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An integrated simulation-assessment study for optimizing wind barrier design

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ABSTRACT

Wind barriers are artificial structures that are widely built to abate wind erosion by reducing wind velocity near surface, which requires optimal design in aeolian engineering. Previous studies have shown that numerical simulation is an effective method for optimal design of wind barriers. However, there still exist two challenging questions: 1) how to resolve fine-scale airflow fields around barriers? and 2) how to systematically evaluate the shelter efficiency? In the current study, we have conducted high-resolution 3D computational fluid dynamics (CFD) simulations for airflow passing through wind barriers then explored optimal designs. To validate the simulation results, we compared the simulated airflow results with those from wind-tunnel measurement. Moreover, we innovatively proposed a shelter index to evaluate the shelter efficiency, which has taken wind velocity reduction, economical cost and shelter degree into account. According to the calculated shelter index, wind barriers with porosity of 0.3–0.4 could provide the longest effective shelter distance, and a 2-row-a-belt scheme with inter-row spacing of 5–7*h* (*h* as the height of wind barriers) is the most effective. The optimal inter-belt spacing is suggested as 12–15*h* depending on local wind velocity. This study is intended to provide design references for constructing wind barriers in aeolian engineering.

1. Introduction

Wind erosion becomes a critical problem since it poses a significant threat to land degradation in arid and semi-arid regions. It lowers soil productivity (Larney et al., 1998), damages plants and constructions (Papesch, 1992) and even causes severe sandstorms (Alfaro et al., 2004). Wind erosion control aims to reduce surface wind velocity and increase soil resistance (Judd et al., 1996). The most effective management strategy to reduce surface wind velocity is to build windbreaks, including natural vegetative shelterbelts and artificial wind barriers (Skidmore and Hagen, 1977; Guan et al., 2003). However, in arid and semi-arid regions, limited water resources and unique soil texture cannot sustain large vegetative shelterbelt system such as forest (Wang and Takle, 1996). Due to their low cost and water demand, artificial wind barriers have been successfully used in aeolian engineering projects in order to reduce wind velocity and trap sand grains. For example, more than 400*km*-long upright wind barriers constructed along the highway across the shifting sand dunes in China's Taklimakan Desert, has greatly improved local climatic conditions and protected the highway from being buried by floating sand (Dong et al., 2007).

Theoretically, a wind barrier exerts a drag force to the airflow field, causing a net loss of momentum to create the shelter effect (Raine and Stevenson, 1977). A better understanding of the airflow field around wind barriers is essential to optimize wind barrier design. There have been extensive studies in optimizing wind barrier design, including field measurements (Grant and Nickling, 1998; Leenders et al., 2007; Mayaud et al., 2016; Gillies et al., 2017a; Çoşkun et al., 2017), wind-tunnel experiments (Dong et al., 2007; Guan et al., 2009; Zhang et al., 2015; McClure et al., 2017; Gillies et al., 2017b) and numerical simulations (Santiago et al., 2007; Li et al., 2007; Rosenfeld et al., 2010; Bitog et al., 2012; Liu et al., 2014; Lima et al., 2017). Field measurement is the traditional method to investigate wind flow characteristics around barriers (Hagen and Skidmore, 1971; Wilson, 1997) and conduct optimal designs by evaluating structural parameters (e.g., porosity and wind barrier height, Lin et al., 1984). However, field measurements are limited due to the uncertainties of wind conditions and measuring ranges (such as barrier heights and local wind velocities), thus cannot be used to quantitatively evaluate the shelter effects in larger-scale

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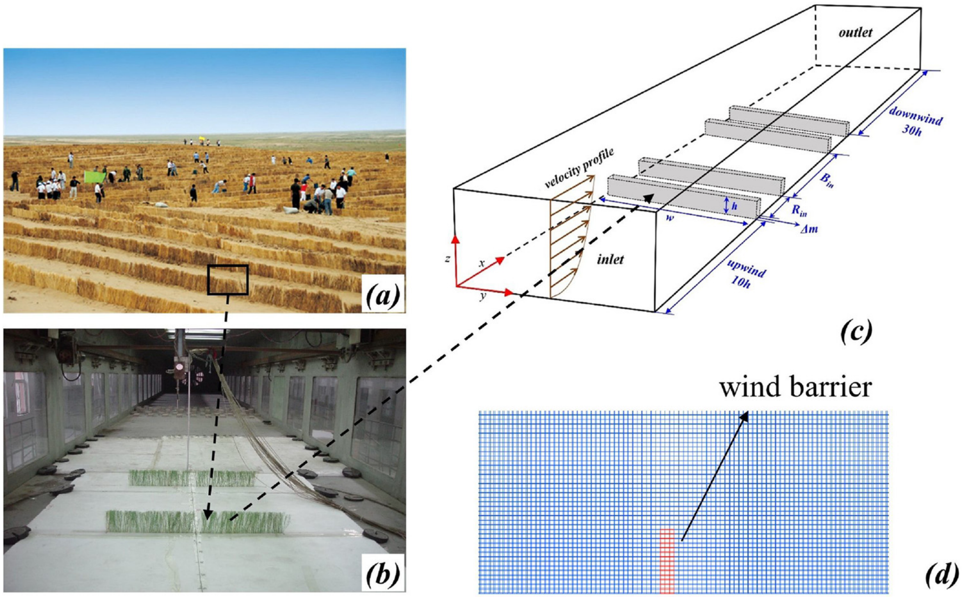

