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WIND TUNNEL EXPERIMENTS ON HOW A POROUS FENCE AFFECTS FLOW AND EROSION ON SAND DUNE

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ABSTRACT

For the purpose of combating desertification, it is important to understand mechanisms of the wind-blown sand movement, which is essentially a complicated two-phase flow phenomenon of sand particles and air. Therefore, we investigated the flow field around a model dune and the erosion process of the dune. In this study, we employed a porous fence, which was installed on the model dune, and examined its effect on the sand movement. The erosion process and its relationship with the turbulent intensity and the flow around the dune were discussed focusing on dependence of the flow field on the fence porosity. We tested four types of porous fences, which had different porosities: 0% (no permeability), 10%, 30%, and 50%. How a position of the fence affects suppression of the dune erosion was also examined. In the present experimental range, it can be concluded that the most effective fence position to suppress the sand movement should depend on porosity of the fence.

INTRODUCTION

Recently, it is commonly recognized that desertification has been accelerating and occurring worldwide. About 1/4 of the land in the earth is classified to desert area or desertification area, and its expansion is of about six million hectares annually. Therefore it is important to clarify the mechanism of the blown sand and how to control effectively the blown sand. There have been many studies on the wind-blown sand movements, and several comprehensive reviews provides some highlights of the progress in understanding of this subject: see, for instance, Shao [1] and Zheng [2]. For the same purpose, we have made the model dune, which simulated a typical shape of dune, in a wind tunnel and examined the sand movement by the wind.

The wind erosion is a process of wind-forced movement of soil particles on and above a ground surface. The pattern of the sand-particle transport can be classified into three types as saltation, suspension, and surface creep. They were defined by Bagnold [3] as follows: the ‘creep’ is a phenomenon where a sand particle moves with tumbling on the sand bed surface but without flying up into the air flow. The ‘saltation’ is that a sand particle flies up due to the shear force in the upward vertical direction by the wind and, after that, it falls again due to the gravity. Once it falls on the surface, the sand particle might hit other particles and flick them out. The ‘suspension’ is the suspending of very small particles within the wind-blown sand flow. These three types of the sand movement are determined by the diameter of sand particles and flow field conditions. Also a threshold of the air-flow velocity about sand movement was firstly introduced by Bagnold [3]. The velocity at which sufficient force is exerted to initiate motion of a sediment particle is called a ‘critical friction velocity’. Under the condition of a high critical friction velocity, the sand movement hardly occurs. Generally, sand particles begin to move under the condition of air-flow speed higher than the critical friction velocity. Shimazu et al. [4] had carried out experiments, in which the diameter of test sand grains, the moisture contained in the sand bed, and the turbulence statistics of air flows were measured. They clarified those effects on the critical friction velocity and revealed that, as the wall-normal velocity fluctuation increased, the sand particles moved by a low air-flow velocity corresponding to the decreased critical friction velocity. For the purpose of avoiding sand movements responsible for the sand-dune erosion (and the desertification), Kim & Patel [5] and Lee and co-workers [6-8] researched the effect of a wind fence, which was the same height of a relevant dune, on the wind erosion of the sand dune. However, such a fence is impractical because of the difficulty of dealing with an actual-scale size comparable to dunes in desert. Therefore, our group employed and tested a much smaller fence than the height of dune. The fence used by Sakamoto et al. [9] was of height of 1/4 or 1/8 of the relevant dune and was installed on an upstream surface of the dune. They investigated its effect on erosion of the dune and measured the flow field around the initial shape of the dune using laser-Doppler velocimetry (LDV) system, in order to discuss the relation between the flow field around the dune and the erosion process. It was found that the erosion was suppressed in the upstream of the fence, but enhanced in the downstream of the fence. Hence, the dune was deformed to be trapezoidal shape, and its surface became roughly parallel to the shear layer leaving from the top of the fence, where the turbulence intensity was high. Their fence was without permeability and thereby produced the strong shear layer. Therefore, it can be expected that the use of a porous fence should be more effective manner for avoiding the erosion without inducing the shear layer.

