NUMERICAL STUDY OF THE FORMATION OF LINEAR DUNES

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Three-dimensional flow over the sand dunes have been studied numerically by using Large-Eddy Simulation (LES) method. In the direction of initial flow and span direction cyclic boundary conditions are imposed for velocity and pressure. The movement of the sand dune which is formed by converging wind direction has been investigated. The numerical method employed in this study can be divided into three parts: (i) calculation of the air flow over the sand dune using standard MAC method with a generalized coordinate system; (ii) estimation of the sand transfer caused by the flow through the friction; (iii) determination of the shape of the sand surface. Since the computational area has been changed due to step (iii), (i)-(iii) are repeated. The simulated dune, which has initially elliptic cross section, extends at the converging direction, which is known as linear dunes.

Keywords: Simulation of Linear Dunes, Finite Difference Method, Incompressible Flow, LES Method.

1. INTRODUCTION

In the recent years, one of the typical earth-environmental problems on the world is the desertification of more and more tracts of land. There are various reasons for desertification such as excessive herding of domestic animals and excessive farming that leads to the salinization of land. Therefore, we need the advance researches from many fields in order to prevent the desertification. Numerical simulation is one of the fields. If we can know what will happen on the basis of what has happened many years ago, we can find a way to prevent it. This fundamental research is performed in order to predict the movement of the sand dunes.

Linear dunes are the most common sand dunes of all inland dunes. It is formed by winds blowing from two dominant directions. In general, it is a straight ridge with slip faces on both sides, groups of these ridges, as seen in Fig. 1, appear as parallel straight lines.

Linear dunes can occur in simple or compound forms. Simple linear dunes are single ridges with slip-faces of the same size and location along the dune flanks. The simple ridges of the simple linear dunes are smaller than the ridges of compound linear dunes. The large sinuous compound forms of the compound linear dunes are also known as seifs.

It is considered that the formation of the sand dunes depend on the mass of the sand supply, the power of the wind and the steadiness of the wind direction.[4] However, it is difficult to find out these effects on the formation and the movement of the typical sand dunes by observation or experiment because of the large spatial scale of the sand dunes and the long time scale of these formations. On the other hand, using high speed computer, numerical methods seem to be powerful to investigate these phenomena. In this study, we are trying to simulate the formation of linear dunes and to make clear the mechanism of the formation of their typical shape. We also discuss the genesis of the dune formation, formed by different wind strength and different wind direction.

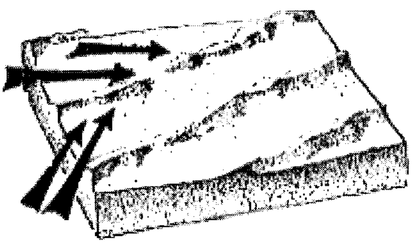

Fig. 1 Linear dunes[1]

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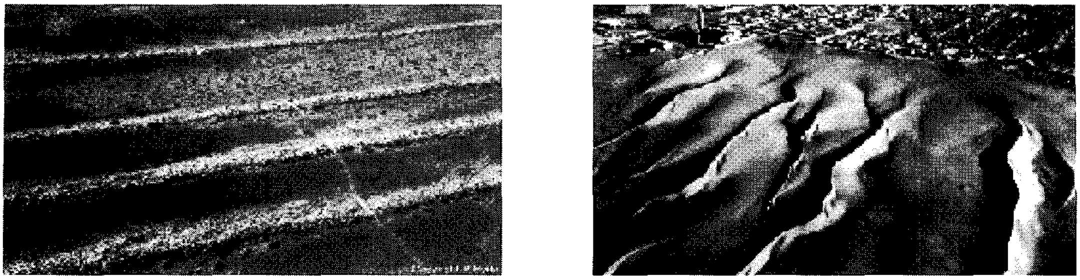


Fig. 2 Simple linear dunes (left)[2] and compound linear dunes (right)[3]

2. NUMERICAL METHODS

The numerical method employed in this study consists of the following three parts:

(i) Calculation of the air flow over the sand dune.
(ii) Estimation of the sand transfer caused by the flow through the friction.
(iii) Determination of the shape of the sand dune.

