Influence of bedforms on the transverse bed slope effect

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ABSTRACT: the deflection of sediment transport on a transverse slope due to gravity determines the large scale morphology by influencing bar dimensions and bifurcation dynamics. However, existing transverse bed slope predictors in morphodynamic models are based on a small range of flow conditions and sediment sizes, and do not account for the presence of bedforms. The objective of the current research is to quantify the transverse slope effect for a large range of flow conditions and sediment sizes, using an annular flume. Preliminary results show that the transverse slope is related to helical flow intensity and sediment size. Also, different bed form types developed during the experiments and appear to have a large influence on flow patterns. In order to quantify the effects of bed forms on the transverse slope, a Large Eddy Simulation model of the annular flume is needed.

1. INTRODUCTION

A crucial part of morphodynamic models is the transverse bed slope effect, which determines the deflection of sediment transport on a transverse sloping bed due to gravity (Fig. 1). Overestimating this effect leads to flattening of the morphology, while underestimating leads to unrealistic steep bars and banks (Fig. 2). Thus an incorrect estimation of the transverse bed slope effect could also have major consequences for the predicted large-scale morphology, as it influences the development of river bifurcations, meander wave length and the degree of braiding in rivers and estuaries.

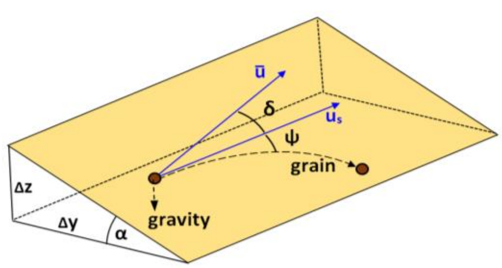

Figure 1. Transverse bed slope effect (after Sekine & Parker, 1992)

In current models, the prediction of the magnitude of sediment transport is based on a situation of a flat bed with a single grain size, and only the direction is afterwards corrected for transverse gradients (e.g. Ikeda, 1982; Talmon et al., 1995). However, in reality sediment transport is also affected by bedforms, grain size distribution and suspension rate. Therefore, in current modelling practice the angle of sediment deflection needs to be calibrated on measured morphology afterwards.

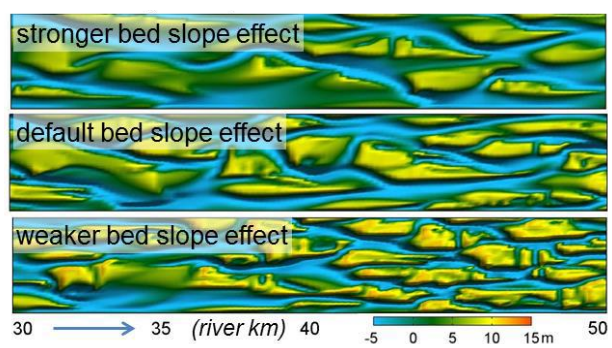

Figure 2. The effect of stronger and weaker transverse bed slope effect on channel morphology (Schuurman et al., 2013)

2. PREVIOUS RESEARCH

Current transverse bed slope predictors are based on theoretical model studies (e.g. Odgaard, 1981; Sekine & Parker, 1992) and laboratory experiments. Experimental studies focused on experiments with bended flumes (e.g. Zimmerman & Kennedy, 1978; Struiksma et al., 1985; Ikeda & Nishimura, 1986), or straight flumes initiated with a transversely sloped bed that relaxed to a horizontal bed, to reduce secondary currents (e.g. Ikeda, 1982; Talmon et al., 1995; Talmon & Wieseman, 2006). In bended flumes the transverse bed slope is also affected by helical flow, whilst in the experiments with a straight flume it is impossible to measure an equilibrium slope. Finally, existing predictors can only apply for a certain range of conditions as all previous transverse bed slope experiments were performed with a small range of flow conditions and mostly uniform grain sizes, varying from 0.09 mm (e.g. Talmon & Wieseman, 2006) to 0.79 mm (e.g. Talmon et al., 1995).

The effect of bedforms on the transverse slope that develops is not yet taken into account. Either the experimental conditions were chosen to avoid bedforms (Hasegawa, 1981; Engelund, 1995), or the presence of bedforms only resulted in a different calibration factor of the transverse slope predictor (Talmon et al., 1995, Wieseman et al., 2006). Wieseman et al (2006) observed that downslope sediment transport decreased when dunes were present, while Sieben & Talmon (2011) show that avalanching at lee sides of dunes slightly enhances the slope effect.