In the present work, we employed a porous fence and examined its effectiveness on controlling the sand movement. The relation between the flow field around the dune and the erosion process was discussed focusing on its dependence on the porosity rate of the fence. The air-flow velocity distribution was measured using a two-component LDV. The erosion process of the dune was observed by a laser-sheet visualization method. We tested four types of porous fences, which had different porosities: 0% (no permeability), 10%, 30%, and 50%. The details of the experimental setup and techniques used are to be found in the next section.

EXPERIMENTAL APPARATUS AND METHOD

Figure 1 shows the outline of the wind tunnel used in the present experiment. The blower and rectification part was of 2910 mm long, and its internal dimension at the outlet was 250 × 250 mm^2. The maximum air velocity was 20 m/s, and its minimum relative turbulence intensity was 0.05%. The developing section was 1000 mm long, and the test section was 2000 mm long. The spanwise width of each section was 250 mm, and the upper surface of both sections was movable. Turbulent intensity and scale can be modified by changing the

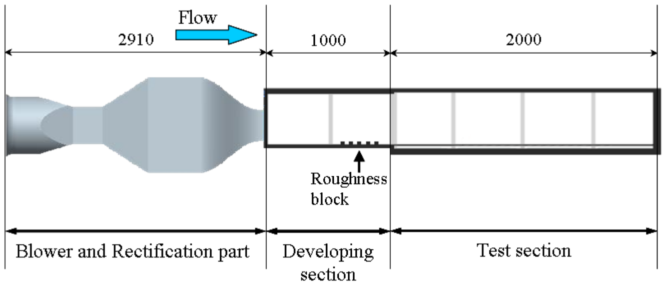


Fig. 1: Experimental setup: wind tunnel.

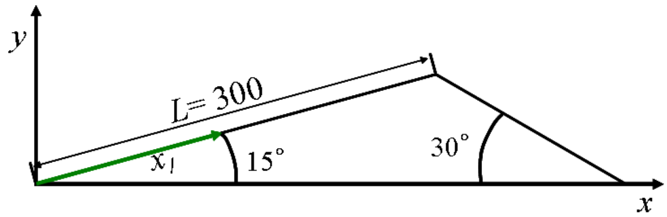


Fig. 2: Schematic diagram of the model dune.

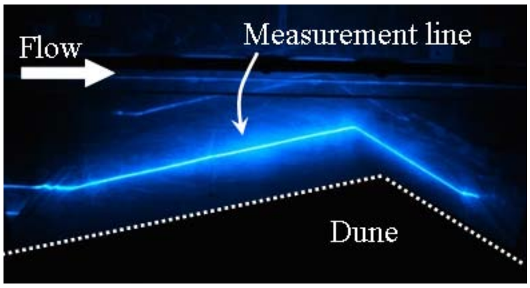


Fig. 3: Sand dune irradiated by laser-sheet.

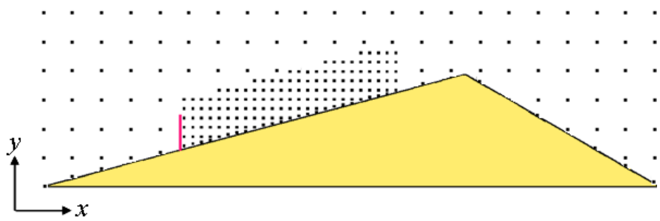


Fig. 4: Measurement points for flow field by LDV.

height and spacing of roughness blocks placed on the bottom plate of the developing section. The test section was equipped with measuring windows for illuminating laser beams and for taking pictures.

