Modeling the Inhibition Effect of Straw Checkerboard Barriers on Wind-blown Sand

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Abstract

Straw checkerboard barriers (SCBs) are usually laid to prevent or delay desertification caused by aeolian sand erosion in arid and semiarid regions. Understanding the impact of SCBs and their laying length on aeolian sand erosion is of great significance to reduce damage and laying costs. In this study, a three-dimensional wind-blown sand model in the presence of SCBs was established by introducing the splash process and equivalent sand barriers into a large-eddy simulation airflow. From this model, the inhibition effect of SCBs on wind-blown sand was studied qualitatively, and the sensitivity of aeolian sand erosion to the laying length was investigated. The results showed that the decrease in the wind speed in the SCB area oscillates along the flow direction. Moreover, the longer the laying lengths are, the lower the wind speed and the sand transport rate in the stable stage behind SCBs will be. We further found that

the concentration of sand particles near the side of SCBs is higher than that in its central region, which is qualitatively consistent with previous research. Our results also indicated that whether the wind speed will decrease below the impact threshold or the fluid threshold is the key factor affecting whether sand particles can penetrate the SCBs and form stable wind-blown sand behind the SCBs under the same conditions. Although our model does not include the collision between sand particles and SCB walls, which makes the suppression of wind-blown sand by SCBs obtained from the current model conservative, our research still provides theoretical support for the minimum laying length of SCBs in anti-desertification projects. ~~Our research provides theoretical support for the minimum laying length of SCBs in anti-desertification projects.~~

1. Introduction

In arid and semiarid areas, aeolian sand erosion is becoming increasingly serious. Preventing or delaying the process of desertification is a major challenge worldwide, especially in the transitional areas between deserts and oases. At present, shelterbelts (Wang et al., 2010), sand fences (Bitog et al., 2009; Hatanaka and Hotta, 1997; Li and Sherman (2015); Lima et al., 2017; Pye and Tsoar, 2008; Wilson, 2004), wind-break walls (Bouvet et al., 2006; Santiago et al., 2007), hole plate-type sand barriers (Chen et al., 2019) and straw checkerboard sand barriers (Bo et al., 2015; Huang et al., 2013; Wang and Zheng, 2002; Xu et al., 2018) are the main structures used to prevent desertification. Among these structures, straw checkerboard barriers (SCBs) are the most commonly used in anti-desertification projects because of their advantages of

being easy to obtain and relatively low cost (Zheng, 2009). Laying SCBs could play

an important role in the ecological restoration of sandy land ecosystems (Zhang et al.,

2018) and vegetation restoration. Some research has shown that SCBs can effectively

reduce the surface wind speed (Qu et al., 2007), increase the surface roughness

(Zhang et al., 2016), weaken the sand transport rate (Bo et al., 2015), and change the

distribution of aeolian sandy soil particles and soil organic carbon (Dai et al., 2019),

thus protecting the survival of vegetation and achieving sustainable development of

oases and ecological environments.

In recent decades, SCBs have been widely used in Northwest China, which is

seriously damaged by aeolian sand erosion. For example, SCBs have been laid on the

sides of roadbeds along railways such as the Baotou-Lanzhou Railway, Wuda-Jilantai

Railway (Wang, 1996), Gantang-Wuwei Railway (Yang, 1995), Lanzhou-Xinjiang

Railway (Binwen et al., 1998; Cheng et al., 2016), and Qinghai-Tibet Railway (Cheng

and Xue, 2014; Zhang et al., 2010), as well as in windy sand areas beside desert roads

such as the Taklamakan Desert Highway (Li et al., 2006; Qu et al., 2007), Tarim

Desert Highway (Xu et al., 1998) and Minqin Desert Highway. In addition, SCBs are

adopted by some countries that are also affected by aeolian sand erosion, such as

Ghana, Egypt, and Iran (Zheng, 2009). Although SCBs have been widely used, their

design size and laying methods are mainly determined by practical experience or

repeated tests. For example, for the sand fence, which has a similar effect to the SCB,

Li and Sherman (2015) combined experimental and field data to conclude that the

optimal design of a sand fence is closely related to its aerodynamics and

morphodynamics. The effect of sand fences with different porosities, spacings and

heights on the wind field is significant (Lima et al., 2017; Lima et al., 2020). However,

the complexity of the flow field around the SCBs and the movement of sand particles,

as well as the coupling of particles and flow field, make this problem more difficult.

Therefore, it is necessary to study the characteristics of turbulence inside and behind

the SCBs as well as the influence mechanism of the laying length on wind speed and

erosion.

Wang and Zheng (2002) proposed an ideal single-row uniformly distributed

vortex model to simplify the flow field of wind-blown sand. Based on their model, the

corresponding relationship between the side length and the height of a single SCB

was analysed. Their theoretical results are similar to the size of the SCBs laid in the

Tarim Desert Highway (1 m in side length and 15-20 cm in height). Qiu et al. (2004)

noted that since the concentration of wind-blown sand below 10 cm near the surface is

relatively high, the height of the SCBs should be designed to be 10-20 cm to

effectively prevent aeolian sand erosion. The experimental results of Zhang et al.

(2018) indicated that the SCB has the best protective effect when its side length is 1 m.

These works are of great help to the design of a single SCB. Based on these empirical

sizes of the SCBs, researchers have tried to analyse the effect of SCBs on the flow

field and particles from the perspective of turbulence. Huang et al. (2013) used a

two-dimensional large eddy simulation and discrete particle tracking methods to

simulate wind-blown sand movement inside simplified two-dimensional SCBs. The

effect of SCBs on surface wind speed was analysed. They found that sand particles

90   could be aggregated at the inner walls of the SCBs due to the influence of the vortex

91   or the backflow. Then, a V-shaped sand trough was formed, which is similar to the

92   actual situation. Bo et al. (2015) equated the SCBs to the source term of the standard

93   k-ε turbulence model and analysed the influence of SCBs on the wind speed profile in

94   a two-dimensional flow field without sand particles. They divided the streamwise

95   velocity profile in a flow field containing SCBs into approximately three different

96   log-linear functions and obtained the relationship between them and friction wind

97   speeds. Although these two-dimensional models can reflect the effect of the SCBs on

98   the flow field to some extent, they are far from the real turbulence. Moreover, since

99   the three-dimensional SCB is simplified into a two-dimensional plane with only the

100   streamwise direction and vertical direction, the impact of this simplification is

101   uncertain. For this reason, Xu et al. (2018) simulated wind-blown sand movement on

102   the SCB surface under a three-dimensional flow field using OpenFOAM and mainly

103   analysed the influence of the flow field inside the SCBs on the movement of sand

104   particles. They concluded that the wind vortex is the main cause of the internal

105   morphology of the straw checkerboard. They found that the vortex drives particles

106   inside the SCBs towards the front and sidewalls, making the erosional form in SCB

107   cells low in the middle and high near all sides. However, the SCBs are completely

108   equivalent to the solid as the bottom boundary condition in their model. As a nonsolid

109   material, SCBs can be penetrated by wind in practice. It only weakens the wind speed

110   and is thus not equivalent to a solid. For example, Dupont et al. (2014) equated

111   surface vegetation to a resistance force through the resistance coefficient and leaf area

112 coefficient, that is, the wind will be resisted as it passes through these equivalent

113 regions.

114   To reasonably introduce the SCBs and consider their coupling with turbulence,

115 SCBs and the surface splash process, the development of a three-dimensional model

116 is needed. In this paper, a three-dimensional numerical coupled model of wind-blown

117 sand in the presence of SCBs was carried out to study the inhibition effect of the

118 laying length on aeolian sand erosion. The large eddy simulation approach was used

119 to simulate clean air flow with the saltation process. Furthermore, we added a volume

120 drag force into the Navier-Stokes equations by using the drag source method to realize

121 the coupling between the SCBs and the wind-blown sand movement. Section 2 and

122 Section 3 present the three-dimensional numerical coupled model and its validation,

123 respectively. In Section 4, the effects of the SCB laying length on clean air flow and

124 sand-laden flow under different friction wind speeds are studied. Finally, Section 5

125 summarizes the main conclusions.

126 **2. Models**

127   The Advanced Regional Prediction System (ARPS) has been widely used to

128 simulate turbulent boundary-layer particle-laden flow, such as wind-blown sand

129 (Dupont et al., 2013; Huang, 2020) and wind-blown snow (Huang and Wang, 2016; Li

130 et al., 2018). The standard version of the program is described in the ARPS User's

131 Manual (Xue et al., 1995), and its validation cases are referred to Xue et al. (2000)

132 and Xue et al. (2001). For this study, some suitable models were added to simulate

133   turbulent boundary-layer flow in the presence of SCBs with saltating sand particles. A

134   detailed description of these modifications is shown in the following subsections.

