# Measurements of flow dynamics associated with interacting, subaqueous barchans: Exploring bedform asymmetry and three-dimensionality in a novel flume environment

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ABSTRACT: While barchan dunes are traditionally associated with aeolian environments, recent efforts now highlight the emergence of barchans in subaqueous environments as well, particularly in rivers. To this end, herein the flow associated with interacting barchan dunes is quantified in the laboratory as a means of understanding a range of morphodynamic issues associated with their evolution. The interaction between barchans of different sizes produces complex processes such as collision, amalgamation and breeding. In this study, idealized, fixed physical models are utilized to permit accurate interrogation of the flow with both high-resolution planar and volumetric particle image velocimetry. Specific simplified geometrical configurations of two fixed barchan dunes in tandem reveal the flow modifications induced by dune proximity as compared to the baseline case of flow around an isolated dune. Initial measurements focused on the latter, followed by measurements of several tandem configurations replicating sequential stages in a dune-dune collision.

## 1. INTRODUCTION

Barchan dunes are three-dimensional (3D) topographic features generated by geophysical flows in the presence of a limited sediment supply over an underlying substrate, and are important in a number of engineering and geophysical applications (Lancaster, 1994). While barchan dunes are traditionally associated with aeolian environments, recent high-resolution maps of river bed topography using new methods (i.e. multibeam echosounding) have revealed the occurrence of such dunes in subaqueous environments. These observations, and ongoing research in aeolian environments, have sparked interest in these bedforms among the scientific river community, particularly for their geomorphological, environmental and engineering significance.

Barchans typically occur in fields with significant heterogeneity in dune size and migration rate. In this situation, the interaction between barchans of different sizes produces complex processes such as collision, amalgamation and breeding (Endo et al., 2004). While the morphology of barchan dunes has been widely studied, the interaction between turbulent flows and barchans is limited to a few recent studies (Palmer et al., 2012; Charru and Franklin, 2012). The number of direct flow measurements is even fewer with respect to the interaction mechanisms occurring when barchans are in close proximity. This lack of data is partially due to the geometric complexity of these bedforms that introduces significant challenges in high-resolution optical flow diagnostic techniques such as particle image velocimetry (PIV). As a result, the processes involved in the interaction and collision of barchan dunes remains poorly understood, with the impact of turbulence not being incorporated in current numerical models.

In particular, models based on mean bed shear stress (Parteli et al., 2014) struggle to accurately predict the morphodynamics of barchans when they come in close proximity, including dune-dune collisions. This model deficiency is readily observed in the Figure 4 which compares the model results (a-e) (Parteli et al., 2014) of a smaller barchan approaching a larger one (barchan migration rate is inversely proportional to size) with a similar scenario observed in laboratory experiments (f-j) (Hersen et al., 2005). Figure 4 highlights the contrasting dynamics, with erosion of the downstream dune occurring prior to contact, indicating that models based solely on mean bed shear stress fail to capture the key flow physics associated with such interactions. Thus further experimental work is needed to inform these deficiencies and elucidate the role of unsteady turbulence in barchan morphodynamics.

In this paper, we study the flow field surrounding idealized, fixed physical models with high-resolution planar and volumetric PIV. Several different configurations of models are used, including a baseline isolated case and a number of dune-dune collision cases. Access to the flow field around these geometrically complex dunes is achieved using a refractive index matching (RIM) approach. Transparent models of barchan dunes, whose shape was based upon previous work (Palmer et al., 2012), were fabricated by casting urethane material into 3D printed molds. The models were fixed in a RIM flow tunnel that employs an aqueous solution of sodium iodide (~ 63% by weight) as the working fluid, and rendered invisible, thus facilitating unimpeded data collection around the entire bedform configuration. Planar measurements at high spatial and temporal resolution were conducted in both the *x-z* (i.e. wall-parallel) and the *x-y* (i.e. wall-normal) planes, at several different elevations and spanwise positions respectively, in order to reveal the 3D nature of the flow. An example of these measurements is shown in Figure 1, where the case of an *offset* collision is shown. In addition to planar measurements, volumetric measurements were performed using the TSI V3V PIV system to reveal the instantaneous 3D flow structures shed from the barchan crests, as well as observe their evolution as they convect and impinge onto the downstream barchans (Lai et al., 2008). Figure 2 reports an example of such volumetric measurements. The measurements

