Quantitative Measurements of Aeolian Sand Transport.

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Quantitative Measurements of Aeolian Sand Transport.

By Hans Kuhlman.

In Geografisk Tidsskrift, volume 56 (Kuhlman 1957) it was reported that in 1954 and 1955 quantitative determinations had been carried out of the aeolian sand transport on Skallingen, north-west of Esbjerg; the numerical values were not given on that occasion, however, they are indicated below. As far as the description of the field of research and the measuring methods are concerned, I refer to the above-mentioned publication, which also contains illustrations of the sand-traps used for the measurements, the results of which are given below. The traps were partly collecting tubes, partly a gully-shaped screen of cloth.

In my first article I tried to decribe the actual coastal region by classifying it schematically into 6 surface types, whose extent in these aeolian localities is shown (1957 a and b). For each surface type, indicated by OT and a number, the aerodynamic roughness parameter (z_0, cf. equation 3) was determined, and the sand-content was thoroughly described. The expediency of classifying the surface by means of types is a natural consequence af the formulae for aeolian sand transport found by *R. A. Bagnold* (1954), whose work is based on the modern science of hydraulics and aerodynamics, which can be studied in the following papers: *Martin Jensen* 1954, *O. G. Sutton* 1955 and *Å. Sundborg* 1955 and 1956. The relevant point in that science is the connexion between surface, turbulence and boundary layer.

Formulae for sand transport.

Let me start by defining the concept of sand: I interpret this term as a sedimentary mass whose grain diameters may be described by a distribution curve with its modal values situated in the interval from 2 to 1/16 mm. (Wentworth's classification).

On the western shore and in the dunes of Skallingen the predominant sediment is sand with a representative grain size of 0.2 mm. and sporadically with a variant of nearly 0.5 mm. When this sand is moved by the wind the process is mainly one of grain saltation or creeping (cf. Kuhlman 1957 b). If the aeolian movement of the grains takes place by saltation and surface creep the following equation, according to *R. A. Bagnold*, is applicable to the optimum transport:

$$q = b_o \, V_*'^{\,3} \qquad \text{in the C. G. S. system} \qquad 1$$

$$\text{where } b_o = C \sqrt{\frac{d_1}{D}} \cdot \frac{p}{g} \qquad 2$$

q indicates the maximum mass of sand which per unit of time passes a plane of unit width at a right angle to the wind direction. C is an empirical constant which changes according to the structure and the material of the surface. $\frac{p}{g}$ is the ratio between the density of the air and the gravity acceleration. d_1 = the grain diameter of the existing sand or the mean grain size. D = the standard grain diameter. $V_*' = V_*$, the drag-velocity,

measured on the surface covered by the sand movement, $V_* = \sqrt{\frac{\tau_o}{p}}$ where τ_o is the drag in the surface per unit of area, and p represents the density of the air.

Equation 1 is based on the conditions 1) that the moisture of the sand is insignificant or of no influence; 2) that the movement takes place on an almost horizontal plane; 3) that the variation of the wind velocity according to the height may be described by the »logarithmic profile« or derivations thereof (cf. equation 3). If v(z) represents the wind velocity at the height z the following general formula may be applied to the logarithmic wind profile:

$$v(z) = \frac{1}{ka} V_* \log_e \frac{z}{z_o} \qquad \text{for } z \geqq z_o \qquad 3$$

ka is Kármán's universal constant. z_o is the aerodynamic roughness parameter. In equation 3, and consequently in equation 1, it is assumed that the wind is turbulent and that the air has an almost adiabatic temperature gradient. *Å. Sundborg* 1955 has demonstrated that the temperature conditions above the surface are of essential importance to the transport capacity of the wind. The measurements which I have carried out and which are reported here are, strictly speaking, only valid under the above-mentioned conditions; however, in Denmark these conditions are very often satisfied thanks to the climate characterized by the common cyclones.

It is difficult to accept equation 1, *Bagnold's* formula, without reservation, because the definition has been given for all wind forces. There is no sand transport at very low wind-speeds; however, for any given grain size, there is a minimum wind force called the impact threshold, which is capable of keeping the sand moving. It is a trifle less than the wind force which starts the movement. It will be natural if with decreasing wind the value of the sand transport converges to zero at a wind force equal to the impact threshold; if so, equation 1 must be re-written as follows:

$$q = b_o \, V_*{'}^3 - K_o \qquad 4$$

$$\text{where } K_o = b_o \, V_{*t}^3 \qquad 5$$

V_{*t} is the lowest drag-velocity capable of sustaining the sand transport. I have used equation 4 as a working hypothesis.

As V_* is not directly connected with any notion and is but rarely measured via a determination of τ_o (though it was done by *A. W. Zingg* 1953) it is useful to change equation 4 by means of equation 3, so that the "wind force" is expressed by the velocity at a chosen standard height, z:

$$q_f = b_f \, v^3 \, (z) - K_f \qquad 6$$

$$\text{where } b_f = C \sqrt{\frac{d_1}{D}} \cdot \frac{p}{g} \left(\frac{ka}{\log_e \frac{z}{z_o}} \right)^3 \qquad 7$$

$$K_f = b_f \, v_t^3(z) \qquad 8$$

$v_t(z)$ is the lowest wind velocity (at the height z) capable of sustaining the sand movement. Equation 6 expresses the optimum transport capacity of the wind over firm and less firm surfaces, types 5 and 4, cf. *Bagnold* 1954 pp. 83 and 172.

As the sand transport over an incoherent, bare sand surface necessitates a modification of equation 3, as proved by *Bagnold* (1954) and *Zingg* (1953), the modified sand-transport equation for this surface, type 6, must be as follows:

$$q_l = b_l \, (v(z) - V_t)^3 - K_l \qquad 9$$

$$\text{where } b_l = C \sqrt{\frac{d_1}{D}} \cdot \frac{p}{g} \left(\frac{ka}{\log_e \frac{z}{k'}} \right)^3 \qquad 10$$

$$K_l = b_l \, (v_t(z) - V_t)^3 \qquad 11$$

V_t is the velocity at k', which is the height of the focus of the velocity profiles above the surface of type 6 covered by the sand movement. The size $v_t(z)$ is expressed, according to *Bagnold* and *W. S. Chepil*, by the following equation:

$$v_t(z) = \frac{1}{ka} A \sqrt{\frac{\sigma - p}{p} g\, d_1} \cdot \log_e \frac{z}{z_o} \qquad 12$$

A is a constant 0.08, when $d_1 \geqq 0.25$ mm. according to *Bagnold*. *W. S. Chepil* indicates A as a constant for $d_1 > 0.1$ mm. σ = the density of the sand, p = the density of the air, g = the acceleration due to gravity.