135   **2.1 Turbulent boundary-layer flow**

136   The basic flow fields in our numerical simulation are established based on ARPS

137   (version 5.3.4). The filtered continuity and momentum equations, including the

138   viscous drag force terms of sand particles as well as SCBs, are shown as follows

139   (Dupont et al., 2013; Vinkovic et al., 2006):

140   $$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\overline{\rho}_f} \frac{\partial}{\partial x_i} (\tilde{p} - v \frac{\partial \overline{\rho}_f \tilde{u}_j}{\partial x_j}) - \frac{\partial \tau_{ij}}{\partial x_j} - \delta_{i3} g (\frac{\tilde{\theta}}{\overline{\theta}} - \frac{c_p}{c_v} \frac{\tilde{p}}{\overline{p}}) + \frac{F_i}{\overline{\rho}_f},$$ (1)

141   where $i = 1, 2$ and 3 correspond to the streamwise, spanwise and wall-normal

142   directions (i.e., $x_1 = x$, $x_2 = y$, $x_3 = z$, $u_1 = u$, $u_2 = v$, $u_3 = w$), respectively; $\tilde{u}_i$, $\tilde{p}$ and

143   $\tilde{\theta}$ represent the filtered wind speed, pressure and potential temperature, respectively; v

144   is a damping coefficient of the attenuate acoustic waves; ρ_f is the air density; g is the

145   acceleration of gravity; $F_i = F_{pi} + F_{di}$ is the main feedback force, including the

146   feedback force provided by sand particles (F_{pi}, as shown in Section 2.2) and the SCBs

147   (F_{di}, as shown in Section 2.5); $\delta_{ij} = 1$ if $i = j$, otherwise $\delta_{ij} = 0$; $\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$ are the

148   SGS (sub-grid-scale) stresses (Smagorinsky, 1963); c_p and c_v are the specific heat of

149   air at constant pressure and volume, respectively.

150   To solve above equations, the SGS stresses can be closed as follows:

151   $$\tau_{ij} - \frac{1}{3} \tau_{kk} \delta_{ij} = -(C_{sgs}\Delta)^2 \frac{1}{\sqrt{2}} \left| \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right| (\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}),$$ (2)

152   where Δ is the grid scale; C_{sgs} depends on the Germano subgrid-scale closure

153   method (Germano et al., 1991).

154   For the governing equations mentioned above, periodic boundary conditions are

155   applied for the spanwise direction. The upper and lower boundaries are set as a

156   stress-free condition and a rigid ground condition, respectively. The outlet boundary is

157   used as an open radiation condition in this paper. The inlet boundary is a given

158   logarithmic profile:

159    $$\tilde{u}(0, y, z) = (\frac{u_*}{\kappa})\ln(\frac{z}{z_0}). \tag{3}$$

160   Here k=0.41 is von Kármán constant; $z_0=d_{mean}/30$ is the aerodynamic surface

161   roughness (Kok et al., 2012), and d_{mean} is the mean diameter of the sand particles; u_*

162   is the friction speed of inflow. Additionally, the simulation is driven by a constant

163   flow corresponding to the given logarithmic wind profile. To accelerate the

164   development of boundary layer flow, the LWS method (Lund et al., 1998) is applied

165   to the inlet condition and the recycling plane at x_{ref}/Lx=12.5% (Inoue and Pullin,

166   2011). x_{ref} =5 m is the position of the recycling plane, and Lx=40 m is the total length

167   of the flow direction. The specific method reassigns the calculated mean velocity and

168   fluctuation at the recycling plane to the inlet at each fluid time step. A similar

169   application is described by Xu et al. (2018).

170   **2.2 Movement of the sand particles**

171   Saltating particles are moved by the drag force, gravity, electric field force,

172   Magnus force, Saffman force and so on (Murphy and Hooshiari, 1982). In our model,

173   the drag force and gravity are considered, ignoring other minor factors (Kok et al.,

174   2012; Zou et al., 2007). We employ the Lagrangian point-particle method to describe

175 particle motions, and the equations of particles with different sizes in three directions

176 can be expressed as

177 $$m_p \frac{d^2 x}{dt^2} = F_{px} = \frac{C_D \pi D^2 \rho_f}{8}(\tilde{u} - \frac{dx}{dt})^2 + F_{nx} + F_{sx},$$ (4)

178 $$m_p \frac{d^2 y}{dt^2} = F_{py} = \frac{C_D \pi D^2 \rho_f}{8}(\tilde{v} - \frac{dy}{dt})^2 + F_{ny} + F_{sy},$$ (5)

179 $$m_p \frac{d^2 z}{dt^2} = F_{pz} = -\frac{\pi g \rho_p D^3}{6} + \frac{C_D \pi D^2 \rho_f}{8}(\tilde{w} - \frac{dz}{dt})^2 + F_{nz} + F_{sz},$$ (6)

180 where m_p is the mass of sand particles; $C_D = (0.63 + 4.8/\mathrm{Re}_p^{0.5})^2$ is the drag coefficient

181 of sand particles (Cheng, 1997). The particle Reynolds number can be expressed as

182 $$\mathrm{Re}_p = (V_f \rho_p D / \mu)[(\tilde{u} - dx/dt)^2 + (\tilde{v} - dy/dt)^2 + (\tilde{w} - dz/dt)^2]^{1/2}.$$ (7)

183 ρ_p and ρ_f are the density of sand particles and air, respectively; D is the diameter of

184 sand particles; $V_f = 1 - \sum_{k=1}^{k=n} V_P / \Delta V$ is the bulk fraction which is the total sand volumes

185 within grid to the bulk of unit grid; ΔV is the bulk of unit grid; μ is the kinetic

186 viscosity coefficient of air; F_{nx}, F_{sx}, F_{ny}, F_{sy}, F_{nz} and F_{sz} are the normal and tangential

187 force of contact in three directions.

188 **2.3 Particle collision**

189 Modeling the collision process in the air among the ejection particles has been

190 the focus of previous studies (Carneiro et al., 2013; Huang et al., 2007). In this paper,

191 the "spring-damping model" is used to calculate the contact force when particles

192 collide in the air. The contact force can be described as follows (Huang et al., 2017):

193 The normal force of contact is

194
$$\vec{F}_{n,ij} = \begin{cases} -k_n \zeta_{n,ij}\, \vec{n}_{ij} - d_n\, \vec{v}_{n,ij} & , \quad \zeta = \left| R_i + R_j - \vec{r}_{ij} \right| \\ 0 & , \quad \zeta < 0 \end{cases},$$
(8)

195   where $k_n = 2\times 10^6$ is the normal stiffness coefficient; ζ is the amount of overlap

196   between particles during contact; R_i and R_j are the radius of particle i and j; $\vec{r}_{ij}$ is

197   distance vector between particles; $\vec{v}_{n,ij}$ is the normal relative velocity vector. The

198   normal damping coefficient can be expressed as

199
$$d_n = \sqrt{\frac{4 k_n \dfrac{m_i m_j}{m_i + m_j}(\ln \varepsilon)^2}{\pi^2 + (\ln \varepsilon)^2}},$$
(9)

200   where m_i and m_j are the mass of particle i and j, and $\varepsilon = 0.7$ is restitution coefficient.

201   The tangential force of contact is

202
$$\vec{F}_{t,ij} = \begin{cases} -k_t \zeta_{t,ij}\, \vec{\tau}_{ij} - d_t\, \vec{v}_{t,ij} & \left| \vec{F}_{t,ij} \right| \le \dfrac{R_i}{R_j}\left| \vec{F}_{n,ij} \right| \\ -\mu_i \left| \vec{F}_{n,ij} \right| \vec{\tau}_{ij} & \left| \vec{F}_{t,ij} \right| > \dfrac{R_i}{R_j}\left| \vec{F}_{n,ij} \right| \end{cases},$$
(10)

203   where $k_t = 2\times 10^6$ is the tangential stiffness coefficient, $\zeta_{t,ij}$ is the tangential

204   displacement, and $\vec{v}_{t,ij}$ is the tangential relative velocity vector. The tangential

205   damping coefficient can be expressed as

206
$$d_t = 2\sqrt{\frac{m_i m_j}{m_i + m_j} k_t}.$$
(11)

207   **2.4 Splash process**

208   Splash processes not only serve as an indispensable part of the near-surface

209   particle motions but also relate to the accuracy of emissions during particle upwards

210   transport. There are a large number of collisions between particles and the ground.

