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Threshold velocity for wind erosion: the effects of porous fences

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Abstract Porous fence is a kind of artificial windbreak that has many practical applications. The threshold wind velocities at different distances downwind from porous fences were measured and the corresponding characteristics of particle movement observed to assess their shelter effect. It is found that the fence's porosity is the key factor that determines the resulting shelter effect. The area near a fence can be typically classified into five regions, each with a different mode of particle movement. Dense fences, and especially solid fences, favor the accumulation of sand upwind of the fences. Fences with porosities of 0.3–0.4 produce the maximum threshold wind velocity; those with porosities of 0.3–0.6 (depending on the fence height) provide the maximum effective shelter distance. It is confirmed that the fence porosities of 0.3–0.4 that have been proposed for practical application in previous research are the most effective for abating wind erosion.

Keywords Porous fences · Aeolian transport · Threshold wind velocity · Shelter effect

Introduction

Windbreaks have long been used throughout the world to control drifting sand and snow (Gandemer 1979). Fences provide a kind of artificial windbreak that offers a range of porosities (Guan et al. 2003). Windbreaks created by vegetation usually offer more nearly ideal erosion control because they have a width and internal structure that is lacking in most fences, but fences nonetheless have many practical applications because their use does not depend on natural conditions such as the availability of water and suitable soil (Lin et al. 1984; Qu et al. 1996; Lee and Kim 1999). For this reason, many studies have focused on the shelter effect provided by fences (Hagen and Skidmore 1971a; Seginer 1975; Raine and Stevenson 1977; Perera 1981; Hagen et al. 1981; Ranga raju et al. 1988; Richardson 1989; Papesch 1992; Lee and Kim 1999). Most previous studies have emphasized the mean velocity deficit and flow characteristics behind fences, and have especially examined the basic physics of the wake flow because surface-mounted vertical fences create complex flow patterns characterized by a high shear rate, a large pressure gradient, and high turbulence intensity in the wake region.

Perera (1981) found that the porosity of a fence was the design parameter that most strongly influenced the wake characteristics behind the fence. Various attempts have been made to define an optimum fence porosity for abating wind erosion by analyzing the reduction in mean velocity and in turbulent fluctuations behind fences (Hagen and Skidmore 1971b; Lee and Kim 1999). It was found that fences with porosities of 0.3–0.4 provide good flow characteristics for reducing wind erosion (Lin et al. 1984; Lee and Kim 1999). However, determination of the shelter effect by direct measurement of sand movement around fences has rarely been done. What is more, previous studies paid little attention to the shelter effect created upwind of the fence. For practical engineering purposes, the overall shelter effect of a fence should include both the upwind and downwind effects.

The threshold velocity (the minimum wind velocity required to initiate wind erosion) is a key variable in wind erosion (Bagnold 1941). All control measures reduce wind erosion by increasing the threshold wind velocity (Shao 2000). Therefore, the magnitude of the shelter effect provided by fences in terms of reducing wind erosion can be directly defined by measuring the effects of the fences on threshold velocity. It is for this purpose that fences with different porosity values are simulated in a wind tunnel: to measure the threshold wind velocity for wind erosion, describe the particle movement characteristics at the threshold, and estimate the effective shelter distance provided by the fence, all as a function of the characteristics (height and porosity) of the fence. In the present study, this data is used to propose an optimum fence porosity for controlling wind erosion.

Materials and methods

The experiments were performed in a blowing-sand wind tunnel at the Key Laboratory of Desert and Desertification of the Chinese Academy of Sciences. The blow-type non-circulating wind tunnel has a total length of 37.8 m, with a 16.2-m-long test section. The cross-sectional area of the test section is 0.6×1 m^2. The free-stream wind velocity in the wind tunnel can be adjusted from 1 to 40 m s^{-1}. The thickness of the boundary layer in the test section is 0.12 m.

Fence models were constructed from rigid stainless-metal wires 1.2 mm in diameter. Wires were cut into straight segments of the required length (height). The wire segments were then inserted in a row into a bed made of talcum powder paste contained in a wooden groove that was 1 m long (equal to the cross-sectional width of the wind tunnel) by 50 mm wide to create the fence (Fig. 1). The vertical wires were spaced at regular intervals, and the porosities of the fences were adjusted by changing the spacing between wire segments. A total of 33 fence models were created, with 3 heights (20, 40, and 80 mm) and 11 porosities (0.05, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, and 0.90). These porosity values were defined by subtracting the total width of the wires from the 1-m width of the fence, and expressing the result as a ratio of the width of fence. For each height, a solid fence (zero porosity) was also tested using a 1-m-long, 3-mm-thick piece of plywood. During testing, the fence models were positioned 12 m downwind from the start of the test section of the wind tunnel.