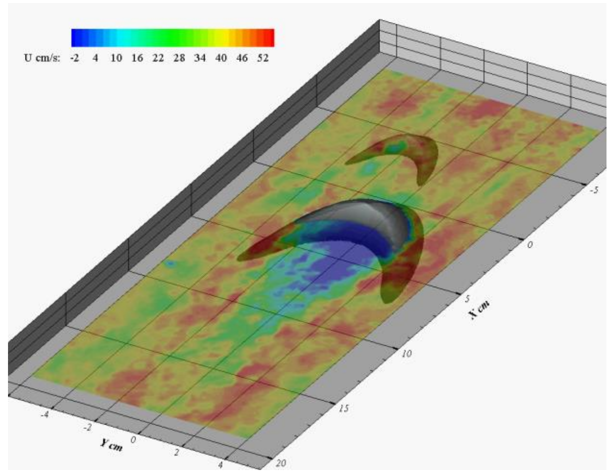


Figure 1. Instantaneous distribution of the streamwise component of velocity around two interacting barchan dunes in an offset collision configuration at $y = 0.5h$.

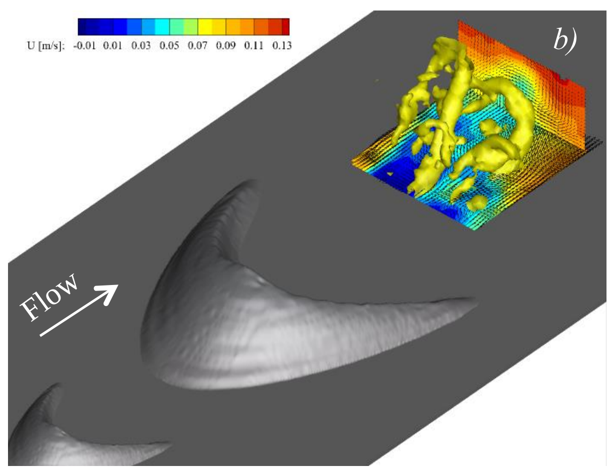


Figure 2. Instantaneous flow structures captured by the V3V system at two different streamwise positions downstream of the larger barchan dune for the inline collision configuration. Iso-surfaces are 3D swirling strength.

conducted in this work would be impossible in either a wind or water tunnel owing to laser blockage and/or aberration upon light interaction with the barchan models. In contrast, because the refractive indices of the fluid and solid models are matched precisely in the present experiments, no loss of laser energy or laser deflection is present as light passes through the solid models, while optical aberrations are also minimized.

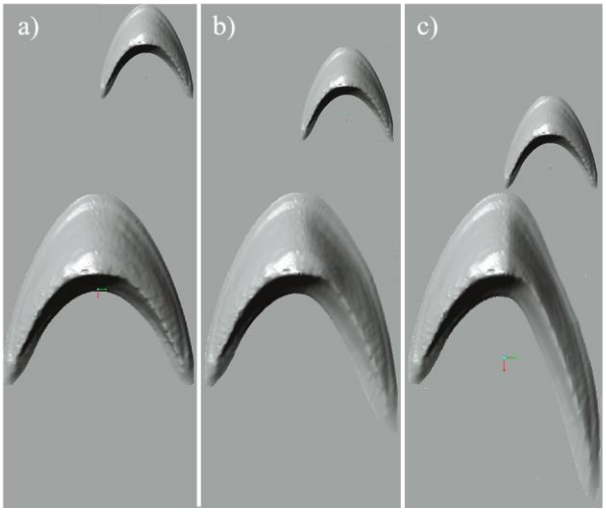

Figure 3. Barchan dune model configurations in a dune-dune offset collision sequence.

Each barchan offset collision configuration simulates a successive stage in the process of a dune-dune collision whereby a smaller, spanwise offset, upstream dune collides with a larger downstream dune, the two dunes having a 1:8 volumetric ratio. Inspired by the experimental work by Hersen et al. (2004), the final two stages in this collision involve asymmetric, deformed morphologies. The three stages in this dune-dune collision are shown in Fig. 3.