3. AIM AND METHODOLOGY

The aim of the current research is to experimentally quantify the bed slope effect for a large range of flow velocities, helical flow intensities and particle sizes (0.1 - 4 mm), while taking into account the effect of bed forms. The experiments are being executed in the annular flume of Delft University of Technology (Fig. 3). This flume functions as an infinitely long bended flume, which therefore avoids boundary effects. Flow is generated by rotating the lid of the flume, which can be controlled to create a large range of flow conditions. Also, the intensity of the helical flow can be controlled by counter-rotating the bottom of the flume (Booij & Uijttewaal 1999).

The equilibrium transverse slope that develops during the experiments is a balance between the transverse bed slope effect, the bed shear stress caused by the helical flow and the centrifugal force caused by the rotation of the bottom of the flume (Fig.4). This balance depends on particle size, size range and density, and the rotation velocities of the lid and the bottom of the flume. All these parameters are systematically varied during the experiments in order to determine the separate effect on the equilibrium slope. Also, the effect of bedforms and suspension can be studied by the large range in flow conditions and grain sizes. For the first set of experiments only uniform sediment is being used. At a later stage, also poorly sorted sediment will be used in order to focus on sediment sorting processes. By systematically varying all these parameters, we aim to develop a more physical based transverse bed slope predictor that is applicable in a wide range of model simulations.

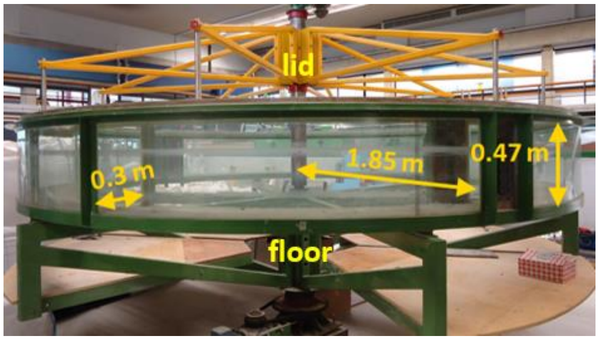

Figure 3. The annular flume at Delft University.

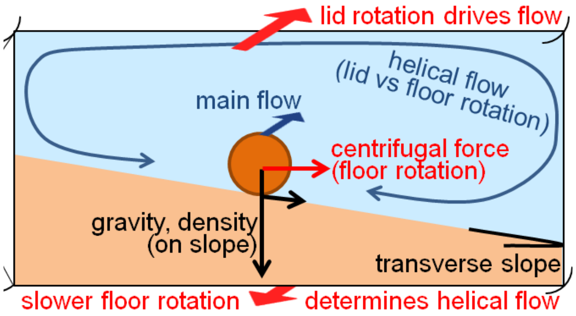

Figure 4. Forces acting on particles that can be controlled in the annular flume (after: Booij and Uijttewaal, 1999).

4. PRELIMINARY RESULTS

Fig 5 shows the morphology of several experiments with a grain size of 0.17 and 1 mm, as well as the corresponding maximum transverse bed slope that developed. During this set of experiments the rotation velocity of the lid of the flume (ω_l) is kept constant, while the rotation of the bottom of the flume in the opposite direction (ω_b) increases. The average flow velocity therefore increases, as the difference between both rotation velocities increases. By increasing the bottom rotation, the centrifugal force on the sediment also increases, which counteracts the helical flow driving sediment inwards. Therefore, the transverse slope decreases with increasing centrifugal force. When the centrifugal force is larger than the helical flow intensity, a steep slope develops towards the outside wall of the flume.

Next to variations in transverse slopes, different bedforms are observed. Dunes developed during the experiments with grainsizes of 1 and 4 mm, of which the dune length varied with different flow velocities and helical flow intensities. During the experiments with finer sediment (0.17 and 0.37 mm), ripples were observed at experiments with a relatively low sediment mobility, while at higher sediment mobilities dunes were formed. In Figure 6 examples are shown of bedforms that occurred during the experiments with a D50 of 0.17 mm. During these experiments even the transition from dunes to an upper plane bed was observed at high flow velocities.