Well-rounded artificial quartz sands 0.1–0.2 mm in diameter were spread at different distances upwind or downwind from the fence to determine the threshold velocities at different locations. The wind tunnel floor was covered with the same grain-sized (as the tested sand sample) sandpaper to avoid accidental rolling of the well-rounded sand grains on the glossy floor. The distance relative to the fence model was measured as a multiple of fence height (Fig. 1).

The initiation of sand motion was determined visually because our experience has shown that under wind tunnel conditions, visual observation is a relatively reliable method for this form of analysis, even though other methods have been proposed (Dong et al. 2002). To minimize any errors in visual observation, we obtained three observations (by three persons) to obtain a mean value. For each combination of fence height and porosity, we adjusted the wind speed in the chamber until it reached the threshold velocity. Particle movement characteristics at the threshold condition were also recorded, together with the threshold wind velocity. The threshold wind velocity was measured at the centerline height (0.3 m above the tunnel floor) at the entrance of the test section using Pitot static tubes connected to a digital data-acquisition system. The data-acquisition rate was set at once per second. The final observed threshold wind velocity represented the average over 30 s (i.e., 30 records).

Results and discussion

Particle movement characteristics at the threshold velocity

The main effect of a fence results from its aerodynamic influence on surface airflow, resulting in changes in the mode and intensity of sand transport. Our observations reveal that there are three main modes of particle movement at the threshold velocity: forward movement (movement in the direction of the open-field wind), backward movement (movement in the opposite

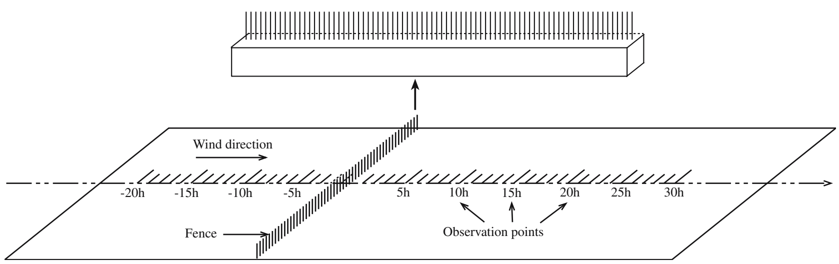

Fig. 1 Fence models and the layout of the measurement points in the wind tunnel. (Distances are expressed as multiples of *h*, the height of the fence being tested.)

direction to the open-field wind), and oscillating movement (alternating forward and backward movements). Figure 2 shows a typical pattern of particle movement in these three modes around a fence. In general, the area near a fence can be classified into five regions with different modes of particle movement. From upwind to downwind, these are: the first forward-movement region (A in Fig. 2), the first oscillating-movement region (B), the backward-movement region (C), the second oscillating -movement region (D), and the last forward-movement region (E).

The complexity of particle movement decreases as the fence porosity increases, and increases as the fence height increases. The classification of the near-fence area into different movement regions results from the creation of reverse flows that result in backward movement of particles. The oscillating region represents the transitional zone between forward movement and backward movement, and results from chaotic reversals of wind flow. The first oscillating region is a region of flow convergence that promotes sand accumulation, but the second oscillating region is a region of flow divergence that impedes sand accumulation. When the fence porosity was greater than 0.3 (for the 20-mm-tall and 40-mm-tall fences) or 0.4 (for the 80-mm-tall fences), the particle movement was relatively simple, with only a single forward-movement region. Lee and Kim's (1999) wind tunnel visualization of 40-mm-tall fences showed that there was no reverse flow behind the fence as a result of the strong ''bleed flow'' that passes through the gaps in the fence when the porosity was greater than 0.4. The Reynolds shear stress and turbulent kinetic energy were strong behind the fence when the porosity was less than 0.3, whereas the bleed flow was strong when the porosity was greater than 0.4. Their results agree well with the modes of particle movement observed in the present study. When the porosity was less than 0.1 (for the 20-mm-tall and 40-mm-tall fences) or 0.15 (for the 80-mm-tall fences), the first forward-movement region shrank to a zone upwind of the fence, and the first oscillating-movement region and the backward-movement region may shift upwind of the fence. When the porosity became less than 0.05, another backward-movement region develops just upwind of the fence due to the creation of an ''echo flow''. This explains the observed phenomena that sand accumulation often occurs upwind of dense fences, and especially upwind of solid fences, but usually occurs downwind (behind) the fence when the porosity is sufficiently high (Lin et al. 1984). Sand accumulation upwind of the fence will soon bury the fence and decrease its effectiveness. For this reason, dense fences (and particularly solid fences) are not used to control blowing sand. Lin et al.'s (1984) field test on the southeastern edge of China's Tengger Desert suggested that porosities of 0.3–0.4 should be used for fences 0.8 to 1.0 m tall to avoid sand accumulation upwind of the fence.

