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Modelling fine sediment transport over an immobile gravel bed

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Abstract

Fine-grained sediments represent a significant component of the total transport load in most fluvial systems around the world, not only including alluvial sand-bed rivers. A variety of natural or human actions, such as fire, logging, flow diversion, road construction, urban or agricultural development can increase the supply of sand to gravel- and cobble-bedded rivers. In rivers with regulated flow regime the coarsest part of the sediments mixture cannot be transported for most of the time, with only the fine fraction being frequently transported, often under conditions of supply-limitation.

The transport of fine sediments is a key and yet relatively unexplored process of many coarse-bed river systems with strong management and ecological relevance. It often affects ecosystem richness and riverine connectivity in the vertical and transverse directions. Sand accumulation over gravel beds can degrade the natural habitat of benthic organisms and therefore their ecological functions, as well as limit oxygen availability to spawning sites for several fish species through excessive pool filling. Moreover flushing flows are often prescribed downstream of dams with multiple objectives, and constitute one component of instream flow requirements for maintenance of aquatic and riparian habitat or for the maintenance of recreation functions. The ability to predict the temporal dynamics of sand surface under different flow scenarios is crucial to properly plan these operations in order for the desired management objectives to be achieved. Increased sand inputs over armored gravel-bed surfaces are also expected in the medium term following dam removals. Hydraulic computations for water level prediction requires quantification of the sand bedforms geometry that contribute to flow roughness thus affecting channel depth.

The present study addresses the dynamics of fine sediment transport in gravel-bed rivers, for which the modelling framework is still far from being complete. The general aim of the present work is to propose a morphodynamic modelling approach for the transport of the coarse fraction of fine sediments (sand) over a gravel bed that is assumed at rest. More specifically, the following research questions are addressed:

- Which are the key physical processes associated with near bed turbulence properties over rough beds, and how do they change when sand is present in variable proportion within the gravel bed? (Chapter 2)

- Which can be an appropriate form of a mathematical model for sand beform dynamics over immobile gravel? How do the continuity and momentum equations, as well as the closure relationships for friction and bedload transport change when the gravel bed is partially sand-covered? (Chapter 3)
- Which are the implications of such model when solved in the form of a stability analysis that aims to predict the conditions for sand bedform stability and preferred wavelength selection over an immobile gravel bed? (Chapter 4)

A mathematical modelling approach is first developed to study the spatially-averaged morphodynamic evolution of a sand bed surface over an immobile gravel bed. The hydrodynamic and sediment transport properties of this mixed configuration differ from those of "homogeneous" bed configurations classically found in fluid mechanics. Here the hydrodynamic forces are directly determined by the interaction between the flow and a rough surface that is largely composed by the same sediment that can be transported.

The present modelling approach is based on (i) a two-fraction assumption for the bed composition (sand and gravel) and (ii) a spatially-averaged description of bed roughness geometry, near bed turbulence properties and closure relationships for bedload and suspended load.

The reach-averaged sand surface elevation and the relative size ratio between the sand and gravel diameter emerge as the key parameters that can be used to distinguish between different types of mixed bed configurations. A key distinction can be made between "gravel-clast framework" and "sand matrix" types of bed; these configurations are discriminated by a relatively sharp transition region in the sand surface elevation.

The analysis builds on a synthesis of a variety of empirical and theoretical work on rough-bed open channel flows and of experimental observations on the transport of fine sediments over gravel beds. A theoretical framework is presented to describe the typical vertical and horizontal scales of the mixed bed that can be relevant for spatial averaging. This allows to propose novel physically-based mathematical relations that link the variation of relevant flow and sediment transport properties with the sand surface elevation and the grain size ratio. Depending on these two parameters, the near-bed shear stress and bedload transport of sand depend on a varying dynamic balance between a "hiding" and a "bridge" effect, that are physically discussed and mathematically quantified.

The proposed relationships serve as closure formulaes to link the computation of the near-bed shear stress and of the sand bedload rates with the spatially-averaged flow field within a 2D (x,z) morphodynamic model that includes:

- the momentum conservation equations for the fluid phase in the x and z directions;

- the mass conservation equations for the fluid phase;

- a novel formulation of the mass conservation equations for the sand layer within an immobile gravel bed.

The flow model is formulated referring to physical balances formally valid only within the central flow layer, and indirectly accounting for the role of physical processes governing the hydrodynamics within near-bed (roughness) layer in the proposed closure relationships

Application to spatially-averaged uniform flow conditions shows satisfactory agreement with the few available experimental data and allows to make a preliminary

quantifcation of the effect of the two key parameters describing different types of mixed bed configuration. The limits of validity of the model are also discussed.
The morphodynamic model is finally used to predict the sand bed morphodynamics under supply-limited conditions. The sand surface elevation is a measure of the sediment supply-limitation that crucially controls the sand bedform development. A limited volume of bedload sediment leads either to smaller dimensions, the sediment starved bedform or fewer isolated bedforms. The model is solved through a linear stability analysis that incorporates recent developments in the theoretical study of sand dune stability in homogeneous conditions. The theoretical outcomes allow to focus on the physical phenomena controlling the development of sand bedforms when sand is transported over an immobile gravel bed and to determine the hydraulic conditions under which sand dunes formation can be expected to develop within immobile gravel beds. Results also indicate a consistent effect of supply limitation to extend the instability region towards shorter bedforms, as observed by recent experimental investigations.