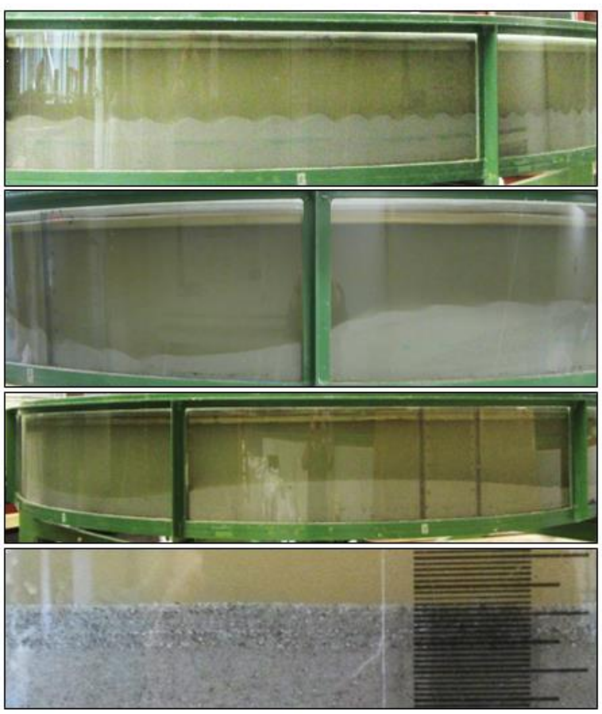

Figure 6 – Examples of bedforms that developed during the experiments. Sediment mobility increases from top (ripples) to bottom (upper plane bed).

In figure 7 the average equilibrium transverse slope (dz/dy) is plotted against the sediment mobility (Θ) for three different sediment sizes. For the experiments with a D50 of 0.17 mm also the bedform type that developed is indicated. As visible, the transverse slope increases with increasing mobility during the 4 mm experiments, while during the experiments with finer sediment the slope first increases and then locally decreases for intermediate Θ. This temporary decrease could be the result of changing bed form height, type (ripple/dune) and dune crest orientation.

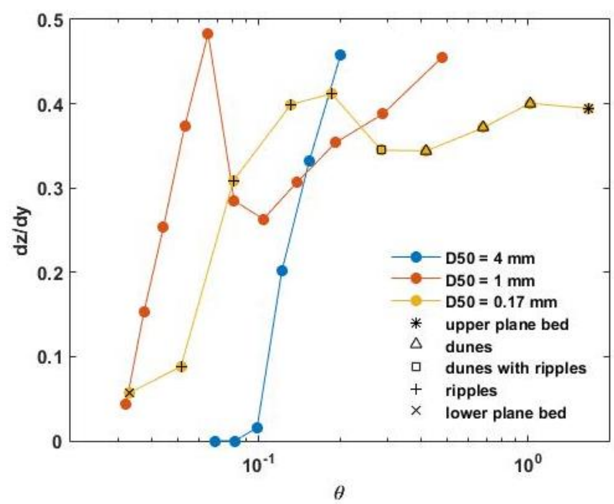

Figure 7 – Trend of the average transverse bed slope (dz/dy) with increasing sediment mobility (Θ) of three different sediment sizes. Sediment mobility was increased by higher lid rotation velocities.

5. FUTURE WORK

The resulting transverse bed slopes described above are based on average bed levels, while figure 5 shows a large variation in bed levels when dunes are present. Also, it is observed during the experiments that the dunes appear to have a large effect on the secondary circulation. We aim to use a Large Eddy Simulation model of the annular flume for idealized bed forms of varying height and orientation to quantify effects of bed forms on near-bed flow patterns and the resulting transverse slope.

6. REFERENCES

Booij, R., Uijttewaal, W.S.J. 1999. Modeling of the flow in rotating annular flumes. Engineering Turbulence Modeling and Experiments 4:339–348.

Hasegawa, K. 1981. Bank-erosion discharge based on a non-equilibrium theory. Proc. JSCE, Tokyo, 316:37-50.

Ikeda, S., Nishimura, T. 1986. Flow and bed profile in meandering sand-silt rivers. Journal of Hydraulic Engineering 112: 562-579.

Odgaard, A. J. 1981. Transverse bed slope in alluvial channel bends. Journal of the Hydraulics Division 107(12):1677-1694.

Schuurman, F., Marra, W.A., Kleinhans M.G. 2013. Physics-based modeling of large braided sand-bed rivers: Bar pattern formation, dynamics, and sensitivity. Journal of geophysical research: Earth Surface 118.4:2509-2527.

Sekine, M., Parker, G. 1992. Bedload transport on transverse slopes. Journal of Hydraulic Engineering 118:513–535.

