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Vortex shedding and morphodynamic response of bed surfaces containing non-erodible roughness elements

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ABSTRACT

A series of wind tunnel experiments was carried out to investigate particle entrainment from surfaces in which one or more roughness elements were embedded. Thin sand strips were employed to eliminate impact and ejection, and thus isolate entrainment by fluid drag. The pattern of erosion is consistent with the presence of coherent vortices, inclusive of trailing vortices in the wake flow. The shape and orientation of the roughness element strongly influence this pattern. When an upwind supply of saltators is introduced, the majority of particles within the bed are entrained through impact, with the exception of a sand tail to the lee of the roughness element. That is, the effect of coherent structures within the airflow, as related to spatial variation in the fluid drag exerted on the bed surface, is completely overprinted by the saltation cloud and the blocking of particle trajectories by the upwind face of the roughness element. In a repeated set of experiments, the bed was allowed to fully adjust its morphology to the transport system. In this case, particle entrainment did not selectively occur within the zone of wake flow, and by inference the fluid stress across the test surface appeared to be uniform. These experiments support the hypothesis that vortex annihilation occurs on morphodynamically adjusted surfaces. In summary, the system response to the emergence of non-erodible roughness elements on surfaces affected by wind erosion involves a suite of geophysical processes, each of which attains varied levels of dominance within a given morphodynamic domain.

1. Introduction

Much attention in the geophysical literature over the last several decades has been devoted to demonstrating that characteristic patterns of erosion and deposition appearing on bed surfaces are the direct result of perturbations in the fluid shear stress associated with the presence of coherent vortex structures, many of which are generated by the protrusion of roughness elements into the flow. Evidence for this linkage is found in a wide range of environments inclusive of confined flows at the base of glaciers (Shaw, 1994), river beds surrounding bridge piers and abutments (Olsen and Melaaen, 1993; Khosronejad et al., 2012), nearshore and deltaic structures (Hay, 2005), and even on the surfaces of other planets with dynamic atmospheres (Greeley and Iversen, 1985). Examples from aeolian systems on Earth appear to be ubiquitous, given their high degree of visibility as compared to subaqueous forms. The scaling of aeolian bedforms varies over many orders of magnitude in length, from tiny, grain-scale features (e.g. sand tails in the lee of pebbles) that lie entirely within the saltation cloud, to yardangs and lee dunes that protrude well into the atmospheric boundary layer, and to wind streaks on Mars.

The present paper provides qualitative evidence obtained from wind tunnel experiments designed to confirm and further explore the relative importance of sheltering, vortex shedding and particle ricochet in the topographic deformation of the bed surface surrounding a roughness element. The development of deep depressions or wells along the upwind face of a bluff body, for example, constitutes an additional source of form drag. Through feedback, features such as these have the potential to either reinforce or annihilate the coherent flow structures responsible for the stress perturbation that initiated their development, although very little is known about these effects. A further knowledge gap concerns the trajectories of particles transported near the bed surface that are either blocked or redirected by the presence of a solid roughness element, and the extent to which the consequent patterns of impact, erosion and deposition on the bed surface are modified from those expected to arise from the stress perturbation alone.

2. Context

Whereas prediction of the aeolian mass transport rate for level bed surfaces is primarily dependent upon the degree to which the wind speed exceeds that for required for particle entrainment, the emergence of surface obstacles (e.g. cobbles, boulders, and vegetation) gives rise to a range of complex responses that can be difficult to anticipate or explain, and particularly to model. Following the shear stress partitioning approach of Schlichting (1955), the classic treatment has been to solve for the amount of stress that remains to mobilize the bed surface (τ_S) after form drag (τ_R) has been accounted for. In early

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wind tunnel experiments utilizing drag plates, Marshall (1971) was able to directly measure the relationship of τ_R and τ_S to the roughness element density (λ, the ratio of the silhouette area to the unit bed area) for surfaces containing large numbers of roughness elements of identical size and ideal geometry. In further experimental work that specifically addressed aeolian transport, Gillette and Stockton (1989) explored the effect of roughness on the threshold friction velocity required for particle entrainment (u_{*tR}), as compared to that for an unsheltered (smooth) surface (u_{*tS}). They introduced the threshold friction velocity ratio, $R_t = u_{*tS}/u_{*tR}$, for which the following predictive relation is provided by Raupach et al. (1993)

$$R_t = \frac{u_{*tS}}{u_{*tR}} = \sqrt{\frac{\tau''_S}{\tau}} = \sqrt{\frac{1}{(1-m\sigma\lambda)(1+m\beta\lambda)}} \tag{1}$$

where R_t decreases from a value of 1.0 as roughness elements are added to the bare soil surface. The roughness element basal area per unit silhouette area is given as σ. The ratio of the drag coefficient for the roughness element ($C_R \cong F_d/u^2A$) to that for the bare, smooth bed ($C_S \cong u_*^2/u_h^2$) determines β. The drag force (F_d) can be measured by mounting the element of a given shape, height (h) and frontal area (A) on a drag plate in a wind tunnel with the freestream wind speed (u_∞) set to a constant value. Published values for C_R can be substituted for elements having nearly ideal geometry, e.g. $C_R = 0.3$ for a cylinder (Taylor, 1988).