211   Meanwhile, other particles will be blown upwards when particles hit the ground,

212   which is referred to as the splash process. If energy-based collision analysis is

213   performed on a single particle, considerable time will be consumed. Therefore,

214   researchers have parameterized some key variables in accordance with the

215   characteristics of splashing, thereby simplifying the problem. We assume that there

216   are enough sand and dust particles on the ground to splash when the particles impact

217   the surface. If the particle collides with the bed, we assume the rebound probability as

218    $$p_{reb} = 0.95(1 - e^{-\lambda v_{imp}}),$$ (12)

219   where v_{imp} is the impact speed, and λ is an empirical parameter in the order of 2 s/m

220   according to the previous study (Anderson et al., 1991). The rebound sand speed is

221   0.55 times of the impact sand speed, and the rebound angle θ_{reb} is 40 ° (Zhou et al.,

222   2006). Of course, at a certain speed, some new sand particles will be splashed. The

223   ejection number is

224    $$\overline{N_{ej}} = n_0 \left(1 - \left(A - B sin\theta_{imp} \right)^2 \right) \left(\frac{v_{imp}}{\zeta \sqrt{g d_{mean}}} - 1 \right)(e^{\mu_{imp}/C} - D),$$ (13)

225   where n_0=0.4, A=0.68, B=0.39, ζ=5, C=0.92, and D=1.39 (Huang et al., 2017). θ_{imp} is

226   the impact angle, μ_{imp} is the ratio of impact grain size to the mean size of the bed, and

227   d_{mean} is the mean diameter of the sand particles. The ejection angle θ_{ej} distributes

228   randomly between 50 °~60 ° (Rice et al., 1995). The probability density distribution of

229   the initial lifting speed follows

230    $$p(v_{ej}) = \exp(-v_{ej} / \overline{v_{ej}}) / \overline{v_{ej}},$$ (14)

where v_{ej} is the ejection speed and the overbar represents a mean value (Anderson et al., 1991; Werner, 1990). The mean ejection speed can be expressed as (Kok and Renno, 2009)

$$\overline{v_{ej}} = \sqrt{gD_{mean}} \frac{\alpha_{ej}}{a} (1 - \exp(-\frac{v_{imp}}{40\sqrt{gD_{mean}}})). \tag{15}$$

Moreover, the sand particles satisfy the periodic boundary condition in the streamwise and spanwise directions. Following the idea of Dupont et al. (2013), aerodynamic entrainment is not considered in our model. A total of 10000 initial particles are randomly released in the flow field (Huang, 2020), and the release height should be lower than 0.3 m (Shao and Raupach, 1992). The results of Dupont et al. (2013) showed that the number of released particles does not affect the final results but only the speed of wind-blown sand development.

2.5 Parameters and the equivalent method of SCBs

According to the experience of laying SCBs in practical engineering (Chang et al., 2000) and the theoretical results of Wang and Zheng (2002), in this paper, the height of the SCB (S_h) is set to 10 cm, the side length of a single SCB (S_l) is set to 100 cm, and the side thickness of the SCB (S_n) is set to 10 cm. The diagram of a single SCB is shown in Fig. 1b. Moreover, to study the inhibition effect of the laying length of SCBs (represented by N) on aeolian sand erosion, we set N=5~10 m, 5~20 m, and 5~30 m in the simulation cases. The diagram of the laying SCBs is shown in Fig. 1a, and the main parameters of the SCBs are listed in Table 1.

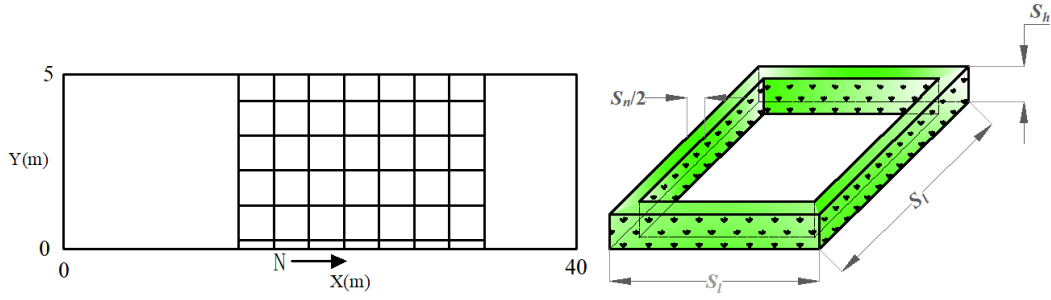



Figure 1. (a) The diagram of the laying SCBs. (b) The diagram of a single SCB.

The SCBs are equivalent to a volume resistance force through the resistance coefficient and leaf area coefficient; that is, the flow in these regions will be subject to an additional resistance force, which can be expressed as

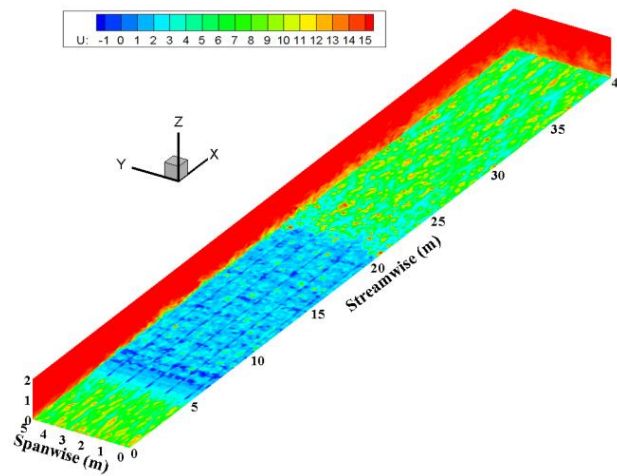
$$F_{di} = -C_d a_d |U| u_i, \tag{16}$$

where C_d is the drag coefficient, a_d is the leaf area coefficient, and U is the inflow wind speed. In the simulation, the value of C_d is 0.2 according to the parameters of Dupont et al. (2013). Nepf (2012) concluded that when the diameter of vegetation is 4-9 cm, the value of the leaf area coefficient a can reach 20 m^{-1}. Therefore, according to the side thickness of the SCB presented in this paper, the leaf area coefficient is set as 40 m^{-1}. Due to the limitation of the drag force method, the SCBs only affect the velocity of the flow field rather than the real presence. Current model considers more the inhibition effect of the flow field on the particles and does not simulate the collision process between the sand particles and the SCBs. Therefore, this collision-obstruction process can be approximately simplified as the sudden drop in the drag force as the saltating particles pass through the region of the SCBs. The consequences of such a simplification may lead to an underestimation of the inhibition effect of the SCBs. Therefore, this limitation of the current model needs to be noted.

271 **Table 1** SCB Parameters

Name	Symbol	Value	Unit
SCB height	S_h	10	cm
SCB side length	S_l	100	cm
SCB side thickness	S_n	10	cm
laying length of SCBs	N	5~10, 5~20, 5~30	m
drag coefficient	C_d	0.2	
leaf area coefficient	a	40	m^{-1}

272

273 **2.6 Calculation parameters**

274
275 **Figure 2.** Schematic diagram of three-dimensional wind-blown sand in presence of SCBs.

276 Wind tunnel experiments conducted by Shao and Raupach (1992) indicated that

277 a complete "overshoot" was more than 10 m in streamwise (Huang et al., 2014; Ma

278 and Zheng, 2011). In Fig. 2, the computational domains are Lx=40 m, Ly=5 m, and

279 Lz=2 m in the streamwise, spanwise and wall-normal directions, respectively. Field

280 experiments conducted by Baas and Sherman (2005) showed that the mean lateral size

281 of sand streamers is approximately 0.2 m. To capture this structure, the mesh spacing

282 is N_x=0.1 m and N_y=0.05 m in the streamwise and spanwise directions, respectively.

283 In addition, in the near-wall region, logarithmic stretching has been adopted to ensure

284 precision. The mean and minimum mesh spacing in the vertical direction is N_z=0.025

m and N_{zmin}=0.005 m, respectively. Therefore, the grids of the streamwise, spanwise

and vertical directions are 400×100×80, respectively. The sand particle diameter

satisfies the normal distribution: the mean diameter equals 200 μm, and the variance

is ln(1.2). We first simulate the clean air field flow in the presence of SCBs for 30

seconds to obtain the full development of the flow field. Then, we add sand particles

to the flow field to obtain a sand-laden flow. After the wind-blown sand flow becomes

saturated, the simulations continue for another 20 seconds to perform the statistics.

The fluid time step is Δt_s=0.0002 s, and the particle time step is Δt_p=0.00005 s. The

sand grain density is 2650 kg/m^3, and the air density is 1.225 kg/m^3. The main

calculation parameters are listed in Table 2.

