Simulation, Prediction and Experiment on Windblown Sand Movement and Aeolian Geomorphology

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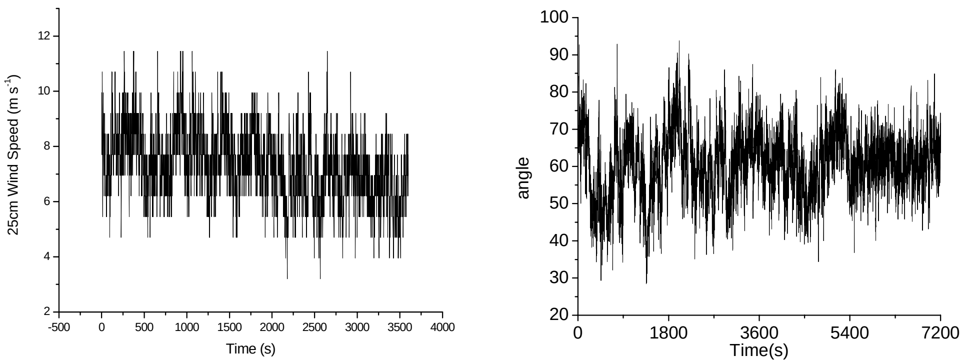
ABSTRACT: *In the evolution processes of wind blown sand movement and aeolian geomorphology, it always contains some complex behaviors, for example, the nonlinear character of turbulence and attractors, the stochastic character of wind gust, liftoff and movement of sand, the interaction among wind field, sand movement, electric field in wind blown sand flux and thermal diffusion, multi-scale character from sand ripple to dune, which deserve to be paid attention by mechanical researchers. In this paper, we introduce the recent works of our research group in Lanzhou University, China on the measurement, modeling and simulation of wind blown sand movement and aeolian geomorphology in detail.*

1. THE FLUCTUATION AND INTERMITTENCE CHARACTERS OF WIND VELOCITY AND SAND TRANSPORT INTENSITY

With instruments jointly developed and integrated by our researchers and American colleagues, we realized to simultaneously measure the natural wind profile, sand transport intensity, sand transport rate, temperature and humidity in the near-surface layer in real-time with high frequency.



(a) (b)

Fig.1 The wind velocity (a) and wind direction (b) measured respectively at the height of 0.25 meters and 2 meters above sand dune versus time.

Fig.1 shows the wind velocity at the height of 0.25meter above sand dune versus time. From Fig.1 it can be seen that in nature environment, the wind field in the near-surface layer has intense fluctuation characters. Our analysis on measured data shows that sand transport intensity also has intense intermittence character which is correspondent to the fluctuation of wind field, and wind profile does not always obey the logarithmic distribution. The wind velocity is considered as a function of two parameters: time t and height h and the whole prediction intermittent model can be expressed as:

$$u(h,t_i) = u(h_0,t_i) - u'(t_i) = U_0 + \langle u(h_0) \rangle + u''(h_0) - u'(t_i) = U_0 + p \cdot T_i \cdot (-1)^{i+1} + u''(h_0) - u'(t_i) \quad (1)$$

Based on the wind model, sand transport intensity is calculated which compare well with the measured counts (shown in Fig.2). The calculated sand transport rate with intermittent wind, however, is about 16.5% larger than that calculated with logarithmic wind (shown in Fig.3).

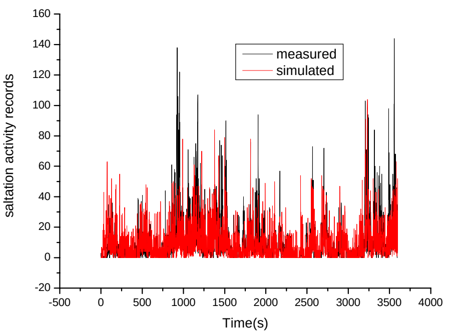


Fig.2 Comparison of saltation activity records at the height of 0.04m meter above sand dune versus time with the simulation results