If $v_t(z)$ is placed equal to V_t and z to k', equation 12 must be satisfied by the point (V_t, k'), cf. *Bagnold* 1954 p. 105; further, from *Zingg* 1953 p. 121, we know about the point (V_t, k') that:

$$V_t = 20\ d_1 \qquad 13$$

$$k' = 10\ d_1 \qquad 14$$

when d_1 is indicated in mm. and V_t in miles per hour.

It will be seen from the above that all the elements of formula 4 have been or may be transformed into known or easily measured values. p, g, ka and σ may be considered as commonly known values. D and C are found in *Bagnold*. For six different surface types on Skallingen I have measured q, z, z_o, d_1 and v(z). As for C, D, d_1 and z_o, which describe the structure and the materials of the surface, they may vary greatly within short distances, whereas the elements $\frac{p}{g}$ and v(z) (z has been chosen as a constant), which represent certain properties of the flowing air, are but little variable within a limited experimental period. The elements of equation 4 which I particularly wanted to measure is the correlation between the wind velocity and the sand transport and the influence which the other parameters have on this correlation.

The moisture in the sand.

In a formula for aeolian sand transport it would be reasonable to introduce a parameter to express the moisture cohesion between the sand grains; or, in a more general sense, one could say that it was desired to introduce a parameter indicating the influence of rain and humidity on the masses of the sand transport. However, this would be difficult. After the discovery of the existence of sporadic, constantly dry layers of sand (Kuhlman 1957 a) it became evident that the water content of the surface had such a complicated variation that the moisture of the sand was very difficult to express representatively. 2—5 % humidity (per cent. of the dry weight) was common at the surface; but the humidity often oscillated between 0 and 15 % from one place to another in the course of short periods.

The blown sand, i. e. the sand captured by the traps, had a much smaller humidity variation, the moisture content not exceeding 1 %; however, surprisingly often the sand was sticky when the water content was a few per thousand. Although the water content of the blown sand can be expressed fairly representatively and doubtless does not exceed a certain maximum value for a given wind force, it is still doubtful whether a measured moisture content has any considerable relation to the size of the sand transport; for instance, a dry, pebbly locality in the neighbouring area may receive too little sand to saturate the wind. Further, the moisture in the blown sand is often subjected to marked changes in the course of a short time, so that a measured water content is valid only for a very limited time interval.

On account of these circumstances I have found it more useful to associate the concept of »humidity« with the weather within a certain period than with the sand. I have chosen a period which I have called »wet« and measured within this period the maximum size of the aeolian sand transport, whereas I have not examined the frequency of the measured values.

The choise of the experimental periods proved to be favourable, as July-August 1954 was extraordinarily rainy — almost each day the sand was moistened by the numerous showers — whereas July-August 1955 was unusually dry, as previously described (Kuhlman 1957 a). These two summers represent a »wet« and a »dry« weather period, respectively. My measurements of the transport capacity of the wind during the two periods are compared below with formulae for sand transport, without factors for the moisture cohesion. It may be said that the validity of formulae 6 and 9 has been examined in the dunes of Skallingen for a wet summer and a dry summer. On this basis the sand transport of each surface type will be dealt with in the following.

Transported sand masses.

Surface type 5 (OT 5). OT 5 was a firm, moist sand surface with a roughness parameter (z_0) of 0.002 cm. The moisture content varied from 1 to 10 %; 2—5 % was common. In 1955 this type was some-

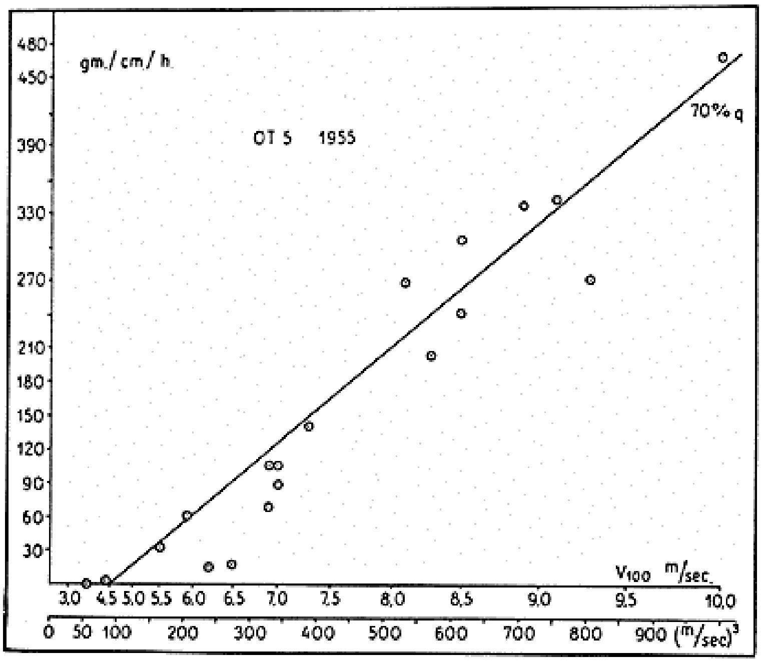

Fig. 1. The aeolian sand transport over firm, moist sand, OT 5, with wind velocities between 0 and 10 m./sec. at a height of 1 m. in the dry summer 1955 on Skallingen. The straight line is 70% of the theoretical transport, calculated from equation 15 in the text. The dots indicate the measured sand transport, for which the figures are given in table 1. The abscissa, which indicates the wind velocity, is placed along an axis which is 3-powerly divided; in order to illustrate this, the corresponding linear scale is placed immediately below. The ordinate indicates the transported sand masses in grammes.

Fig. 1. Den æoliske sandtransport over fast, fugtigt sand, OT 5, for vind mellem 0 og 10 m/sec. i 1 m's højde i den tørre sommer 1955 på Skallingen. Den rette linie er 70% af den teoretiske transport, der er udregnet fra ligning 15 i teksten. Prikkerne markerer den målte sandflugt, som ses optegnet i tabel 1. Abscissen, som angiver vindhastigheden, er afsat ud ad en akse, der er 3-potentialt inddelt; for at tydeliggøre dette er den tilhørende lineære skala anbragt lige under. Ordinaten angiver i gram de transporterede sandmasser.

times firm and almost dry as a consequence of salt-crusts in the sand. Over OT 5 the sand grains moved exclusively in long jumps, with the effect that the inertia of the grains was so great that they were able to leap far into the gully-shaped cloth screen. Collecting tubes which had been bored down into the surface measured only the bombardment per unit of surface. The capturing capacity of the traps was arrived at by a visual estimate, which should be rendered probable by the measuring material. The immediate impression received on seeing the screen being filled in a moment with half-moist sand was that the screen was a rather effective instrument in this locality. The screen together with a collecting tube seemed to capture about three-fourths of the transported mass.

Table 1.

