3D numerical simulation of the evolutionary process of aeolian downsized crescent-shaped dunes

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A B S T R A C T
A dune constitutive model was coupled with a large eddy simulation (LES) with the Smagorinsky subgrid-scale (SGS) model to accurately describe the evolutionary process of dunes from the macroscopic perspective of morphological dynamics. A 3D numerical simulation of the evolution of aeolian downsized crescent-shaped dunes was then performed. The evolution of the 3D structure of Gaussian-shaped dunes was simulated under the influence of gravity modulation, which was the same with the vertical oscillation of the sand bed to adjust the threshold of sand grain liftoff in wind tunnel experiments under the same wind speed. The influence of gravity modulation intensity on the characteristic scale parameter of the dune was discussed. Results indicated that the crescent shape of the dune was reproduced with the action of gravity during regulation of the saturation of wind-sand flow at specific times. The crescent shape was not dynamically maintained as time passed, and the dunes dwindled until they reached final decomposition because of wind erosion. The height of the dunes decreased over time, and the height–time curve converged as the intensity of modulation increased linearly. The results qualitatively agreed with those obtained from wind tunnel experiments.

1. Introduction

Barchans are crescent-shaped dunes formed under the actions of wind field with a single wind direction. Barchans attract widespread attention because of their unique structure, self-organising evolution and high-rate migration. Field observations indicate that migrating dunes of natural scale may take several months to several years to achieve total migration (Bagnold, 1941; Pye and Tsoar, 2009; Ewing et al., 2015). Downsized dunes are typically used to simulate dunes in real scale because of the finite size of a wind tunnel (Andreotti et al., 2002; Dauchot et al., 2002; Faria et al., 2011; Zhang et al., 2014). Dynamic numerical simulation is an alternative technique to field research to study dunes. This approach not only reveals the evolution of dunes at any scale but also enables the exploration of the influence of various factors on dune evolution under controllable conditions. Numerical simulation of the evolutionary process of dunes consumes reduced amount of time and is characterised by continuity, repeatability and independence from environmental factors. Therefore, numerical simulation provides great benefits as a supplement to wind tunnel simulation.

Simulation of the evolution and migration of dunes in a wind field poses greater challenges compared with simulation of near-surface wind-sand flow. The formation and migration of dunes are caused by interaction among three processes, namely, surface air flow movement, macroscopic surface changes and microscopic sand grain transport. The evolution and migration of dunes on the macroscopic scale are related to the characteristics of air and sand flow, as well as the erosion and deposition patterns of sand phase. Generally, dunes can be more comprehensively described by macroscopic parameters than by microscopic parameters. Studies have shown that the mesoscale aspects of sand flux are of greater significance than the characteristics of grains that constitute dunes in morphological research (Sauermann et al., 2001a; Hersen et al., 2002). Sauermann et al. (2001b) conducted field measurements of dunes and found that the content of grains that constitute an independent barchan reached an order of magnitude of about $10^{15}$ (one thousand trillions). Therefore, simulating discrete grain size is difficult in the field of dune morphology.

Numerous studies adopt the macroscopic scale to investigate the migration dynamics of dunes (Kok et al., 2012). Thus far, the proposed representative models include the continuous minimal model (Sauermann et al., 2001a,b; Kroy et al., 2002) and the discrete cellular automaton (CA) model (Werner, 1995). These two models have been constantly improved in subsequent studies.
on models for dunes. The application of the continuous minimal model has been extended from 2D dunes to 3D dunes (Schwammle and Herrmann, 2005; Parteli et al., 2014a), from a single dune to multiple dunes (Duran et al., 2010) and even to dunes on Mars (Parteli et al., 2007). Katsuki et al. (2005) drew on the principle of the CA model and proposed a calculation model to simulate the evolution of 3D aeolian downsized dunes and compares it with actual cases in the corresponding experiments. Firstly, a large eddy simulation (LES) model was proposed to investigate the influence of gravity modulation intensity on the spatial scale parameters of the dune. Simulation results are evaluated using wind tunnel experiment data, particularly at the evolutionary process of dune body at such scale. This study aims to deepen our understanding of the new mechanism to modulate the saturation level of sand flux during the evolutionary process of macroscopic dune configuration. Finally, the applicability of the proposed model and further developments are presented.