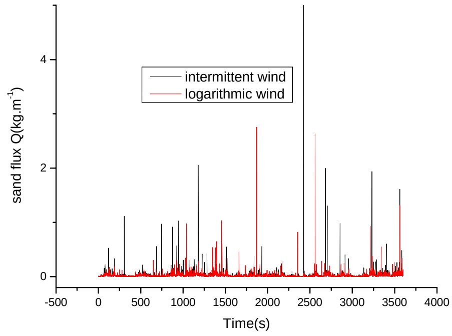
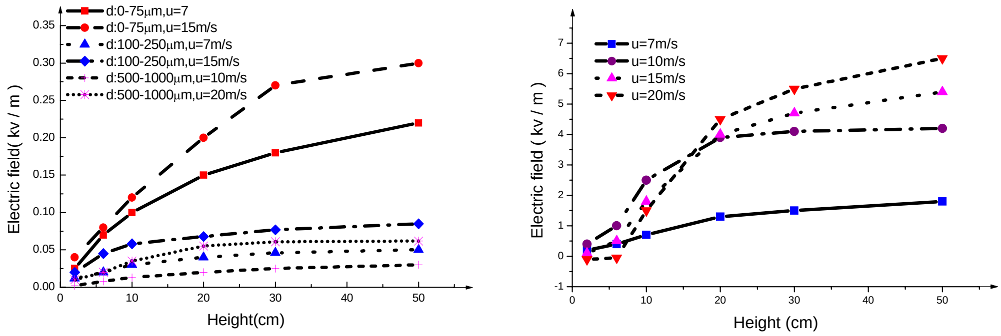


Fig.3 Simulated sand mass flux with the measured logarithmic wind versus intermittent wind

2. THE ELECTRIC FIELD IN WIND BLOWN SAND FLUX AND ITS EFFECTS

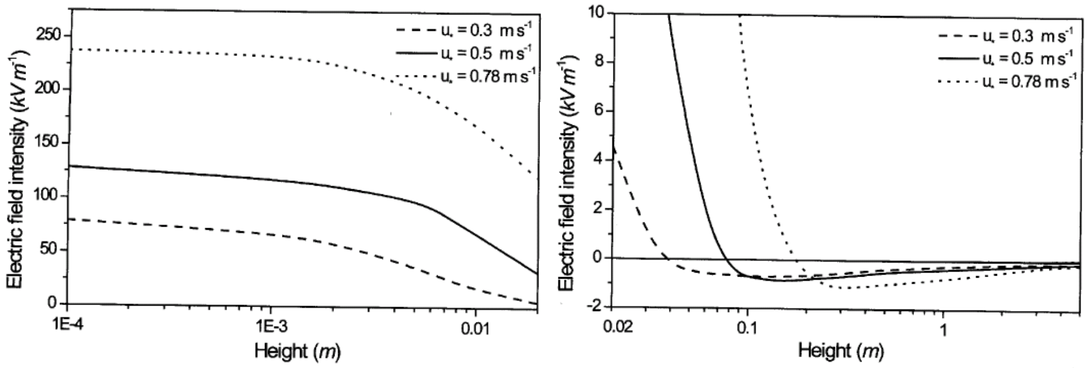
In order to investigate the electrification of wind-blown sands, we conducted experiments in the environmental wind tunnel, measuring the electric charge of sands, the distribution of electric field, sand flux and wind profile of wind-blown sand cloud. After that, we obtained the rule of Charge-to-mass Ratio and electric field changing with several controllable parameters such as the wind velocity, the height from sand bed, and the diameter of sand. The measured data shown in Fig.4 exhibit that for “uniform” sands, negative charge is gained when the diameter is smaller than $250um$; and positive charge is obtained if the diameter is larger than $500um$; and that for both “uniform” and mixed sands, the average charge-to-mass ratio decreases with increasing the wind velocity, and increases with height from sand bed. Meanwhile, the measurement of electric field in wind-sand cloud related to the electric charge displays that the magnitude of electric field increases generally as the wind velocity and the height increase, and the direction of the field is always upwardly vertical to the Earth’s surface, which is opposite to that of the fair-weather field [1].



(a) (b)

Fig.4 Measurement of magnitude of electric field strength versus height in wind-blown sand cloud. (a) “uniform” sands and (b) mixed sand.

