

CHAPTER EIGHTY SIX

SAND TRANSPORT BY WIND ON A WET SAND SURFACE

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ABSTRACT

Using those results which were judged to be reasonable among various experiments, an equation predicting the threshold shear velocity on a wet sand surface was obtained. Then, based on a literature survey, results from fundamental experiments, and information obtained from a series of field observation carried out by the authors, a hypothesis to explain the blown sand phenomena on a wet sand surface was developed. Experiments with a well-sorted sand having a median diameter of 0.3 mm showed that the prediction was valid if the water content of the sand layer was less than 8 %.

I INTRODUCTION

One of the important problems in coastal engineering in recent years has been the unraveling of the processes of beach change. Extensive studies have been carried out on this topic throughout the world. Most research has been concerned with the study of waves on beaches and the resultant beach change due to wave action. However, on beaches where a strong seasonal wind blows, the sand transport by wind will be an important factor affecting beach change. In such a case, the transport by wind should be included in the sand budget on beaches. Therefore, we undertook comprehensive field investigations and laboratory studies to establish calculation methods for the transport of sand by wind on beaches (Horikawa, Hotta and Kubota, 1982; Kubota, Horikawa and Hotta, 1982; Horikawa, Hotta, Kubota and Katori, 1983; Horikawa, Hotta, Kubota and Katori, 1984).

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At the first stage of this study, the troublesome fact was encountered that sand transport by wind on beaches often occurs during seasons when the sand surface is wet with rain or snow, e.g., beaches on the Japan Sea Coast in winter. Few studies of blown sand on a wet sand surface have been carried out, in contrast to the considerable number of studies of blown sand on a dry plane sand surface.

In order to fully evaluate the contribution of transport by wind in the sand budget, the problem of blown sand on a wet sand surface should not be neglected. As a first step in grappling with this problem, a literature survey was made and the present state of knowledge was summarized. To fill in various information gaps, two simple fundamental experiments were performed for 1) the threshold shear velocity of sand with high water content and 2) the sand transport rate by wind on a wet sand surface. These results are described in Horikawa, Hotta and Kubota (1982). The purpose of the present paper is to describe the work performed subsequent to the above work.

II DISCUSSION OF SELECTED PREVIOUS WORKS

For convenience in later discussion, we will first give a brief summary of the present state of blown sand on a wet sand surface, based on our previous work (Horikawa et al., 1982). That is:

1. A considerable amount of laboratory and field data exists on the threshold wind speed or threshold shear velocity of sand grains on a wet sand surface. However, the definition of the critical condition at which grains begin to move, the elevation from the sand surface at which the wind speed as an external force was measured, and the sand characteristics varied among the experiments. Therefore it is difficult to quantitatively compare the relationships obtained.

Figure 1 shows the experimental results of threshold wind speed obtained by various workers. Generally speaking, with a water content up to 10% the threshold wind speed increases linearly with an increase in the water content of the sand surface. Also, the larger the median diameter of the sand the higher the threshold wind speed will be.

Theoretical and empirically-based equations for the threshold wind speed or the threshold shear velocity have been proposed by Belly (1962), Kawata and Tsuchiya (1976), and Nakashima and Suematsu (1976). They are:

$$u_{*c} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a}} g d (1.8 + 0.8 \log_{10} w) \quad (\text{Belly}) \quad (1)$$

$$\begin{aligned} \tau_{*c} &= \frac{u_{*c}^2}{((\rho_s/\rho_a) - 1) g d} \\ &= A^2 \left\{ \frac{\sin(\varphi - \theta)}{\cos \varphi} \right\} \left\{ 1 + \frac{2\sqrt{3}}{5} \sqrt{\alpha_1} \alpha_2 \sqrt{n_0} \frac{\sin 2\varphi}{\sin(\varphi - \theta)} T_k \right\} \end{aligned}$$

$$T_k = \sqrt{\frac{\rho_s}{\rho_w}} \frac{T \sqrt{w} \cos \xi}{(\rho_s - \rho_a) g d^2} \quad (\text{Kawata \& Tsuchiya}) \quad (2)$$

$$u_{15f} = \sqrt{\frac{B'}{A'}} \sqrt{g \cdot d \cdot \frac{\rho_s}{\rho_a}}$$

$$A' = -2.0 \times 10^{-7} + 22.0 \times 10^{-7} \exp(0.39w)$$

$$B' = 1.0 \times 10^{-5} \exp(-0.34w) \quad (\text{Nakashima \& Suematsu}) \quad (3)$$

where u_{*cw} is the threshold shear velocity on a wet sand surface, ρ_s , ρ_a and ρ_w are the densities of sand, air and water, A is a constant with an approximate value 0.1, g is the acceleration of gravity, d is the grain diameter and w is the water content which is defined by the ratio of water weight contained in sand and dry sand weight. The quantity φ is the friction angle of a sand grain at rest, θ is the average angle of the sand surface slope, T is the surface tension, n_0 is the number of contact points of a grain in the sand layer, $\sqrt{\alpha_1}$ and α_2 are constants, ξ is the angle of contact between sand grain and water, u_{15} and u_{15f} , are the wind speed and the threshold wind speed at a height of 15 cm, and A' and B' are constants.