Table 2 Main Simulation Parameters

Name	Symbol	Value	Unit
streamwise computational domain	Lx	40	m
spanwise computational domain	Ly	5	m
wall-normal computational domain	Lz	2	m
fluid time step	Δt_s	0.0002	s
friction wind speed	u_*	0.3, 0.44, 0.6	m/s
particle time step	Δt_p	0.00005	s
sand density	ρ_a	2650	kg/m^3
air density	ρ_f	1.225	kg/m^3
gravity	g	9.81	m/s^2
streamwise mesh spacing	N_x	0.1	m
spanwise mesh spacing	N_y	0.1	m
wall-normal mean mesh spacing	N_z	0.025	m

3. Model validations

3.1 Particle field validation

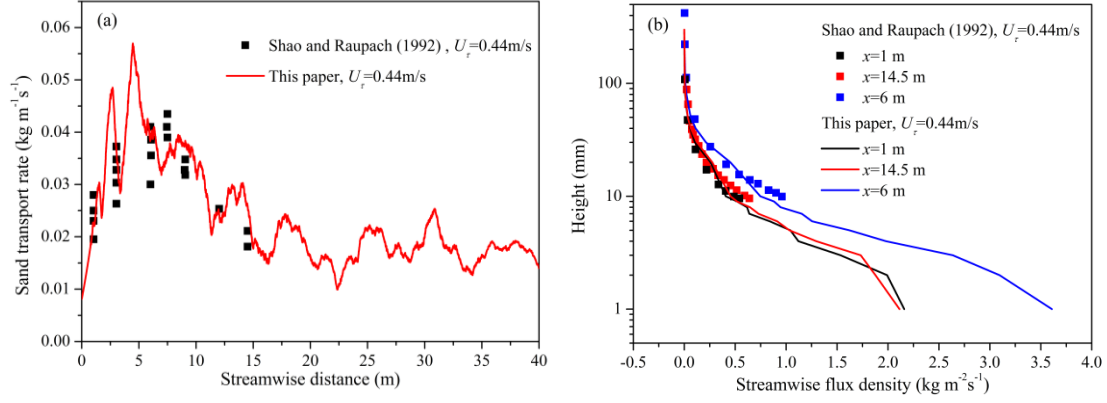



Figure 3. (a) The spatial variation of the streamwise sand transport rate in the sand-laden flow. (b) The streamwise sand transport rate density with the height at the three flow direction positions.

In section 3.1, we will verify the validity of the model from the following two aspects. The sand transport rate is an important physical quantity in wind-blown sand, which is the embodiment of the sediment carrying capacity of the flow field (Zheng, 2009). Therefore, without considering the SCBs, we first compare the spatial variation in the sand transport rate in the sand-laden flow with the experimental results of Shao and Raupach (1992). The sand transport rate is calculated according to the formula

$$q(x) = \sum_{z=0}^{z=Lx} \sum_{y=0}^{y=Ly} m(x, y, z) \, / \, \Delta x \, / \, \Delta t_s, \tag{17}$$

where $m(x, y, z)$ represents the sand mass, and Δx is the grid size in the flow direction. Whether the wind-blown sand flow is saturated depends on the change in sediment transport at a certain streamwise position. The condition for judging saturation is given by Ma and Zheng (2010). The wind tunnel experimental results of Shao and Raupach (1992) showed that the streamwise sand transport rate first increased and then decreased until it was stable, which is called the "overshoot" phenomenon (Anderson and Haff, 1991; McEwan and Willetts, 1991). Fig. 3a shows the comparison between the simulation results of the sand transport rate along the flow

318 direction and the experimental results of Shao and Raupach (1992) under the same

319 friction wind speed. As shown in Fig. 3a, our simulation results also show this

320 phenomenon. However, unlike the other numerical simulation results (Huang et al.,

321 2014; Ma and Zheng, 2011), our sediment transport rate results have an obvious

322 fluctuation characteristic and are not smooth curves, which may be caused by the

323 turbulence intermittency unique to the three-dimensional wind-blown sand model.

324 Moreover, we give the distribution results of the streamwise sand transport rate

325 density with the height at the three flow direction positions, which are compared with

326 the experimental results. From Fig. 3b, we can see that the distribution of the

327 streamwise sand transport rate density with height follows the trend of exponential

328 decline, and the sand transport rate density at $x = 6$ m is significantly higher than that

329 at $x = 1$ m and $x = 14.5$ m, which is consistent with the experimental results of Shao

330 and Raupach (1992). This is because the streamwise position of $x = 6$ m is in the peak

331 region of the "overshoot" phenomenon, while the streamwise positions of $x = 1$ m and

332 $x = 14.5$ m are in the rising region and stable region, respectively. Due to the massive

333 accumulation of sand particles near the surface (0-20 mm), the concentrations cannot

334 be easily measured. In Fig. 3b, our simulation results also show that the distribution of

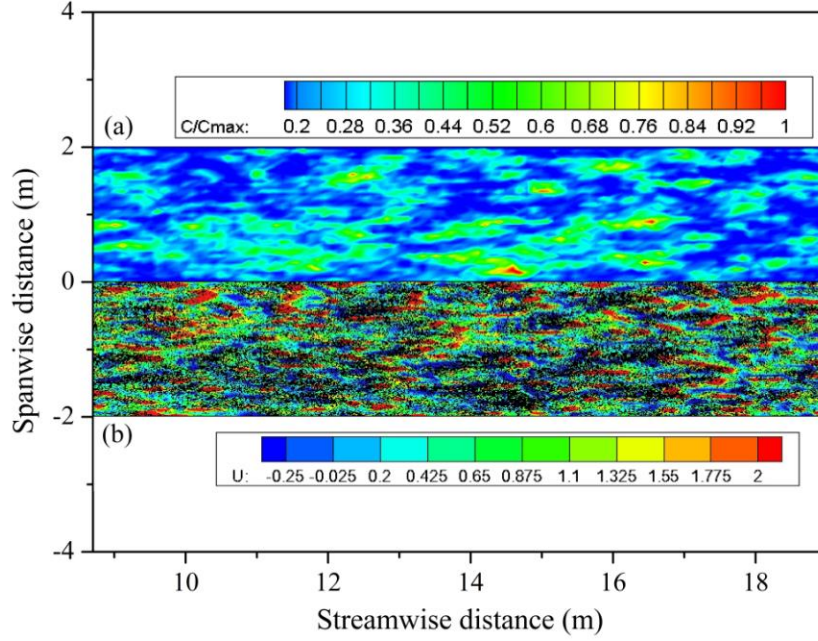
335 the streamwise sand transport rate density with heights below 10 mm still satisfies the

336 trend of exponential decline. However, at a height of 2~3 mm, there is a slight change

337 in this trend; that is, the rate of increase in the sand transport rate density slows down,

338 which is not revealed in the experimental results. Due to the limitations of the large

339 eddy simulation, the simulation results near the wall may be distorted and requires

340   further experimental verification.

341

342   **Figure 4.** (a) The top view of the sand streamer concentrations, where C represents the particle
343   concentrations, C_{max} represents the maximum particle concentrations. (b) The top view of the
344   whole particle positions and the streamwise velocity diagram of flow field with the height of 0.005
345   m, and the y coordinates are correspondingly shifted down by 2, where the black dots represent
346   the sand particles, U represents the streamwise wind speed of the sand-laden flow (u_τ=0.3 m/s).