2. Mathematical model

2.1. Governing equations for wind flow

The turbulent flow in wind field at the near-surface atmospheric boundary layer is described by using incompressible LES equations. After spatial filtering, the following continuity and momentum equations for the resolved field are applied:

\[ \frac{\partial \tilde{u}_i}{\partial x_i} = 0 \]  

\[ \frac{\partial (\tilde{u}_i + \bar{u}_i)}{\partial x_j} \frac{\partial \tilde{u}_j}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial \tilde{p}_s}{\partial x_i} + \frac{1}{\rho_0} \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{1}{\rho_0} \frac{\partial \sigma_{ij}}{\partial x_i} \]  

where superscript “*” represents the spatially filtered variable, \( \nu_f \) is the kinematic viscosity of air and \( \tau_g \) is the subgrid-scale stress. Based on the Boussinesq hypothesis,

\[ \tau_g = -2\mu_{gg} \tilde{S}_{g,g} + \frac{1}{3} \tau_{kk} \delta_g \]  

where \( \tau_{kk} \) is the isotropic part of the subgrid-scale stress, which is not modelled but added to the filtered static pressure term; \( \delta_g \) is the Kronecker delta; \( \tilde{S}_{g,g} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \) is the rate of strain tensor of the resolved flow; and \( \mu_{gg} \) is the eddy viscosity. Based on the model of Smagorinsky (1963), eddy viscosity is modelled by

\[ \mu_{gg} = \rho_g |C_\lambda| \Delta^2 |\tilde{S}| \]  

\[ S = \sqrt{2 \tilde{S}_{g,g} \delta_{g,g}} \]  

where \( C_\lambda \) is the Smagorinsky constant, with a value of 0.1; and \( \Delta = (\Delta x \Delta y \Delta z)^{1/3} \) is the filtered width.

2.2. Constitutive equations for dune evolution

The following equation represents the mass conservation of dune:

\[ \rho_s \frac{\partial h}{\partial t} + \nabla \cdot (h \nabla q) = 0 \]  

where \( \rho_s \) is the density of sand phase, \( h \) and \( q \) are the apparent density of sand phase, dune height and total vertically integrated sand flux, respectively; \( \rho_s = \rho_m (1 - \lambda) \), where \( \rho_m \) is the density of sand grains, with value set as \( \rho_m = 2650 \text{ kg} \cdot \text{m}^{-3} \); and \( \lambda \) is the sand porosity. Total vertically integrated sand flux is divided into three parts: saltation, reptation and creep fluxes. The use of Sorensen’s empirical formula (Sorensen, 1991) for saturated saltation flux exhibits good agreement with the wind tunnel experiments (Sauermann et al., 2003)

\[ q_{sat} = \begin{cases} \frac{\rho_s}{\tau} u_s \left( u_t + 7.6u_t + 2.05 \right), & u_s > u_t \\ 0, & u_s \leq u_t \end{cases} \]
where \( C_{m} \) is the model coefficient; \( g \) is the gravity acceleration constant; and \( u_{t} \) and \( u_{t} \) are the friction and critical friction velocities, respectively. The expression of critical friction velocity considering the slope effect is as follows (Iversen and Rasmussen, 1994):

\[
u_{t} = \theta \sqrt{(\rho_{m} - \rho_{s})gd_{s}(\cos \theta_{t} \sin \theta_{t} / \tan \theta_{rep})/\rho_{s}}
\]

(8)

where the coefficient \( \theta \) is 0.1 (Bagnold, 1941); \( d_{s} \) is the average grain size; \( \theta_{t} \) is the slope angle; \( \tan \theta_{t} = \nabla h; \) and \( \theta_{rep} \) is the angle of repose, \( \theta_{rep} = 32 \degree \) (Iversen and Rasmussen, 1994).