The curves for Eqs. 1, 2, and 3 are drawn in Fig. 2 for comparison. Figure 2 will be explained a later. Otherwise, the threshold shear velocity on a dry sand surface is given by

$$u_* = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} g d} \quad (\text{Bagnold, 1954}) \quad (4)$$

2. The sand transport rate by wind on a wet sand surface is as yet an unsolved problem. The empirical coefficient value obtained various worker on a wet sand surface is small compared with the case of a dry sand surface, if the Bagnold formula is assumed. Also, there is no evidence that the Bagnold formula is applicable. The mechanism of sand movement on a wet sand surface has not been theoretically formulated and developed. However, equations empirically obtained for predicting the sand transport rate by wind on a wet sand surface have been presented by Iwagaki (1950), and Nakashima and Suematsu (1976):

$$q = 0.3 (u_{100} - 6) \quad (\text{Iwagaki}) \quad (5)$$

$$q' = A' \frac{\rho_s}{g} u_{15}^2 (u_{15} - u_{15f}) \quad (\text{Nakashima \& Suematsu}) \quad (6)$$

where q and q' are the transport rate and u_{100} is the wind speed at a height of 1 m. Here q is given in tf/m/day and u_{100} in m/s . The coefficient A' is given in Eq. 3.

The above is a brief summary. Now, Eqs. 1, 2, 3, 5 and 6 are discussed and examined in more detail.

First, we shall examine Eq. 1, due to Belly. It is questionable as to whether we may discuss this equation on the same level as the other equations, because the way of moistening the sand layer was different than in the other experiments. In his experiment, the air was saturated and the sand layer was moistened by absorption from the air. Therefore, there was no evaporation to the air and the layer under the surface was

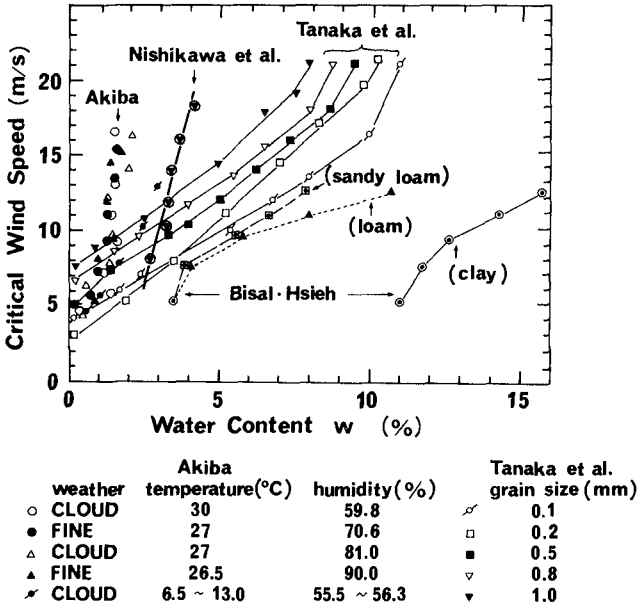


Fig. 1 Relationship between threshold wind speed and water content. (Redrawn by writers from data of original papers)

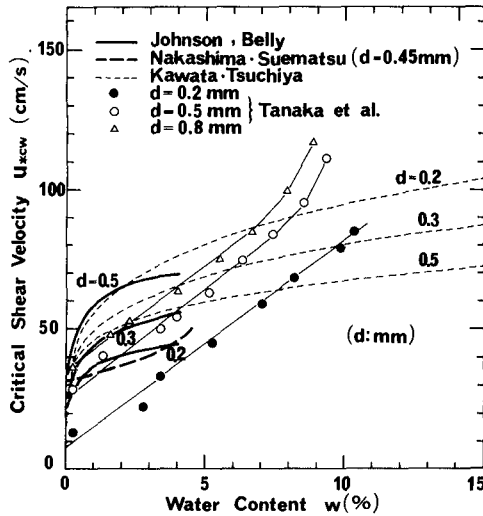


Fig. 2 Comparison of threshold shear velocities.

