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INTERACTION BETWEEN WIND AND SAND SURFACE

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ABSTRACT

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Sand transport takes place when the wind speed is higher than some critical value. When the wind speed is not too high and the sand has a monodisperse size distribution it is possible that ripples are formed. Simple relationships are derived between the wavelength of the ripples, the sand-grain motion, and the increase in drag due to sand transport. The theoretical results are in agreement with field observations.

INTRODUCTION

During the summer of 1978 a micrometeorological study was carried out on the beach of the island of Schiermonnikoog (VUGTS & CANNEMEIJER, 1981). The goal of that experiment was to check the assumption that the aerodynamic roughness of the sea/surf zone and the roughness of the beach are of the same order. The assumption is valid for windspeeds below 6 ms^{-1}, measured at a height of 10 m. However, for windspeeds above 8 ms^{-1} the roughness length of the sand beach is a factor of fifteen higher than the value obtained for wind velocities below 6 ms^{-1}. This jump is caused by aeolian sand transport. Knowledge of sand transport by the wind is essential for the sand balance of a coastal area, the growth rate of artificial dunes, etc. (VAN DIEREN, 1934; SVASEK & TERWINDT, 1974). This paper explains some of the small-scale processes near the surface. Some of the relationships derived are checked quantitatively against some field data.

THE BEHAVIOUR OF SAND GRAINS IN THE AIR

Whenever the wind speed reaches a critical threshold velocity, aeolian sand transport will start. In the process of sand transport three possible types of grain motion are distinguished: suspension, surface creep and saltation (BAGNOLD, 1973). In a high wind, grains which are very small may approach suspension and remain in the air for some time. In this situation they travel at the average wind speed and cannot offer appreciable obstruction to it. Similarly the grains in the surface creep remain always on the ground and receive their forward momentum from the impact of other grains. They also offer no considerable drag to the wind by virtue of their motion. During saltation, however, when the grain is lifted into the air, it extracts momentum from the air. The momentum is dissipated in a number of surface grains at the end of the trajectory when the sand grain strikes the surface at an angle of 6 to 12 degrees. The energy dissipated drives the continuing surface creep and ejects other grains upwards to maintain the saltation process. Because the great bulk of winddriven sand moves by saltation (about 75%: BAGNOLD, 1973), momentum is removed from the air and the wind profile will be changed. Under neutral conditions the wind profile is given by:

$$u(z) = \frac{u_*}{k} \ln \frac{z}{z_0} \qquad (1)$$

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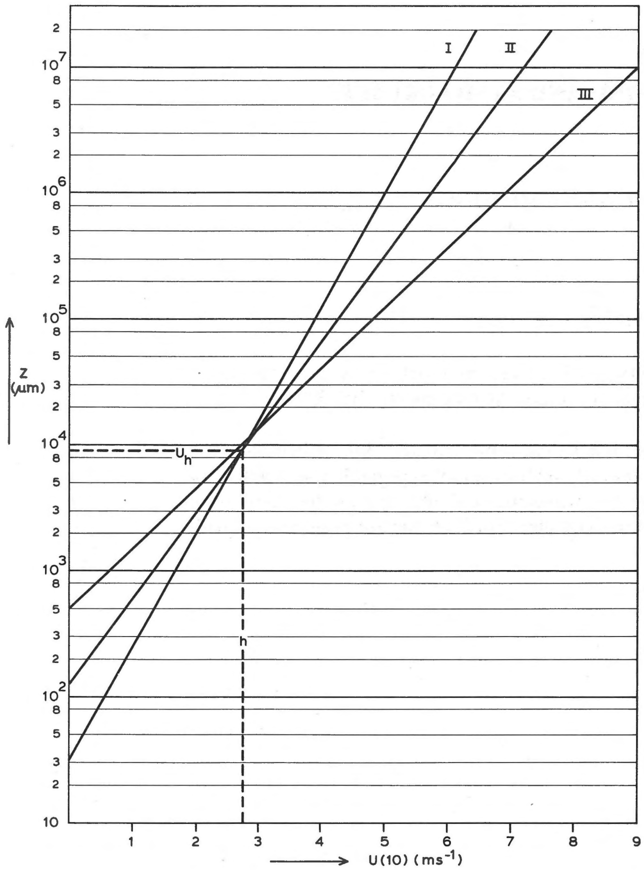

Fig. 1
Three average windprofiles taken from figure III of the paper by Vugts & Cannemeijer (1981).

	u(10)	z_o
profile I	6.1	30 μm
profile II	7.2	125 μm
profile III	9.0	500 μm

h is the height of the intersection point of the profiles I and II and u_h the corresponding wind speed.