A model dune was installed at 500 mm downstream from the entrance of the test section. The upstream-side slope of the model dune was set to be 300 mm long, and its height was h = 80 mm, as shown in Fig. 2. The coordinate along the slope is referred as x_l. This shape imitated a typical dune shape observed in desert areas. For observation of sand deposition and erosion, a model dune made of sand was prepared. The mean sand-particle diameter was 115 μm, which is categorized into the saltation type of sand movement under the present range of wind velocity. The shape of the dune surface was

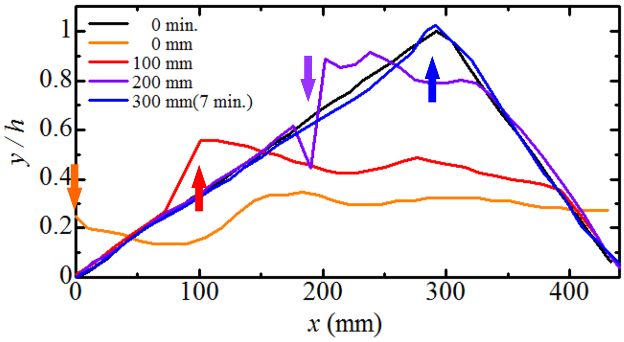


Fig. 5: Dune shape eroded by the air flow at 10 minutes after starting of the flow: $\varepsilon = 0\%$. Vectors show fence positions.

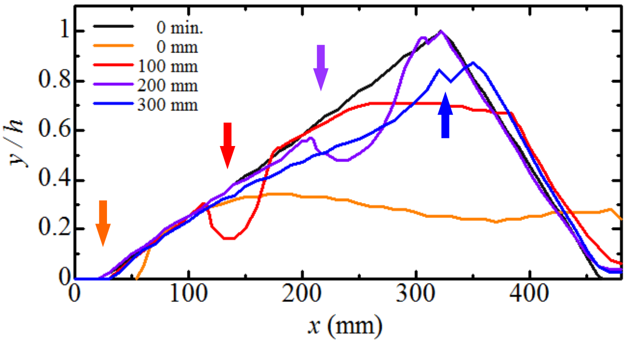


Fig. 7: Same as Fig. 5 but for $\varepsilon = 30\%$.

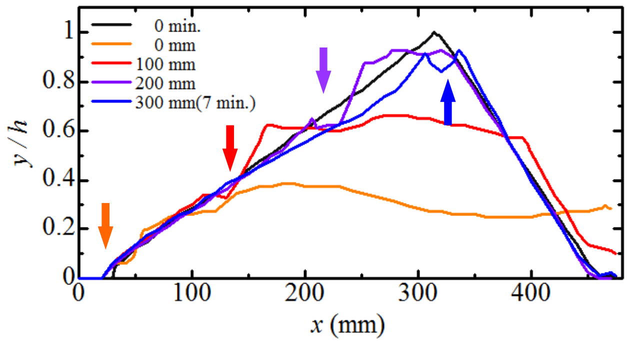


Fig. 6: Same as Fig. 5 but for $\varepsilon = 10\%$.

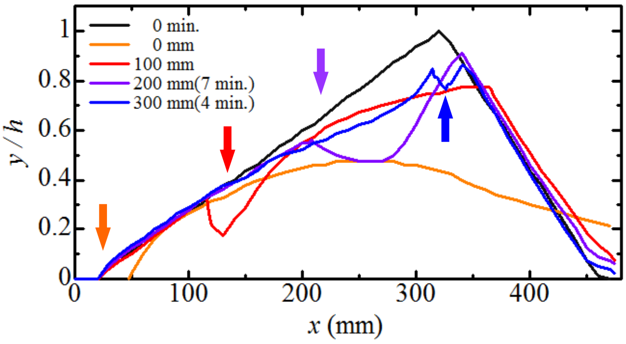


Fig. 8: Same as Fig. 5 but for $\varepsilon = 50\%$.

