OBSERVATIONS OF VORTEX-INDUCED PRESSURE FORCES ACTING ON SAND GRAINS OVER RIPPLES

Donya Frank-Gilchrist, United States Geological Survey, dfrank-gilchrist@usgs.gov
Margaret Palmsten, United States Geological Survey, mpalmsten@usgs.gov
Allison Penko, United States Naval Research Laboratory, allison.penko@nrlssc.navy.mil
Joseph Calantoni, Naval Meteorology and Oceanography Command, joseph.calantoni.civ@us.navy.mil

ABSTRACT
Two-dimensional moveable sand ripples were generated in an oscillatory flow tunnel, and high-resolution measurements of fluid-sediment interactions were made with a Particle Image Velocimetry system to assess sediment transport processes. Here we present observations of vortex-induced pressure forces acting on coarse sand grains suspended above the ripple slope, just prior to flow reversal. The sand grains were observed to move from a region of high dynamic pressure to low dynamic pressure perpendicular to the ripple slope, as would be expected from an object being impacted by a lift force. Further analyses will be conducted to calculate the lift and drag forces acting on the grains, as well as to determine the role of shear stresses and pressure gradients in mobilizing and transporting the sediment grains under these oscillatory flows.

INTRODUCTION

Large-scale sediment transport processes in coastal regions may be impacted by underlying small-scale fluid-sediment interactions. Small-scale sand ripples can increase suspended sediment transport and wave energy dissipation due to increased bed roughness. Field observations have also shown that gradients in surf zone sediment fluxes could be driven by the migration of small-scale sand ripples having wavelengths of 0.2 – 2.5 m and heights of 0.02-0.4 m (Wengrove, 2022), which may lead to sandbar evolution.

Many studies have demonstrated the role of shear stress in mobilizing and transporting sediments based on the work of Shields (1936). Critical thresholds of the Shields parameter have been estimated for a range of sediment transport regimes such as incipient motion, ripple evolution and sheet flow. There has also been evidence of pressure gradient-induced mobilization of sediment grains in the field (Foster (1999)) and laboratory (Frank (2015)) based on the formulations of Sleath (1996), who measured pressure-gradient driven plug flow. However, fewer studies have focused on the role of pressure gradients on sediment transport in the ripple regime. There have been several studies that illustrate that vortices shed from ripples can induce pressure gradients in the flow, but less is known about their role on sediment transport. This paper describes observations of vortex-induced pressure forces on sand particles transported over ripples under oscillatory flows.

METHODS

Movable sand ripples were generated from an initially plane bed in the small oscillatory flow tunnel at the U.S. Naval Research Laboratory at Stennis Space Center, Mississippi, USA. The test section was approximately 2 m long with a flow cross-section of 0.25×0.25 m. Fluid and sediment grain velocities were measured simultaneously with combined particle image and tracking velocimetry under the oscillatory flows in a two-dimensional vertical plane. Three high-speed cameras equipped with varying optical filters were used to distinguish between fluorescent fluid tracers and the grains, from which the fluid and grain velocities were determined, respectively. The overlapping, simultaneously recorded images provided sediment particle and fluid velocities at 100 Hz with spatial resolution ≤ 1 mm (Frank-Gilchrist et al., 2018).

RESULTS

Two-dimensional sand ripples generated in the oscillatory flow tunnel had a wavelength of 0.13 m and a ripple height of 0.025 m. The sediment grains consisted of coarse quartz sand with median grain diameter of 0.7 mm and density of 2,650 kgm^{-3}. The oscillatory flow period, T, was 2.35 s and the orbital velocity amplitude, U_0, was 0.26 ms^{-1}. The raw flow velocities were smoothed temporally and spatially to reduce noise and improve data quality. Ripples were generated from an initial flat bed until they were in equilibrium with the flow. The free-stream velocities and two-dimensional flow velocities across the domain are depicted in Figure 1.