Sieben, J., & Talmon, A. M. 2011. Bed-load transport in obliquely dune-covered riverbeds. Journal of Hydraulic Research, 49(3): 317-324.

Struiksma, N., Olesen, K.W., Flokstra, C., de Vriend, H.J. 1985 Bed formation in curved alluvial channels. Journal of Hydraulic Research 23:57-79.

Talmon, A., Struiksma, N., van Mierlo, M. 1995. Journal of Hydraulic Research 33:495–517.

Talmon, A., Wiesemann, J. 2006. Influence of grain size on the direction of bed-load transport on transverse sloping beds. Proc. 3rd Int. Conf. on Scour and Erosion, Amsterdam, Netherlands.

Wieseman, J., Mewis, P., Zanke, U.C.E. 2006. Downslope transport (transverse sediment transport). Third Chinese–German Joint Symposium on Coastal and Ocean Engineering, Tainan, Taiwan.

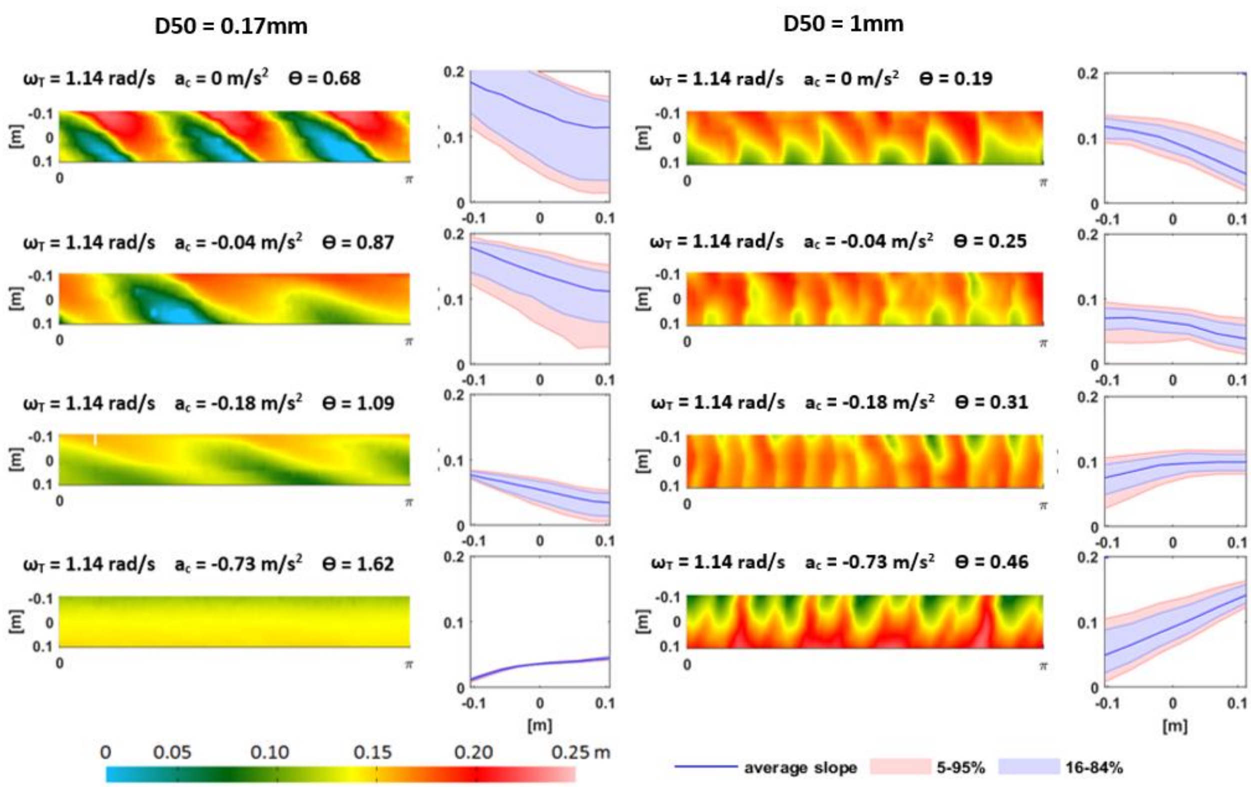

Figure 5. Resulting morphology (top view) of a series of experiments with a constant rotation velocity of the lid of the flume (ω_l) and increasing centrifugal acceleration (a_c), and corresponding transverse bed slopes. The width of the flume is measured relative to the average radius.