Date *Dato* 1955	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 5. g./cm./h.	Moisture content of blown sand *Fugtighed i flyvesandet* % net dry weight *% torvægt*
24/7	3.8	0.0	
21/7	4.4	3.5	
29/7	5.5	32.7	
4/8	5.9	60.9	
30/7	6.2	15.3	+
30/7	6.5	17.2	+
2/8	6.9	116.	0.4
,,	,,	69.5	
,,	7.0	116.	
26/7	,,	88.5	
29/7	7.3	141.	+
2/8	8.1	268.	0.7
23/7	8.3	203.	+
2/8	8.5	304.	0.7
23/7	,,	240.	+
,,	8.9	335.	+
2/8	9.1	340.	0.4
,,	9.3	269.	
,,	10.0	465.	0.7

Equation 6 is presumed to be applicable to the sand transport over OT 5. I shall first deal with the measurements from the dry summer 1955, as it is most probable that *Bagnold's* theories held true in that period. In equation 6 the following values are presumed: C = 3.5, D = 0.025 cm. *(Bagnold)*, d_1 = 0.020 cm. (Kuhlman 1957 b), $\frac{p}{g} = 1.25\ 10^{-6}$, ka = 0.4 and $\log_e \frac{z}{z_o} = 2.3 \log_{10} \frac{100}{0.002}$. $v_t(100)$ is calculated from equation 12 for A = 0.08, $\sigma = 2.65$, $p = 1.22 \cdot 10^{-3}$, and g = 982; that gives $v_t(100) = 4.5$ m./sec. When these values are applied and when v_{100} is measured in m./sec., equation 6 gives:

$$q_{OT5} = 0.715\ v_{100}^3 - 65 \qquad \text{gramme/width of cm./hour} \qquad 15$$

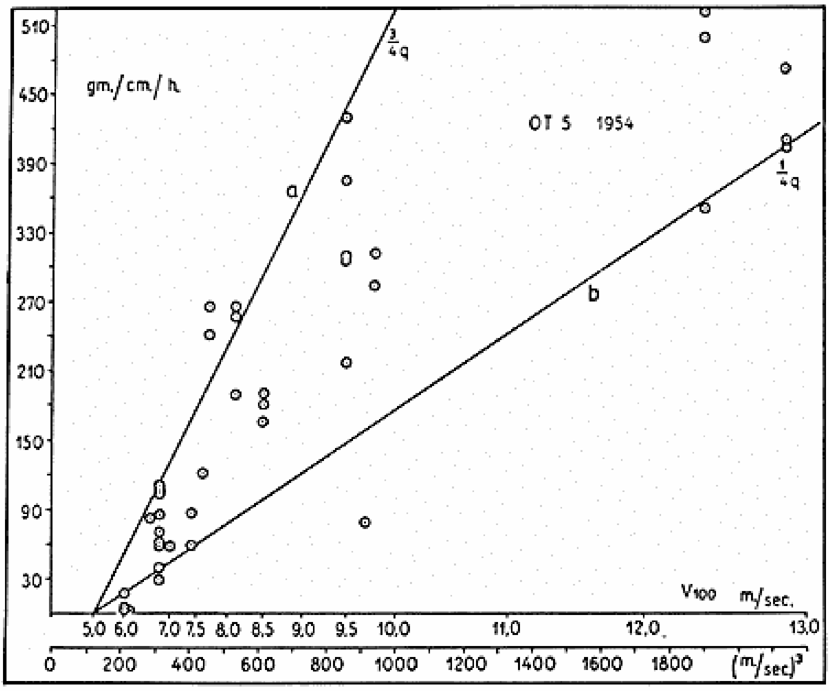

Fig. 2. The sand transport on surface type 5 during the wet weather period in 1954 with wind velocities less than 13.0 m./sec. at standard height. The two straight lines a and b are ¾ and ¼ respectively of the optimum theoretical transport, equation 16. The dots indicate the measured sand transport. The co-ordinates are the same as in fig. 1.

Fig. 2. Sandflugten over overfladetype 5 i den fugtige vejrperiode i 1954 for vindhastigheder mindre end 13,0 m/sec. i standardhøjde. De to rette linier a og b er henholdsvis ¾ og ¼ af den optimale, teoretiske transport, ligning 16. Prikkerne viser den målte sandflugt. Koordinaterne som i fig. 1.

In fig. 1, on the basis of equation 15 I have drawn the correlation between 70 % q and the wind velocity (at the standard height 100 cm. for the interval 0—10 m./sec.); the wind velocity is plotted along the abscissa axis, which has been 3-powerly divided in order to give the graphic picture the appearance of a straight line.

In table 1 are indicated the measured transported sand masses and the corresponding wind velocities at a height of 1 m. The moisture of the blown sand is also indicated; + signifies a very small water content in the sand. The values of table 1 have been plotted into fig. 1, the constructed curve of which seems to be an acceptable trend line for the measured values. It is difficult to decide which trend line is the most reasonable, when one wishes to examine whether nature is capable of producing the theoretically optimum sand transport. The scattering of the points of the diagram is no doubt attributable to other causes besides the normal distribution

Table 2.

Date *Dato* 1954	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 5. gm./cm./h.	Moisture content $^0/_0$ net dry weight *Fugtighed $^0/_0$ tørvægt*	
			Blown sand *Flyvesandet*	Surface *Overflade*
$^{31}/_7$	6.0	2		2
„	„	5		„
„	„	16		2
$^7/_8$	6.1	0.4	f	3
$^{19}/_7$	6.6	84		5
$^{28}/_7$	6.8	68		3
„	„	109		3
$^{29}/_7$	6.8	28		2
„	„	38		„
„	„	56		7
„	„	59		2
„	„	84		„
„	„	105	t	„
$^{16}/_8$	6.8	57		
„	„	104	f	
$^{13}/_7$	7.0	57	f	14
$^{30}/_7$	7.4	58		2
$^{19}/_7$	„	86		5
$^{19}/_7$	7.6	121	f	5
„	7.7	239	„	„
$^{13}/_7$	„	264	„	14
$^{19}/_7$	8.1	188		5
„	„	255		„
„	„	264		„
$^{13}/_7$	8.5	164		1
„	„	179		„
„	„	188		„
$^{13}/_7$	9.5	215		„
„	„	304		„
„	„	307		„
„	„	373	t	„
„	„	428	t	„
$^{13}/_7$	9.7	77	f	„
„	9.8	282		„
„	„	310		„
$^{16}/_7$	12.4	348	f	11
„	„	496	t	11
„	„	521	t	„
$^{16}/_7$	12.9	401	0.6	„
„	„	417	0.5	„
„	„	470	„	„
$^{10}/_8$	15.5	0.9	1.1	5

law; still, I feel justified in establishing as a fact that the fundamental in the q-function (equation 15) has been realized, although a reduction of the absolute, anticipated values is seen.

This reduction is undoubtedly due to defects of the traps and to a humidity cohesion between the particles; it must be presumed that in the velocity interval mentioned here the influence of the latter factor is particularly noticeable at lower wind velocities.