To realize the theoretical prediction on electric field of wind-blown sand movement, we established a theoretical model incorporating the mutual coupling interaction between the wind flow, sand motion and electric field, to describe the trend of electric field versus the height from sand bed in quantity, shown in Fig.6. The results indicate that: As the height increases, the electric field changes from upward to downward; In the near-surface layer, the electric field directs opposite to the fair-weather field, and the magnitude decreases quickly with height; For $10cm \le z \le 20cm$, the field becomes zero; As the height grows further, the field varies gently, with its absolute value first increases from zero to an order of several kilovolts per meter and then decrease with height to that of the fair weather field [2].



(a) (b)

Fig.5 Profile of the electric field produced by all charged particles in windblown sand flux for different wind velocities ($D = 0.25mm, c = -60\mu Ckg^{-1}$). (a) For $0.0001m \le z \le 0.02m$. (b) For $z \ge 0.02m$.

Recently, we proposed a theoretical model of wind blown sand flux, considering the interactions among wind flow, sand particles, electrostatic force, and thermal diffusion, to simulate the development process of wind blown sand flux and quantitatively analyze the effect of electrostatic force on it. The numerical results show that during the evolution of wind-blown sand flux the electric field varies along with time and height, and the electrostatic force in wind blown sand flux has an obvious influence on the development of wind blown sand movement, thermal diffusion from the sand-bed makes electric field produced by charged sand grains plays a more important role in wind-blown sand motion as its natural existence does. The comparisons between the numerical results and the experimental data for the transport rate of grains is shown in Fig.2 in which the initial friction velocity and the uniform grain-size are respectively taken as $u_* = 0.5m/s$ and $D = 0.25mm$ and the charge-mass rate are taken as $c = +60\mu C/kg$ [3].

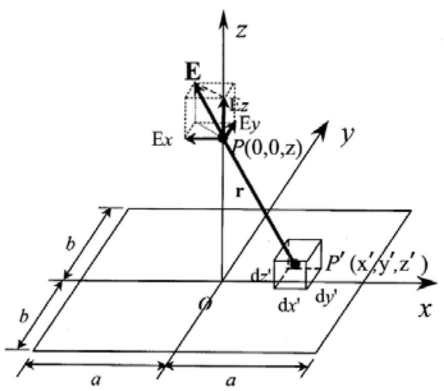


Fig.6 Schematic of the electric field produced by a point charge.

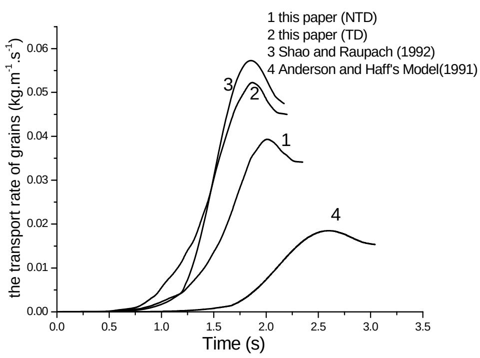


Fig.7 Comparison of simulated transport rate with and without thermal diffusion with Anderson & Haff [4] and the experimental data [5].

The study of phenomena of the effect of the sandstorms medium on electromagnetic waves can be dated to the 1940s. Haddad et al. [6] measured an attenuation of $34dB/km$ for electromagnetic waves of $9.4GHz$ in a sandstorm with $10m$ visibility, which is about 30 times higher than the estimation of $1dB/km$ predicted by conventional scattering theory. With taking into account the electric charges generated on the sand grains, we present the Rayleigh approximate solution for scattering electromagnetic wave produced by a spherical sand particle and the exact solutions for scattering field caused by sand particles with arbitrary radius and electric charge on its surface. This work successfully explained the great difference between the measured and the calculated attenuation which is as much as 30 times. The results indicate that the electric charges distributed partially on the surface of sand particles, which therefore can be concluded that friction and collision among the moving particles is a main reason for the charging of sand particles [7].

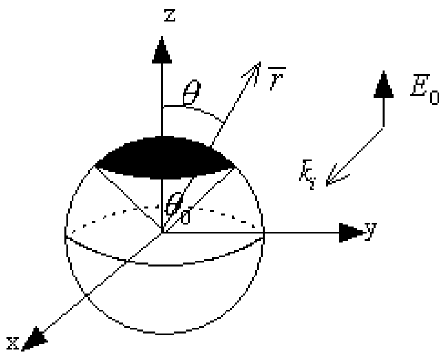


Fig.7 Schematic drawing of a sand particle with the electric charges distributed on a spherical cap (marked by the black domain) with angle θ_0 and density of surface charge σ. E_i and E_s represent the incident and scattering electromagnetic wave penetrating in the spherical sand particle, respectively.

