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Unified theory of non-suspended sediment transport mediated by a Newtonian fluid

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We present a unified theory of steady, homogeneous, non-suspended transport of nearly uniform spheres mediated by an arbitrary Newtonian fluid. The theory consists of elements that are rigorously derived from Newton's axioms and of semi-empirical elements that well describe simulation data, obtained using a coupled DEM/RANS numerical model of sediment transport in a Newtonian fluid (Durán et al., POF 103306, 2012), for the entire simulated range of the particle-fluid-density ratio $s = \rho_p/\rho_f$, particle Reynolds number $\mathrm{Re}_p = \sqrt{(s-1)gd^3}/\nu$, and Shields number $\Theta = \tau/[(\rho_p - \rho_f)gd]$, where g is the gravitational constant, d the mean particle diameter, and ν the kinematic viscosity. The theory takes into account our recent numerical finding that the mode of entrainment of bed sediment is controlled by the 'impact number' $\mathrm{Im} = \mathrm{Re}_p\sqrt{s+0.5}$ (https://arxiv.org/abs/1605.07306), with entrainment through particle-bed impacts dominating most conditions (including turbulent bedload transport). Despite not being fitted to experimental data, the theory simultaneously reproduces measurements in air ($s \approx 2100$) and liquids ($s \approx 1{-}5$) of the transport cessation threshold Θ_t^{ex} (https://arxiv.org/abs/1602.07079), obtained from extrapolation to vanishing transport, and the dimensionless value $Q^* = Q/(\rho_p\sqrt{(s-1)gd^3})$ of the sediment transport rate Q. From the theory and simulations, we learn that considering added-mass, lubrication, fluid lift, and/or history forces is not required to quantitatively reproduce measurements. However, collisions between transported particles cannot be neglected as they are strongly influencing the scaling of Q_* with Θ. We find such collisions are behind the asymptotic scaling $Q_* \propto \Theta^3\mathrm{Re}_p$ measured for transport in viscous liquids and also indirectly behind a transition from a linear scaling $Q_* \propto \sqrt{\Theta_t^{\mathrm{ex}}}(\Theta - \Theta_t^{\mathrm{ex}})$ to a non-linear scaling $Q_* \propto \sqrt{\Theta}(\Theta - \Theta_t^{\mathrm{ex}})$ of the transport rate in turbulent bedload and saltation transport, which we find occurs when the bed surface becomes fully mobile ('stage-3 bedload') at $\Theta \approx 0.1$. Our theory and simulations indicate that the impact number Im together with the particle-fluid density ratio s are more appropriate in characterizing the threshold than the shear-velocity-based particle Reynolds number, and we therefore propose a modification of the classical Shields diagram. We also propose a novel universal distinction of non-suspended sediment transport regimes: bedload is the regime in which the transport layer extent is mainly determined by interparticle collisions (i.e., contact contributions to the particle pressure dominate), whereas saltation is the regime in which the transport layer extent is mainly determined by the ballistic motion of particles (i.e., kinetic contributions to the particle pressure dominate).