During the »wet« weather period, July-August 1954, the sand transport over the moist, firm surface was measured indirectly by means of collecting tubes alone; they were placed in spots of dry sand which received sand from OT 5. In these there was a heavy sedimentation; at the same time the jumps of the grains were subdued, so that, as the sand transport was now close to the ground, the tubes were effective traps. The quantity of sand caught by the tubes was considered identical with the quantity transported over OT 5.

The theoretical transport was calculated as for the observations of 1955, except for the modification that d_1 was equalled to 0.025 cm., because the humidity seemed to coarsen the blown sand (Kuhlman 1957 b); consequently, the result of equation 12 was that $v_t(100)$ became 5.0 m./sec. Equation 6 would then give for v_{100} indicated in m./sec.:

$$q_{OT5'} = 0.80\ v_{100}^3 - 100 \qquad \text{gramme/cm./hour} \qquad 16$$

In fig. 2, by means of equation 16, have been drawn two straight lines signifying the theoretical correlation between ($^1/_4$ and $^3/_4$) q and the wind velocity.

In table 2 are shown the measured values of the transport capacity of the wind over OT 5 during the wet period; f signifies unknown degree of humidity, and t signifies dry sand. It will be seen that the results of the measurements vary greatly; however, on plotting the values into fig. 2 it appears that for the greater part the transport quantities observed are situated between $^1/_4$ and $^3/_4$ q for the velocity interval shown in this figure: 0—13 m./sec. Many measurements are close to 75% of the theoretical optimum. Further, the fundamental in the sand-transport formula is again confirmed by the fact that at increasing wind velocity the mass transport grows rapidly. Even if the registered sand transport did not prove to have the expected dimensions — the cause of which may have been humidity as well as defects of the traps — it was astonishingly big; contributing to his large transport was the same mechanism as that which is a condition for the existence of the hygrophobic layers of sand.

As a summary of the above it may be said that both in the dry and in the wet weather period the aeolian sand transport in surface type 5 was astonishingly high, the drift seemingly being describable by a formula of the same type as equation 6. It must be pointed out that although equation 6 is undoubtedly useful when the sand transport takes place, the movement is probably less frequent in wet periods than in dry periods at the same wind force. At any rate, as will be seen from table 2, a wind of 15—16 m./sec. was scarcely able to move the sand because af the accompanying rain.

Surface type 6 (OT 6). Dry and incoherent sand without vegetation was found at the lowest part of the dune and at the innermost part of the foreshore at such places as were named *surface type 3* in the measurements of the wind velocity profiles; however, this characterization is only an approximation to a common denominator for a mosaic of scattered tussocks of marram-grass and interjacent areas of sand. The sand transport in OT 3 was a local occurrence and had no direct relation to the wind profile measured on the whole of the surface. The local sand-transport areas in OT 3 had to be characterized as OT 6. The sand was often modelled in wind ripples on account of the regular length of the leaps of the grains and the large size of the bed-load transport. In this surface the collecting tubes seemed to be of some use by capturing a small part of the sand in saltation and almost all the creeping material, which according to *Bagnold* amounts to a fourth of the total transport. Around the cloth screen there was so much eddy and lee that the sand grains moving by small bounds lacked the inertia to jump into the trap which, therefore, was almost useless.

The theoretical sand transport over OT 6 may presumably be expressed by equation 9, which will be compared only with the 1955 measurements, because the numerical material for the wet period is too imperfect to be published.

The values of V_t and k' were not found experimentally, but were calculated by means of the equations 12, 13 and 14. *Zingg's* relations (equations 13 and 14) for $d_l = 0.2$ mm. give: $k' = 0.2$ cm. and $V_t = 1.79$ m./sec. This point (V_t, k') almost satisfies equation 12, the abscissa-deviation being only $-$ 0.1 m./sec. *Bagnold's* work (1954 p. 69) seems to indicate that if the mean grain size remains constant, while the range of the distribution of the grain sizes is augmented, V_t and k' will increase. Taking into consideration the research work of both authors, I have chosen $V_t = 2.0$ m./sec. and $k' = 0.26$ cm.

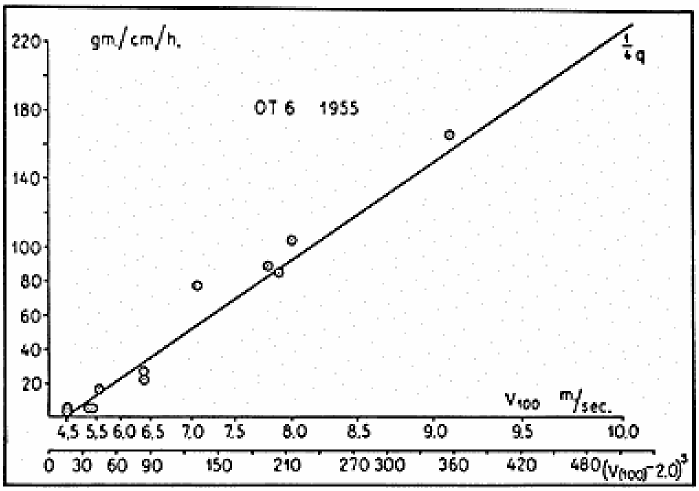

Fig. 3. The theoretical sand transport (the line, ¼ q) and the measured sand transport (the dots) over an incoherent naked sand surface (OT 6) in the dry weather period. The abscissa has been divided according to the 3rd power of the difference between the measured wind velocity and V_t; the corresponding linear scale is also indicated. The ordinate is the same as in fig. 1.

Fig. 3. Den teoretiske (linien ¼ q) og den målte (prikkerne) sandtransport over en løs, nøgen sandflade (OT 6) i den tørre vejrperiode. Abscisseaksen er inddelt efter 3. potensen af differensen mellem den målte vindhastighed og V_t, den tilhørende lineære skala er også anført. Ordinaten er som tidligere.

If these values and those proviously used are inserted into equation 9, applied to the dry period, the following result is obtained, when C = 1.5 and v(z) is measured in m./sec.:

$$q_{OT6} = 1.84\ (v_{100} - 2.0)^3 - 29 \qquad \text{gm./cm./hour} \qquad 17$$

By means of equation 17 the theoretical correlation of 1/4 q with $(v_{100} - 2.0)$ is drawn as seen in fig. 3.

The measured transport capacity, the values of which have been plotted into fig. 3, appears from table 3, where + signifies very small quantities. The sand was dry. The measured quantities are close to the calculated values, if it is accepted that the collecting tubes captured the creeping material. The inadequate measurements from 1954 showed the same tendency.

Surface type 4 (OT 4). The sand transport over the semi-firm surface, OT 4, may theoretically be expressed by equation 6, cf. *Bagnold.* The surface pebbles (pebbles of a size of 2—6 cm.) varied in density with inter-pebble intervals of from 1.5 to 10 cm., though 2—4 cm. was common. Judging from my measurements, this variation seemed not to have much influence on the roughness parameter

Table 3.