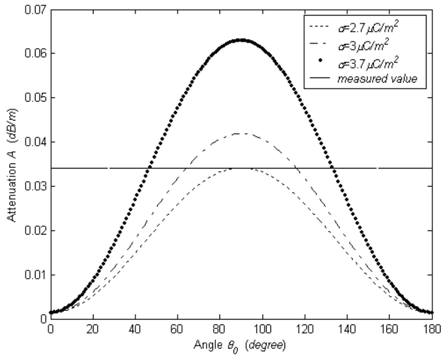
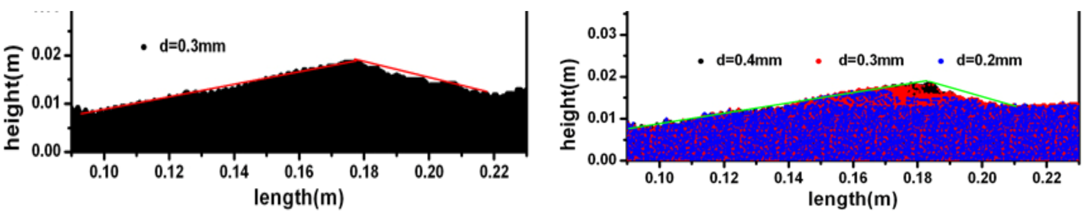


Fig.8 Characteristic curves of the attenuation coefficient varying with angle θ_0 of electric charge distribution for different densities of surface charge σ. Measured value: attenuation coefficient $A = 0.034 dB/m$

3. SIMULATIONS OF AEOLIAN GEOMORPHOLOGY

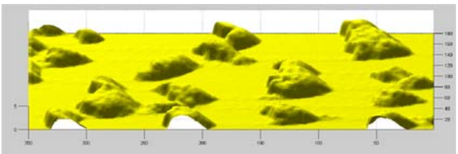
After taking into consideration of three main factors related to the formation of natural sand ripple, that is, the wind-blown sand flux above the sand bed formed by lots of sand particles with different diameters, the particle-bed collision and the rebound of impact sand particles and the ejection of sand particles in sand bed after the particle-bed collision, and the saltation of high speed sand and the creep of low speed sand, respectively, we proposed a so called discrete particle tracing method to simulate sand ripple. Using this method, we simulate the aeolian sand ripple for both single-particle-size and mixed-particle-size cases (shown in Fig. 9), and they are close to the natural aeolian sand ripples not only in shape, wavelength and amplitude, particle size segregation and stratigraphy, but also in saturated time, propagate speed and critical friction wind speed when aeolian sand ripple appear and disappear. From the simulation, it can be found that the ripple essentially propagate without changing shape and amplitude when it saturates under a given wind speed. For 0.5m/s friction wind speed, the propagation speeds of saturated aeolian sand ripple are 1.454×10^{-4} m/s and 1.885×10^{-4}m/s, respectively, of single-particle-size (0.3mm) and mixed -particle-size aeolian sand ripples, which agrees with one (2.586×10^{-4}m/s) observed in wind tunnel [8] in magnitude. Both the simulated and natural propagation speeds increase directly with friction wind speed increasing. In addition, we obtain the critical friction wind speeds of emergence and disappearance of aeolian sand ripple in simulation. For mixed-particle-size case and single-particle-size case (0.3mm), the critical friction wind speeds are same, 0.3m/s and 0.7m/s, which means that when the value of the friction wind speed is less than the 0.3m/s, the wind speed is too weak to have the aeolian sand ripples emerge. However, the sand deposition becomes difficult so that the wind ripples cannot be formed when the wind speed is stronger than 0.7m/s. Further, we investigated the effect of particle diameter on the physical characteristic and behavior of aeolian sand ripple, that is: the ripple index increases with the particle diameter decrease [9, 10].



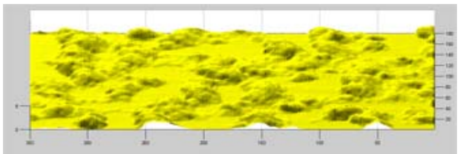
(a) (b)

Fig.9 Cross section of simulated aeolian sand ripple for (a) single-particle-size case and (b) mixed-particle-size case.