where u(z) is the wind speed, z the height above the ground, u_* ($= \sqrt{\tau/\varrho}$) is the friction velocity, τ is the stress and ϱ the air density and k is von Karman's constant, which we take as 0.4. The roughness of the underlying surface is characterized by the roughness length z_o, the value of the intercept of the velocity profile when extrapolated to u = 0 as in figure 1. At Schiermonnikoog it was found that the sand grains start moving at a wind speed of u(10) = 6.1 ms^{-1}. This wind speed we will call threshold velocity. Below the threshold velocity the roughness length has a value of 30 μm (VUGTS & CANNEMEIJER, 1981). As the wind speed increases, more and more sand grains will participate in the saltation process which results in an increase of the roughness length z_o. Some characteristic values obtained at Schiermonnikoog are z_o = 125 μm at a windspeed u(10) = 7.2 ms^{-1} and z_o = 500 μm at u(10) = 9.0 ms^{-1}. The three wind profiles from which the values of z_o were derived, are shown in figure 1. From this figure we see that the 'u(10) = 7.2 ms^{-1} profile' has an intersection point with the 'threshold velocity profile' at a height of 0.9×10^{-2} m. The 'u(10) = 9.0 ms^{-1} profile' intersects the 'threshold profile' at a height of 1.4×10^{-2} m. The height of the intersection point, which we call h, can be interpreted as a measure for the average height to which the grains rise. This has been verified by measurements with sand collectors (BAGNOLD, 1973; CHEPIL, 1945).

Calculations show that the grains get the bulk of their forward momentum from the wind when they are travelling very near the top of the trajectory. Besides the height we have found here, there also exists a characteristic path for any given set of conditions, which is made visible by ripples on the sand surface (see figure 3). Therefore we will now consider the grain motion in more detail.

CALCULATION OF THE GRAIN MOTION

Sand grains on beaches vary in shape and diameter. Since a lot of theoretical and experimental work in laboratories has been done on the behaviour of spherical objects, the main diameter of the sand grains d_m is multiplied by a suitable shape factor to get the equivalent spherical diameter d_e. For desert and beach sand this factor can be taken as 0.75.

When a sand grain moves through the air two forces are acting on it: the force of gravity downwards, and a force due to the resistance of the air in a direction opposite to that of the relative motion u_{rel}. To simplify the calculation of the grain motion through the air the ratio of these two forces, called susceptibility S, is introduced (BAGNOLD, 1973). It varies according to the grain diameter and its velocity. Values for it can be found for spheres from existing experimental data. We start with the initial condition that the grain shoots vertically upwards with an initial velocity w_1 and a horizontal velocity u_1 = 0 ms^{-1}. This assumption is confirmed by wind tunnel studies (BAGNOLD, 1973). Then the forces of gravity and of air resistance act downwards. The grain will be retarded and after reaching the highest point it will fall. The retardation due to gravity is equal to g; and since the susceptibility S is the ratio of the two forces, the retardation due to the airdrag is gS. The total retardation at any instant is g(1 + S) and it is continuously changing in value. Actually a numerial computer calculation is necessary, but for a simple case the calculation can be done with a pocket calculator. For a description of the calculations see appendix A. Some calculated trajectories are shown in figure 2. Starting with a vertical speed of 0.50 ms^{-1} the highest point of the trajectory is 0.9×10^{-2} m. The distance travelled in this case is 8.3×10^{-2} m. In figure 3 a photograph is shown made during the conditions described above on May 31st. The small wooden poles were placed at equal distances of 20 cm, and from this picture it can be concluded that the wavelength of the ripples is about 7.8×10^{-2} m. This value is in close agreement with the length of the calculated grain trajectory. If we had started with w_1 = 0.40 ms^{-1}, the height would be 0.61×10^{-2} m and the path length 5.5×10^{-2} m, while with w_1 = 0.60 ms^{-1} the values are 1.19×10^{-2} m and 11.4×10^{-2} m respectively.

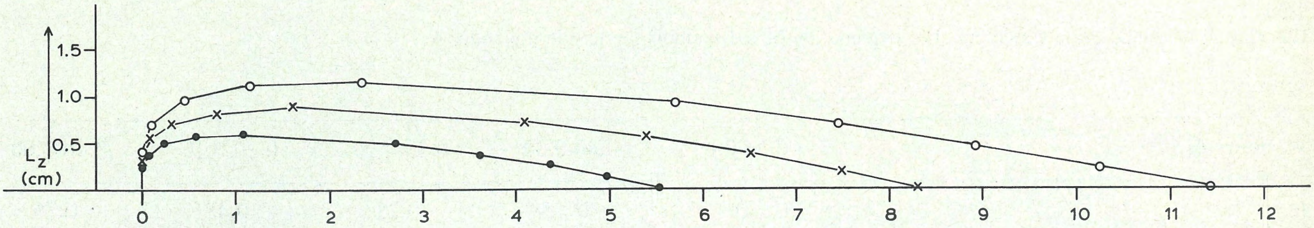

Fig. 2
Three calculated trajectories of a sand grain.
.——. : $w_1 = 0.4$ ms^{-1}; $h = 0.61$ cm; $L_x = 5.5$ cm.
x——x : $w_1 = 0.5$ ms^{-1}; $h = 0.89$ cm; $L_x = 8.3$ cm.
o——o : $w_1 = 0.6$ ms^{-1}; $h = 1.19$ cm; $L_x = 11.4$ cm.