Fig. 1. From field practice to wind-tunnel experiments to numerical simulations: (*a*) actual wind barriers in the field; (*b*) downscaled wind-tunnel experiment based on the field practice; (*c*) the computational domain for CFD simulations adapted from the wind-tunnel experiment; (*d*) a zoomed-in view of the structured hexahedron mesh.

engineering applications. Wind-tunnel experiment provides an alternative way to quantitatively analyze airflow fields around wind barriers in a wide range of velocities. Previous wind-tunnel experiments have determined the optimal porosity and row number for wind barriers (Wooding et al., 1973; Guan et al., 2003; Wilson and Yee, 2003; Dong et al., 2007; Gillies et al., 2017b). However, wind-tunnel experiments are subject to the spatial size/range of the test section and the measuring resolution (both in time and space) of different technologies (such as hot-wire anemometer, particle-image velocimetry, etc., Guan et al., 2003; Dong et al., 2007).

To overcome the limitations of the above methods, numerical simulations using computational fluid dynamics (CFD) methods become more popular and have been extensively applied as they can efficiently and accurately predict the wind flow patterns with the presence of porous wind barriers. In CFD simulations, the computational domain can be set as large as needed; while wind velocities can be captured in any direction and resolution. There have been a series of CFD simulations trying to optimize wind barrier structural parameters (Patton et al., 1998; Kim and Lee, 2002; Liu et al., 2014; Lima et al., 2017). For example, Lima et al. (2017) conducted a comprehensive study on optimization of sand fences in a 2D domain and concluded that at least 4 rows of barriers are needed in realistic applications, however the simulation results were not compared to either field measurements or wind-tunnel experiments. To our best knowledge, most previous simulations were using 2D CFD models, which obviously cannot resolve detailed 3D turbulent flow characteristics. Lima et al. (2017) also highlighted the importance of 3D simulations and believed that it is certainly important to obtain more accurate results of flow patterns around wind barriers. In addition, most of these studies only investigated selected parameters, such as porosity and wind barrier height. In reality, wind velocity condition, row number, inter-row spacing and inter-belt spacing are also critical for optimal wind barrier design. In addition, it is important to validate the numerical models by comparing to the wind-tunnel experiments (Liu et al., 2014). In summary, it is important yet challenging to perform 3D numerical simulations using validated CFD models to systematically explore the optimal designs of wind barriers.

Optimal design of wind barriers aims to determine the optimal parameters by evaluating the shelter efficiency that considers both shelter effect and economic cost. Several indexes have been proposed by previous studies to quantify the shelter efficiency. Cornelis and Gabriels (2005) proposed a dimensionless reduction coefficient (R_c) to represent the wind velocity reduction degree at different locations, and then computed the average total reduction coefficient (TR_c). Dong et al. (2006) proposed the concept of effective shelter distance, within which the wind velocity was reduced below the threshold velocity. Another research by Dong et al. (2011) proposed the concept of shelter degree, which referred to the degree of required wind velocity reduction. They concluded that the optimal wind barrier design that provided the longest effective shelter distance was a function of the required shelter degree. We noticed that most previous studies evaluated the shelter efficiency only based on the shelter effect (wind velocity reduction). However, in aeolian engineering practices, wind barriers are constructed in multi-row and multi-belt arrangements, which are then constrained by the labor cost and construction materials expenses. Therefore, the economic cost should be considered when evaluating the shelter efficiency. The optimal wind barrier design should provide the longest effective distance at the minimal cost for different required shelter degrees. Lima et al. (2017) introduced a cost function to quantify the construction material expenses. However, an integrated index that considers effective distance, shelter degree and economic cost together hasn't been reported yet still needed to evaluate the wind barrier design.

In this study, to address the challenges raised in CFD simulations and shelter effect assessment, we performed a series of 3D numerical simulations to study the airflow fields around wind barriers with different systematical structural parameters including porosity, row number, inter-row spacing, and inter-belt spacing, then analyzed the shelter efficiency using a new index that considers both shelter and economic factors. It is also noted that the simulation setups were configured based on our previous sand-blown wind velocity statistics (Wu and Zou, 2011) and wind-tunnel experiments (Wu et al., 2013).

2. Method

2.1. Numerical simulation

2.1.1. Simulation setup

Fig. 1 showed the 3D computational domain configured following the same setup used in a previous wind-tunnel experiment (Wu et al., 2013) that downscaled realistic wind barriers in the field (Fig. 1a). Each row of the wind barriers was modeled as a thin porous zone (see Section 2.1.3 for the porous media model), perpendicular to the incoming velocity direction. Based on our previous wind-tunnel experiments

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