measured by laser-sheet visualization technique, through which the model dune was irradiated so that the measurement points can be detected as shown in Fig. 3. On the other hand, it was necessary to prepare a non-erosive model dune (made of metallic) to measure the flow field around the dune because the temporal change in the dune shape by the wind-brown sand movement. To measure the flow field, a two-component fiber-optic LDV system (Dantec dynamics, Co.) was used. The LDV probe was set up on a two-dimensional traverse device. The LDV measurement was done only in the metallic model dune. It should be noted that, when we measured flow fields around the dune, we employed the metallic model dune without using sand. There was no influence of suspended sand particles during measurement, while oil mist was applied as tracer particles for the LDV measurement. The measurement points are shown in Fig. 4, where a fence is located at x_l = 100 mm. Their interval was set to be 6 mm in the region close behind the fence and 20 mm in other areas.

The height, width and thickness of the fence were 20 mm, 249 mm and 1 mm, respectively. This height is of 1/4 of the model dune. We tested four types of porous fences, which had different porosities: $\varepsilon = 0\%$ (no permeability), 10%, 30%, and 50%. The porosity rate was defined based on the area ratio of the pore of the fence. The porosity rates and the pore diameters of the fences we used are listed in Table 1. Either one was installed at x_l = 0, 100, 200, or 300 mm on the upstream surface of the dune. The approaching mean air velocity was fixed at 7.1 m/s.

Table 1: Specification of porous fence

Porosity ε	Pore diameter d	Pitch p
10%	1.8 mm	5.0 mm
30%	3.1 mm	
50%	4.0 mm	

RESULT AND DISCUSSION

1. DUNE EROSION

In this section, we will discuss the erosion of dune with emphasis on the effect of an installed porous fence on the dune surface at x_l = 0, 100, 200 or 300 mm. Also, the dependence of surface deformation on the porosity rate will be examined.

Figures 5-8 show the shapes of dune surface at 10 minutes after the air flow was started for each condition of the experiments. The results for the porosity rate ε of 0% are given in Fig. 5, and those for 10%, 30%, and 50% are in Figs. 6-8, respectively. Note that the horizontal axis (x) in the figure denotes the distance from the dune foot in upstream side. The vertical axis is local height of a dune surface normalized by the height of the initial dune. The initial condition (at 0 min.) is given in a black solid line. When the fence located at x_l = 0 mm, the shape of the model dune had been deformed as given

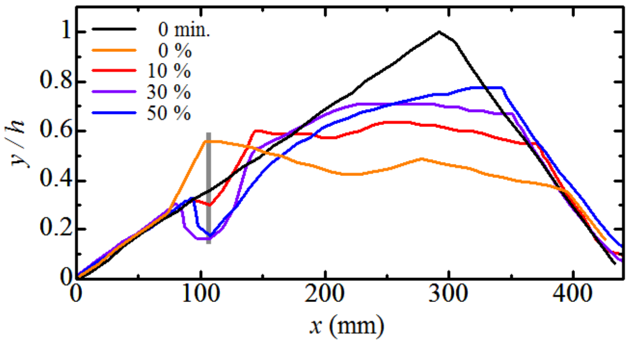


Fig. 9: Dune shape eroded by the air flow at 10 minutes after starting of the flow: x_l = 100 mm.

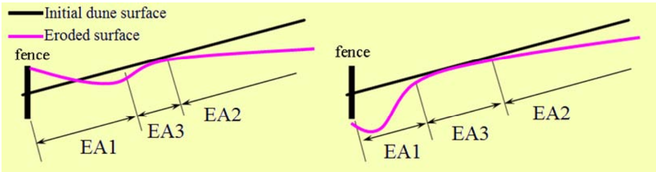
by an orange line in each figure. Note that each line color represents a different condition. Vectors show fence locations in each figure. It can be seen from the figures that, when a fence was installed near the foot of the dune, the erosion was gradually suppressed with the increase of the porosity rate. On the other hand, when the porosity was low, a fence near the top of dune was effective to suppress the erosion. Therefore, in the present experimental range, it can be conjectured that the most effective fence position for suppression of the sand-movement depends on porosity of the fence.