The relative threshold wind velocity

To compare the influence of fences on the threshold wind velocity, the measured threshold wind velocities were normalized to the dimensionless relative threshold wind velocity using the following equation:

$$U_{\mathrm{tr}} = \frac{U_{\mathrm{tf}}}{U_{t0}} \qquad (1)$$

where, U_{tr} is the dimensionless relative threshold wind velocity, U_{tf} is the threshold wind velocity as influenced by the fences, and U_{t0} is the threshold open-field wind velocity, which equaled 5.5 m s^{-1} for the tested sand sample.

Figure 3 shows the typical variation in the relative threshold wind velocity as a function of the distance from the fence, with negative distances representing locations upwind of the fence. The curves show similar trends for various values of fence porosity, with a peak value downwind from (behind) the fence. The peaks shift downwind as porosity increases, in agreement with Hagen and Skidmore's (1971b) field measurements, which showed that the position of the minimum wind speed moved increasingly downwind as windbreak porosity increased. Both the position of the minimum wind speed in Hagen and Skidmore's field measurements and that of the peak relative threshold wind velocity in the present study reveal the location of the best-sheltered point. Another peak with a much smaller value occurs

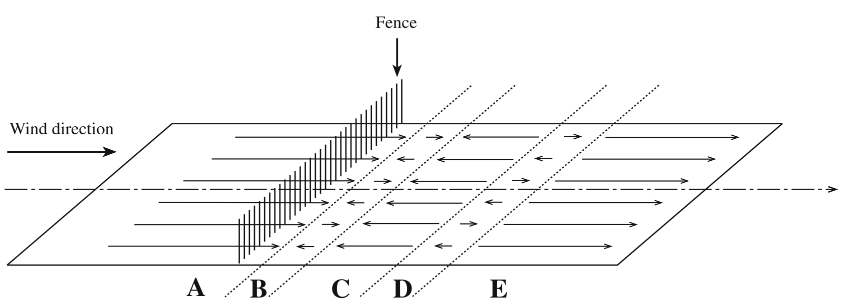

Fig. 2 Diagram of typical modes of particle movement near a fence. *A* The first forward-movement region, *B* The first oscillating-movement region, *C* The backward-movement region, *D* The second oscillating-movement region, *E* The last-forward movement region

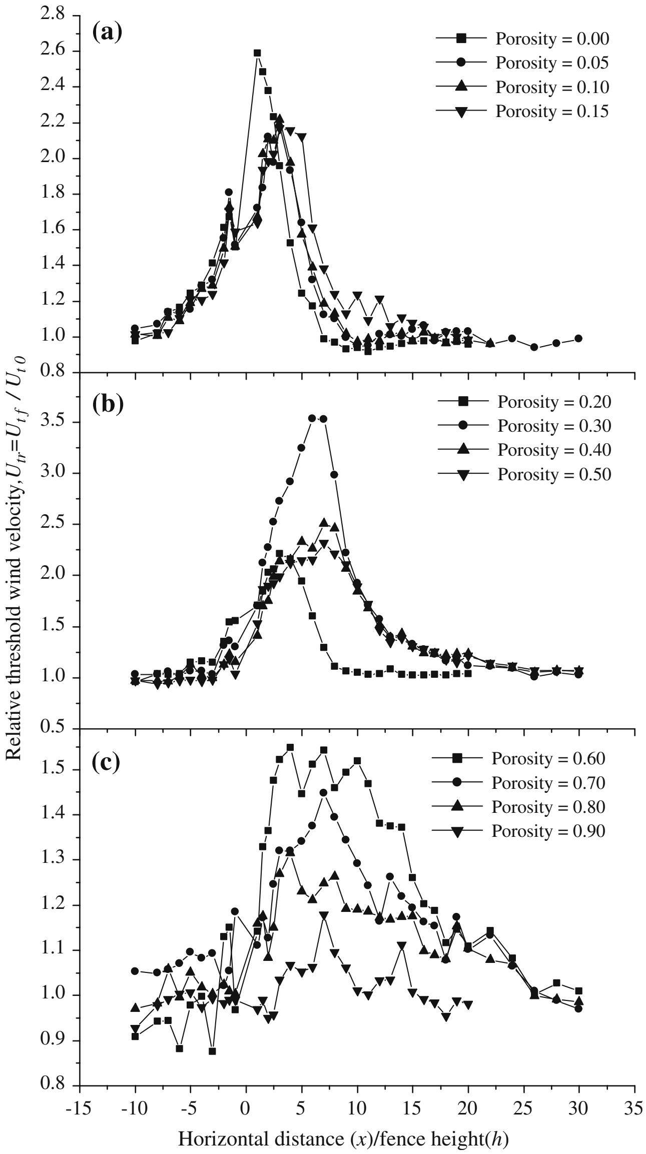

Fig. 3 Typical variation in the relative threshold wind velocity as a function of fence porosity and distance from the fence (40-mm-tall fences)

upwind of the fence when the porosity is less than 0.15. This is attributable to the upwind shift of the oscillating-movement region discussed in the previous section.