Fig. 3
Photograph of sand ripples observed on May 31st, 1978 at $15^h 38'$ on the beach at Schiermonnikoog.
Distance between the wooden poles is 20 cm.

RELATION BETWEEN THE RIPPLES AND THE DRAG BY MOVING SAND

If a sand grain rises from the surface with a horizontal velocity u_1 and it strikes again after travelling a distance L with a horizontal velocity u_2 the momentum extracted from the air will be m $(u_2 - u_1)$ where m is the mass of one grain. This momentum is lost on impact, so if we distribute the loss over the length L, the loss per unit length will be: $m\dfrac{(u_2 - u_1)}{L}$. Similarly, if a mass q of sand in saltation moves along a path of unit width and passes a fixed point in one second, the rate of loss of momentum by the air will be $q\dfrac{(u_2 - u_1)}{L}$ per second, per unit width of path and per unit length of travel. This resisting force per unit area is the drag, and when u_1 is small compared to u_2, which is valid as we have seen, we can write:

$$q\frac{u_2}{L} = \tau' = \varrho\, u_*'^{\,2} \tag{2}$$

where the prime stands for drag on the air under sand movement conditions i.e. $u(10) > 6.1$ ms^{-1}. The actual sand transport has not been measured in our situation, so we have to use an estimated value. From the report of HSU (1971) who determined the aeolian sand transport coefficient, we take the relationship:

$$q = K\left(\frac{u_*'}{(gd_m)^{1/2}}\right)^3 \tag{3}$$

where K is defined as a dimensional aeolian sand transport coefficient with the same dimension as q. The variable K was

Table I
Calculation of a sand-grain trajectory. For explanation of the symbols see text in appendix A.

upwards

w_1 intervals	0.50-0.40	0.40-0.30	0.30-0.20	0.20-0.10	0.10-0.00
u_1	0	0	0.22	0.48	0.76
$u_{rel} = u(z)\text{-}u_1$	0	2.06	2.20	2.12	1.94
$w = w_2^2 - w_1^2$	−0.090	−0.070	−0.050	−0.030	−0.010
$v = \sqrt{\bar{w}^2 + u_{rel}^2}$	0.45	2.09	2.21	2.13	1.94
$S = 1.32\, v^{1.31}$	0.46	3.47	3.74	3.55	3.15
$S_z = \frac{\bar{w}}{v} S$	0.46	0.58	0.42	0.25	0.08
$S_x = \frac{u_{rel}}{v} S$	0	3.42	3.71	3.54	3.15
$\alpha_z = 9.81(1+S_z)$	−14.36	−15.51	−13.95	−12.27	−10.61
$L_z = \frac{w_2^2 - w_1^2}{2}$	0.0031	0.0023	0.0018	0.0012	0.0005
$t = \frac{-0.10}{\alpha_z}$	0.0070	0.0065	0.0072	0.0082	0.0094
$\alpha_x = 9.81\, S_x$	0	33.56	36.43	34.77	30.92
$L_x = u_1 t + \frac{1}{2}\alpha_x t^2$	0	0.0007	0.0025	0.0050	0.0085
$u_2 = u_1 + \alpha_x t$	0	0.22	0.48	0.76	1.05

found to be a function of the mean grain size of sand particle d_m and is given by HSU (1971):

$$\ln K = -11.98 + 4970\, d_m \quad (4)$$

with d_m in m and K in kg $m^{-1}\, s^{-1}$. Because $d_m = 18 \times 10^{-5}$ m K will be equal to 1.53×10^{-5} kg m^{-1}, and with $u_*' = 0.26$ ms^{-1} the sand transport will be 3.62×10^{-3} kg $m^{-1}\, s^{-1}$. If we substitute in the left-hand side of eq. (2) $u_2 = 1.67$ ms^{-1} (see table I) and $L = 7.8 \times 10^{-2}$ m, the left-hand side is equal to 7.75×10^{-2} Nm^{-2}. The right-hand side of eq. (2) gives (with $\varrho = 1.18$ kg m^{-3}) a drag of 7.98×10^{-2} Nm^{-2}. It is concluded that the drag calculated by the ripple length agrees with the value obtained from the wind profile. As a comparison we give the drag under the same conditions but without sand transport. Then, with $u(10) = 7.2$ ms^{-1} and $z = 30$ μm, u_* will be equal to 0.226 ms^{-1} and $\tau = 6.03 \times 10^{-2}$ Nm^{-2}. In this case the increase in drag due to sand movement is about 30%.