The erosive process with the fence located at x_l = 100 mm is shown in Fig. 9. Also shown by a gray line is the fence position at x_l = 100 mm. It is found that a localized erosion rather than the sedimentation close behind the fence became remarkable as the porosity rate was increased. However, the dune with such a high porosity-rate fence can avoid severe erosion around its top, where the dune surface should be subjected to intensive erosion in the case of non-porosity.

It can be supposed that there should occur two intensive-erosion regions in the downstream of the fence: the first one is the vicinity of the fence, where the amount of erosion depends on the porosity rate; the second is around the top of the dune, where the erosion is rather gentle. Although these regions are located side-by-side, there exists a non-eroded point between them. This feature is schematically illustrated in Fig. 10. Here, a black and a purple lines represent the initial dune shape and an eroded surface behind the fence, respectively. The intensive erosion region behind the fence is labeled as erosion area 1 (EA1), while the other erosion region in the downstream of EA1 is as EA2. The area between EA1 and EA2 is called EA3. To consider the difference of these erosive magnitudes, the flow field around the initial shape of the model dune will be discussed in the following section.

2. FLOW FIELD AROUND MODEL DUNE

We measured the flow field around the initial shape of the model dune using LDV, as given in Figs. 11 and 12. Figure 11 shows the velocity vectors around the fence of the porosity rate ε = 0%. The vectors for ε = 10-50% are shown in Fig. 12. The yellow part in the figures shows the initial shape of the model dune. In the case of the porosity rate 0%, it can be confirmed that a large reverse-flow region has been generated in the downstream corner of the fence. This region was extended to about 60mm away from the fence. On the other hand, when a porous fence was applied, the favorable flow toward the dune top existed there because some air flow passed the fence. Although the flow field for ε = 10% was almost similar to that for ε = 0%, the size of the reverse-flow region was slightly decreased. This is because the difference of the velocities between air-flow over the fence and flow through it. The reverse-flow region was not clearly observed in the porosity rate 30%.



(a) ε = 0% (b) ε = 30%

Fig. 10: Diagrammatic illustration of fence, sand bank and eroded surface of sand dune.

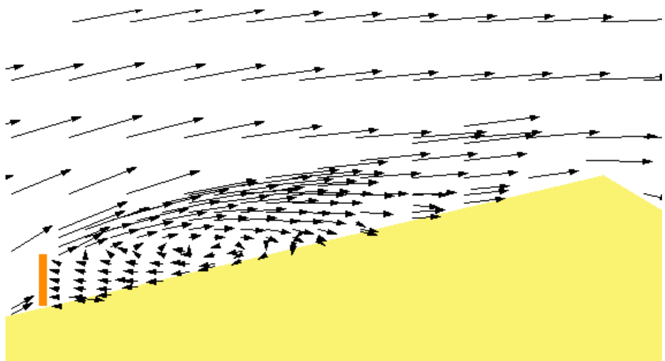


Fig.11: Mean velocity vectors around the non-erosive model dune: black vector, ε = 0% at x_l = 100 mm.

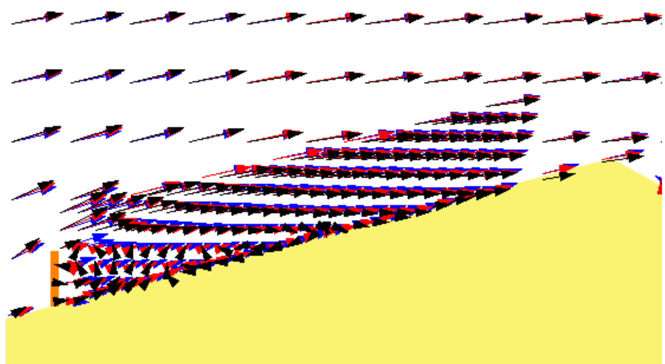


Fig. 12: Mean velocity vectors around the non-erosive model dune: black vector, ε = 10%; red, ε = 30%; blue, ε = 50% at x_l = 100 mm.