The parameter m addresses the importance of the maximum instantaneous shear stress acting on the intervening bed surface (τ''_S) with regard to the initiation and maintenance of sediment transport. Raupach et al. (1993) argue that τ''_S for a rough surface characterized by λ is the same as the instantaneous shear stress (τ'_S) for a surface with a lower roughness element density:

$$\tau''_S(\lambda) = \tau'_S(m\lambda) \tag{2}$$

where $m \approx 0.5$ for a planar sand surface. For all surfaces having a fully adjusted form in response to a given set of airflow/sediment transport conditions, m is assigned a value of unity; that is, the fluid stress is assumed to be uniform over the intervening bed surface. Derivation of Eq. (1) assumes that the roughness elements provide a wedge-shaped area of shelter immediately to their lee (Fig. 1A), within which τ_S is set to zero.

There are as yet innumerable challenges associated with the application of shear stress partition models in their current form to natural settings. As stipulated above, details of the coherent flow structure and the associated turbulence intensity in relation to the geometry of the obstacle are not accounted for. As reviewed by Nickling and McKenna Neuman (2009), published measurements of m vary considerably in magnitude, with no consensus on an appropriate value for any given situation. From field testing of the Raupach model well over a decade ago, Wyatt and Nickling (1997) concluded that the difficulty in determining m is attributed to a lack of understanding of the flow conditions and resulting spatial distribution of τ_S in the vicinity of roughness elements of complex geometry with varied spacing. In other words, without knowledge of the actual distribution of stress in the vicinity of the obstacles on a given surface, and given that there is likely to be a high degree of flow interaction among these, the precise pattern of erosion and deposition can be neither understood nor predicted. As a consequence, reliable estimation of the aeolian mass transport rate for such rough surfaces is beyond present capability.

In comparison, there have been innumerable experimental studies of the large-scale coherent flow structures that form in response to the presence of a roughness element (e.g. Mason and Morton, 1987; Hobson and Wood, 1997; Hunt and Eames, 2002; Sau et al., 2003), particularly as related to water flow, with many of these empirical observations now successfully replicated in CFD (computational fluid dynamics) models. Whereas most treatments of shear stress partitioning (Schlichting, 1955; Marshall, 1971; Wooding et al., 1973) consider the surface shear stress to be uniform over all areas of the exposed bed, apart from the sheltered area behind each roughness element, coherent flow structures have long been identified as capable of localized erosion, as described in the early work of Allen (1965) and Richardson (1968), for example.

Among several noted coherent flow structures illustrated in cartoon form in Fig. 1B and in the ink flow image in Fig. 2A, the classic horseshoe vortex arises when the spanwise vorticity generated by descending airflow along the upwind face of a bluff body is bent around the roughness element and stretched for some distance downwind. Immediately adjacent to the rear, counter-rotating eddies arise from strong shear within the flow as it separates along each side of the element (Fig. 2A). Here, the axis of rotation is normal to the bed surface. Martinuzzi and Tropea (1993) suggest from their flow visualization work with surface mounted cubes that these paired structures may represent the 'footprints' of a single arch vortex. For tall elements where the fluid flow is primarily diverted to the sides, Kawamura et al. (1984) and Mason and Morton (1987) report that the upwind edge is responsible for shedding a pair of counter-rotating vortices with a central zone of bed directed flow (Fig. 1B). This is opposite to the sense of rotation in trailing vortices formed behind short, sloped roughness elements where the flow is redirected primarily over the top. Similarly, the far wake zone in Fig. 2A demonstrates an ink flow pattern that is consistent with a pair of counter-rotating, corkscrew vortices with an axis of rotation aligned parallel to the mean flow in the freestream.

Wooding et al. (1973) and Yan and Shao (2005) speculate that a slight increase in the bed shear stress may occur beneath trailing vortices formed behind a given roughness element, and indeed, wind tunnel experiments carried out by Iversen et al. (1991) demonstrate substantial erosion downwind of simulated, raised-rim craters. Where convergence of the trailing vortices results in bed directed flow, wind tunnel measurements obtained by Sutton and McKenna Neuman (2008b) provide direct evidence that the temporally averaged shear stress has a local maximum (Fig. 2B; $\tau_S = 0.24$ kg m^{-1} s^{-2}) which exceeds that for a smooth bed in the absence of a surface mounted roughness element (Fig. 2B; $\tau_S = 0.2$ kg m^{-1} s^{-2}). The slight increase in τ_S within the far wake appears from this work to persist over a distance exceeding 60 roughness element heights. Temporally averaged values of τ_S surrounding the cylinder array shown in Fig. 2B also confirm that a zone of elevated bed shear stress ($0.28 < \tau_S < 0.3$ kg m^{-1} s^{-2}) lies between each pair of roughness elements, corresponding to strong compression of the perturbed outer flow. Relatively low values of τ_S derive from both the adverse pressure gradient on the windward face of the roughness element, and flow separation and reattachment within the near wake region. These general patterns demonstrate Reynolds number independence when $10{,}000 < Re < 18{,}000$, where Re is based on the velocity in the freestream flow and the element height. They also are similar to, but do not exactly match, those observed for particle entrainment when the solid tunnel floor is replaced with loose sand particles, as demonstrated in further experiments by Sutton and McKenna Neuman (2008a).

In overview, it is clear from a great deal of work that vorticity strongly governs the pattern and magnitude of shear stress acting on a bed surface when roughness elements are present and the flow is devoid of particles. While perhaps of direct relevance to situations where bedload is the dominant transport mode (e.g. the design of bridge piers in fluvial and coastal systems), significant adjustments are needed in transferring such knowledge to geophysical systems (e.g. aeolian) where particle-borne momentum partitioning (i) plays a key role in the entrainment of particles from the bed surface, and (ii) modifies the vertical distribution of shear stress and vorticity within the fluid. In addition, alteration of the trajectory of any given particle that collides with a fixed roughness element is imprinted upon the pattern of particle impact and ejection within the surrounding area, and ultimately,