presumably dry. In all other experiments under discussion, the sand layer was moistened by directly spraying on water. Therefore, evaporation from the surface probably occurred to some degree. Putting this problem aside, we shall examine Eq. 1. We can see that the threshold shear velocity for a wet sand surface is given by adding an amount of increase due to the water to the threshold shear velocity for a dry sand surface. The curves given by Eq. 1 for the grain diameters of 0.2, 0.3 and 0.5 mm are drawn in Fig. 2. This equation is of the same type as Eq. 2. The amount due to the water is proportional to $\log_{10} w$. Therefore, the rate of increase of the shear velocity is large until 1% of the water content is reached. At a water content higher than 1%, the rate becomes gentler. This behavior does not agree with other experimental results.

Next, Eq. 2, obtained theoretically by Kawata and Tsuchiya (1976), is examined. Converting the shear stress to the shear velocity, and considering the condition of $\varphi = 45^\circ$ and $\theta = 0^\circ$ for simplicity, Eq. 2 becomes

$$u_{*cw} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} gd} \sqrt{1 + D} \quad (7)$$

$$D = \frac{2\sqrt{6}}{5} \sqrt{\alpha_1 \alpha_2} \sqrt{n_0} \sqrt{\frac{\rho_s}{\rho_w}} \frac{T\sqrt{w} \cos \xi}{(\rho_s - \rho_a)gd}$$

The amount of increase due to the water, D , is directly proportional to the square root of the water content and is inversely proportional to the sand grain diameter. This means that D increases rapidly to unity and the rate of increase of D becomes small when the water content is greater than unity. In addition, D will be greater for smaller grain sizes. Therefore, this formulation predicts that for a given water content the threshold shear velocity of small grains is greater than that of large grains.

These characteristics of Eq. 7 are completely contrary to the experimental facts, i.e., the threshold shear velocity increases linearly with increases in the water content of the sand surface; it also increases with the median diameter of the sand, and the threshold shear velocity increases suddenly at a certain water content of the sand surface.

Now we will move to a discussion of Eqs. 3 and 6. The definition of the threshold condition by Nakashima and Suematsu as expressed in Eqs. 3 and 6 was quite reasonable if their experiments were carried out correctly. Their results were given as a function of the wind speed at the height of 15 μ m. To compare to the other equations and experimental results, the threshold wind speed in Eq. 3 was converted to the threshold shear velocity using a method proposed by Horikawa and Shen (1960). The results expressed in terms of the shear velocity are drawn in Fig. 2. The results are limited to less than 4% in the water content. The applicability of the constants A' and B' to other grain diameters has not been examined yet. In addition, the sand transport rate given by Eq. 6 becomes rather small if we accept this result. Equation 6 cannot explain the experimental results of Nishikawa, Tanaka

and Ikeda (1975) nor the results of the our observation carried out on January 1983, described Horikawa et al. (1984), namely that the sand transport rate on a wet sand surface is comparable to that on a dry sand surface when the wind speed is sufficiently high. Sand will be blown off when evaporation rate is high enough even though the sand layer has high water content. Equation 6 cannot explain this phenomenon. Thus Eqs. 3 and 6 are not applicable to calculation of the sand volume on a wet sand surface.

Finally, Eq. 5, due to Iwagaki (1950), is examined. Equation 5 was obtained from a field measurement of sand transport. In the process of determination of the empirical Eq. 5, the threshold wind speed of 6 m/s at a height of 1 m was assumed. But the threshold wind speed of 6 m/s is too small for a wet sand surface. Due to experimental limitations, Eq. 5 cannot be applied for wind speeds over 12 m/s. In addition, the same argument as for Eq. 6 pertains to Eq. 5. Therefore, Eq. 5 cannot be used for practical applications.

The conclusion of this discussion is that, at present, there are no appropriate general formulas for the threshold shear velocity and the sand transport rate by wind on a wet sand surface.

III FORMATION OF THRESHOLD SHEAR VELOCITY

In the next section, a mechanism of blown sand on a wet sand surface is proposed according to laboratory results and field observation. The threshold shear velocity for a wet sand surface is required. Therefore, using the experimental results of Tanaka, Sano and Kakinuma (1954), the threshold shear velocity will be formulated.

As described in Section II, it was concluded that Eqs. 1, 2 and 3, which express the threshold shear velocity or the threshold wind speed on a wet sand surface, could not be applied under general conditions. This was due to the fact that there were considerable differences in the threshold shear velocity, or the threshold wind speed, obtained in previous experiments, because the criteria defining the threshold condition and the experimental method differed from one another. Therefore, the above experiments offer no way to reliably estimate the threshold shear velocity on a wet sand surface. To extend our results to include blown sand on a wet sand surface, it is necessary to formulate an expression for the threshold shear velocity.