Because the shape of the sand surface is changed, steps (i)-(iii) are repeated until prescribed times.

2.1 CALCULATION OF THE AIR FLOW

All physical variables are made dimensionless by using characteristic length L_0, characteristic velocity U_0. For example, when the flow of the circumference of a hill is calculated, the uniform flow far away is chosen as a characteristic velocity, the diameter of a hill is used as a characteristic length as shown below.

The Reynolds number of the flow over the sand surface is high enough that the flow is in turbulence regime, therefore we use Large-Eddy Simulation (LES) method to compute turbulent flow over the complex geometry.[5] Standard MAC method is employed to solve three-dimensional Navier-stokes equations.

The shape of the sand dune is rather complex and will change in time. In order to impose boundary condition accurately along the sand surface, the time dependent body fitted coordinate system is used

$$\xi = \xi(x,y,z,t), \quad \eta = \eta(x,y,z,t), \quad \varsigma = \varsigma(x,y,z,t)$$

in this study. Then the computation can be done on the time independent rectangular grids.[4] Because the grid points on the sand surface are removed when the sand moving every time, so the space between the grid over the sand surface must be remade again. Namely, the space between the grid point on the sand surface and the space over the sand surface must be divided again.

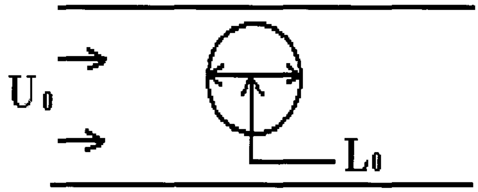


Fig. 3 Characteristic length and velocity

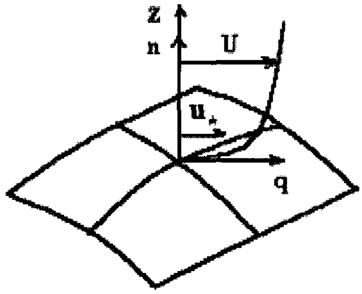


Fig. 4 Vector q, z and U on the sand surface

2.2 ESTIMATION OF THE SAND TRANSFER

According to the study of Bagnold[6], there are three types of sand transfer. They are surface creep, saltation and suspension. These processes are depending on the radius of the sand granularity and the power of the wind. It is considered by the observation in the actual sand dune that saltation is dominant among three types. In this study, we assume that the sand is transferred only by saltation and the radius of the sand granularity is the same. Equation of sand transfer is given by

$$\mathbf{q} = c\frac{\rho}{g}\mathbf{u}_*^3 \qquad (1)$$

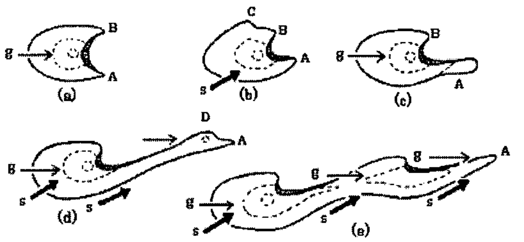


Fig. 5 The formation of linear dunes from barchan cunes[8]

Where u_* is the friction velocity, ρ is the density of the air and q is the mass transfer of the sand. [6,7] c=5.5 is the constant which is determined by the experiments. The friction velocity is given by

$$|u_*| = \sqrt{\upsilon \frac{d|U|}{dz}}, \qquad u_* \,//\, U \tag{2}$$

Where U is the velocity parallel to the sand surface and υ is the turbulent kinematy viscosity (Fig. 4).

2.3 Determination of the Shape of the Sand Dune

The sand dune will change its shape by the sand transfer estimated by the equation (1). Considering the local coordinate system along the sand surface, continuity equation of sand becomes

$$\rho_s \frac{dh}{dt} = -\frac{dq_X}{dX} - \frac{dq_Y}{dY} \tag{3}$$

Where h is the normal distance from the base plane parallel to the sand surface, $\rho_s$is the density of the sand and q_X,q_Y are the X,Y components of the vector q. X and Yare the axes determined by the base plane and the original x-z plane and y-z plane respectively. This equation means that the increment of h with time equals to the net influx of the sand into the small region. By discretizing this equation, the shape of the sand dunes are determined in every time step.