Considering the transition of saltation flux from non-saturation to saturation (Hersen, 2004), then

\[
\nabla \cdot q_{sat} = (q_{sat} - q_{sal})/l_{sat}
\]

(9)

where \( q_{sal} \) is the salting flux; and \( l_{sat} \) is the saturation length, which is the length scale for measuring whether \( q_{sal} \) reaches \( q_{sat} \). In accordance with the case in which grain inertia is the dominant mechanism of transport rate saturation, the saturation length is proportional to the drag length of sand grain (Sauermann et al., 2002) and slightly depends on the friction velocity (Pahtz et al., 2014).

\[
l_{sat} = a_{d}d_{s} = a_{m}d_{s}/\rho_{s}
\]

(10)

where \( a \) is the proportional factor with a value of 20 after considering field and laboratory measurements (Bagnold, 1941; Hersen et al., 2002); and \( l_{d} \) is the drag length of sand grain and represents the distance through which the sand grain reaches the wind speed from standing at a site on the surface.

Studies show that reptation induced by sand grain saltation considerably affects the transverse deposition of dune (Andreotti et al., 2002; Hersen, 2004). Reptation flux should be considered in describing dune shaping and evolution. On the basis of the relationship between saltation and reptation, the following expression is used to represent reptation flux (Andreotti et al., 2002; Andreotti, 2004):

\[
q_{rep} = C_{rep} \sqrt{gd_{s}q_{sat}}/u_{t}
\]

(11)

Creep also influences dune shaping. The relevant model derived by Wang and Zheng (2004) is considered to correlate creep flux with friction velocity:

\[
q_{crep} = \frac{2\rho_{m}C_{0}}{\rho_{m}^{2}C_{1}} \left(1 + v_{0}\right) \ln \left(1 + v_{0}v_{m}\right) \left(\frac{v_{m} - v_{0}}{v_{m}}\right) u_{t}^{2}
\]

(12)

where \( C_{0} \) and \( C_{1} \) are model constants; and \( v_{0} \) and \( v_{m} \) are volume fraction and maximum volume fraction of sand, respectively. The value of \( v_{m} \) is set as 0.75 by simplifying sand grains into regular spherical grains.

Avalanche phenomenon on the barchan surface during evolution can be explained by the slope angle \( \theta_{t} \), which exceeds the angle of repose \( \theta_{rep} \). Instantaneous slippage occurs under the action of gravity, and sands are reallocated to different positions of the dune. Avalanche is a mechanism that drives the evolution of dunes and should be described using a specific model. The avalanche flux related to dune height (Duran et al., 2010) is converted into the concept of diffusion flux proposed by Ortiz and Smolarkiewicz (2006) to introduce a diffusion term in the dune evolution equation:

\[
q_{ava} = -\rho_{s}K\nabla h
\]

(13)

where \( K \) is the diffusion coefficient, which depends on the time step and the grid spacing of the simulation. When \( \theta_{t} \leq \theta_{rep} \), no avalanche or slippage will occur. At this time, \( q_{ava} = 0 \). Thus,

\[
K = \begin{cases} E(\tan h(\nabla h) - \tan \theta_{rep})/|\nabla h|\rho_{s}, & |\nabla h| > \tan \theta_{rep} \\ 0, & |\nabla h| \leq \tan \theta_{rep} \end{cases}
\]

(14)

where \( E \) is the empirical model parameter. The empirical value is set as –0.9 to ensure the stability of the calculation.