Except for the solid fences, the relative threshold wind velocity increases with increasing fence porosity until it reaches the maximum value at 0.3 (for the 20-mm-tall and 40-mm-tall fences) or 0.4 (for the 80-mm-tall fences), then decreases as porosity increases. In terms of the relative threshold wind velocity, the fences with a porosity of 0.3 or 0.4 provided the best shelter effect against wind erosion, which is in good agreement with the conclusions of previous research (Lin et al. 1984; Lee and Kim 1999).

Effective shelter distance

Assessment of the shelter effect of fences should consider not only the absolute reduction in wind velocity or increase in threshold wind velocity, but also the area or distance that is sheltered. Here, we introduce the concept of an "effective" shelter distance, which is defined as the distance within which the threshold wind velocity is greater than the open-field threshold wind velocity (i.e., the relative threshold wind velocity is greater than 1). However, due to the turbulent properties of airflow around a fence, the measured relative threshold wind velocities will fluctuate around a constant value. To provide a conservative estimate, we chose a relative threshold wind velocity of 1.1 to define the effective shelter distance.

Figure 4 shows the variation in the effective shelter distance as a function of fence porosity and height (*h*). The maximum effective shelter distance ranged between 26 and 33 *h*. Because the effective shelter distance is expressed in terms of fence height, the actual effective shelter distance increases with increasing fence height. For the three fence heights in our study, the relationship between effective shelter distance and porosity was similar: the effective shelter distance increases with increasing porosity until it reaches its maximum value, then decreases thereafter with increasing porosity. The maximum occurred at a porosity of 0.3 for the 20-mm-tall fence, between 0.3 and 0.5 for the 40-mm-tall fence, and between 0.4 and 0.6 for the 80-mm-tall fence. This conclusion is similar to that in Hagen and Skidmore's (1971b) field measurements: the windbreak with a porosity of 0.4 produced the lowest wind speed over the largest downwind area. From the viewpoint of effective shelter distance, fences with a porosity of 0.3–0.6 can

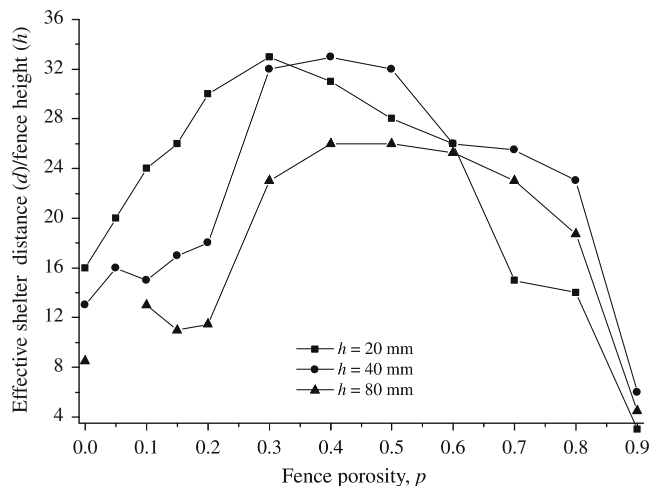

Fig. 4 Variation in the effective shelter distance as a function of fence porosity and height

provide the best shelter against wind erosion. These findings also suggest that the higher the fence, the greater the porosity required to provide the best shelter effect. The pattern of change in the effective shelter distance and relative threshold wind velocity as a function of porosity is clearly relevant. The greater the relative threshold wind velocity, the greater the effective shelter distance.

Conclusions

Fences with 3 heights and 11 porosities were simulated in a wind tunnel and the threshold wind velocity and movement characteristics of sand under threshold conditions were measured to assess the shelter effect provided by the fences.

As a result of reverse-flow phenomena, the area near a fence can be classified into several regions with different modes of particle movement under threshold conditions. The complexity of particle movement decreases as the fence porosity increases. Dense fences, and especially solid fences, promote sand accumulation upwind of the fence and are thus not suitable for controlling blowing sand.

Fences with porosities of 0.3–0.6 (depending on fence height) have the maximum threshold wind velocity and effective shelter distance, and are thus most suitable for controlling wind erosion. The shorter the fence, the lower the required porosity to provide the best shelter effect. These conclusions confirm the results of previous studies of the dependence of a fence's shelter effect on its porosity, and thus provide strong guidance for operational control of wind erosion.

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