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APPENDIX A

For the calculation the trajectory of the grain is divided into two parts. One part in which the grain leaves the surface with a vertical speed of w_1 ms^{-1} and reaches its highest point where the vertical speed has been diminished to zero. The initial value of w_1 is such that the maximum height attained by the grain is equal to 0.9×10^{-2} m, the height h in figure 1. We start by splitting the upward motion up into a series of short equal intervals of w_1. If the intervals are small enough we can take the susceptibility S as constant for that interval. The second part of the trajectory consists of the gradual return of the grain towards the surface. The calculation for this part can be easily performed for equal vertical path length divisions.

In table I such a calculation is presented for a situation we measured on May 31st. The following values and formulae have been used:

— u_1 and w_1 are the horizontal and vertical velocities of the grain at the start of an interval in ms^{-1}; the initial conditions are: $u_1 = 0$ ms^{-1} and $w_1 = 0.50$ ms^{-1}.

— u_2 and w_2 are the horizontal and vertical velocities at the end of the interval in ms^{-1}.

— α_x and α_z are the accelerations in horizontal and vertical direction during the interval in ms^{-2}.

— L_x and L_z are the distances travelled during the interval in *downwards*

L_z intervals	0.0089 0.0071	0.0071 0.0053	0.0053 0.0035	0.0035 0.0017	0.0017 0.0000
u_1	1.05	1.52	1.63	1.68	1.69
w_1	0	0.19	0.25	0.30	0.33
$u_{rel} = u(z)-u_1$	1.62	0.99	0.66	0.27	−0.48
$v = \sqrt{w_1^2+u^2_{rel}}$	1.62	1.00	0.70	0.40	0.58
$S = 1.32\ v^{1.31}$	2.48	1.33	0.83	0.39	0.65
$S_z = \frac{w_1}{v} S$	0	0.25	0.29	0.29	0.37
$S_x = \frac{u_{rel}}{v} S$	2.48	1.30	0.78	0.26	−0.53
$\alpha_z = 9.81\ (1-S_z)$	9.81	7.37	6.92	6.94	6.14
$w_2 = \sqrt{2\alpha_z L_z+w_1^2}$	0.19	0.25	0.30	0.33	0.36
$t = \frac{w_2-w_1}{\alpha_z}$	0.0192	0.0082	0.0066	0.0057	0.0049
$\alpha_x = 9.81\ S_x$	24.36	12.80	7.64	2.58	−5.22
$L_x = u_1t + \frac{1}{2}\alpha_x t^2$	0.246	0.0130	0.0109	0.0096	0.0082
$u_2 = u_1 + \alpha_x t$	1.52	1.63	1.68	1.69	1.67

horizontal and vertical direction in m.
— $u_{rel} = u(z)-u_1$ the relative wind speed with respect to the grain in horizontal direction in ms^{-1}.
— the wind profile on May 31st with $u(10) = 7.2\ ms^{-1}$ can be represented by eq. (1), with substituting $u_* = 0.26\ ms^{-1}$, $k = 0.40$, $z_o = 125\ \mu m$ and z is the height of the sand grain in m.
— $\bar{w} = \frac{1}{2}(w_1 + w_2)$ is the mean vertical wind speed in an interval in ms^{-1}.
— $v = \sqrt{\bar{w}^{2} + u^2_{rel}}$ is the total relative wind speed with respect to the grain in ms^{-1}.
— $S = 1.32\ v^{1.31}$ is the susceptibility for sand grains with equivalent sphere diameter $d_e = 0.14 \times 10^{-3}$ m and $d_m = 0.18 \times 10^{-3}$ m. This formula is an approximation for values taken from the susceptibility diagram given by BAGNOLD (1973).
— t is time in seconds.

We have to start our calculation procedure with $w_1 = 0.50\ ms^{-1}$, because then the highest point of the trajectory will be 0.9×10^{-2} m which is the average height h the grains rise according to figure 1. When the grain reaches its highest point it has travelled 1.7×10^{-2} m horizontally ($= \Sigma\ L_x$ of the 'upwards' part of table I). When the sand grain strikes the surface the total distance travelled will be 8.3×10^{-2} m (see also table I). The parts of the calculated trajectory are given in figure 2. In the same figure the trajectories are given for initial values of $w_1 = 0.40\ ms^{-1}$ and $0.60\ ms^{-1}$ respectively.

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