Changes in the sum of \( q_{ava}, q_{rep} \) and \( q_{crep} \) are equivalent to alterations in the average velocity of dune in the horizontal direction \( u_{t} \) and in the dune height \( h \). The total vertically integrated sand flux is obtained by considering the avalanche flux.

\[
q = \rho_{s}(u_{t}h - \kappa \nabla h)
\]

(15)

After substituting Eq. (15) into Eq. (6), the mass conservation equation of dune used for discretisation is obtained.

\[
\nabla (uh) + \nabla \cdot u_{t}h = \nabla \cdot \kappa \nabla h
\]

(16)

2.3. Numerical method

SIMPLE algorithm (Patankar, 1980) based on finite control volume technique is used to couple gas phase velocity field and pressure field. Eq. (16) is a continuous equation for dune height and has a similar form to the momentum equation for the gas phase. The transient, convective and diffusion terms are shown from left to right of the equation. Therefore, discretising scheme is adopted for the corresponding terms in the equations for gas phase and dune. The stability-guaranteed second-order difference scheme is employed for spatial discretisation of convective term (Li and Tao, 2002); the second-order central difference scheme is used for diffusion term; and the fully implicit scheme is used for the transient term. The numerical process is as follows. (1) Gas phase field is calculated iteratively using the time step \( \Delta t \). (2) After iteration for two time steps, the evolution of the dune is calculated iteratively using the time step in equation for dune \( \Delta t \). (3) After obtaining the dune height \( h(x,y,z,t) \) at different positions at this point in time, the iterative steps before the iteration of gas phase field are repeated, and a new distribution of heights of dune \( h(x,y,z,t + \Delta t) \) is obtained. (4) These steps are repeated until the entire structural evolution process of the dune is simulated.

3. Coordinate conversion and simulation conditions

3.1. Coordinate conversion

The equation under the physical coordinate system \((x,y,z,t)\) must be converted under the calculation coordinate system \((\xi, \eta, \zeta, t)\) to conduct discretisation. The following treatment is adopted based on the actual physical process of the evolution of dunes (Wedi and Smolarkiewicz, 2003): \( x = \xi, y = \zeta, t = t \) and \( \eta = L_{p}(y - h)/(L_{p} - h) \). Thus, the Jacobian determinant for the transformation of governing equations is obtained. \( J \) can be expressed as \( J = \frac{1}{\partial \xi/\partial x \partial \eta/\partial y \partial \zeta/\partial z} = \frac{1}{L_{p}} = (L_{p} - h)/L_{p} \). An analogy is inferred with the general conversion of coordinates by combining the Jacobian determinant \( J \) and the terms that involve the geometry of the grid, namely, \( \partial /\partial \xi, \partial /\partial \eta, \partial /\partial \zeta \). The specific implementation process is shown in the work of Anderson (1995). The size of the calculation domain in stream-wise, vertical and span-wise directions is \( L_{x} \times L_{y} \times L_{z} = 7.225 \times 2.131 \times 3.825 \) m; and the grid number is \( N_{x} \times N_{y} \times N_{z} = 72 \times 42 \times 39 \). The equation is discretised using the staggered grid system. The calculation domain and staggered grid system are shown in Fig. 1(a).

3.2. Simulation conditions

3.2.1. Boundary conditions

Wind flows from the inlet to the outlet of the calculation domain. Periodic boundary conditions are set for stream-wise
and span-wise directions of the calculation domain. Symmetrical boundary conditions are set at the top interface in the vertical direction. The vertical component of wind speed is set to zero at the top interface. The gradients of other variables of the flow field along the vertical direction are set to zero. The bottom interface is the wall boundary layer (including the dune surface). No slip is set for the wind field at the bottom interface. A semi-empirical formula is adopted as wall functions based on the work of Werner and Wengle (1991) to model the near-wall region of the high Reynolds turbulent wind flow field because of the large eddy simulation in the computational fluid dynamics framework. After the wall shear stress in the near-wall control volume is calculated as shown in Fig. 1(b). The symbol \( \tau_w \) is the position of the ensemble average. Here, \( \langle U \rangle \) is the ensemble-averaged stream-wise wind speed at the inlet of the calculation domain; hence, the inlet stream-wise wind speed is averaged spatially along the span-wise direction of the calculation domain at each step and then averaged temporally over the entire statistical time step. The wind speed of the main flow \( U_0 = 14.5 \text{ m} \cdot \text{s}^{-1} \), and the friction velocity is \( 0.608 \text{ m} \cdot \text{s}^{-1} \). The initial values of the vertical component \( v \) and span-wise component \( w \) of wind speed are set to zero.

