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Numerical simulation of the evolution and propagation of aeolian dune fields toward a desert–oasis zone

Tian-Li Bo *, Xiao-Jing Zheng

Key Laboratory of Mechanics on Western Disaster and Environment, Lanzhou University, Lanzhou, 730000, China
Department of Mechanics, Lanzhou University, Lanzhou, 730000, China

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ABSTRACT

In this study, the evolution and propagation of aeolian dune fields toward a desert–oasis transitional zone are numerically investigated through considering the spatial variation of wind speed and the influence of vegetation on sand erosion and transportation etc. The propagation speed at the edge of desertified land and the influence of a straw checkerboard are quantitatively analyzed. Results show that evolution time, wind speed and sand diameter have obvious impacts on the propagation of desert and desertified land. A formula describing the propagation speed of desertified land with respect to wind speed and vegetation coverage is given. In addition, when considering the effects of straw checkerboards, the propagation speed of the downwind desertified land is found to be related to the length of and distance from the checkerboard area.

1. Introduction

As a typical geomorphologic feature in arid and semi-arid areas, dune fields are often accompanied by oases adjacent to the edge of deserts (Wang et al., 2006). Due to the influence of human activities, such as overgrazing and excessive land reclamation, oases in arid and semi-arid areas are gradually degrading into desert–oasis transitional zones with the development and spread of desertification (Li et al., 2001; Fu and Lu, 2006; Chen et al., 2008). The desert–oasis transitional zone plays an important role in the ecological system of arid and semi-arid areas, which maintains the sustainable development of local economy and internal stability of agriculture, helps to fix mobile sand dunes, and protects the oasis from wind-blown sand damage. In addition, the mobility of the dune field is an important index for reflecting global climate change and desertification (Thomas et al., 2005; Yizhaq et al., 2009), which therefore becomes an important issue in environmental science.

Minqin, located at 103.09°E, 38.62°N, is an oasis wedging itself between the 5th and 6th largest deserts in China, the Badain Jaran Desert and Tengger Desert respectively (Wang and Cui, 2004), and prevents the two deserts from merging, as shown in Fig. 1. The area of desert and desertified land in Minqin has already reached up to 14,450 km^2, taking up 91% of the total area, and the edge of desertified land is approaching the oasis at a speed of 3–4 m per year, which makes the county one of the four most important sand (dust) storm sources in China (Zheng, 2009). Since a decade ago, desertification monitoring schemes and sand control measures, including setting sand fences and straw checkerboards, have been implemented to maintain the oasis from the invasion of aeolian dunes at the edge of deserts and desertified lands.

Due to the extremely large spatial and temporal scales involved in the evolution and propagation of aeolian dune fields, existing observational facilities and schemes have not achieved a panoramic survey of the whole process of dune fields in the desert–oasis transitional zone. However, theoretical modeling and numerical simulations have provided important insights to the evolution of dune fields in desert–oasis transitional zones (Nishimori and Ouchi, 1993; Werner, 1995; Momiji et al., 2000; Sauermann et al., 2001; Schwammle and Herrmann, 2003; Parteli et al., 2007; Narteau et al., 2009).

It has been argued that vegetation coverage has an important impact on the morphology of aeolian dunes (Wasson and Hyde, 1983; Rubin and Hunter, 1987), which therefore has an influence on the evolution of dunes and dune fields. In this field, the most significant issue is dunes' stability and the barchan–parabolic dune transition process. Parabolic dunes have long arms that point upwind and noses that point downwind. They arise commonly as a result of the stabilization of barchan dunes by vegetation (Hack, 1941; Gaylord and Stetler, 1994; Muckersie and Shepherd, 1995; Anthonsen et al., 1996; Tsoar and Blumberg, 2002; Yizhaq et al., 2007). The barchan–parabolic dune transition process has been observed on individual dunes where changes in climate or land-use have introduced vegetation to a dune surface, the reversal of parabolic to barchan shape upon the removal of vegetation has also been observed, and barchan–

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* Corresponding author at: Key Laboratory of Mechanics on Western Disaster and Environment, Lanzhou University, Lanzhou, 730000, China. Tel.: +86 931 8915336; fax: +86 931 8915336.
E-mail address: btl@lzu.edu.cn (T.-L. Bo).

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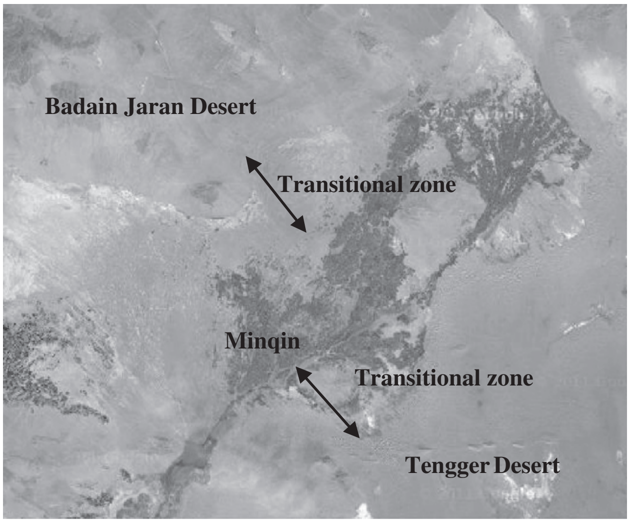

Fig. 1. The desert–oasis transitional zone of Minqin, China.

parabolic dune pattern transition from vegetation stability threshold has been proposed (Hack, 1941; Anthonsen et al., 1996; Tsoar and Blumberg, 2002; Wolfe and Hugenholtz, 2009; Reitz et al., 2010).