Date *Dato* 1955 (1954)	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 6 gm./cm./h.	Date *Dato* 1955 (1954)	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 6 gm./cm./h.
$^{24}/_{7}$	2.1	0.0	$^{29}/_{7}$	5.5	16.2
$^{26}/_{7}$	2.8	0.0	$^{21}/_{7}$	5.6	+
$^{25}/_{7}$	3.4	0.0	$^{2}/_{8}$	6.4	22.0
$^{30}/_{7}$	4.5	3.2	$^{29}/_{7}$	"	27.3
"	"	3.5	$^{23}/_{7}$	7.1	76.8
$^{29}/_{7}$	4.9	+	$^{2}/_{8}$	7.8	89.3
($^{9}/_{7}$)	5.3	5.1	$^{26}/_{7}$	7.9	85.5
($^{9}/_{7}$)	"	5.4	$^{2}/_{8}$	8.0	104.
$^{21}/_{7}$	5.4	4.7	$^{23}/_{7}$	9.1	166.
"	"	5.7			

(z_o). *Schlichting's* laboratory experiments with the flow over spherical segments also prove that it requires considerable alterations in the density of roughness elements of this sort to bring about any great changes in the roughness parameter. I found that $z_o = 0.01$ cm. was a characteristic mean value for the varied and pebbly beach in question. OT 4 is also complicated, in that it contains two different sorts of sediments without smooth transitions. For this reason it is improbable that in equation 8 $v_t(z)$ can be deduced from equation 12, which would give an impact threshold of 3.8 m./sec. at a height of 1 m.; such a wind did not produce sand transport over the pebbly beach. If the sand transport is not to come to a standstill, it is evidently necessary that the wind velocity at the height k' above OT 4 is $\geqq V_t$ for OT 6; this condition will be satisfied for $v_{100} \geqq 5.6$ m./sec., if z_o is reckoned as = 0.01 cm. and (V_t, k') = (2.0 m./sec., 0.26 cm.), if the conditions ruling in the dry period alone are considered; therefore, 5.6 m./sec. at a height of 1 m. is regarded as the impact threshold for OT 4.

If the new impact threshold and C = 2.8 are used in equation 6, other parameters having the values previously employed, we have:

$$q_{OT4} = 0.93\ v_{100}^3 - 163 \qquad \text{gm./cm./hour} \qquad 18$$

For the usual velocity interval, 1/2 and 1/4 q are shown in fig. 4.

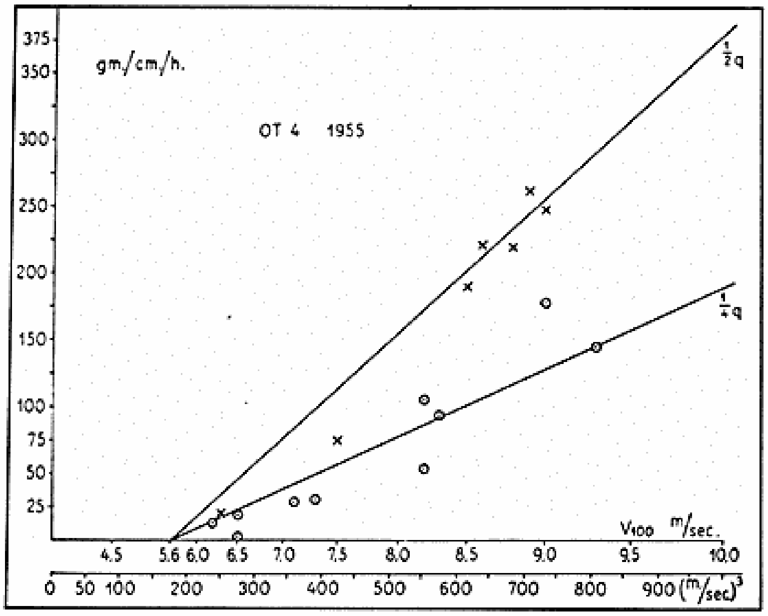

Fig. 4. The sand transport on the pebble-covered shore (OT 4) on Skallingen in 1955. The lines indicate the theoretical transport, equation 18. The crosses show the measured sand transport over scattered pebbles, and the dots indicate measurements on pebbles of a "normal" density (OT 4). The same co-ordinates as in fig. 1.

Fig. 4. Sandflugten over den småstenede sandstrand (OT 4) på Skallingen i 1955. Linierne betegner den teoretiske transport, ligning 18. Krydsene viser den målte sandflugt over spredt liggende pebbles, mens prikkerne angiver målinger over pebbles med „normal" tæthed (OT 4). Koordinaterne som i fig. 1.

The measured aeolian transport is given in table 4, where + signifies very small quantities. The sand was dry. Fig. 4 contains the values from table 4; the crosses indicate the value of the sand transport over scattered pebbles. The varying effectivity of the traps is the reason why relatively larger masses are measured over scattered pebbles than over densely situated pebbles, because in the latter case the collecting tubes are half concealed, whereas the gully-shaped screen is very effective, cf. OT 5. What guaranty we have for the validity of equation 18 is open to discussion, but there can hardly be any doubt that the sand transport over OT 4 requires a greater minimum drag-velocity (V_{*t}) than over OT 5 and 6 in order to sustain the movement, cf. *Bagnold* 1954 pp. 167—174.

Surface types 1 and 2. On OT 1 the sand was almost hidden by the tall, evenly distributed vegetation. The measurements of the wind profiles showed that between the plants there was a stationary air layer which had a thickness of some decimetres. No wonder, there-

Table 4.

Date *Dato* 1955	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 4. gm./cm. h.	Distance between pebbles *Pebble-afstand* cm.
24/7	4.1	0.0	2—4
21/7	4.9	0.0	„
25/7	5.3	+	
„	5.4	+	
26/7	5.8	+	
27/7	6.0	+	
26/7	6.2	12.6	2—4
29/7	6.3	21.0	7—10
„	6.5	18.8	2—4
4/8	„	2.4	„
27/7	6.8	+	„
„	7.1	28.7	„
29/7	7.3	30.9	„
„	7.5	75.0	7—10
23/7	8.2	53.7	2—4
„	„	105.	„
2/8	8.3	93.3	„
„	8.5	190.	7—10
23/7	8.6	221.	„
2/8	8.8	220.	„
23/7	8.9	262.	„
„	9.0	248.	„
2/8	„	177.	2—4
23/7	9.3	144.	„

fore, that is was impossible to prove any sand movement in the »grey dune« during the two experimental periods.

The »white dune«, OT 2, often presented a mosaic of bare sand and sand covered with vegetation, but large areas of the dune surface were evenly covered with straws of marram-grass (Ammophila arenaria). The profile measurements of the wind velocities proved that normally there was also a stable layer af air above the sand at OT 2; at places, however, the wind would find its way to

Table 5.