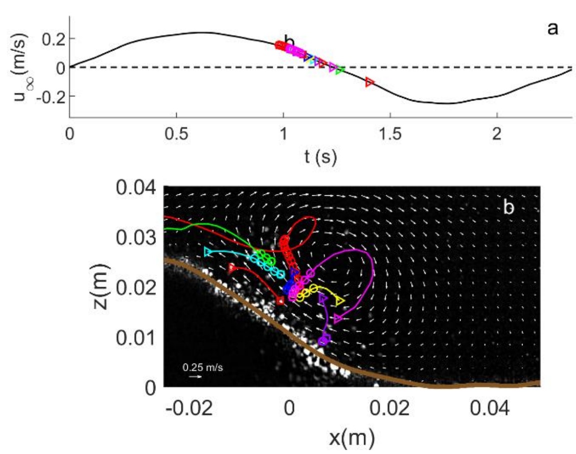

Figure 1. Free-stream velocity (a) and Particle Image Velocimetry image of mobilized sand grains over the sand ripple with fluid velocity vectors in white. Circles indicate sediment grain locations at the corresponding time steps in (a), with the last circle indicating the time stamp of the image. The triangle marks the time of the end of the tracks. Sediment grain trajectories are outlined with solid lines and the approximate ripple bed location is indicated by the brown line.

The fluid velocity vectors illustrate the presence of a vortex being generated just before the flow reverses from right to left. Grains had been suspended into the water column during the peak flow and additional grains were being mobilized by the vortex impinging the bed. A particle finder algorithm was used to determine the sediment grain trajectories (Ouellette, 2010). The magenta, yellow and dark blue grain trajectories highlight paths that were perpendicular to the velocity vectors, unlike the other grains being advected with the flow.

The smoothed fluid velocities illustrate regions of higher speed surrounding the vortex core where the speed was much smaller in magnitude (Figure 2 b). Maximum speed near the bed at this time step was 0.23 m/s while the speed in the center of the vortex was near 0 m/s. The dynamic pressure was calculated with $P_{dyn} = {}^{1}/_{2}\,\rho(u^2 + w^2)$ (Pa), where ρ is the density of water (1000 kgm^{-3}), u and w are the horizontal and vertical components of the flow velocity. The dynamic pressure was at a maximum of 25 Pa near the bed in the region where the three grains mentioned previously were forced with trajectories perpendicular to the flow velocity and to the ripple slope. This demonstrates that the vortex-induced pressure forces changed the sediment grains' trajectories, and therefore could impact sediment resuspension processes quite significantly. Further analyses will be conducted to aggregate all such occurrences observed throughout the datasets and calculate the lift and draft forces acting on the grains.

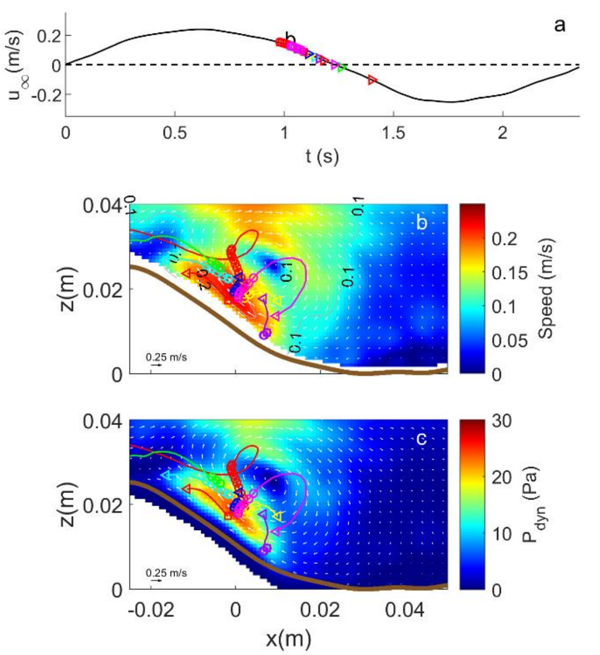

Figure 2: Free-stream velocity (a), velocity field (b) and dynamic pressure field (c) over the sand ripple. Sediment grain trajectories are outlined by the solid color lines and the approximate bed location is indicated by the brown line. Velocity vectors are indicated with the white arrows. Circles indicate sediment grain locations at the corresponding time steps in (a), with the last circle indicating the time stamp of the image. The triangle marks the end of the track.

CONCLUSION

Our observations indicate that vortex-induced pressure gradients are important for sediment transport over ripples under oscillatory flows. The dynamic pressure was maximum near the bed where the sediment grains in the region of peak dynamic pressure were seemingly forced on trajectories that were perpendicular to the flow velocity and to the ripple slope, quite like the lift force generated over an aircraft wing. The next steps in this analysis will be to calculate the lift and drag forces on the sand grains in the domain and determine which force was dominant for the various grains mobilized during the oscillatory flow cycles. In addition, further analysis will investigate the role of shear stresses and pressure gradients in mobilizing the sand grains on the ripple slope as well as how the vortex-induced pressure gradients may impact the transportation of the sand at larger scales in the nearshore.

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