Because the time scale of the change of the air flow is quite different from that of the change of the sand surface, the time increment to integrate the equation (3) is 400 times of that used to integrate the Navier-Stokes equation ($\Delta t_h = 400\Delta t$). It means that we estimate the sand transfer every $400\Delta t$.

If the slope of the sand exceeds the maximum angle which is about 32° (an experimental constant), the height of the sand at the grid point is changed artificially both to keep the maximum value and to satisfy the conservation of the sand.

3. Results and Discussion

Bagnold suggests that linear dunes are formed when barchan dunes migrate from an area of unimodal wind into an area of bimodal winds, with one of the barchan' arms begin extend into the linear dunes. The following figure shows the formation of linear dunes from barchan dunes

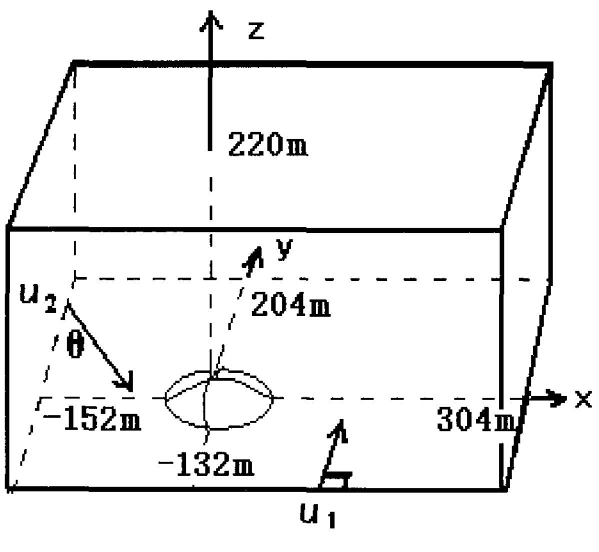


Fig. 6 Computational domain

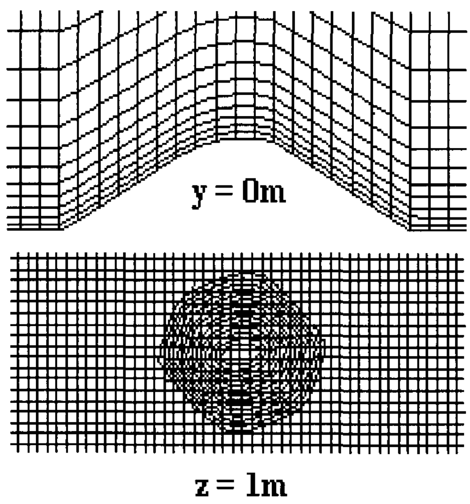


Fig. 7 Computational grid

which is suggested by Bagnold.[8]

Fig. 5(a) shows the first barchan dunes formed by wind blowing from g direction. Fig. 5(b) is the result when wind blowing from a new direction s. Barchan dune will be formed in opposition to the s-axis if the wings A progresses in a new direction, and new wings will appear in C direction when wings B shrinks. However, when wind direction is changed back to g-direction again as shown in Fig. 5(c), although it recovers symmetry to the windward side of barchan dune, but in the lee side, wings A progresses too much. When wind blowing from g-direction continuously, wings A extend to wings D as shown in Fig. 5(d). In Fig. 5(e), linear dune formed by the growing up of wings A.

In this study, we will simulate the formation of linear dunes suggested by Bagnold.