The following Gaussian function is used to simulate a single initial dune:

\[
h = h_0 \exp\left(-\frac{(2r/r_0)^2}{\ln 2}\right),
\]

where \( h_0 \) and \( r_0 \) are the height of the highest point on the surface of the dune and the radius of the bottom of the dune, respectively; and \( r \) is the position function, that is, \( r = \sqrt{(x-x_0)^2 + (z-z_0)^2} \), where \( x_0 \) and \( z_0 \) are the coordinates of the central point at the bottom of the dune in the stream-wise and span-wise directions, respectively. The initial structure and position of the dune in the physical domain are shown in Fig. 2.

### 3.2.2. Simulation conditions

The simulation parameters are set as follows: average grain diameter, \( d_i = 250 \mu\text{m} \); sand porosity, \( \lambda = 0.38 \); air density, \( \rho_a = 1.225 \text{ kg} \cdot \text{m}^{-3} \); and dynamic viscosity of air, \( \mu_a = 1.8 \times 10^{-5} \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \). The Courant–Friedrichs–Lewy (CFL) condition is considered to determine the limited range of time step. The maximum Courant number can be estimated as follows (Koutsourakis et al., 2012):

\[
\text{CFL}_{\text{max}} = \Delta t \max \left(\frac{|u|}{\Delta x} + \frac{|v|}{\Delta y} + \frac{|w|}{\Delta z}\right) \leq 0.3.
\]

In this case, the time step is less than or equal to \( 2.0 \times 10^{-3} \text{ s} \). The iteration time step value should be reduced at least in the order of one for the wind flow equation to obtain high precision of the large eddy simulation. Therefore, in the present simulation, the time step for the equation for wind is \( \Delta t = 2.0 \times 10^{-4} \text{ s} \), and time step for the equation for dunes is \( \Delta t = 2.0 \times 10^{-3} \text{ s} \). As shown in Fig. 3, based on the fact that the threshold of grain liftoff in sand motions can be adjusted through oscillation, a vertically oscillating plate used to hold the sand bed and the dune were introduced in the wind tunnel experiment of Zhang et al. (2014). The instantaneous acceleration of gravity of individual grain can change over time because of the effect of plate oscillation. In this case, the initiation and the amount of sand grains for splash can be regulated to influence the evolution of dunes. This modulation approach is called “gravity modulation” (Fig. 3(b)). In the present model, changes in dune height in every grid cell position on the \( x-z(\xi-\zeta) \) surface are used to show the variation in dune surface with time. This morphological process is related to the mesoscale aspects of sand flux, and the tracking of the movement of individual sand grains on dune surface is infeasible. Considering this narrow limitation, the upward influx, as one modulation similar to the natural evolution of barchans, cannot be realised. The same form of gravity modulation used in the wind tunnel experiment (Zhang et al., 2014) is used in the present simulation because upward influx and gravity modulation are comparable (Zhang et al., 2014). The oscillation of the bed surface is simulated using the cosine function of gravity acceleration, which changes over time. The threshold for sand...
grains to start oscillation is changed through gravity modulation. Therefore, the saturation of wind-sand flow can be regulated. The influence of modulation of gravity on the evolution of downsized crescent-shaped dunes is also discussed. The cosine function of gravity modulation is expressed as
\[ g(T) = g_0 + 4\pi^2 M \cos(2\pi T), \]
where \( g_0 = 9.81 \text{ m} \cdot \text{s}^{-2} \); \( M \) is the modulation factor with values of 0.2, 0.4, 0.6 and 0.8, which correspond to four simulation conditions. This function can be used to characterise the intensity of gravity modulation. The initial height of the dune is 0.075 m, and the radius of its bottom is 0.390 m.

