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Near-wake flow patterns in the lee of adjacent obstacles and their implications for the formation of sand drifts: A wind tunnel simulation of the effects of gap spacing

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ABSTRACT

A wind tunnel and particle image velocimetry were used to study the ground-level mean secondary airflow patterns and statistical turbulence quantities in the lee of adjacent rectangular obstacles, the influence of gap spacing on the near-wake flow patterns, and their role in the onset of sand particle deposition and sand drift formation. The flows separated both horizontally and vertically, and paired vortices shed from each of the structures created reversed-flow cells downwind of the obstacles. Four wake patterns (single vortex flow, gap-enveloped flow, wake-interference flow, and couple vortex-streets) were observed behind obstacle pairs with different gap ratios. In the first three flow modes, airflow increased through the gap, but decreased a short distance downwind and then recovered to a steady state as the air stream merged with the general flow. The larger the gap spacing between obstacles, the more quickly wind velocity recovered downwind of the gap. Vorticity and kinematic Reynolds stress exhibited different features for the four wake patterns, resulting in different sand particle entrainment capacities in the lee of the adjacent obstacles.

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1. Introduction

'Sand drifts' was the term first used by Bagnold (1941) to describe accumulations of sand in the lee of a gap between two obstacles that were created by the funneling of airflow through the gap. The accelerated airflow increases the wind's sand-carrying capacity, but expansion and deceleration downwind of the gap result in the deposition of entrained sand and the formation of sand drifts. Sand drifts are common in arid and semi-arid regions on Earth and other planets, and in the dune classification system of Pye and Tsoar (1990) they belong to the class of lee dunes that form in a zone of flow separation downwind of the edges and crest of topographic obstacles. Sand particles frequently accumulate downwind of gaps in the lee of topographic obstacles (e.g., rocks, yardangs) and some human structures (e.g., cairns, buildings) and generate this kind of sediment deposit (Bagnold, 1941; Greeley and Iversen, 1985; Goudie, 2008). The arrangement of the obstacles strongly influences the generation, development, and spatial distribution of sand drifts (Greeley and Iversen, 1985; Livingstone and Warren, 1996). Understanding the dynamics of these aeolian bedforms thus requires insights into the airflow fields that develop in the lee of adjacent obstacles. However, since Bagnold first provided a qualitative description of the evolution of sand drifts in his early research (Bagnold, 1941), little work has been done to investigate the aerodynamic mechanisms of their formation and development in detail (Pye and Tsoar, 1990; Cooke et al., 1993; Lynch et al., 2010; Jackson et al., 2011, 2013).

Dunes related to topographic obstacles have attracted less attention than most types of self-accumulated dunes because of their limited distribution; that is, although they are common, they occupy less space than dune fields (Livingstone et al., 2007; Qian et al., 2011). Previous research has identified similar aeolian deposits on Mars and Venus (Mutch et al., 1977; Greeley and Iversen, 1985), but their origin and interpretation of the processes that shape their evolution the wind-blown deposits on those planets is even more uncertain than for terrestrial deposits (Greeley and Iversen, 1985; Bourke et al., 2004). A complete investigation of their terrestrial analogs will provide basic information for interpreting these aeolian phenomena in all locations (Bourke et al., 2004).

When the wind blows over a smooth, unobstructed surface, shear stress is distributed more or less uniformly across the entire surface, but when non-erodible roughness elements are present (Udo et al., 2008), a proportion of the shear stress is absorbed by the roughness elements, which protect the underlying erodible surface (Sutton and McKenna Neuman, 2008a,b). The degree of protection is a function of the size, geometry, and spacing of these elements (Raupach et al., 1993; King et al., 2005, 2006; Sutton and McKenna Neuman, 2008a,b; Walter et al., 2012a,b). When a sufficiently strong wind flows around a pair of rectilinear obstacles, flow separation and reattachment occur (Delgado-Fernandez et al., 2013), and sand drifts can form in the lee

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of the gap, particularly after a storm, but can also be created by a weaker wind that exceeds the threshold velocity required to entrain sand particles (Bagnold, 1941; Allen, 1982; Pye and Tsoar, 1990; Cooke et al., 1993; Livingstone and Warren, 1996). The nature and significance of the secondary flows are controlled by the interactions among at least two factors: the shape of the obstacle (Jackson et al., 2011, 2013) and the gap spacing (Bagnold, 1941; Sumner, 2010).

In recent decades, with the overexploitation of natural resources and the increased mobility of the populace, progressively more buildings have been constructed in the desert and its margins. This has led to sand accumulations in the lee gap between two parallel, closely arranged buildings after a wind storm. Local populations now face the technical difficulties of preventing this new type of sand hazard. In the present study, we investigated the mechanisms responsible for the formation and evolution of sand drifts under a range of gap spacing and studied the complicated airflow conditions through scaled wind tunnel simulations. The results would provide guidance for local populations to use well-defined gap sizes when they construct buildings in desert regions, and would be used to develop better sand fences or other sand-trapping and mitigation structures when they address sand hazards.

It is important to understand the relationships between sand deposition stratigraphy and airflow patterns and paleoclimate on Earth or other planets. Even though researchers have made considerable efforts to explain these relationships, there is still some uncertainty because the origin and evolution of the possible windblown deposits on other planets are more difficult to resolve than on Earth (Greeley and Iversen, 1985; Bourke et al., 2004). Hence, a complete investigation of their analogs on Earth provides basic information for interpreting both terrestrial and extraterrestrial aeolian phenomena (Bourke et al., 2004). Therefore, the study of topographic dunes has both theoretical and practical significance.