Date *Dato* 1955 1954	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 2 gm./cm./h.	Date *Dato* 1955 1954	Wind *Vinden* z = 100 cm. m./sec.	Sand transport *Sandtransport* OT 2 gm./cm./h.
24/7—55	2.0	0.0	23/7—55	6.3	10.7
25/7—55	2.4	0.0	2/8—55	6.4	12.3
26/7—55	»	»	23/7—55	6.8	17.3
21/7—55	3.8	»	13/7—54	»	14.
16/8—54	4.0	»	26/7—55	7.3	30.9
2/8—55	4.2	+	2/8—55	7.8	7.3
29/7—55	4.4	0.0	7/8—54	7.9	1.1
25/7—55	»	»	»	»	6.4
2/8—55	4.7	1.1	26/7—55	8.6	51.9
13/8—55	»	15.3	2/8—55	9.1	20.0
21/7—55	4.8	0.0	12/8—54	10.3	0.6
23/7—55	4.9	8.4	16/7—54	11.9	0.3
24/7—55	5.0	17.0	»	»	2.9
13/7—54	5.2	6.9	11/8—54	12.3	0.3
21/7—55	5.3	0.0	»	»	0.7
26/7—55	5.6	19.6	16/7—54	12.5	37.
29/7—55	5.8	0.0	»	»	44.
13/7—54	5.9	6.5	11/8—54	12.7	2.9
»	»	9.3	11/8—54	14.4	45.
13/8—55	6.0	70.9	»	»	14.
24/7—55	»	11.7	10/8—54	17.0	1.5
26/7—55	6.2	7.8			

naked areas of sand, because there was a certain variation in the density of the dune grass. At such places the sand transport could proceed, but it was not easily comparable with the wind velocity at standard height, as there is one sort of turbulence where the sand is in movement, another at a height of 1 m. On the basis of the applied methodology it was impossible to verify a theoretical transport. In a »white dune« it is easy to err in the placing of the sand traps because localities with sedimentation may be mistaken for places where a real transport takes place. Consequently, I tried as far as possible to avoid such regions as received blown sand from other surface types; hence the trasnport masses shown in table 5 solely describe the mobility of the dune sand in surface type 2.

Bearing in mind that the measured wind velocities do not have the usual regular relation to the movement, it will be seen from table 5 that at all wind forces the sand transport is insignificant, and that no regularity is perceptible. Conditions in the two periods are almost the same. The following conclusion can be established: the measurements proved that the dune grasses protect the dune sand very effectively against aeolian activity, so that OT 2 and 1 may have considerable sedimentation, whereas transport and erosion must be insignificant phenomena.

Comparison of the sand transport over the different surface types.

A comparison of the sand transport over the different surfaces and a general estimate of the variation of the transport capacity can only be carried out if one compares such transport-masses as correspond to »the same wind conditions«, i. e. the same wind-creating pressure-gradient, which in nature means identical drag-velocity (V_*). The wind velocity at standard height may vary from one place to another even under »constant wind conditions«; therefore, an indication of the wind velocity without mentioning the turbulence and the measuring height would be meaningless. Moreover, V_* is a rather unknown concept and, therefore, should be converted into wind velocity at standard height over one particular, well-known surface type.

In the preceding paragraph some formulae for the relation between wind, surface structure and sand transport have been rendered probable; these theoretical formulae, equations 15 to 18, for the optimum aeolian sand transport may be illustrated by a common diagram showing the correlation between the converted V_* and q for each surface type, the parameters having the values previously used.

Fig. 5 shows the theoretical correlation between the sand transport over the different surfaces and the wind velocity at a height of 1 m. above OT 5, applicable to the velocity interval 0—13 m./sec. For the construction of fig. 5 I have calculated, by means of equation 3 and its variations, the related velocities at standard height for the different surfaces at the constant V_*; in this way it is possible to learn the wind force which for other surfaces corresponds to a given velocity over OT 5 and, consequently, to deduce from equations 15—18 related transport quantities. These sand masses which blow over different surfaces at the same drag-velocity may be described as equivalent. If the sand transport area can be described exclusively by surface types, and if the surfaces are situated more or less at the same level, fig. 5 will express the variation in

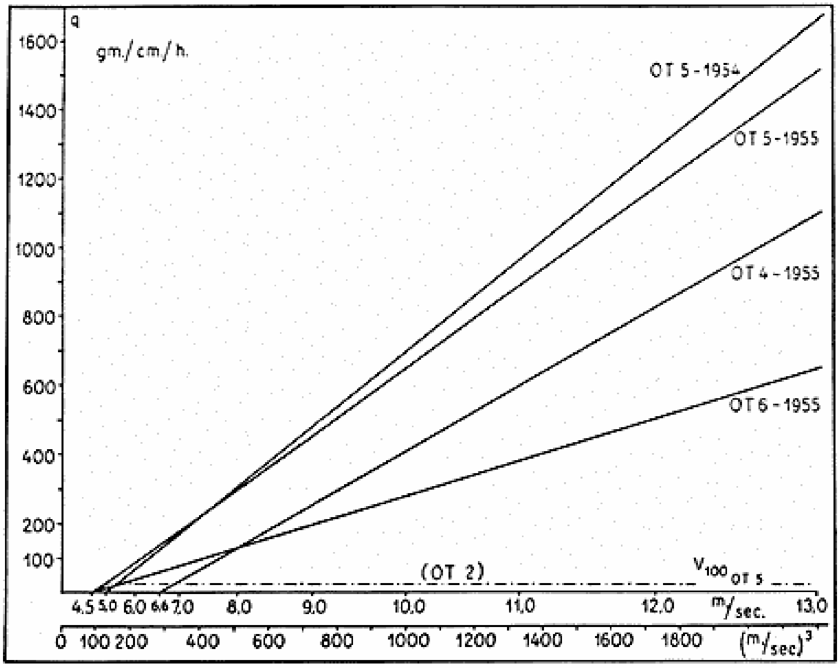

Fig. 5. The theoretical optimum equivalent transport of blown sand over different surface types. The lines are the theoretical relations, the probability of which appears from figures 1 to 4: equations 15 to 18. The abscissa indicates the velocity (0—13 m./sec.) at a height of 1 m. above surface type 5, which is a reference surface for the equivalent transport masses. Otherwise, the co-ordinates are the same as in fig. 1. Ordinate differences between the curves show the theoretical optimum deposition and erosion; especially should be noticed the transport of OT 4 as compared to that of the other types. The probable transport over OT 2 is indicated by a dot-and-dash line.