347   Sand streamers, as a natural phenomenon in wind-blown sand, have been widely

348   studied. Therefore, without considering the SCBs, we analyse the morphology of the

349   sand streamer and its relationship with the flow field. In the meantime, the airborne

350   particle concentration within a certain area can be calculated as

351
$$C = \sum_{z=0}^{z=Lz} \sum_{y=0}^{y=Ly} \sum_{x=0}^{x=Lx} m(x,y,z) \, / \, Lx \, / \, Ly \, / \, Lz. \tag{18}$$

352   Fig. 4a shows the top view of the particle-aggregation morphology in the stable stage

353   of sand-laden flow. It can be seen from Fig. 4a that the concentration of sand particles

354   is intermittent in both streamwise and spanwise directions. Moreover, we can see

355   clearly that the morphological characteristics of the sand streamer are consistent with

356 the observations of Baas and Sherman (2005), that is, it is up to a few metres in the

357 streamwise direction and approximately 0.2 metres in the spanwise direction. Our

358 model can sufficiently reproduce the "sand streamer" phenomenon in wind-blown

359 sand. Here, we need to point out that the intermittence of turbulence complicates

360 particle movement, especially when multiple streamers are connected end to end and

361 the concentration is sufficiently close, and then super sand streamers up to tens of

362 metres long will exist. Whether in sand-laden flow or other two-phase flows,

363 researchers are generally concerned about the aggregation of particles. We plot the

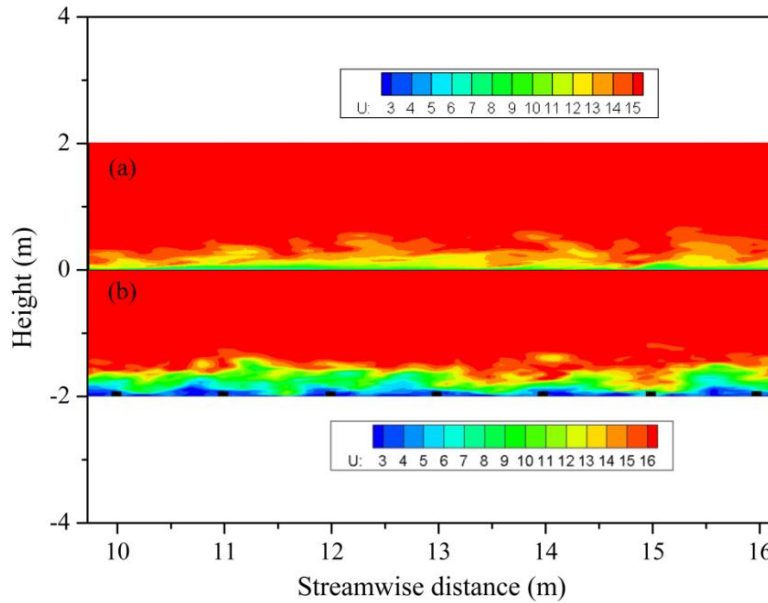
364 position of particles and the streamwise velocity of the flow field in Fig. 4b and find

365 that most particles are assembled in the low-speed streaks, which is consistent with

366 the conclusion of the other particle-laden flow studies (Lee and Lee, 2015; Richter,

367 2015).

368 **3.2 Velocity field validation**

369

370 **Figure 5.** The side view of X-Z plane streamwise velocity before (a) and after (b) containing the

371 SCBs (u_τ=0.6 m/s, N=5~20 m, y=0 m). The y coordinates are correspondingly shifted down by 2

372   in the case (b).

373

374

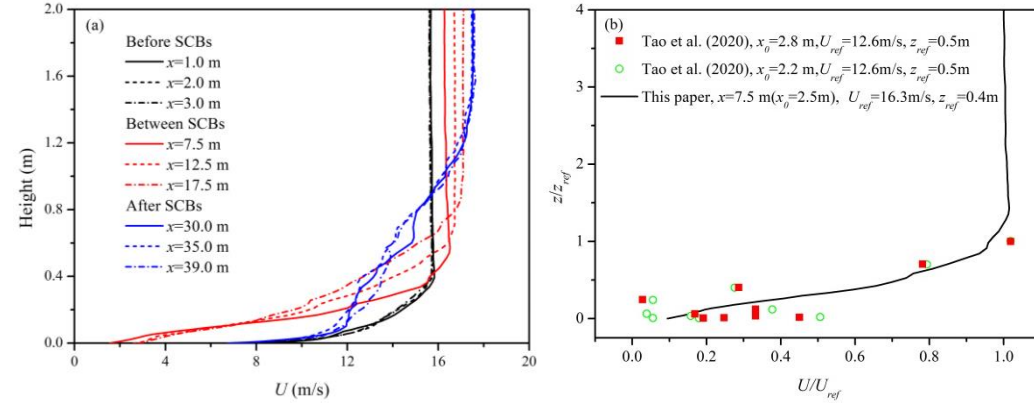



Figure 6. (a) The wind speed profiles of different streamwise positions in the clean air flow
containing the SCBs (u_τ=0.6 m/s, N=5~20 m); (b) The dimensionless wind speed varying with
dimensionless height, comparison between our simulated results and the existing experiment.

The verification of the flow field part of the program is covered in detail in our

previous works (Huang, 2020). In section 3.2, we focus on the flow field verification

after considering the SCBs. We verify the difference in the velocity profile as well as

the surface roughness in the clean air flow with and without the SCBs.

In previous work, the wind speed and surface roughness near the SCBs were well

studied (Dong et al., 2000; Qu et al., 2007; Wang et al., 1999). These works all

pointed out that laying the SCBs can effectively increase the surface roughness and

reduce the wind speed near the surface to play a role in inhibiting the wind-blown

sand and fixing the sand particles. Fig. 5a and 5b are the tangent plane (X-Z plane) of

the streamwise wind velocity without and with the SCBs, respectively. It can be seen

intuitively that the existence of the SCBs significantly reduces the surface wind speed

and increases the boundary layer thickness of the flow field. To reveal the difference

quantitatively, we plot the wind speed profiles of different streamwise positions in the

clean air flow containing the SCBs in Fig. 6a. The selected positions are x = 1, 2, and

3 m in front of the SCBs, x = 7.5, 12.5, and 17.5 m in the area containing the SCBs,

393   and $x = 30$, 35, and 39 m behind the SCBs. We can see that the wind speed profiles at

394   the three positions in front of the SCBs are basically the same. In the area containing

395   the SCBs, the existence of the SCBs reduces the surface wind speed and increases the

396   thickness of the boundary layer (equivalent to increasing the surface roughness) as

397   well as the incoming wind speed outside the boundary layer. Moreover, the longer the

398   SCBs are, the thicker the boundary layer becomes, and the incoming wind speed

399   outside the boundary layer will also increase. The flow field behind the SCBs may be

400   complicated by the influence of the attached vortex generated by the SCBs, but the

401   overall trend is the same, and the boundary layer thickness remains consistent. These

402   results are qualitatively consistent with the conclusions of previous work (Dong et al.,

403   2000; Qu et al., 2007; Wang et al., 1999), which indicates that our model has

404   effectively introduced the SCB module.

405   In addition, we compared the wind speed profiles with the experimental results

406   of Tao et al. (2020). In Figure 6b, the streamwise wind speed in the horizontal

407   coordinate is dimensionless with the reference wind speed U_{ref} and the height in the

408   vertical coordinate is dimensionless with the reference height z_{ref}. In the wind tunnel

409   experiment conducted by Tao et al. (2020), the maximum boundary layer thickness is

410   given as 0.5 m, so the reference height is taken as z_{ref}=0.5 m. Then, the wind speed at

411   z=0.5 m is determined as the reference wind speed U_{ref}=12.58 m/s based on their inlet

412   wind profiles. In our simulation case, z_{ref}=0.4 m is the initial inlet boundary layer

413   thickness, and U_{ref}=16.3 m/s is the reference wind speed. We select the experimental

414   results of wind speed profiles at the SCB belt positions x_0=2.2 m and 2.8 m along the

415   flow direction to compare with our numerical results at x_0=2.5 m (streamwise position

416   x=7.5 m). The dimensionless results show that our results are consistent with the

417   experimental results in quantitative and qualitative, which indicates that our model

418   can well reveal the inhibition effect of SCBs on the flow field. In the following

419   section, we will reveal more about the influence of the laying length on the wind field

420   and its inhibition effect on wind-blown sand.

