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Sediment Transport Mechanics

PREFACE TO THE TOPICAL ISSUE

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> The Editor of *Acta Geophysica* and the Guest Editors wish to dedicate this Topical Issue on Sediment Transport Mechanics to the memory of Stephen Coleman, who died recently. During his career, Stephen had made an outstanding scientific contribution to the topic of Sediment Transport. The level of his contribution is demonstrated in the paper by Aberle, Coleman, and Nikora included in this issue, on which he started working before becoming aware of the illness that led to his untimely death. For scholars and colleagues Stephen remains an example of intellectual honesty and scientific insight.

The general term of “sediment transport” includes a number of environmental processes that take place at a wide range of spatial and temporal scales. Sediment transport is the physical process responsible for river platform development such as meandering and river braiding. At a fluvial reach scale, aggradation of the river bed may increase flood risk and distributed bed erosion may undermine river structures. For example, reservoir silting may have negative economic consequences for water storage, for use toward energy production and raw water supply. This may be addressed by planned sediment evacuation by flushing to tackle the reduction of reservoir storage but this operation may alter the sediment transport dynamics downstream of the reservoir, with environmental impact on the downstream river. At a sub reach scale, local erosion processes at hydraulic structures such as bridge piers or sills may induce their failure during floods. Finally, sediment transport processes also influence the morphodynamics of coastal areas.

Often the spatial and temporal scales of such applications justify the traditional approach of treating sediments as a continuous matter within a conceptual Eulerian scheme. We can identify at least three physical sub-systems that need to be characterized and modelled:

1. **Water flow.** Most classical models in morphodynamics describe the flow field within a depth- or section-averaged approach, the main variables being water depth, bulk water velocity, and time-averaged shear stress on the channel boundary.
2. **Bed geometry (static sediments).** Macro geometry of the boundary is expressed by distributions of bed elevations; sub-scale geometry is modelled by means of bulk properties such as a resistance parameter expressing the average effect of the sediment boundary on the fluid and a porosity term describing the average packing of the deposit. Normally the resistance to erosion is characterized by some deterministic threshold of motion.
3. **Moving sediments.** Sediment motion is described by means of mass fluxes across reference surfaces (solid discharge) or, alternatively, by the average concentration and velocity of the moving sediments. Typically, but not necessarily, bed load and suspended load are considered separately. In certain applications, further variables are used to describe mass exchanges between the different phases (static particles on the bed, bed load, suspended load).

To comply with the continuum approach, all variables must be defined (averaged) over space and time scales much larger than those of the moving water and sediments, the latter phase typically imposing the actual constrains on the choice of the averaging scales. With this respect, we should recognize that the choice of a correct support scale for the analysis of sediment transport processes is not always straightforward, as a consequence of at least two classes of problems: (i) morphological processes often cover a wide range of scales that are not necessarily well separated so that the distinction between resolved and not resolved features is sometimes ambiguous (for example, the effects of bed forms on flow resistance); (ii) in some applications (*e.g.*, local scour, bed forms dynamics), morphological processes to be characterized do not have scales much larger than those of the kinematics of the individual grain, so that the continuum "hypothesis" may be difficult to justify. Whatever is the selected scale for analysis, for some applications a further source of conceptual inconsistency for the distributed continuous approach is generated by features developing at scales below the resolved scale. For example, changes in the granulometric distributions due to selective transport of different grain sizes, and hiding and exposure effects at the bed load layers.

We currently benefit from a base of phenomenological knowledge about the relevant physical processes but, at present, our skill of transposing such knowledge into predictive models is still unsatisfactory. As a result, although standard (commercial) numerical codes are available for the morphological modelling of surface water bodies, expert users are well aware of how uncertain the results from such models can be. Additionally, such (standard) models are typically designed for relatively large-scale, regular processes and they typically fail to capture the physics of the problem when more detailed analyses are required for non-conventional situations (*e.g.*, geometrical singularities, unsteady flows, breaking waves, non-equilibrium turbulence, complex sediment characteristics, and non standard rheology).

As a counterpart to large-scale descriptions, analyses at the grain scale have been used as a fundamental interpretation tool since the very beginning of the discipline. The work by Einstein in the 1940's being a classical example of this approach. Many models for sediment entrainment and transport are first developed conceptually at the grain scale and subsequently upscaled into a continuous framework. Undoubtedly, researchers who have directly observed, often in a laboratory, sediment motion above a loose bed, and particularly for low intensities of transport, often describe the sediment transport process as an ensemble of discrete particles moving more or less randomly rather than as a continuous phase to be characterized as a deterministic process.