## 2. RESULTS

Analysis of the isolated barchan case shows that the flow separates at the crest of the barchan, producing a 3D shear layer that is suggested to present a symmetrical (in the spanwise direction) arc-like shape. The flow region behind the leeside is characterized by low momentum. Under such conditions in a mobile bed, a fraction of the sediment that was entrained upstream would be deposited, resulting in bedform migration. Our results indicate that the shear layer may have important morphodynamic implications, since it embodies a significant fraction of the Reynolds shear stress (RSS) and thus plays a central role in the erosion processes induced by barchans. These measurements are the first step towards linking, in a quantitative fashion, the energy dissipation due to turbulent mechanisms (i.e. shear layers) to localized erosion phenomena (i.e. erosion on the stoss side) that have been highlighted by previous qualitative mobile bed experiments involving interacting bedforms (Endo et al., 2004).

While flow symmetry for an isolated barchan was confirmed, our results indicate that the presence of an upstream dune may break this symmetry around the downstream barchans, unless the two dunes are perfectly symmetrical and perfectly aligned. The in-line case studied shows that the symmetry of the mean flow is highly sensitive to dune alignment, and this can provide insight to understand the imperfect symmetry of barchans in natural environments. The offset cases enhance this flow asymmetry, as is particularly apparent in the single point statistics (turbulent kinetic energy (TKE) and RSS). The streamlines show an enhanced recirculation near the horn of the larger barchan dune that is closer to the smaller barchan in both of the offset cases. A reduction in TKE, that is spatially coincident with the enhanced recirculation, is also noted at the same location. RSS shows a contrasting behaviour, with enhancement for the case of offset collision and reduction in the case of offset ejection. Finally, the 3D flow fields obtained by extracting the iso-contour of the swirling strength from the V3V dataset, reveal the presence of horseshoe-like vortical structures that are shed from the crest of the barchan. For the in-line case considered herein, these vortices convect and impinge upon the larger downstream barchan dune. Their behaviour is consistent with recently published LES simulations using similar geometries.

## 3. CONCLUSIONS

This study provides accurate 2D and 3D flow measurements of the turbulent flow field surrounding fixed, interacting barchan dune models. Using both planar and volumetric PIV in conjunction with a refractive index matching technique, the instantaneous and mean flow structure around dunes in different configurations was measured and is presented here. This preliminary study is key to further experimental investigations that will consider a wider range of dune volumetric ratios and interacting configurations. Future work will focus on the morphodynamic implications of the turbulent events revealed using our unique experimental approach as well as targeted numerical simulations using large-eddy simulation to explore a broader range of dune interaction scenarios.

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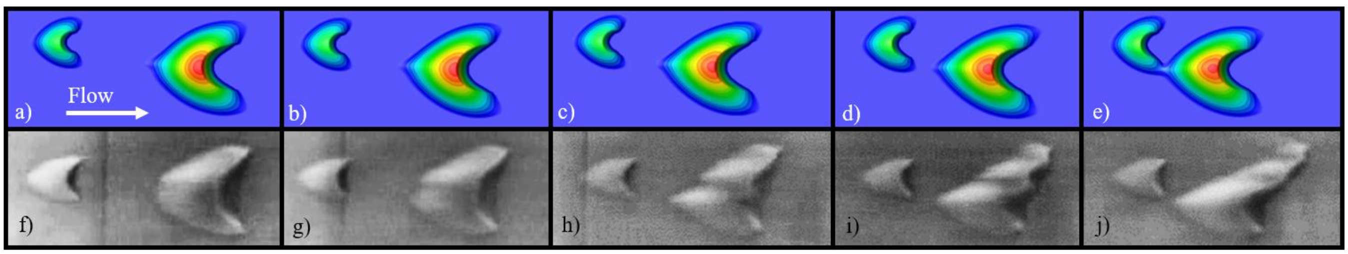


Figure 4. Comparison of (a-e) morphodynamic model and (f-j) mobile-bed flume experiments (Hersen et al., 2005), highlighting model deficiencies for a barchan collision. Code courtesy Parteli et al. (2014) (modified by us for this scenario).