421

4. Results and discussion

4.1 Influence of the SCBs on the clean air flow

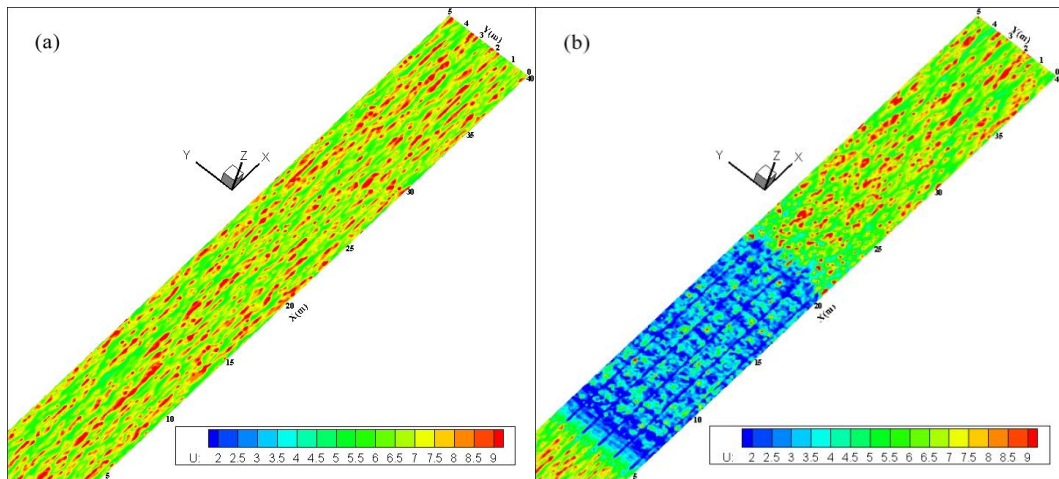
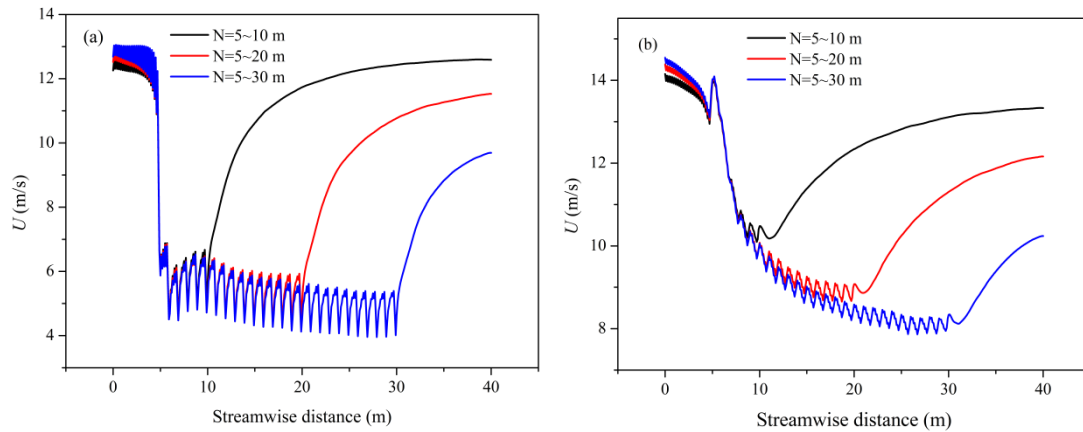



Figure 7. The top view of X-Y plane streamwise velocity without (a) and with (b) the SCBs
(z=0.005 m, u_τ=0.6 m/s, N=5~20 m).

 Figure 8. The streamwise wind speed in the clean air flow containing the SCBs at the height of

430   0.1 m (a) and the height of 0.2 m (b), u_τ=0.6 m/s, N=5~10 m, 5~20 m, 5~30 m.

431   Fig. 7a and 7b show that the presence of the SCBs destroys the original streaks

432   of the clean air flow and decreases the wind speed. In most cases, the wind speed in

433   the central area of a single SCB is significantly higher than that in the surrounding

434   area, showing a block of velocity distribution characteristics. Although the wind speed

435   behind the SCBs will recover rapidly, there is a significant difference between the

436   newly formed streaks and the original streaks of the flow field; that is, the streamwise

437   scale of the streaks behind the SCBs is significantly shorter than before. The variation

438   in streamwise wind speed at the different laying length cases (N=5~10 m, 5~20 m,

439   5~30 m) under the same friction wind speed (u_τ=0.6 m/s) is plotted in Fig. 8, where

440   Fig. 8a corresponds to the wind speed at a height of 0.1 m, and Fig. 8b corresponds to

441   the wind speed at a height of 0.2 m. Fig. 8 shows an oscillating decrease in wind

442   speed in the SCBs. In addition, behind the SCBs, the wind speed gradually increases

443   and then stabilizes. The trend of wind speed reduction in the SCBs is consistent with

444   the existing experimental results (Xu et al., 1982). The difference is that the reduction

445   process of the wind speed around the SCBs exhibited an oscillatory attenuation

446   instead of a continuous decrease, which was not revealed in the previous simulation

447   results (Bo et al., 2015). Moreover, when the incoming wind speed is stable, the

448   longer the laying lengths are, the lower the wind speed in the stable stage behind the

449   SCBs will be. This is very useful information. On this basis, we can obtain the

450   relationship between the laying length of the SCBs and the wind speed in the stable

451   stage according to an actual situation. For example, the wind speed in the stable stage

452 can be reduced to the impact threshold or the aerodynamic threshold on both sides of

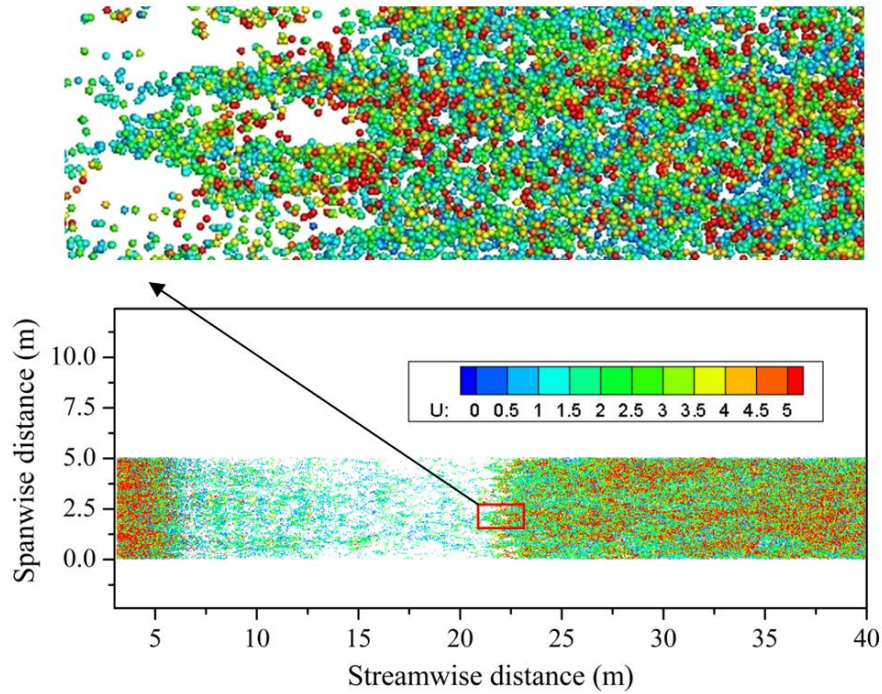
453 the desert highway to determine the minimum laying length of the SCBs and save

454 laying costs. This is a potential application of our model and needs further

455 experimental verification.

456

457 **4.2 Effect of sand particles on the flow field and its aggregation location**

458

459 **Figure 9.** The top view of the particle positions of the wind-blown sand in presence of SCBs,
460 where U represents the speed of the particles (u_τ=0.6 m/s, N=5~20 m).

461

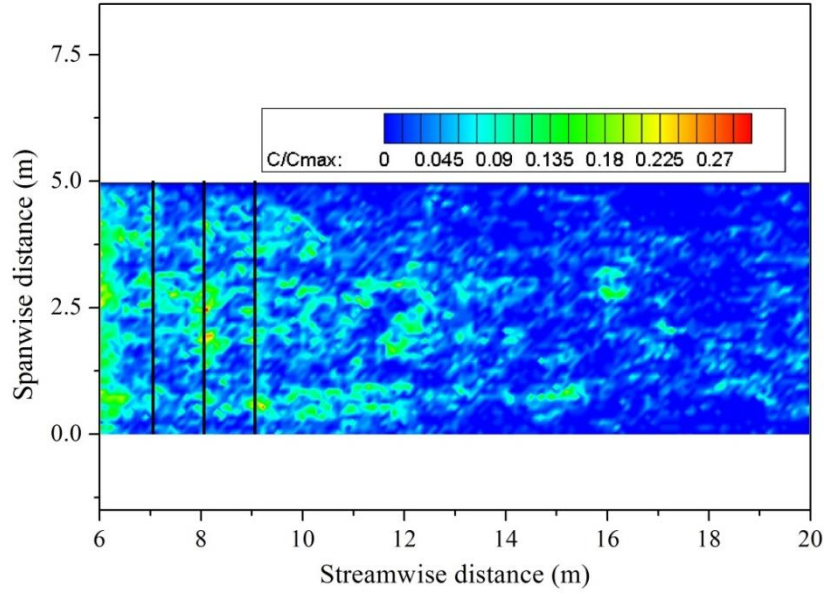



Figure 10. The top view of the sand concentrations in the regions of the SCBs, where C represents
the particle concentrations, C_{max} represents the maximum particle concentrations (u_τ=0.6 m/s,
N=5~20 m). The black lines represent the schematic diagram of the side of SCBs.