3.1 SIMULATION OF THE FORMATION OF LINEAR DUNES WHEN $|u_1|=|u_2|$

The initial sand dune is shown in Fig. 6. A hill with circular cross section parallel to x-y plane and

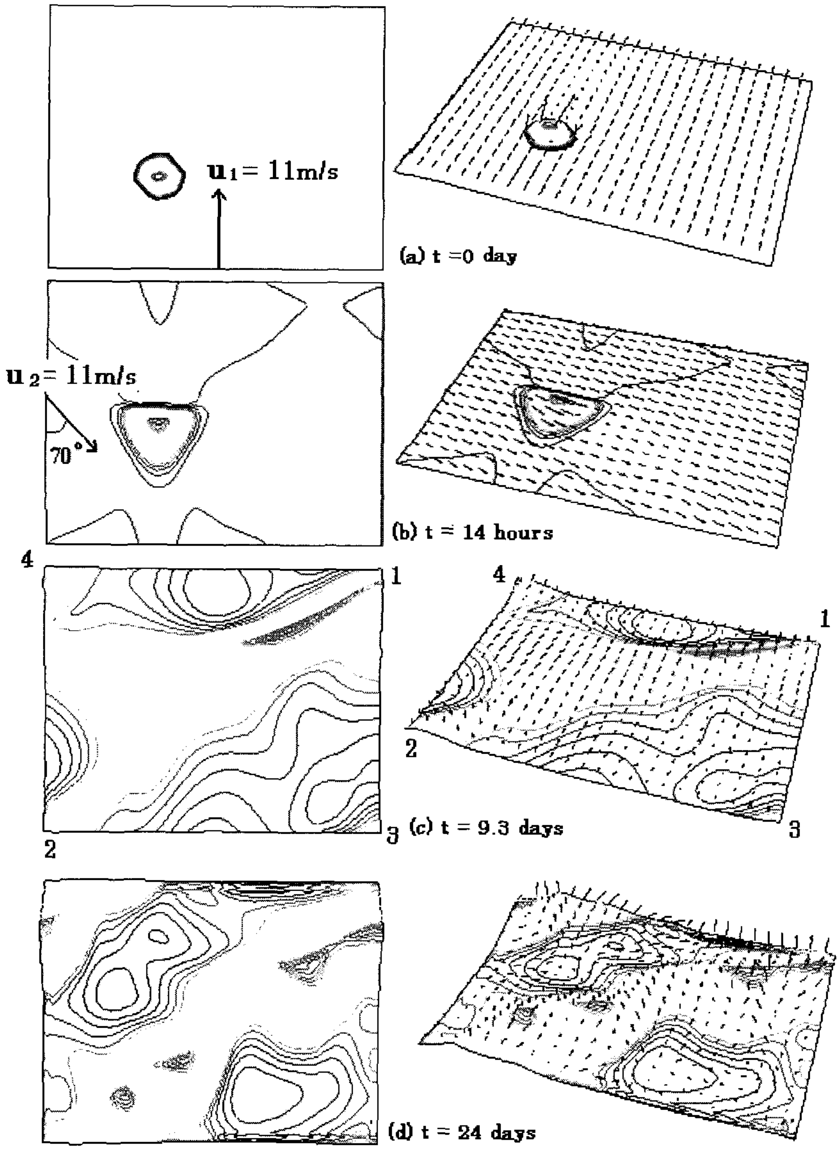


Fig. 8 Surface contours (left) and Bird's eye view of the sad surface (right) (Arrows show the velocity vectors)

parabolic cross section parallel to both x-z and y-z planes is considered in the simulation analysis. The height of the hill is 25m and the radius of the base is 30m. The number of grid points is 139 in x-direction, 117 in y-direction and 20 in z-direction. The non-uniform grids which are fine near the sand dune and the sand surface of the sand are employed (Fig. 7).

Initially uniform wind is applied in velocity of y-direction with intensity $|u_1|$=11m/s (Fig. 8). After 14 hours the wind velocity is changed with $|u_2|$=11m/s and the angle between negative y-axis and wind direction is 70°. There after, identical set of winds is applied again. It is assumed that the wind blow over the whole region.

The flow field over the fixed sand dune is calculated without movement during the first 2000 steps (40 seconds) in order to obtain the initial conditions. Time increment Δt for the Navier-Stokes equation is set to 0.02s, By using these initial conditions, the steps (i)-(iii) are repeated as mentioned in section 2 and the change of the shape of the sand dune is computed. Although the shape of the sand surface changes with time, no-slip condition is imposed because the sand moves very slowly.

