 was 0.063m, indicating that bed 1 was hydraulically smoother than bed 2. This suggested that this difference was due to the different particle arrangements between the beds as the surface grain size distribution and the distribution of the bed elevations was similar between both beds.

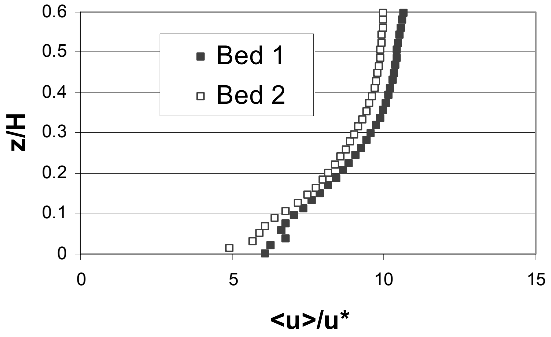

Figure 4 – Vertical distribution of double averaged streamwise velocity for Bed 1 and 2.

The vertical distribution of the magnitude of the temporal turbulent velocity fluctuations (U_{rms}) and the variance of the time-averaged velocity (σ_u) in each measurement plane are presented in figure 4. The first is a measure of the turbulence and the second a measure of the spatial distribution in time averaged velocity over the water worked bed. Figure 5a indicates that the scale of the turbulence rises in the bottom 10% of the flow and then reduces linearly towards the free surface. Figure 5b indicates that the spatial variability is highest close to the mean bed level and then reduces quickly, so that it reduces to insignificant values within the bottom 20% of the flow. Comparing these plots appears to indicate that it is change in the near bed turbulence that is causing the additional hydraulic roughness, rather than a significant change in the spatial organization of the bed. In figure 5a, it is shown that the higher hydraulic resistance experienced by Bed 2 is associated with higher levels of near bed turbulence.

.

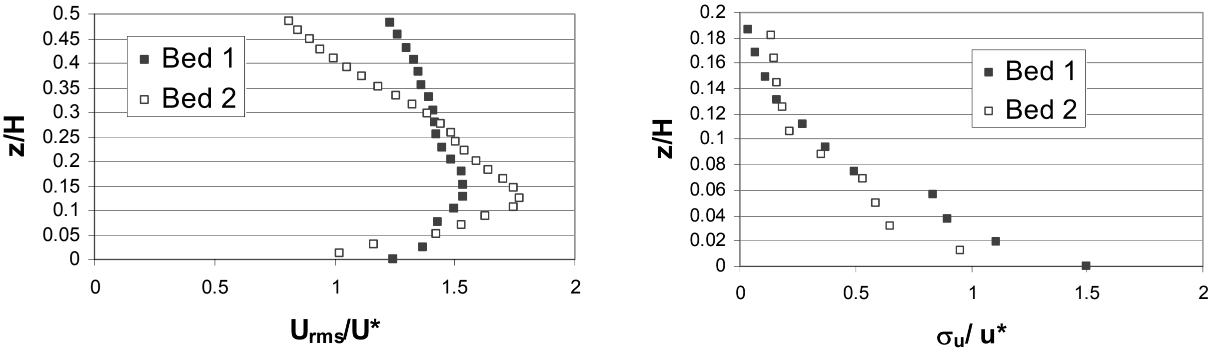

Figure 5 – Vertical distribution of the magnitude of the turbulent velocity fluctuations and (U_{rms}) and the variance of the time-averaged velocity (σ_u), z = depth from mean bed elevation, H = total flow depth.

DISCUSSION AND CONCLUSIONS

This paper aimed to examine whether a systematic difference in bed surface topography in a natural water worked deposit had a major effect on the vertical velocity distribution. It was suggested that the effect on the vertical velocity distribution can be related to the pattern of grain orientation and not simply the statistical distributions of the bed elevations. Two water-worked deposits were created, in which they had very similar grain surface size distributions and bed elevations, but that the grains were arranged in orthogonal directions. This was achieved by first producing a static armour layer in a laboratory flume, then after the first experiment had been completed, by carefully rotating that bed by 90°. Analysis of the bed surface elevation data using 2D structure functions indicated systematic differences between the two bed surfaces in that the streamwise and lateral length scales were different. This result and examination of surface photographs indicated the method used to rotate the bed had caused little surface disturbance.

PIV measurements were taken at three lateral positions. This data was used to describe the near bed flow field, the vertical distributions of double averaged streamwise velocity, and the typical magnitude of the temporal and spatial fluctuations. This showed that there was a greater flow retardation of the flow over the rotated bed. Preliminary analysis indicated that this difference was reflected in change in the turbulence close to the bed rather than the spatial distribution of the time-averaged velocities. In order to compare hydraulic roughness scales, the equivalent sand roughness k_s was calculated using the Clauser method. This method was selected as it is commonly used to describe the vertical velocity distribution in the logarithmic layer. The calculated k_s values confirmed that the rotated bed is rougher than the original bed. This result indicated that the use of some representative surface grain size of some simple statistical measure of bed surface elevations are not sufficient to describe the effect that a water worked bed has on the near bed flow. Estimates of the streamwise length scale of the water worked beds, obtained by use of 2D structure functions, may provide a better means to predict flow resistance.

ACKNOWLEDGEMENTS

This project was financially supported by the Hydralab III Transnational access scheme, part of the European Community's Sixth Framework Framework Programme.

REFERENCES

Aberle J., Nikora V. (2006) Statistical properties of armoured gravel bed surfaces, *Water Resources Research, 42, doi: 10.1029/2005WR004674.*

Bray D.I. (1982) Estimating average velocity in gravel-bed rivers. *Journal of the Hydraulic Div. ASCE, 105(9), 1103-1122.*

Butler J.B., Lane S.N., Chandler J.H., (2001) Characterisation of the structure of river-bed gravels using two-dimensional fractal analysis. *Mathematical Geology, 33, 301-330.*

Hey R.D. (1979) Flow resistance in gravel-bed rivers, *Journal of the Hydraulics Division, ASCE, 105(3), 365-379.*

Griffiths G.A., (1989) Form resistance in gravel channels with mobile beds. Journal of Hydraulic Engineering, ASCE, 115(3) 340-355.

Marion A., Tait S. McEwan I. (2003) Analysis of small scale gravel bed topography during armouring, *Water Resources Research 39(12) doi: 10.1029/2003WR002367*

Nezu I., Nakagawa H., (1993) Turbulence in Open Channel Flows, *Rotterdam: A.A. Balkema.*

Nikora V.I., Goring D.G., Biggs B.J.F. (1998) On gravel bed roughness characterisation, *Water Resources Research, 34(3) 517-527.*

Nikora V. and Walsh J. (2004) Water-worked gravel surfaces: high-order structure functions at the particle scale, Water Resources Research, 40, doi:10.1029/2004WR003346.

Robert A. (1990) Boundary roughness in coarse grained channels, Progress in Physical Geography, 14 (1) 42-70.

Robert A. (1991) Fractal properties of simulated bed profiles in coarse-grained channels, *Mathematical Geology, 23(3), 367-382.*