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Sediment transport processes on transverse bed slopes

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Problem definition

Large-scale morphology is greatly affected by the amount of downslope sediment transport on slopes transverse to the main flow direction. When secondary currents are present, downslope sediment transport due to gravity is balanced by helical flows dragging the sediment upslope. This balance determines e.g. the length of river bars and braiding index and influences bifurcation dynamics. Consequently, the transverse slope parameter is a crucial part of morphodynamic models.

Morphodynamic models include a slope factor (B) that determines the proportionality of transverse slope (dz/dy) to helical flow intensity (u_n/u_s) when in equilibrium:

$$\frac{\partial z}{\partial y} = B\frac{u_n}{u_s} \qquad (1)$$

where u = flow velocity [m/s] in either transverse (n) or streamwise (s) direction. Slope factor B is often a function of sediment mobility (e.g. Struiksma et al., 1985; Talmon et al., 1995). However, existing functions for B were validated with a small series of experiments with a limited range in flow characteristics and sediment mobility, depending on the objective of the study. Furthermore, the separate effect of helical flow intensity and main flow velocity could not be isolated, since experiments were either executed in straight flumes (e.g. Ikeda, 1984), or in bended flumes with a fixed radius (e.g. Koch and Flokstra, 1981). As a result, existing models have the tendency to over-predict channel depth and braiding index, and therefore slope effects are often artificially increased when calibrating on existing morphology, by decreasing B (Van der Wegen and Roelvink, 2012).

Current predictors only assume uniform sediment, and therefore do not account for different slope effects on varying grain sizes in a sediment mixture. Furthermore, the influence of vertical sorting by bedforms on bend sorting is unknown. As a result, sediment sorting is implemented in the transverse slope equation in Delft3D by another set of calibration parameters.

Objective and methodology

The objective of the current research is to experimentally quantify slope effects for a large range of flow velocities, helical flow intensities and sediment characteristics. In order to isolate all parameters, a rotating annular flume was used (Fig. 2) in which helical flow intensity can be varied separately from the main flow velocity. Flow is generated and controlled by rotating the lid of the flume. Helical flow can be decreased by rotating the flume itself in opposite direction, since this adds an outward directed centrifugal force on the flow low in the water column (Booij and Uijttewaal 1999). Flow velocities were determined with an analytical model based on extensive velocity measurements with an acoustic Doppler velocimeter.

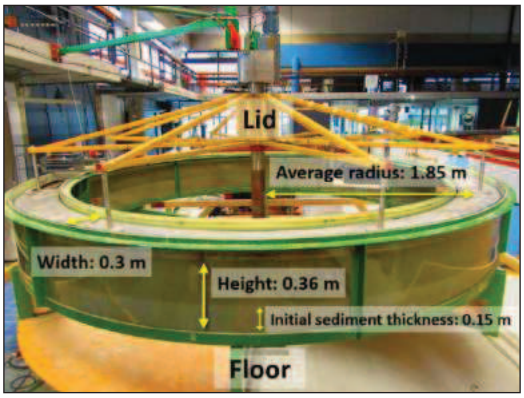

Figure 1. Dimensions of the rotating annular flume at Delft University.

Sediment characteristics were varied in three ways: we used uniform sediment with different grain sizes ranging from fine sand to fine gravel (0.17mm – 4mm), low-density sediment to study the effect of centrifugal forces on the sediment itself, and a sediment mixture with a median grain size of 0.75 mm to quantify sediment sorting processes. The large range in uniform sediment sizes and flow velocities enabled us to study the effects of sediment transport mode and bed state on transverse slope effects. In total 327 experiments were conducted.

The aim of the experiments with a sediment mixture was to establish relations of sediment sorting along a cross-section as a function of transverse slope and sediment mobility, in order to determine the sedimentological and morphodynamic response to bend flow. To this end, in total 340 sediment samples of 13 experiments with varying helical flow intensity and sediment mobility were analyzed.

Results: uniform sediment

The equilibrium transverse slopes in the experiments with uniform sediment show a clear trend with sediment mobility and helical flow intensity. However, this trend is not a linear relation with a power function of sediment mobility, as existing predictors suggest, but are strongly influenced by bed state and sediment transport mode. For fine sand we obtained bed states from a lower plain bed, across the ripple-dune threshold and up to an upper plane bed. During the experiments with coarse sand and fine gravel, dunes developed with varying dimensions depending on the flow conditions. Therefore, the resulting trend in slope factor differs for fine sediments and coarse sediments. Surprisingly, resulting slope factors are generally comparable or higher than suggested in literature (Fig.2). A higher slope factor implies less downslope sediment transport (Eq. 1), which is in contrast with the tendency to increase slope effects in current morphodynamic models.

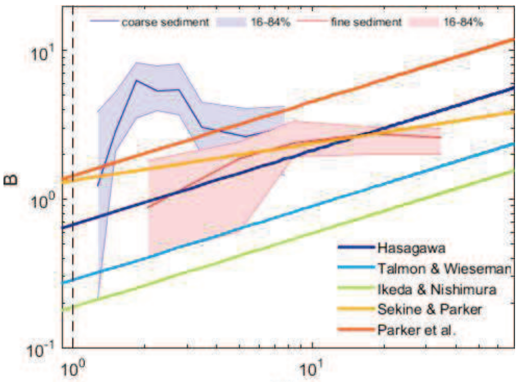

Figure 2. Range in slope factor of the experiments with fine and coarse sediments, compared with existing predictors that include a ratio of sediment mobility (θ) to critical sediment mobility (θ_c).

Results: poorly sorted sediment

Results of the experiments with a sediment mixture showed that mild slopes caused a gradual transition of fine sand at the inner bend to coarse sand in the outer bend. At slopes steeper than 0.15, a sharper transition was observed and all coarse sediment was located at the outer bend. Experiments with high sediment mobility resulted in higher dunes, which caused more vertical sorting and somewhat reduced the pronounced lateral sorting (Fig.3).

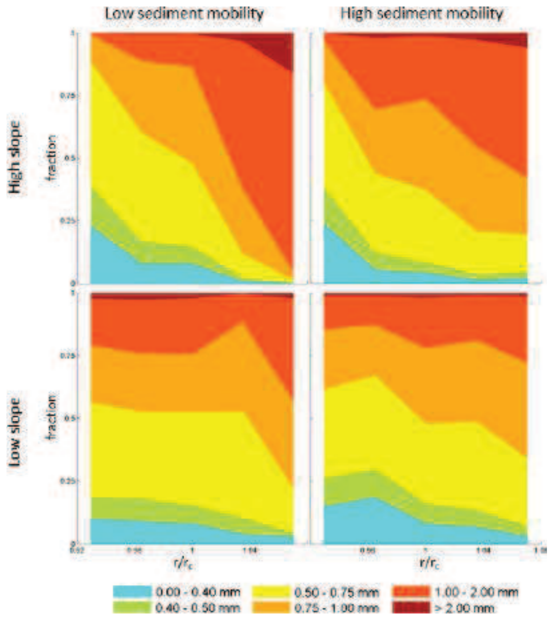

Figure 3. Fraction of grain sizes at several locations along the cross-section relative to flume radius (r/r_c), for experiments with high and low transverse slopes, and high and low sediment mobility.

Conclusions

We experimentally tested the effect of a large range in helical flow intensity and sediment mobility on equilibrium transverse slopes, which resulted in a function for slope effects depending on bed state and sediment transport mode, that deviates from linear functions with sediment mobility in literature. Furthermore, we obtained basic relations for sorting patterns as a function of transverse slope and sediment mobility.

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