Time development of sand surface contours are presented on Fig. 8. When wind is changed every 14 hours, the simulated dune which has initially

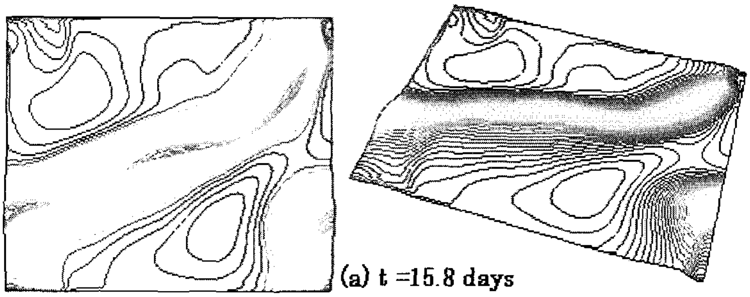


Fig. 9 Surface contours and Bird's eye view when $|u_1|=|u_2|$=10m/s

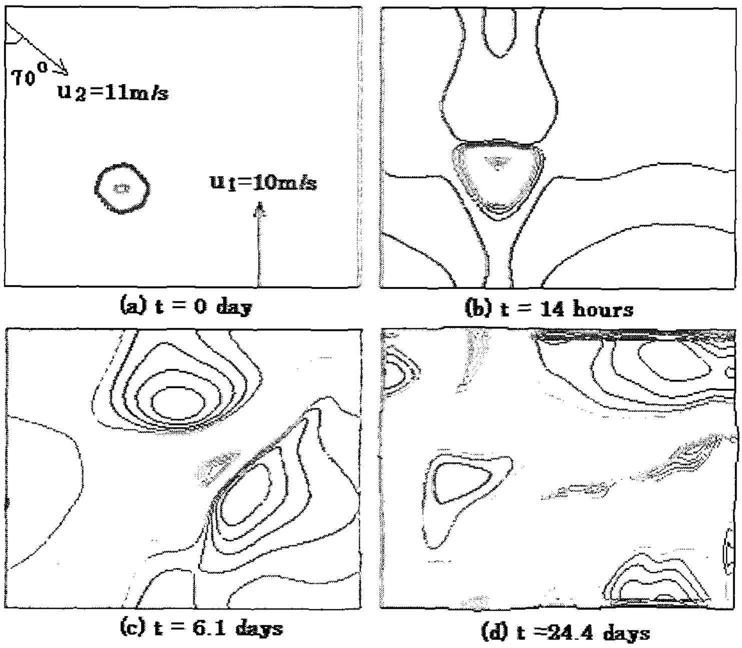
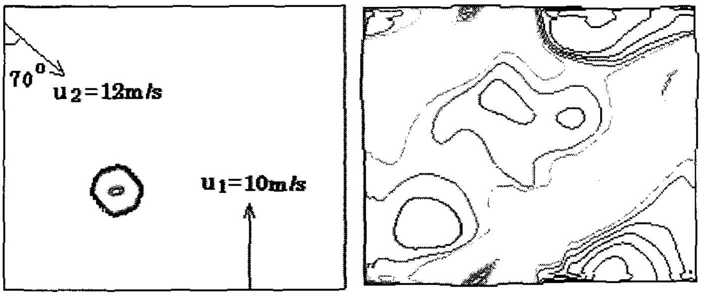
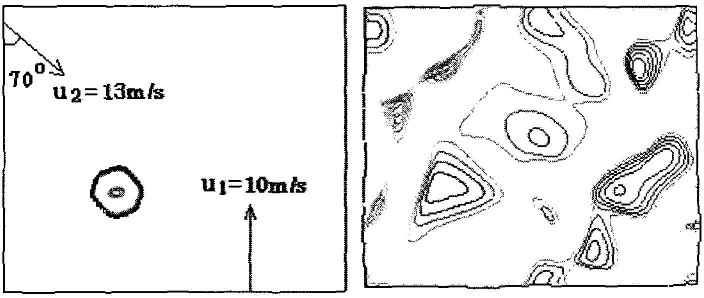


