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# Hydrodynamic Controls of Immobile Boulders on Bed Load Grain Movement in Mountain Streams

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Understanding the interaction between the turbulent fluid flow and bed load sediment flux in a river is fundamental for predicting erosion and landscape evolution, managing riverine infrastructure, and protecting and improving aquatic habitat. To date, this fundamental understanding is lacking especially in steep mountain streams, where transport occurs close to the threshold of entrainment and bed load flux is highly intermittent. A unique feature of mountain streams that warrants special attention, and which is the focus of this study, is the presence of large, rarely-mobile boulders. Because of their large size, these boulders may become fully or partially submerged, thus exhibiting high or low relative submergence, $H/d_c$, respectively, with $H$ and $d_c$ denoting the approach flow depth and the boulder diameter. It is speculated that the type of submergence affects the dominant vortex topology around the boulders. We test two hypotheses, namely: (1) that the topology of the vortex structures resulting from the interaction of the boulders with the approach turbulent flow varies with varying relative submergence; and (2) that the patterns of motion of mobile sediment around the boulders are influenced by the vortex structure topology developing for each relative submergence condition. A series of detailed flume experiments were conducted for a single boulder mounted atop a flat rough bed under full and partial submergence conditions. For each condition, detailed flow field measurements were acquired using Particle Image Velocimetry (PIV). The PIV measurements revealed that the topology of the developing vortices around the boulder was distinctly different for the high and low relative submergence conditions. More specifically, the wake of the fully submerged boulder was dominated by arch structures, which tilted downstream under the intense ambient flow shear, as well as by a pair of inner vortices resulting from the roll-up of the secondary vorticity layer on the boulder surface. In contrast, under low relative submergence conditions, a pair of strong von-Karman vortices tilting into the downstream direction was observed within the boulder wake. The different vortex structures identified for the high and low relative submergence conditions were found to exert a profound influence on the direction of the bed shear stress vector within the horizontal bed plane. In particular, under the high relative submergence, the bed shear stress vector was directed towards the boulder centerline, which promotes the entrapment of mobile sediment within the boulder wake. In contrast, the von-Karman vortex street was found to deflect the bed shear stress vector away from the boulder centerline, which would, in turn, enhance the entrainment of incoming mobile particles away from the boulder wake. The directionality of the bed shear stress tensor was in accordance with earlier observations of bed load particle movement patterns under high and low relative submergence conditions. The findings of this research highlight the profound influence of large, rarely-mobile boulders on the interaction between surrounding turbulent fluid flow and the bed load grain movement with significant implications in the management of riverine environments.