Geophysical Research Abstracts
Vol. 15, EGU2013-12705, 2013
EGU General Assembly 2013

Relative roughness controls on incipient sediment motion for steep mountain channels

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Sediment transport in steep mountain channels is important for aquatic habitat, mitigating flood hazards, and landscape evolution. For over eight decades, researchers have observed that coarse sediment in steep channels requires much higher nondimensional bed-shear stresses (Shields numbers) for sediment mobilization than in lower-sloping channels. The cause of the larger critical Shields numbers, however, is unclear due to the covariance of several factors with increased channel slope: 1) a greater downstream component of gravity acting on the grains, 2) changes in bed morphology and associated form drag, 3) increased grainsize relative to channel width that may lead to grain wedging or enhanced particle friction angles, and 4) increased grainsize relative to flow depth (relative roughness) that may change flow hydraulics and particle buoyancy. Here, we report on laboratory experiments spanning a wide range of bed slopes (0.6° to 22.3°) designed to isolate the effect of relative roughness from these other factors. To eliminate bed morphology as a factor, we used only planar beds. To preclude the effects of grain wedging, we used large width-to-grainsize ratios of 23:1 and 9:1. To separate the effects of slope from relative roughness, we compared incipient motion conditions for acrylic gravel (submerged specific gravity of 0.15) to natural siliciclastic gravel (submerged specific gravity of 1.65). Different particle densities allowed us to explore incipient motion as a function of relative roughness, independent of channel slope, because lighter particles move at shallower flow depths than heavier ones of the same size. Results show that both acrylic and siliciclastic gravels exhibit a positive trend between bed slope and critical Shields number for planar beds with large width-to-grainsize ratios. Additionally, for any given slope, the critical Shields number was higher for acrylic gravels than for siliciclastic gravels. Together, these results indicate that relative roughness exerts a first-order control on incipient sediment motion, independent of channel slope, or slope-dependent changes in grain wedging, bed morphology, particle friction angles and form drag. Our results are consistent with a force-balance model that considers the effect of relative roughness on flow hydraulics and particle buoyancy. In natural channels this baseline increase in the critical Shields stress driven by increased relative roughness may be augmented by other factors, including slope-dependent changes in bed morphology and particle wedging.