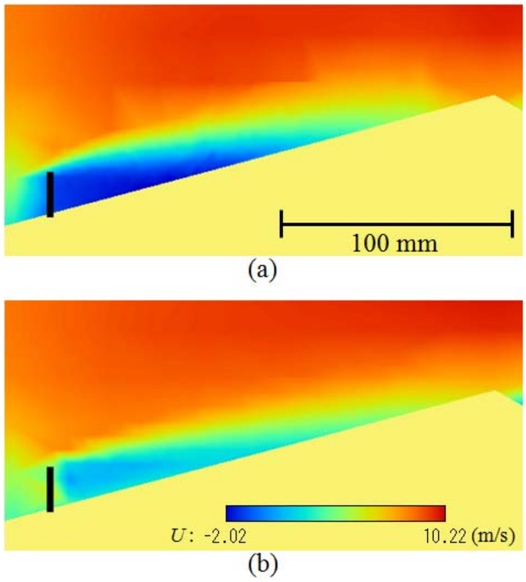


Fig. 13: Contour of the mean streamwise velocity in the downstream of the fence at x_l = 100 mm: (a) ε = 0%, (b) ε = 30%.

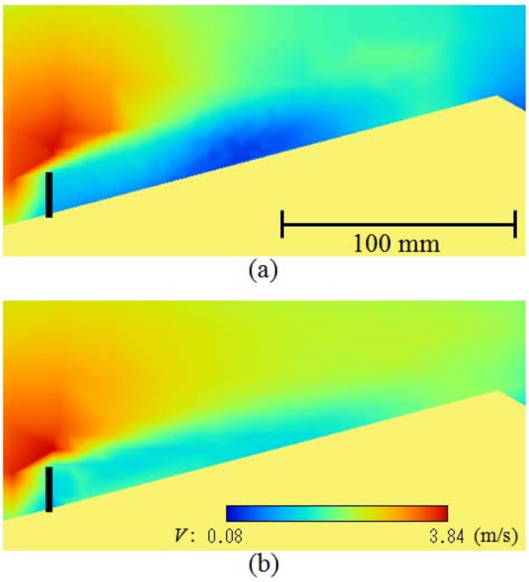


Fig. 14: Same as Fig. 13, but for the vertical velocity.

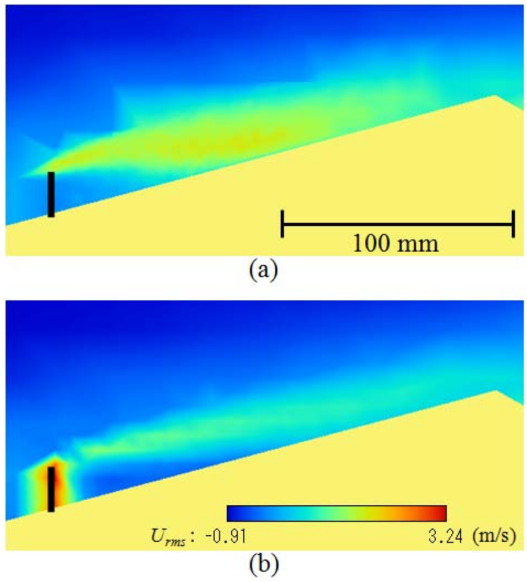


Fig. 15: Contour of the RMS value of the streamwise velocity fluctuation in the downstream of the fence at x_l = 100 mm: (a) ε = 0%, (b) ε = 30%.