Quantitative simulation is another important method with which to study this phenomenon. Cellular automaton and continuum models have simulated parabolic dune formation and furthered our quantitative knowledge of the barchan–parabolic transition. The cellular model of Nishimori and Tanaka (2001) partially succeeded in capturing the transition. In their simulation, barchan dunes temporarily gave rise to parabolic forms that were unstable. A cellular model by Nield and Baas (2008), which simulated the development of parabolic dunes from blowouts rather than barchans, produced stable parabolic dunes by incorporating two plant species requiring different growth environments. The continuum model that simulates the barchan–parabolic transition is that of Durán et al. (Durán and Herrmann, 2006; Luna et al., 2009), which uses a set of differential equations relating the relative timescales of vegetation growth and dune surface erosion/deposition. Their simulation succeeds in qualitatively reproducing the transition process and predicts a critical ratio θ_c of total surface change to vegetation growth rate, above which a barchan is stable and below which vegetation takes hold and a parabolic dune forms. Durán et al. (2008) compared the vegetation cover on a dune blowout in Brazil to a simulated blowout with an arbitrarily selected fixation index and find qualitative similarity. In addition, Luna et al. (2011) achieved the quantitative simulation of coastal dune field which has a length of 512 m transverse to the wind and 1024 m in the wind direction using the continuum model; in their paper, they discussed the influence of sand influx, the width of the vegetation-free backshore, maximum vegetation height, vegetation growth and wind shear velocities on dune field morphology.

From above, existing simulations can be found on the impact of vegetation on the dune or dune field which focus on dune field morphology, the dune stability, and the barchan–parabolic transition process, but there has been little focus on the impact of vegetation on the propagation of the edge of desertified land and the study of the evolution of dune field in desert–oasis transitional zone. Only Yizhaq et al. (2007) proposed a model for dune vegetation cover driven by wind power that exhibited bi-stability and hysteresis with respect to the wind power. However, the establishment of their model was not based on the simulation of the dune field.

Recently, Zheng and co-workers (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a, 2011b) developed a scale-coupled model of dune fields (CSCDUNE), in which the 'sand body element' concept is proposed to bridge the multi-scales involved in the underlying processes, ranging from the motion of sand particles to the evolution of dunes as the representative element used to analyze the spallation in solids (Aidun et al., 1999). The size of the eroded 'sand body element' in the model is determined by the basic processes of wind-blown sand movements, including erosion, deposition, wind-blown sand flux and the wind intensity at various locations. The motion of the eroded 'sand body element' is determined by the transportation and deposition of the wind-blown sand flux, as well as the 'avalanche' behavior of sand particles (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a, 2011b). The relationship between the average saltation length of sand particles and the transportation length of the eroded 'sand body element' was established. Consequently, a correspondence between simulation results and the actual evolution of a dune field is obtained in both the spatial and temporal scales. The temporal and spatial scales in the model which have a span of 8~9 orders of magnitude, from the motion of a single particle (the size and saltation time of sand particles are 10^{-4} m and 10^{-2}~10^{-1} s, respectively) to the formation and evolution of the whole dune field (the size and evolution time of dune field are 10^0~10^4 m and 10^4~10^8 s, respectively), can be established. It has shown that the morphology (the relation between width, length and height) and change law (the relation between average dune height and sand supply, and the relation between dune speed and dune height) of a dune field obtained by the CSCDUNE scheme are consistent with observation results.

In this study, using the treatment of vegetation in the cellular model (Nishimori and Tanaka, 2001) and the continuum model of sand dunes (Durán and Herrmann, 2006) for reference, we conduct quantitative simulations of the formation and evolution of dune fields in the desert–oasis transitional zone, through considering the spatial variation of wind speed, the influence of vegetation cover on sand erosion and transportation of sand particles in CSCDUNE. Further, the variation laws of the propagation speed at the edge of the desert and desertified land with local wind speed, sand diameter and vegetation cover, as well as the influence law of the position and area of straw checkerboards on the propagation of the desertified land are analyzed.

2. Numerical model

2.1. CSCDUNE

In the model, the distribution of sand particle lift-off velocities is required as an initial condition to model macro-scale windblown sand flux; and a covering coefficient and a transportation factor matrix calculated by the probability of deposition and rebound, respectively, are employed to quantify the thickness and the transportation length of the eroded 'sand body element'. Through introducing the above statistical quantities, the different temporal and spatial scales over ranges that vary from the motion of a sand particle (that has an order of magnitude of micrometer) to the formation and evolution of a dune field (that has a magnitude of tens of kilometers) can be coupled within an integrated scheme. The model CSCDUNE contains two main parts. The first part gives the initial condition, that includes the initial values of the thickness of sand supply, wind speed of the incoming wind field, and time interval which is determined according to the real incoming wind field and thus maintains a uniform intensity in each time step. The second part describes the development process of a dune field, in which the following tasks can be achieved: 1) discretization of the sand bed; 2) calculation of the windblown sand flux for eroded 'sand body element'; 3) evaluation of the thickness and the transportation length of the eroded 'sand body element'; and 4) correction of the transportation and the relative position of the 'sand body element'. Details are briefly described as follows:

1) Discretization of the sand bed. In this case, the real local wind speed is calculated according to the significantly varying surface