In the last decades, increasing computational power has pushed researchers towards higher resolution simulations of the flow field in morphological models thus resolving to some degree the local turbulent and unsteady features of the flow. For example three-dimensional RANS/URANS/LES/DES modelling approaches have been used to address channel geometries with high degrees of complexity. The potential of available turbulence-resolving approaches on the modelling of sediment transport processes has been highlighted by a number of recent papers (*e.g.*, Singh *et al.* 2007, Bomminayuni and Stoesser 2011, Escauriaza and Sotiropoulos 2011), especially for configurations where turbulence cannot be assimilated to that of a standard developed boundary layer. Typical examples for the use of such complex flow models are local scour phenomena where the three-dimensional geometry imposed by the fixed structures and the consequent scour hole generates macro vortices (corner vortices, wakes) whose interaction with the standard boundary layer structures (hairpin vortices, burst cycle) can be correctly reproduced by the flow simulations. However, if the morphological model to be coupled with the fluid-dynamic one is currently constrained within an Eulerian/continuous approach, once detailed information on the turbulent characteristics of the flow field in the proximity of the loose bottom is available, it is not obvious how these data could be used to correctly represent the action of the fluid on sediments (Teruzzi *et al.* 2009). In spite of the large amount of studies on this issue (see, among the others, Sumer *et al.* 2003, Coleman and Nikora 2008, Papanicolaou *et al.* 2008, Dey *et al.* 2011), a widely accepted sediment transport model which explicitly incorporates the effect of the turbulent fluctuating field is not yet available. On the contrary, the Lagrangian/discrete approach for the sediment side looks very attractive to be interfaced with detailed flow-field resolution, as entrainment and transport processes for individual particles are conceptually well posed in terms of lift and drag forces exerted over a body which is interacting in a somewhat random manner within similar bodies. Literature provides a good number of such studies, focused on both the flow and stress fields around particles and on the consequent displacement and transport of grains (Papanicolaou *et al.* 2001, 2002, Chang and Scotti 2003, Ancey *et al.* 2006, Lee *et al.* 2006, Vollmer and Kleinhans 2007, Valyrakis *et al.* 2010, Detert *et al.* 2010a, b, Lajeunesse *et al.* 2010, Dwivedi *et al.* 2010, 2011). However, the fully coupled detailed approach still has not been accomplished for description of the motion of both fluid and the sediment phases. Finally, morphological models (whatever is their resolution) should also consider the effect of sediments on the flow field; this is a complex issue which, at least, should comprehend: (i) roughness of the boundary, (ii) the porosity of the boundary, and (iii) the effects of entrained sediments on turbulent structures.

So far, recent developments on the understanding and modelling of sediment transport processes have been briefly discussed; a main conclusion is that the choice of the grain scale for the analysis is not only motivated by fundamental research on basic phenomena but, more and more, it appears as promising with respect to the modelling of morpho-dynamic processes. Therefore, this Topical Issue on Sediment Transport Mechanics has been designed and organized around the idea that the grain scale can provide insight over the whole phenomenological chain resulting from the interactions among the three “phases” (fluid, rough boundaries, and moving sediments). It is clear that contributions to this issue cannot exhaust the complexity of the matter, nor can they give complete answers to most of the open questions within the subject; however, they touch most of the relevant aspects, thus constituting a valuable overview on the variety of problems to be addressed and on possible approaches to face them. Specifically, the issue includes ten papers which can be grouped into four subsets:

1. The first subset includes the papers by Papanicolaou *et al.*, and Dey *et al.*; the two contributions are focused on the flow field in the proximity of a rough bed, near-wall turbulence characteristics being analysed and discussed with reference to grain mobility.
2. The two papers by Haynes *et al.* and Singh *et al.* constitute the second subset. The main topic is the detailed characterization of the active layer in terms of geometric properties of the porous matrix at the grain scale, thus providing experimental data about the effects of transport processes on the micro-geometry of the bed.
3. The third subset comprehends three numerical contributions (Bialik *et al.*, Moreno and Bombardelli, Link *et al.*), all of them simulating motion of discrete particles within a given flow field; different levels of simplification for the modelling of the water phase as well as different choices for flow-particle and particle-particle interactions among the papers allow to identify the weight of distinct processes on the statistics of particle motion.
4. Finally, the three papers by Aberle *et al.*, Campagnol *et al.*, and Liu and Chiew face the critical issue of upscaling results and processes from the grain to a larger scale, where the phenomena can be described within continuous frameworks also for the sediment phase.

We hope that this issue will give a useful contribution to bridge the gap between fundamental analysis of sediment transport processes and full scale applications.

References

Ancey, C., T. Böhm., M. Jodeau, and P. Frey (2006), Statistical description of sediment transport experiments, *Phys. Rev. E* **74**, 1, 011302, DOI: 10.1103/PhysRevE.74.011302.

Bomminayuni, S., and T. Stoesser (2011), Turbulence statistics in an open-channel flow over a rough bed, *J. Hydraul. Eng.* **137**, 11, 1347-1358, DOI: 10.1061/(ASCE)HY.1943-7900.0000454.