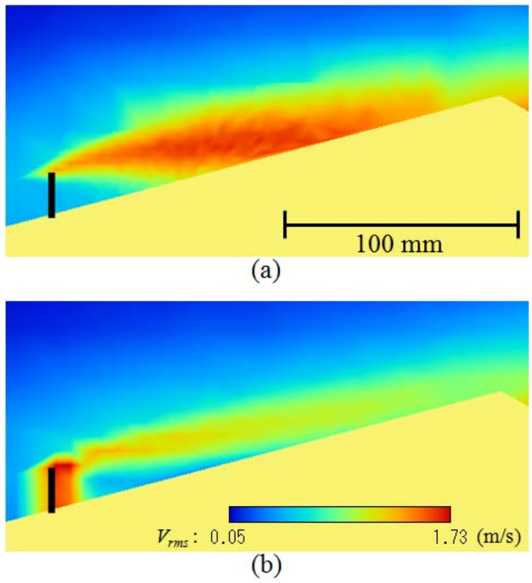


Fig. 16: Same as Fig. 15, but for the vertical component.

Figures 13 and 14 show the distribution of the mean streamwise velocity and that of the vertical component, respectively. In each figure, the results for the non-porous fence (ε = 0%) at x_l = 100 mm and for the porous fence of ε = 30%, the position of which is indicated by a black line, are presented. It is clear from Fig. 13(a) that a negative-U region behind the downstream corner of the fence occurs and it can be interpreted as the reverse-flow region. When the porosity rate was less than ε = 10% (figure not shown here except for ε = 30%), the magnitude of U in the reverse-flow region was decreased. This means that the flow over or through the fence should be straightened along the dune surface. This is consistent with the distribution of V, which reveals that the upward flow along the dune surface is increased slightly for ε = 30% (see Fig. 14).

Figures 15 and 16 show the root-mean-square (RMS) values (U_{rms}, V_{rms}), i.e., the turbulent intensities. In the same conditions of the fence, the distributions of U_{rms} and V_{rms} are similar (but not identical). Both turbulent intensities are found to be increased in the shear layer evolving from the edge of the fence. The RMS values and the thickness of the shear layer for the non-porous fence were remarkably large compared to those for the porous one. It should be also noted that there existed a calm region just behind the fence. For the non-porous fence, the streamwise length of the calm region was expanded and thereby the turbulent intensities on the dune surface were much weaker. As mentioned in the introduction, Shimazu et al. (2008) proposed an empirical equation of the critical friction velocity (U_{ct}), concerning the influence of the turbulent intensity on sand movements, as follows:

$$U_{ct} \propto U_{rms}{}^{-1} V_{rms}{}^{-1.2} . \quad (1)$$

This relation implies that the vertical velocity fluctuations should be more influential on sand movements rather than the streamwise component. Once the vertical fluctuation increases, the sand particle easily moves. In general, the sand particle starts to move under the flow condition of the higher velocity than the critical friction velocity. With a strong turbulent intensity, the critical friction velocity becomes slow. According to this basic finding, the porous fence can suppress turbulent fluctuations in the shear layer and produce much less erosion. With the fence of 50% porosity (figure not shown here), the deceleration behind the fence becomes less remarkable, and the turbulent intensities are larger than those for the 30% porosity. Hence, in the present conditions, the porosity rate of 30% is optimum for avoiding erosion.

CONCLUSION

We carried out the wind-tunnel experiments of the sand-dune erosion and investigated the surrounding flow field around the dune with a porous fence. We found that a fence at the foot of the dune had an effect on the reduction of erosion if the porosity was high. On the other hand, when the porosity was low, a fence near the top of dune was effective to suppress the erosion.

When a fence of low porosity rate (~10%) was applied, a large velocity difference between the main flow and the flow through the porous fence gave rise to a strong shear layer, in which the turbulent intensities were very high. For the porosity of 30%, the reverse flow disappeared and the fence had the effect of decreasing the velocity behind the fence, while the turbulent intensities downstream of the fence were significantly diminished. With a fence of 50% porosity, the deceleration behind the fence was less remarkable, and turbulent intensities became larger than those for the 30% porosity. In the present experimental range, it can be concluded that the most effective fence position to suppress the sand-movement depends on porosity of the fence and that the porosity rate of 30% should be optimum to avoid erosion.

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