Fig. 10 Surface contours when $|u_1|$=10m/s and $|u_2|$=11m/s



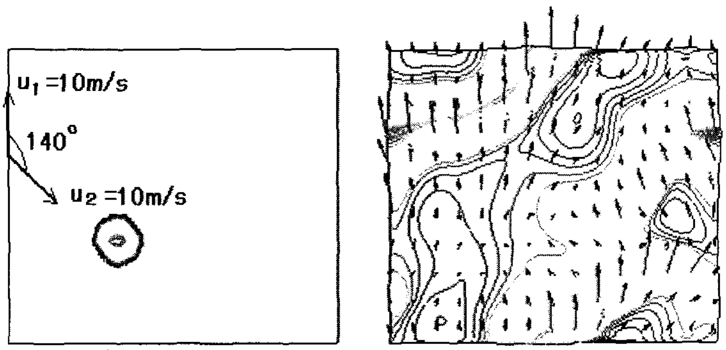
(a) t = 0 day (b) t =12 days

Fig. 11 Surface contours when $|u_1|$=10m/s and $|u_2|$=12m/s



(a) t = 0 day (b) t = 9 days

Fig. 12 Surface contours when $|u_1|$=10m/s and $|u_2|$=13m/s



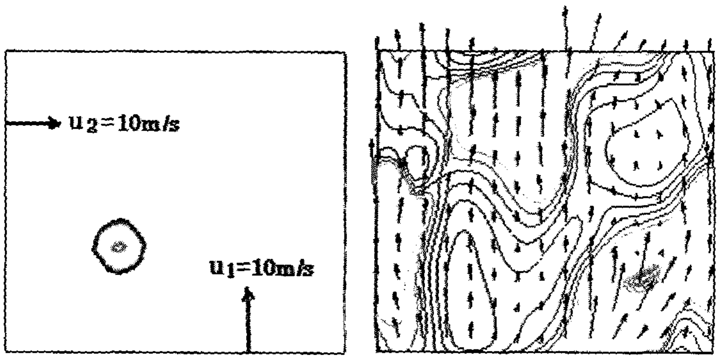
(a) t = 0 day (b) t = 25 days

Fig. 13 Surface contours when the angle between u_1 and u_2 is 140°
(Arrow show the velocity vectors)

elliptic cross section, extending at the converging direction, which is known as linear dunes. Two slip faces are seen because the wind blowing from two directions.

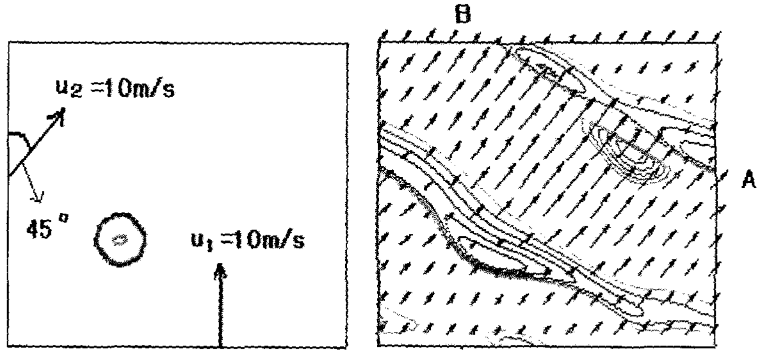
Since both in x-direction and y-direction cyclic boundary conditions are imposed for velocity and pressure, point 1 and point 2 in Fig. 8(c) are considered as the same point, so as does as in the condition of point 3 and point 4.

We also calculate the case when $|u_1|=|u_2|$=10m/s as shown in Fig. 9. When the strength of the wind is small, the formed sand dune is thin just like the simple linear dunes (Fig. 9), otherwise, the formed sand dune is more like the compound linear dunes (Fig. 8).