Sand particles were added to the clean air flow field in the presence of SCBs to

fully develop and reach stability. The top view of the particle positions of the

wind-blown sand after reaching a stable state is shown in Fig. 9. From Fig. 9, we can

see that when the wind-blown sand passes through the SCBs, the particle number

obviously decreases gradually, and the inhibition effect of the SCBs on the

wind-blown sand can be visualized. Moreover, the motion of sand particles behind the

SCBs returns to complete wind-blown sand movement. We then plot the sand

concentrations of the region in the presence of SCBs in Fig. 10. Combining the laying

position of the SCBs as well as the corresponding sand concentrations, we can clearly

see that the concentration of sand particles near the side of the SCBs is higher than

that in its central region, which is consistent with the conclusion of Xu et al. (2018).

On the one hand, the wind speed near the side of SCBs is low, and the drag force of

the sand particles in these areas will be significantly reduced, so that the sand particles

478   will accumulate or deposit in these regions. On the other hand, the wind speed in the

479   central area of every single SCB is significantly higher than that in the surrounding

480   area, so sand particles do not easily accumulate or fall in these regions. This explains

481   why the side of the SCBs tends to be buried in sandy land and loses its effect after

482   long working hours.

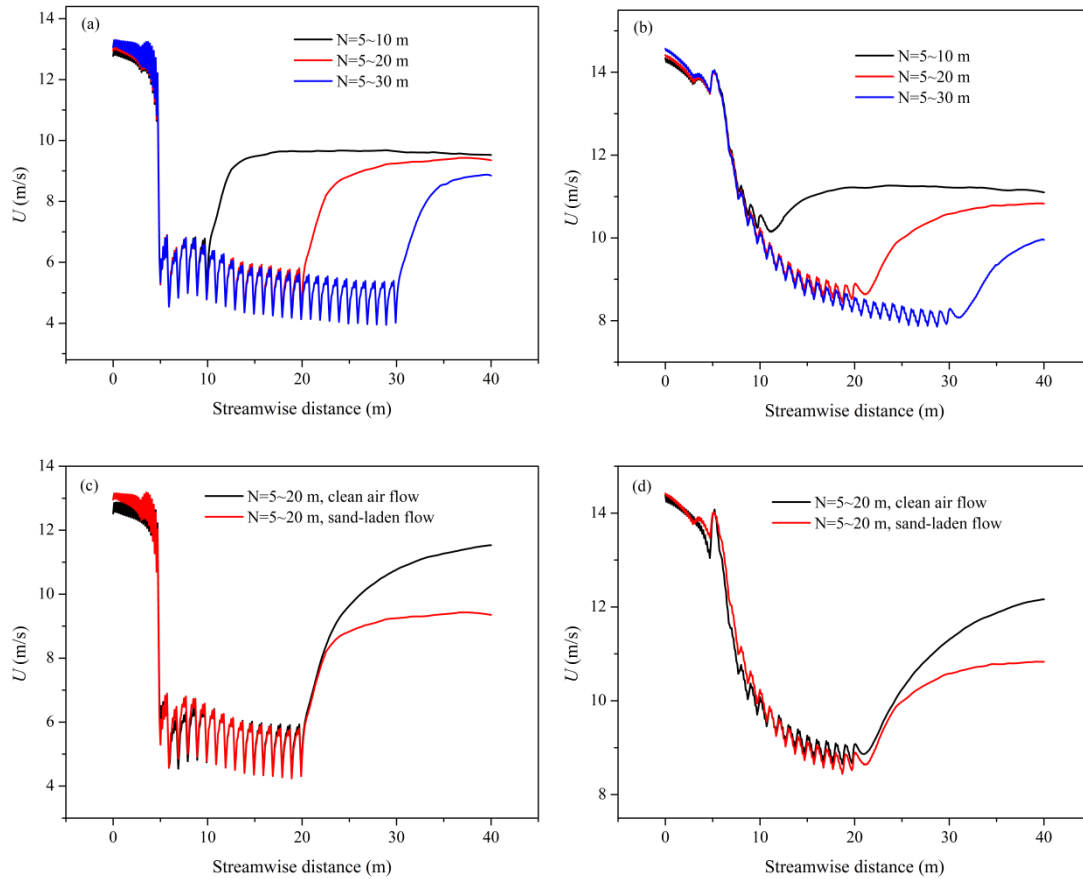



Figure 11. The streamwise wind speed in the sand-laden flow containing the SCBs at the height of
0.1 m (a) and the height of 0.2 m (b), u_τ=0.6 m/s, N=5~10 m, 5~20 m, 5~30 m. The comparison of
the streamwise wind speed between the clean air flow and the sand-laden flow at the height of 0.1
m (c) and the height of 0.2 m (d), u_τ=0.6 m/s, N=5~20 m.

489   Furthermore, we analyse the effect of sand particles on the wind speed in the

490   sand-laden flow. The streamwise wind speed of the sand-laden flow at the different

491   laying length cases (N=5~10 m, 5~20 m, 5~30 m) under the same friction wind speed

492   is plotted in Fig. 11a and 11b. Meanwhile, for the convenience of comparison, the

493   streamwise wind speed under the same laying length (N=5~20 m) in the sand-laden

494   flow and the clean air flow are plotted in Fig. 11c and 11d. Fig. 11a and 11c

495   correspond to the wind speed at a height of 0.1 m, while Fig. 11b and 11d correspond

496   to the wind speed at a height of 0.2 m. From Fig. 11a-d, we can still see an oscillating

497   decrease in the wind speed in the SCBs of the sand-laden. The streamwise wind speed

498   behind the SCBs in the sand-laden flow is significantly lower than that in the clean air

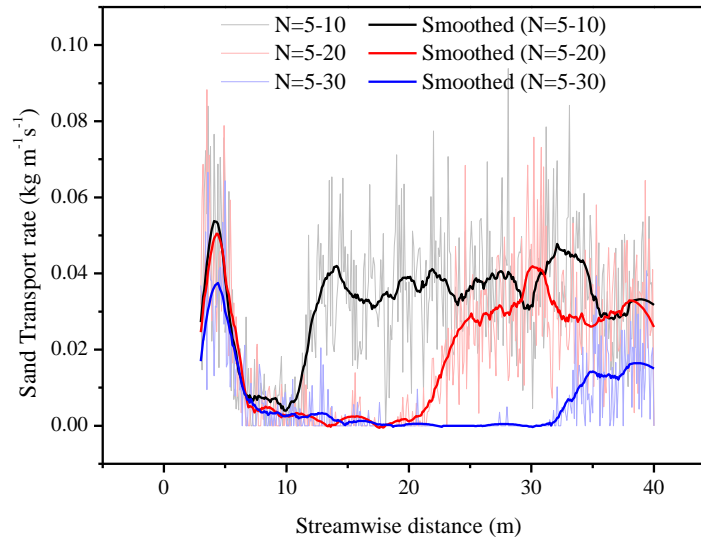
499   flow. Obviously, the presence of sand particles indeed reduces the wind speed.

500   However, the change in wind speed in the SCBs between the sand-laden flow and the

501   clean air flow is not obvious because there are fewer sand particles in the SCBs than

502   behind the SCBs, which has less effect on the overall wind speed.

503   **4.3 Effect of the laying length on the sand transport rate**

504

505   **Figure 12.** The streamwise sand transport rate in the different laying length cases (u_τ=0.6 m/s,

506   N=5~10 m, 5~20 m, 5~30 m). Dark lines are the result of smoothing.

507   The effect of the different laying length cases (N=5~10 m, 5~20 m, 5~30 m) on

508   the sand transport rate under the same friction wind speed is plotted in Fig. 12. It can

be seen from Fig. 12 that the sand transport rate in the SCBs is very low, and as the

laying length increases, the sand transport rate in the SCBs decreases. In the case of

N=5~30 m, the sand transport rate in some regions has been reduced to zero.

Therefore, this result once again shows that the laying length of the SCBs can be

optimized, and we can reduce the laying cost while maintaining the effect of the SCBs.

Especially on both sides of the desert highway, our model can give the minimum

laying length according to the actual parameters. At the same time, we notice that the

sand transport rate will increase rapidly and then reach a stable state behind the SCBs.

It is obvious that when N=5~30 m, the value of the sand transport rate at the stable

stage behind the SCBs is significantly lower than the other results of N=5~10 m and

N=5~20 m. We also notice that the longer the laying lengths are, the lower the sand

transport rate in the stable stage behind the SCBs will be. This result corresponds to

the result shown in Fig. 8. Our results indicate that when sandy land is wide, the

discontinuous laying method can be considered. That is, the minimum laying length

must be determined first, and then the distance between each minimum laying length

can be set as needed. In this way, the sand transport rate can be reduced in sections.

This is another potential application of our model.