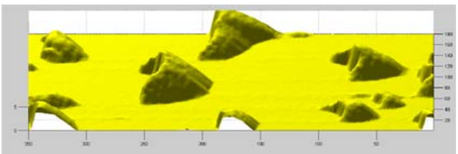
Finally, we have proposed a new simulation model to investigate the three-dimensional formation and evolution of Aeolian sand dune field which incorporates the movement of windblown sand particles, the avalanche behavior and the effect of wind speed and diameter of sand particles on the sand dune field. It is found that simulation methods we proposed not only firstly confirm the observation and measurement results both on space and time scale but also reveal some new phenomena. That is, 1) the sand thickness, for which there exists a threshold one, has very important influence on the evolution of sand field and the type of dunes, and 2) the diameter of sand particles and the intensity of wind speed have direct influence on the number and scales of dunes and the migration speed of dunes. The evolution process of the dune field is simulated and partly shown in Fig.10 for the sand thickness 0.5mm. Starting from a flat bed, we can identify three regimes: appearance of initial sand piles (see fig.10a), coarsening of small-scale dunes (see fig.10b), and finally formation of larger barchan dunes (see fig.10d). Moreover, the interaction between the dunes, such as, coalescence, taken placed in the development process of the dune field can also be searched. For instance, the two small-scale dunes in the 6th year shown in fig.3c catch up with a large-scale dune and are swallowed in the 8th year by the large-scale dune shown in fig.3d. The results exhibit that it takes about 10 years for a 8m height dune evolving from a flat sand bed with the sand thickness 0.5m and the diameter 0.3mm of sand particles under $u_* = 0.5m/s$. Further work will recover the influence of wind direction on the dune field.



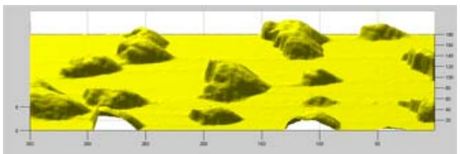
(a)



(b)



(c)



(d)

Fig.10 The development process of the dune field for $u_* = 0.5m/s$, $d = 0.3mm$ and the sand thickness is 0.5m, (a), (b), (c) and (d) are respectively for the second, 4th, 6th and 8th year.

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REFERENCES

[1]X.J. Zheng, N. Huang and Y.H. Zhou. Laboratory measurement of electrification of wind-blown sands and simulation of its effect on sand saltation movement. Journal of Geophysical Research, 108, doi: 10. 1029/2002JD002572, 2003.

[2] X.J. Zheng, L. He and Y.H. Zhou. Theoretical model of the electric field produced by charged particles in windblown sand flux. Journal of Geophysical Research, 109, doi: 10.1029/2004JD004863, 2004.

[3] G. Yue and X.J. Zheng. Electric field in windblown sand flux with thermal diffusion. Journal of Geophysical Research, 111, doi:10.1029/2005JD006972, 2006.

[4] R. S. Anderson and P.K. Haff. Wind modification and bed response during saltation of sand in air, Acta Mech., 1, suppl., 1991, 21-25.

[5] Y. Shao and M.R. Raupach. The overshoot and equilibration of saltation. Journal of Geophysical Research, 97, 20, 1992, 559-564.
[6] S. Haddad, M.J.H. Salman, R.K. Jha, Proceeding of the URSI Commission F Symposium, Louvain-la-Neuve, Velgium, SP-194 (ESA Publication, 1983) p. 153.
[7] Y.H Zhou, Q.S He, and X.J. Zheng. Attenuation of electromagnetic wave propagation in sandstorms incorporating charged sand particles. Eur. Phys. J. E 17, 181-187, 2005.
[8] Andreotti B, Claudin P, Pouliquen O. Aeolian Sand Ripples: Experimental Study of Fully Developed States. Physical Review Letters, 2006, 96:028001
[9] Bo, T.-L. Xie, L. Zheng, X.-J.. Numerical approach to wind ripple in desert. International Journal of Nonlinear Sciences and Numerical Simulation. 2007(2): 223-228
[10] Zheng XiaoJing, BO TianLi, XIE Li. DPTM simulation of aeolian sand ripple. Sci China, Ser. G.， 2008 51 (3): 328-336