Fig. 5. Den teoretiske, optimale, ækvivalente transport af flyvesand over forskellige overfladetyper. Linierne er de i fig. 1 til 4 sandsynliggjorte teoretiske relationer: ligning 15 til 18. Abscissen angiver hastigheden (0—13 m sec.) i 1 m's højde over overfladetype 5, som er referensoverflade for de ækvivalente transportmasser. Koordinaterne er iøvrigt som i fig. 1. Ordinatforskelle mellem kurverne viser den teoretiske, optimale aflejring og erosion, man bemærker især OT 4's transport i forhold til de andre typers. Den sandsynlige transport over OT 2 er markeret med en stiblet linie.

the sand transport caused by the structural alterations of the ground. In fig. 5 we can, for a given wind-force, read differences in the value of the sand transport (gm./cm./hour) at the passage of the transport from one surface to another; the alterations read are quantitative expressions for the optimum deposition and erosion.

The optimum theoretical transport of OT 5, which was especially realized during the dry weather period (1955), is very great, as will be seen from the figure. In the wet period a greater wind force is required to start the movement than in the dry period; but during the wet period the growth of the sand transport increases more rapidly with the rising wind velocity; this is exclusively due to the coarsening of the blown sand (Kuhlman 1957 b); however, in wet periods on Skallingen there will rarely be sufficient quantities of coarse sand for saturating the wind at the high velocities. If the moist sand area is less than 50 m. long the surface moisture seems to be of little significance; for the optimum transport of the firm surface, the sand of which arrives from elsewhere, has almost the double quantity of that of OT 6 at all wind forces.

The transport over the pebbly beach (OT 4) which is equivalent to that of OT 5 is always smaller than the latter; but its relative proportion to the transport of OT 5 increases with the wind force. Over OT 4 the sand transport requires a greater wind velocity in order to start the movement than over both OT 5 and 6 and, for a wind of $<$ 8.0 m./sec. ($z = 100$ cm. $z_0 = 0.002$ cm.) is less than the transport of OT 6; however, at greater wind forces it increases by a constantly growing percentage.

In dunes with some vegetation, surface types 1 and 2, sand transport is practically impossible at all the wind velocities indicated in fig. 5.

In the weather situation on Skallingen in 1954 and 1955 there were few important modifications of the wind force and, consequently, of the sand transport; 5—8 m./sec. at the standard height above OT 5 was common, whereas other velocities were less frequent. Therefore it was evident on the spot that marked modifications of the transport capacity of the wind were mainly due to the shape of the ground and to the structure of the surfaces, as indicated in fig. 5.

Genesis of dunes.

Dunes are accumulations of blown sand in high relief (cf. *A. Schou);* the local concentration of big sand masses forming a very hilly surface is characteristic of dune areas. Large, flat areas of blown sand are called sheets and coverings. The essential of the dune concept is a concentration of sand on relatively small areas; this local accumulation must be due to sporadic changes in the transport capacity of the wind, i. e. q in equation 4. Where different surface types are contiguous there is a possibility, as shown in fig. 5, of marked changes in the masses transported, which may give rise to dune formation. Such changes in the sand transport must in equation 4 find their expression by alterations of the elements b_0 and K_0, while local, negative modifications of q as a consequence of the variation of V_* must take place when isolated ground elements form a wind shelter. Consequently, a distinction may be made between a dune creation which is generally conditioned by surface types and a creation which is caused by isolated wind shelters. It must be borne in mind that in normal terminology not all depositions of blown sand are called dunes.

A dry spot of sand (OT 6) in OT 5 will have a smaller equivalent transport than its surroundings, cf. the preceding paragraph, and, therefore, will always accumulate sand: this mechanism is called psammogenic dune formation (*Capot-Rey* ed. 1953), which is merely a sub-type of the genesis conditioned by surface types; the germ of the latter is often a small wind-shelter, for instance from wreckage or from driftwood, or hollows in the surface. On Skallingen a small area of dry sand in OT 4 with wind velocities greater than 8—9 m./sec. (OT 5) will also accumulate sand; but if the wind force becomes inferior to this threshold the sand spot will have a greater equivalent transport than its surroundings, and the sand spot will therefore be scattered and destroyed. As will be seen, there exists an interval of velocities, in this case about 4.5—9 m./sec., at which the pebbly surface will »steal« sand from adjacent naked sand areas. This interval, which may be called the deposition wind of OT 4, expands with increasing surface roughness, cf. *Bagnold*.

On the moist sand flat on Skallingen dunes of psammogenic formation were very common; they were some metres broad, only a few centimetres high and shaped like a shield. With a constant wind they would have grown into coastal barchans, cf. *A. Schou* 1954, p. 151. On the other hand, sand tongues and lee-side depositions around plants and other isolated objects on the stony beach were most often unstable and less frequent. The pebbly beach would to some extent accumulate sand in the form of a cover which by and by modified the roughness, whereby renewed removal of the sand became possible; therefore, there was a certain equilibrium between the structure of OT 4 and the wind common to a certain period.

An effective and stable creation of dunes did not take place until dune grasses formed a more coherent association as in the bank-dune (OT 2), where all the supplied material was sedimented; this activated the growth of the grass so that the structure of the surface was preserved. Isolated embryonal dunes around plants had very difficult growth conditions, unless the surroundings consisted of unmixed, moist sand, and the vegetation consisted of Ammophila arenaria.

From the observations made on Skallingen I think I am justified in concluding that in Denmark stable formation of dunes at normal wind forces is almost exclusively due to an alternation between the different surface structures of large areas. What is particularly favourable to the creation of dunes is an alternation between the surface types 2 and 6 (5), whereas an alternation between surfaces as OT 4 and pure sand areas to a certain extent is destructive of dunes.

To the latter observation I may add as a digression that in this may be one of the answers to Niels Nielsen's inquiry for dunes in the interior of Iceland *(Niels Nielsen 1933)*.

Danish dune landscapes.

On examining the morphology of the areas in Denmark which are characterized by blown sand in the top soil *(A. Schou* 1949) it will be seen that the only true dune topography is to be found at such places where large well-sorted sand masses predominate. Parabolic dunes and bank-dunes are almost exclusively found in proximity to the marine foreland, whereas in the primarily glacio-morphological landscape the blown sand for the greater part has the form of coverings through which the original structure of the landscape is clearly perceptible; these conditions become particularly evident from a study of the maps. The predominance of the sand covers in regions where the aeolian morphology is of a moraine origin was pointed out by *V. Milthers* 1925.

In my opinion this can be explained by the fact that the surfaces existing during the development of the sand transport on a ground of a marine character were fundamentally different from those in the moraine country, where types such as OT 4 were general and where well-sorted sand constituted a small part of the masses of sediment. In cases where the moraine landscape is characterized by sorted, glacio-fluviatile sand a configuration may be formed similar to that which characterizes large parts of the dune areas of the marine foreland, where surface types 2 and 6 reigned almost supreme at the genesis; an example of this can be seen in the Randbøl Heath to the west of Vejle.