4.4 Particle positions under different friction wind speeds

527

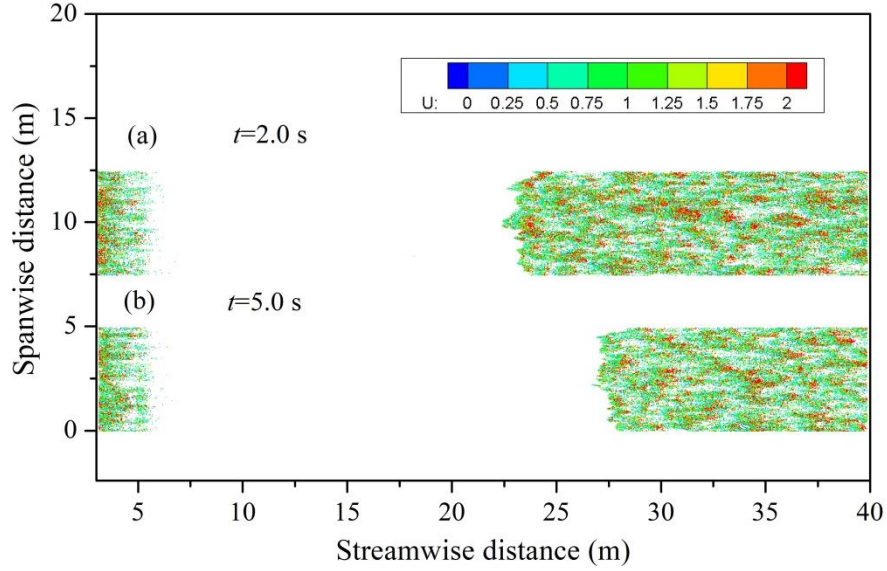



Figure 13. The top view of the particle positions of the wind-blown sand in presence of SCBs at the time t=2.0 s (a) and t=5.0 s (b), where U represents the speed of the particles (u_τ=0.3 m/s, N=5~20 m). The y coordinates are correspondingly shifted up by 7.5 per case.

531

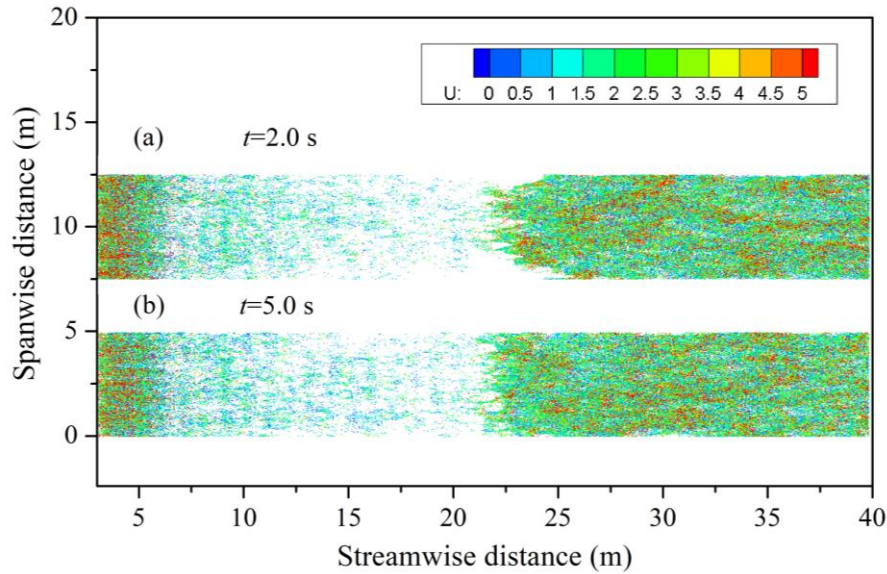



Figure 14. The top view of the particle positions of the wind-blown sand in presence of SCBs at the time t=2.0 s (a) and t=5.0 s (b), where U represents the speed of the particles (u_τ=0.6 m/s, N=5~20 m). The y coordinates are correspondingly shifted up by 7.5 per case.

The above analysis is based on the calculation case when the friction wind speed

is 0.6 m/s, and the sand particles can easily penetrate the SCBs when the wind speed

is large. When the friction wind speed is small, the inhibition effect of the SCBs on

wind-blown sand will become more obvious, and the movement behaviour of sand

particles will change. We focused on the effect of SCBs on the wind-blown sand

within 2 to 5 seconds after the sand-laden flow is saturated. We plot the top view of

the particle positions at different moments (t=2 s, 5 s) when the friction wind speed is

0.3 m/s and 0.6 m/s in Fig. 13 and Fig. 14, respectively. The initial value of time t in

Fig. 13 and Fig. 14 is when sand particles are added. The results show that when the

wind speed is small, the sand particles cannot penetrate the SCBs. There is no obvious

sand movement in the SCBs, and stable wind-blown sand cannot be formed behind

the SCBs. With the passage of time, the wind-blown sand behind the SCBs gradually

disappears. It is worth noting that aerodynamic entrainment is not considered in our

model. This is a considerable limitation of our model in the simulation of wind

erosion in the presence of SCBs. Therefore, a more reasonable situation is that when

the wind speed behind the SCBs returns to the fluid threshold, this part of the

wind-blown sand should still develop. When the wind speed is relatively small, on the

one hand, the sand particles cannot completely penetrate the regions of the SCBs and

cannot continuously provide the impact particles to form the wind-blown sand behind

the SCBs. On the other hand, the SCBs affect the surface wind speed behind it, thus

also affecting the continuous formation of wind-blown sand. When the wind speed is

relatively high, the sand particles can penetrate the SCBs. With increasing laying

length, although the inhibition effect on wind-blown sand is more obvious, stable

wind-blown sand will still be formed behind the SCBs. We think that when the laying

length of the SCBs is fixed, whether the wind speed will decrease below the impact

threshold or the fluid threshold is the key to determining whether the sand particles

can penetrate the SCBs and form stable wind-blown sand behind the SCBs. To present

this phenomenon more clearly, we have animated this process, as shown in the

supplementary materials (Video 1 and Video 2). In actual anti-desertification projects,

the minimum laying length of the SCBs can be determined by our model according to

the local maximum friction wind speed.

5. Conclusion and outlook

In this paper, a three-dimensional wind-blown sand coupling model in the

presence of SCBs was established. The model was verified from the following aspects:

(1) spatial distribution of the sand transport rate; (2) morphological characteristics of

the sand streamer resulting from the instantaneous fields; and (3) changes in the

thickness of the boundary layer before and after the SCBs. From this model, the

inhibition effect of SCBs on wind-blown sand was studied qualitatively, and the

sensitivity of aeolian sand erosion to the laying length was investigated. The results

showed that the wind speed in the SCBs of the clean air flow or the sand-laden flow

both decreases in an oscillating manner, which has not been revealed by previous

studies. Moreover, the longer the laying lengths of the SCBs are, the lower the wind

speed and the sand transport rate in the stable stage behind the SCBs will be, which

may provide theoretical support for the minimum laying length of SCBs in

anti-desertification projects. More importantly, we found that the concentration of

sand particles near the side of SCBs is higher than that in its central region, which is

consistent with previous research. This explains why the boundary of the SCBs tends

583 to be buried in sandy land and loses its effect after long working hours. Our results

584 also indicated that whether the wind speed will decrease below the impact threshold

585 or the fluid threshold is the key factor affecting whether sand particles can penetrate

586 the SCBs and form stable wind-blown sand behind the SCBs under the same

587 conditions. Although our model has been able to reveal the inhibition effect of the

588 SCBs on wind-blown sand, there are still some aspects that need improvement, such

589 as aerodynamic entrainment, particle deposition on the SCB, and collision between

590 the sand particles and the SCBs. The resolution of these issues is expected to reveal

591 more details of particle deposition around the SCBs, which needs in-depth study. The

592 size of the SCB used in our model is fixed. In future work, we plan to analyse the

593 effect of different heights and widths of the SCB on aeolian sand erosion and discuss

594 the reasons for the difference in heights between the SCB and other obstacles, such as

595 sand fences. Another aspect worth noting is that some additional factors, such as

596 terrain and surface roughness, will affect SCB performance in anti-desertification

597 projects, so the influence of these factors should be considered in the future. Using the

598 proposed model, our work significantly analysed some results that are seemingly

599 simple but lack a theoretical basis from the perspective of turbulence.

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Code and Data availability. All relevant code and data used to generate the figures in this paper can be accessed using the following email: hjhuang@usst.edu.cn.

Competing interests. The authors declare that there are no competing interests

Author contributions. HJ performed the programming, analyzed the results, and wrote the paper.

Video supplement. Video 1 and Video 2 can be downloaded at the following link: https://doi.org/10.5281/zenodo.6937805

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