The dimensionless similarity criterion is determined based on simulation parameters. In the simulations, the wind speed of the main flow \( U_0 \) and the initial height of the dune \( h_0 \) are set as two characteristic parameters, which correspond to Reynolds number \( \text{Re} = U_0 h_0 \rho g / \mu_g = 7.40 \times 10^4 \) and Froude number \( \text{Fr} = U_0 / \sqrt{gh_0} = 16.90 \).

4. Results and discussion

4.1. Grid refinement study

A grid refinement study or a grid independence test is required to determine the proper grid size in the present study. Grid independence test is used to study the sensitivity of the numerical solution to the size of the grid and then decide the value of grid number to be used for the simulations. A grid independence test is performed by systematically increasing the number of grid nodes and comparing the results. After comprehensively considering the convergence, precision, and efficiency of the simulation, three grid systems are adopted: \( 62^2 / 32^2 / 29, 72^2 / 42^2 / 39 \) and \( 82^2 / 52^2 / 49 \), which correspond to the coarse, medium and fine grid sizes, respectively. Fig. 4 shows the result of the comparison. As shown in Fig. 4, \( T_u \) is the predicted turbulence intensity of free stream wind flow \( T_u = (\langle u'^2 \rangle)^{1/2} / U_0 \), where \( u'_y \) is the stream-wise component of instantaneous fluctuating velocity of wind. After a grid system of \( 72^2 / 42^2 / 39 \), the profile of \( T_u \) does not significantly change with grid size. Therefore, using the grid number \( N_x \times N_y \times N_z = 72 \times 42 \times 39 \) for the present simulation is appropriate.

4.2. Evolution pattern of a single dune

The evolution of a single downsized dune under the condition of \( M = 0.8 \) over time is shown in Fig. 5. The distribution of instantaneous wind field speed on the dune surface at different time points under the condition of \( M = 0.8 \) is shown in Fig. 6. Fig. 5 shows that the dune dwindles and finally decomposes over time because of the erosion of windward face, deposition, avalanche and low-rate
backflow at the leeside (Fig. 6). At a certain time point during the evolution, the sand body takes a crescent shape, which cannot be maintained dynamically. Similar rules of evolution are observed under other simulation conditions. These unstable dune evolution processes are also observed in the experiment of Zhang et al. (2014) under the same gravity modulation and in the experiment of Andreotti et al. (2002) under the upwind influx effect. Fig. 5 shows that, with the middle point of the dune as the datum, the dune in the span-wise direction is not strictly symmetrical. This feature, which occurs during the reconstruction of the dune surface, is also observed in the wind tunnel experiment and water channel experiment for downsized barchans under the unidirectional medium flow condition (Andreotti et al., 2002; Franklin and Charru, 2011). Field studies (Bourke, 2010) and model simulations (Parteli et al., 2014a) on barchan asymmetry show that asymmetry is caused by four potential mechanisms, namely, bi-directional winds, dune collision, topography and influx asymmetry. However, in the present simulation, only the evolution process of an isolated downsized dune on the flat bed under the actions of wind field with a single wind direction is investigated. This process is simplified compared with the real dune fields. Therefore, the potential causes for existing slight asymmetry are unlikely to be bi-directional winds, dune collision and topography. As upwind influx is not used to influence dune evolution in the simulations, influx asymmetry does not influence dune asymmetry. The slight asymmetry of crescent-shaped dune body could be attributed to several factors. Firstly, in the simulations, periodic boundary conditions are set for stream-wise and span-wise directions of the calculation domain to ensure mass conservation for wind field and dunes. Therefore, the downstream turbulent flow from the leeside of the dune may disturb the upwind flow during dune evolution. In this case, the dune body may become asymmetric. This finding may explain why the upstream distribution of instantaneous turbulent wind field speed on the dune surface at a certain time point displays an asymmetric pattern (Fig. 6). Furthermore, although the crescent shape of downsized dune is reproduced with the action of gravity modulation, the crescent shape cannot be maintained dynamically all the time. Under the influence of wind erosion at the windward side combined with the complex recirculating flow structures at the lee side, the dune body gradually shrinks. These phenomena may contribute to the asymmetrical propagation of the two limbs of crescent-shaped dune.