Chang, Y.S., and A. Scotti (2003), Entrainment and suspension of sediments into a turbulent flow over ripples, *J. Turbul.* **4**, 1, N19, DOI: 10.1088/1468-5248/4/1/019.

Coleman, S.E., and V.I. Nikora (2008), A unifying framework for particle entrainment, *Water Resour. Res.* **44**, W04415, DOI: 10.1029/2007WR006363.

Detert, M., V. Weitbrecht, and G.H. Jirka (2010a), Laboratory measurements on turbulent pressure fluctuations in and above gravel beds, *J. Hydraul. Eng.* **136**, 10, 779-789, DOI: 10.1061/(ASCE)HY.1943-7900.0000251.

Detert, M., V. Nikora, and G.H. Jirka (2010b), Synoptic velocity and pressure fields at the water-sediment interface of streambeds, *J. Fluid Mech.* **660**, 55-86, DOI: 10.1017/S0022112010002545.

Dey, S., S. Sarkar, and L. Solari (2011), Near-bed turbulence characteristics at the entrainment threshold of sediment beds, *J. Hydraul. Eng.* **137**, 9, 945-958, DOI: 10.1061/(ASCE)HY.1943-7900.0000396.

Dwivedi, A., B. Melville, and A.Y. Shamseldin (2010), Hydrodynamic forces generated on a spherical sediment particle during entrainment, *J. Hydraul. Eng.* **136**, 10, 756-769, DOI: 10.1061/(ASCE)HY.1943-7900.0000247.

Dwivedi, A., B.W. Melville, A.Y. Shamseldin, and T.K. Guha (2011), Flow structures and hydrodynamic force during sediment entrainment, *Water Resour. Res.* **47**, W01509, DOI: 10.1029/2010WR009089.

Escauriaza, C., and F. Sotiropoulos (2011), Lagrangian model of bed-load transport in turbulent junction flows, *J. Fluid Mech.* **666**, 36-76, DOI: 10.1017/S0022112010004192.

Lajeunesse, E., L. Malverti, and F. Charru (2010), Bed load transport in turbulent flow at the grain scale: Experiments and modeling, *J. Geophys. Res.* **115**, F04001, DOI: 10.1029/2009JF001628.

Lee, H.Y., Y.T. Lin, J.Y. You, and H.W. Wang (2006), On three-dimensional continuous saltating process of sediment particles near the channel bed, *J. Hydraul. Res.* **44**, 3, 374-389, DOI: 10.1080/00221686.2006.9521689.

Papanicolaou, A.N., P. Diplas, C.L. Dancey, and M. Balakrishnan (2001), Surface roughness effects in near-bed turbulence: Implications to sediment entrainment, *J. Eng. Mech.* **127**, 3, 211-218, DOI: 10.1061/(ASCE)0733-9399(2001)127:3(211).

Papanicolaou, A.N., P. Diplas, N. Evaggelopoulos, and S. Fotopoulos (2002), Stochastic incipient motion criterion for spheres under various bed packing conditions, *J. Hydraul. Eng.* **128**, 4, 369-380, DOI: 10.1061/(ASCE)0733-9429(2002)128:4(369).

Papanicolaou, A.N., M. Elhakeem, G. Krallis, S. Prakash, and J. Edinger (2008), Sediment transport modeling review – current and future developments, *J. Hydraul. Eng.* **134**, 1, 1-14, DOI: 10.1061/(ASCE)0733-9429(2008)134:1(1).

Singh, K.M., N.D. Sandham, and J.J.R. Williams (2007), Numerical simulation of flow over a rough bed, *J. Hydraul. Eng.* **133**, 4, 386-398, DOI: 10.1061/(ASCE)0733-9429(2007)133:4(386).

Sumer, B.M., L.H.C. Chua, N.-S. Cheng, and J. Fredsøe (2003), Influence of turbulence on bed load sediment transport, *J. Hydraul. Eng.* **129**, 8, 585-596, DOI: 10.1061/(ASCE)0733-9429(2003)129:8(585).

Teruzzi, A., F. Ballio, and V. Armenio (2009), Turbulent stresses at the bottom surface near an abutment: Laboratory-scale numerical experiment, *J. Hydraul. Eng.* **135**, 2, 106-117, DOI: 10.1061/(ASCE)0733-9429(2009)135:2(106).

Valyrakis, M., P. Diplas, C.L. Dancey, K. Greer, and A.O. Celik (2010), Role of instantaneous force magnitude and duration on particle entrainment, *J. Geophys. Res.* **115**, F02006, DOI: 10.1029/2008JF001247.

Vollmer, S., and M.G. Kleinhans (2007), Predicting incipient motion, including the effect of turbulent pressure fluctuations in the bed, *Water Resour. Res.* **43**, 5, W05410, DOI: 10.1029/2006WR004919.