2. Background

2.1. Two obstacles in a cross-flow

The flow around two adjacent obstacles is of practical importance in many fields of engineering, and has attracted considerable interest (Inoue et al., 2006; Sumner, 2010; Yen and Liu, 2011). In the past two decades, a number of studies have been performed, especially to describe the flow around cylinders, and many insights have been gained into the features of the flow structure around multiple-obstacle configurations that result from complex interactions between the shear layers, vortices, wakes, and Kármán vortex streets (Robichaux et al., 1999; Kumar and Vengadesan, 2010). Less well studied and understood are the changes to the flow around the individual obstacles when two or more obstacles are placed in close proximity. A few studies have focused on the flow past two blunt bodies or the flow around two adjacent rectangular structures (Wong et al., 1995; Kuroda et al., 2007; Kumar and Vengadesan, 2010; Yen and Liu, 2011).

In the past two decades, researchers have observed many flow patterns and the process of shear layer reattachment induced by separation of the airflow around two obstacles of equal diameter immersed in a steady cross-flow (Sumner et al., 1997, 1999, 2000). Wake and proximity interference effects, which are determined primarily by the longitudinal and transverse spacing between the obstacles and by the Reynolds number of the airflow, have a strong influence on the flow patterns, aerodynamic forces, vortex shedding, and other parameters of the airflow (Sumner, 2010). Okajima (1982) and Kolár et al. (1997) studied vortex-shedding frequencies behind rectangular structures by varying the width-to-height ratio and Reynolds number of the structures. Chen et al. (2000), Kondo (2004), Cheng et al. (2007), and Chatterjee et al. (2010) performed numerical simulations of the aerodynamic characteristics of the airflow past a row of obstacles with a square or rectangular cross-section (which have also been described as "square cylinders" in the literature) for various gap ratios (i.e., the ratio of the gap size to the width of the obstacles perpendicular to the airflow). The wake-flow patterns behind two adjacent obstacles with elliptical or rectilinear cross-sections in these studies were mainly classified as single vortex streets, biased gap flows, and coupled-vortex streets at different gap ratios; a detailed classification has been proposed, although there are some nomenclatural differences in the literature (Sumner, 2010). However, little research has been performed on the three-dimensional flow separation phenomena that occur in the lee of two adjacent rectangular obstacles with different gap ratios, and the sedimentological processes involved are still not clear due to the complex interactions between the wind field and underling topography.

Based on the advances of much more complete spatial coverage of a wind field that could be achieved from an instrumental approach, computational fluid dynamics (CFD) models have been applied widely to a number of natural settings using both 2-D (Jackson and Hunt, 1975; Castro, 1991; Parsons et al., 2004; Wakes et al., 2010) and 3-D simulations (Jackson et al., 2011, 2013). To improve modeling of flows over a complex surface, Parsons et al. (2004) use a 2-D numerical model to simulate wind flow over a single idealized transverse dune of different dimensions to explore the relations between dune size and reattachment points. Wakes et al. (2010) simulated patterns of flow behavior over non-uniform topography. More recently, Jackson et al. (2011, 2013) examined the behavior of offshore-directed winds over coastal dunes and beach morphology through combination of 3-D CFD modeling and field measurement to better characterize the wind field in key areas in the lee separation zone and dune migration patterns in an arid coastal dune field.

2.2. Critical points and flow topology

'Critical points' are defined as points in the flow field where the streamline slope is indeterminate and the velocity is zero (Perry and Chong, 1987; Perry and Steiner, 1987). Knowledge of critical-point theory is important for interpreting and understanding flow patterns, whether they are obtained experimentally or observed in nature. A related subject, the analysis of flow topology, explains the flow structures that arise in a steady flow or during the evolution of an unsteady wake-flow (Yen and Liu, 2011). Singular points (typically represent the saddle and nodal point) may develop at certain positions when the flow moves around a three-dimensional obstacle. A 'saddle point' in the streamline field develops at the intersection of two topological lines, whereas a 'nodal point' represents a position where either flow attachment or flow separation develops (Perry and Chong, 1987). Lighthill (1963) was the first to examine the patterns of viscous flow close to a rigid boundary, and classified the types of critical points that can develop. Following the suggestion of Lighthill (1963), many researchers have utilized flow topology to analyze fluid flow problems (Perry and Fairlie, 1974; Zdravkovich, 1987). Perry and Steiner (1987) adopted critical-point theory to analyze the vortex formation process in the cavity region of several nominally two-dimensional blunt bodies. Recently, Yen and Liu (2011) plotted and analyzed the topological flow patterns during vortex evolution behind twin adjacent obstacles with a square cross-section based on critical-point theory, and identified three flow structures (a single vortex-street mode at low gap ratios, a gap-flow mode at medium gap ratios, and a couple vortex-street mode at larger gap ratios) based on their topological characteristics.

It is difficult to precisely define the flow pattern behind closely spaced twin structures, especially when the pattern is distorted so that different parts of the pattern move relative to one another. The measurement of flow patterns in the laboratory and the field is important in research on the dynamics of aeolian dunes to understand the origin and evolution of dune systems. In addition, much attention has been devoted to demonstrating the flow patterns and the aerodynamic mechanisms responsible for erosion and deposition downwind and upwind of single obstacles (Allen, 1982; Livingstone and Warren, 1996; Walker and Nickling, 2002; Qian et al., 2011; Luo et al., 2012). However, nobody has studied the sand drifts since the studies of sand drifts

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