(a) t = 0 day (b) t = 32 days

Fig. 14 Surface contours when the angle between u_1 and u_2 is 90° (Arrow show the velocity vectors)



(a) t = 0 day (b) t = 20 days

Fig. 15 Surface contours when the angle between u_1 and u_2 is 45° (Arrow show the velocity vectors)

3.2 SIMULATION OF THE FORMATION OF LINEAR DUNES WITH DIFFERENT $|U_1|<|U_2|$

In the case of $|u_1|<|u_2|$, when the second wind is strong, because the sand dune is always orient with their axes at right angle to the wind direction, in Fig. 11(b), the simulated dune extends its axes more perpendicularly to the direction of u_2 than that in Fig. 10(b). In Fig. 12(b), the simulated dune extends its axes more perpendicularly to the direction of u_2 than that in Fig. 11(b).

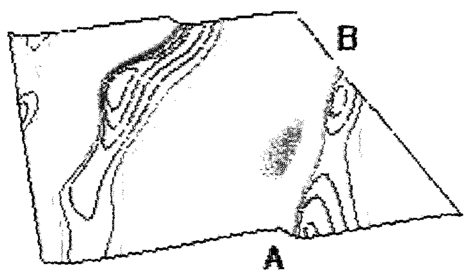


Fig. 16 Bird's eye view of sand surface when the angle between u_1 and u_2 is 45°

3.3 SIMULATION OF THE FORMATION OF LINEAR DUNES WITH DIFFERENT θ

We also simulate the formation of linear dunes with different θ, the results is shown in Fig. 13, Fig. 14 and Fig. 15.

In Fig. 13, when θ=40°, linear dunes are formed. Two slip-faces can be seen in Fig. 13(b).

In Fig. 14, when θ=90°, the simulated dune extends its axes at the converging direction between the two wind directions and becomes sinuous ridges. Two slip-faces can be seen on the two sides of the sand dunes.

In Fig. 15, when θ=135°, linear dunes are not formed, instead of it, transverse dunes are formed because only one slip-face can be seen.[8] We can see more clearly in Fig. 16.

4. CONCLUDING REMARKS

In this study, the formation of the linear dunes are simulated, the flow over the sand dunes are investigated. One hill is put on the sand surface as the initial condition. When the wind blow from two directions, the simulated dune extends in the converging direction at first, then, when a steady state is arriving, it becomes essentially parallel straight ridges in converging direction with two slip-faces on both sides.

The effect of the steadiness of wind on the shape of the formation of linear dunes is also investigated. The steadiness of the wind includes two aspects: (1) the strength of the wind velocity of u_1 and u_2, (2) the angle between u_1 and u_2. Both of the cases when $|u_1|=|u_2|$and $|u_1|<|u_2|$ linear dunes are formed. When the angle between the two directional winds are larger than or equal to 90°, linear dunes are formed, otherwise, linear dunes are not formed, instead of it, transverse dunes are formed.

Remaining problem will be planed to solve in the near future to show the clear relationship of the extending direction of the simulated sand dune.

REFERENCES

[1] Mckee, E.D., 1979, "A study of global sand seas, Introduction to a study of global sand seas," *US Geological Survey Professional Paper 1052*, pp. 1-19.

[2] http://pubs.usgs.gov/gip/deserts/dunes

[3] http://geography.massey.ac.nz/papers

[4] Thompson, J.F., Warsi Z.U.A. and Mastin C.W., 1985, *Numerical grid generation foundations and applications*, Elsevier Science Pubulishing Co. Inc.

[5] Kan, M., 2000, "Application of numerical simulation to some environmental problems in arid land," *Ph.D dissertation*, Ochanomizu University, pp.164-166.

[6] Bagnold, R.A., 1963, "The movement of desert sand," *Proc.Roy.Soc.* A157, pp.594-620.

[7] Frybeger, S.G., 1979, "A study of global sand seas, Dunes forms and wind regime," *US Geological Survey Professional Paper 1052*, pp.137-169.

[8] Bagnold, R.A., 1941, *The physics of blown sand and desert dunes*, Mathuen, London.