In order further to illustrate the characteristic differences between the various Danish landscapes bearing an aeolian stamp I shall refer here to two areas with blown sand, within which there is a distinct demarcation line between the above-mentioned two aeolian configurations: one is the area north of Fjerritslev in Jutland, the other is the region north of Frederiksværk in Zealand. A survey of the history and of the economo-geographical development of these areas shows the radical nature and extent of the morphological demarcation line. In both regions a coastal cliff from the Littorina Age constitutes the dividing line.

SUMMARY

The usefulness of a mathematic expression for sand transport at an adiabatic temperature gradient, equation 4, has been rendered probable by measurements in a Danish dune region. It appeared that the humidity of the weather and of the surface sand had an astonishingly small influence on the size of the sand masses moved by the wind. The humidity seemed in particular to affect the frequency of the occurrence of sand transport.

I have pointed out the great significance of the structure of the surface to the actual mechanism in the creation of dunes, considering that a large and stable formation of dunes is conditioned by an alternation between large areas with differences in vegetation and materials. Relatively small quantities of sand in connection with areas with many pebbles offer unfavourable conditions for a durable formation of dunes; consequently, parabolic dunes are rare in Denmark except on the marine foreland.

SAMMENFATNING

Kvantitative målinger af sandflugt.

På grundlag af forfatterens tidligere artikler i Geografisk Tidsskrift 1957 redegøres der i denne publikation for målinger i 1954 og 1955 på Skallingen af de kvantitative relationer mellem sandflugt og vindforhold; desuden omtales målingernes betydning for forståelsen af klitmorfologien.

Tidligere er offentliggjort en beskrivelse og en typeinddeling (OT 1 til OT 6) af forsøgsområdets overflader, hvis struktur har afgørende indflydelse på vinden og sandbevægelsen, se ligningerne 1 til 14 og jfr. Bagnold 1954.

Fra den generelle ligning 4 er for hver af de vigtigste overfladetyper udledt en formel (6, 9, 15–18), som udtrykker den optimale, æoliske sandtransport. Det ses, at ligning 4 kan omskrives, således at elementerne bliver alment kendte – eller let målelige – fysiske størrelser. De vigtigste forudsætninger for anvendelsen af formlerne er, at luften termisk er i omtrent neutral lodret ligevægt, og at vinden er turbulent.

Der er i de teoretiske udtryk ikke anvendt parametre for fugtigheds-kohæsionen mellem partiklerne, fordi sandets stærkt varierende fugtighed vanskeligt lader sig angive repræsentativt. Dette sidste skyldes især tilstedeværelsen af hygrofobiske sandlinser i overfladen (Kuhlman 1957 a.). Derimod er betegnelserne »fugtighed« og »tørhed« knyttet til vejr-perioder, inden for hvilke det er målt, hvor store sandmasser vinden reelt transporterede. Men det er ikke undersøgt, hvor hyppigt sandflugten forekom i somrene 1954 og 1955, der henholdsvis kan benævnes »fugtig« og »tør«.

Ved brug af fig. 1 til 4 og tabellerne 1 til 5 kan man studere forholdet mellem teori og de eksperimentelle data. Det var et alment træk, at det principielle i q-funktionen (lign. 4) syntes at blive realiseret til trods for fugtigt og regnfuldt vejr. De afvigelser, som ses i de absolutte mål, kan rimeligvis stort set forklares ved mangler i målemetoderne, men nogen reservation bør man nok have over for en fuldstændig godkendelse af resultaterne. Den grå klit (OT 1) viste slet ingen sandbevægelse på grund af det jævne, tætte plantedækkes beskyttende virkning. Den hvide klit (OT 2) havde for alle vindstyrker en ubetydelig transport, i hvilken ingen lovmæssighed kunne spores. Derimod kunne begge klitoverflader naturligvis have en stor sedimentation. Den stenbestrøede strand (OT 4) krævede en relativ stor vindhastighed for at vedligeholde sandbevægelsen, som imidlertid ved store hastigheder fik en betydelig intensitet. Den nøgne, fugtige sandflade (OT 5) havde en chokerende kraftig sandflugt hen over sig, idet overfladens fugtighed øjensynligt havde vanskeligt ved at forplante sig til flyvesandet. Vindtrykkets bevægende kraft var langt mere virkningsfuld end fugtighedens bindende effekt. Man mødte her atter den hygrofobi, som åbenbart er et karakteristisk træk ved sandflugtsdynamikken i et humid klima. De løse, tørre sandarealer (OT 6 og 3) gav resultater, som man kunne forvente ud fra Bagnold's forsøg.

Hvis man godtager, at fig. 1 til 4 i det væsentlige verificerer de hypotetiske formler for relationen mellem sandflugt, vind og overfladestruktur, kan det være nyttigt at sammenligne den optimale sandflugt over de forskellige overflader ved »samme vindforhold«. Det er sket i fig. 5, som angiver den teoretiske korrelation mellem sandtransporten over de forskellige overfladetyper og vindhastigheden i 1 m's højde over OT 5, der er anvendt som referens-overflade. De sandmasser, som fyger over forskellige overflader ved samme V_*, kan betegnes som ækvivalente. Forskellene i ækvivalente masser, som kan aflæses på fig. 5, angiver kvantitativt den teoretisk optimale aflejring og erosion ved transportens passage fra sted til sted, såfremt overfladerne ligger i nogenlunde samme plan. Særlig interesse har det, at OT 4's transportkurve skærer OT 6's for en hastighed på ca. 8 sek. meter, målt i 1955 over referens-overfladen.

Vejrsituationen på Skallingen var sjældent skyld i store ændringer af vindstyrken og dermed sandflugten, hvorimod betydelige svingninger i transportevnen var almindelige som følge af terrænets form og struktur, således som det vises på fig. 5, der yderligere kan anvendes til at belyse klitgenesen.

Ved klitter kan forstås koncentration af flyvesand på relativt små arealer; denne lokale ophobning må skyldes sporadiske ændringer af vindens transportevne. Man kan derfor skelne mellem en klitdannelse, som er overfladetype-betinget, og en, som skyldes isolerede vindskygger. Store og stabile klitter kan her i landet ved normale vindstyrker kun dannes i områder med en mosaik af overflade-typerne 1–2 og 6–5; mens en skiften mellem overflader som OT 4 og nøgne sandarealer almindeligvis er meget ugunstig for klitdannelse, fordi stenede lokaliteter, såsom »afblæsningsflader«, ved lave og middelstore vindstyrker stjæler sand fra embryonalklitter.

I Danmark synes en moderoverflade af enorme mængder af sorteret sand at være nødvendig for fremkomsten af voldklitter og parabelklitter, som er sjældne uden for det marine forland.

Til nærmere belysning af overflade-strukturens betydning for den æoliske landskabsudvikling kan anbefales studier af egnene omkring Frederiksværk og Fjerritslev. Begge steder danner stenalderhavets kystlinie et skarpt skel.

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