4.3. Influence of gravity modulation intensity on structural parameters of dunes

Changes in dune height under different gravity modulation intensities over time are shown in Fig. 7(a). All of the simulated curves are the results of secondary polynomial fitting. The data of the wind tunnel experiment (Zhang et al., 2014) in the figure are the results of nondimensionalisation of the square root of the project area in the top view, which also reflect changes in dune height under erosion. Nondimensionalisation is performed using the following equation to facilitate the comparison of results:
$H = \frac{h_{\text{max}}(T)}{h_0}$, where $h_{\text{max}}(T)$ is the height of the highest point on the dune surface at the time point $T$. The scope of variation of $H$ under different intensities of gravity modulation is shown in Fig. 7(b). Here, $\Delta H$ denotes the range of $H$ for a single $H - T$ relationship at $T = 90.0$ s. Both the simulated data and the corresponding experimental data curves are the results of secondary polynomial fitting. Fig. 7(a) shows that $H$ finally decreases with increasing $T$ under a fixed value of $M$. Therefore, the wind-sand flow on the dune surface is not yet saturated during erosion. As $M$ increases linearly, the curve of $H - T$ gradually converges (Fig. 7(b)). Thus, as $M$ increases, the wind-sand flow reaches saturation gradually. The results are consistent with those from wind tunnel experiments (Zhang et al., 2014). Changes in gravity modulation intensity in the wind tunnel experiments can alter saltation flux, thereby regulating the saturation state. However, the movement of discrete sand grains is not simulated in the present dune model. Therefore, changes in gravity alter the sand flux in the constitutive equation and regulate the saturation. This comparison indicates that the simulation and the experiment achieved consistent results with regard to the regulatory effect of gravity modulation on the saturation of wind-sand flow.

The combination of Fig. 7(a) and (b) shows that the coincidence between the simulation result and the experimental data increases with increasing gravity modulation intensity. The finding also indicates that high gravity modulation intensity result in the saturation of wind-sand flow.

5. Conclusion

In this study, large eddy simulation was coupled with a dune constitutive model. This approach was used in the 3D numerical simulation for the entire aeolian flow field to investigate the evolutionary characteristics of downsized crescent-shaped dunes under the influence of gravity modulation. Results show that the proposed model can reproduce a crescent shape, which is not strictly symmetrical. The unstable evolution rule of dune from the simulation agrees with that from the corresponding wind tunnel experiments. Dune height decreased over time, and the height–time curve gradually converged with the linear increase in gravity modulation; this finding agrees approximately with the result of the wind tunnel experiment. Hence, the gravity modulation mechanism embedded in the present model potentially...

Fig. 6. Low-speed flow region at the leeward face of crescent-shaped dune at a certain time point during evolution ($M = 0.8$).

Fig. 7. Influence gravity modulation intensity on dune height: (a) variation in $H$ with time; and (b) scope of variation of $H$ with linear increase in gravity modulation intensity.
affects the regulation of the saturation level of sand flux above the
dune surface, thereby considerably producing the macroscopic
crescent-shaped dune configuration at the laboratory scale.

The simulation outcome agrees with the experimental results,
thereby indicating that the proposed modelling approach could
facilitate the study of the morphodynamic process of aeolian dunes
at the laboratory scale and their comparison with natural cases.
Furthermore, this model combined with the computational fluid
动力学 framework to investigate the interaction dynamics of
two or more barchans in depth is feasible because it can reveal
reverse flow at the lee. Finally, morphodynamic modelling of aeo-
lion dunes (Parteli et al., 2014b) has provided insights for develop-
ing application models for determining the effect of biogenic crust
or space module of fences on dune morphology. This model is a
potential tool to deepen understanding of the physical processes
and fundamental principles in preventing soil erosion.

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