Among the several experiments previously conducted, the authors judged that the experiment performed by Tanaka, Sano and Kakinuma (1954) was conducted under the most suitable conditions and that the results obtained were reliable. Therefore, using the experimental results of Tanaka et al., a formulation of the threshold shear velocity on a wet sand surface is attempted in this section.

Figure 2 will again be considered. As previously described, Eqs. 1, 2 and 3 are also drawn in this figure. A portion of the results of Tanaka et al. for the grain sizes under consideration are also drawn. The results of Tanaka et al. for the critical condition were expressed in terms of the wind speed at a height of 7 cm. The data in Fig. 2 were converted from wind speed to shear velocity using a logarithmic law for

the vertical wind speed distribution and the empirical formula for the roughness length by Zingg (1952), as proposed by Horikawa and Shen (1960).

In Fig. 2, for the water content of 0 % (which means the threshold shear velocity on a dry sand surface), the shear velocity is about 8 cm/s for 0.2 mm, 25 cm/s for 0.5 mm and 35 cm/s for sand 0.8 mm in diameter. Furthermore, for the water content of 0.5 %, the threshold shear velocity becomes 12 cm/s for 0.2 mm, 30 cm/s for 0.5 mm and 40 cm/s for 0.8 mm in diameter. The threshold shear velocity calculated from Eq. 4 on a dry sand surface is 22 cm/s for 0.2 mm, 32 cm/s for 0.5 mm and 41 cm/s for sand 0.8 mm in diameter. The values for the water content of 0 % given by the experiment of Tanaka et al. are smaller than the calculated values from Eq. 4.

However, the values for the water content of 0.5 % roughly agree with those values calculated by Eq. 4, except for the 0.2 mm-diameter sand. The water content is seldom zero percent and normally the water content is about 0.2 to 0.6 % when we measure sand under natural conditions (air dry condition). An experimental error of about 0.2 to 0.6 % in the measurement of the water content may exist, but it is reasonable to believe that sand absorbs water from the atmosphere as assumed by Belly (1962). In the experiments previously conducted to determine the threshold shear velocity on a dry sand surface, we may consider that the sand had in fact absorbed moisture from the air and the sand had about a 0.2 to 0.6 % water content. Therefore, we may accept the threshold shear velocity at around 0.5 % of water content in the experiment by Tanaka et al. as equivalent to that on a natural dry sand surface. Furthermore, we find another remarkable fact in the experiments, namely, that the gradient of the threshold shear velocity with respect to the water content is almost constant, 7.5 (cm/s)/%, for water contents lower than about 8 %, independent of the sand grain size.

From the above considerations and experimental results, an equation expressing the threshold shear velocity must have the properties (1) at 0.0% water content, the threshold shear velocity must correspond to that of a dry sand surface and (2) the gradient should be 7.5 (cm/s)/% for water content lower than 8 %, independent of the grain size. Therefore, the threshold shear velocity on a wet sand surface is taken to be given by

$$u_{*cw} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} g d} + 7.5w \quad \begin{array}{l} 0.0 < w < 8.0 (\%), \\ 0.2 \text{ mm} < d < 0.8 \text{ mm} \end{array} \quad (8)$$

where w is the water content (%).

It is a matter of course that Eq. 8 will be replaced by a new equation in the future according to the results of further well-controlled experiments and theoretical considerations.

Finally, we shall consider why the experimental results of Tanaka et al. showed a linear increase in the threshold shear velocity with increase in the water content irrespective of the grain diameter. In the model developed before, the sand grain was assumed to be spherical. Now we consider real sand. The diameter of a sand grain will be defined

by the longest diagonal line as schematically shown in Fig. 3. The angles of the edges on the surface will be distributed depending on the history of how the sand grain was produced and on how it weathered. In the sand layer, it might be the case that certain sand grains in contact with each other will have sharp edges as for S in Fig. 3(a). It is natural to consider that as a contact configuration of adjoining grains, a sharp edge of a certain grain will touch the flat part of an adjacent grain as shown by A, B and C in Fig. 3(a). If so, the following model to explain the experimental results by Tanaka et al. might be valid (see Fig. 3(b)).

We assume that the representative angle of a sand grain edge is independent of the grain diameter. Then, at low water content (lower than about 8%), the condition of adhering water is independent of the grain diameter. Therefore, an increase in additional cohesive resistance force due to adherence of water at the contact point will be independent of the sand grain size, and a constant increase as given by Eq. 8 results. The above model helps us to understand the experimental results of Tanaka et al.

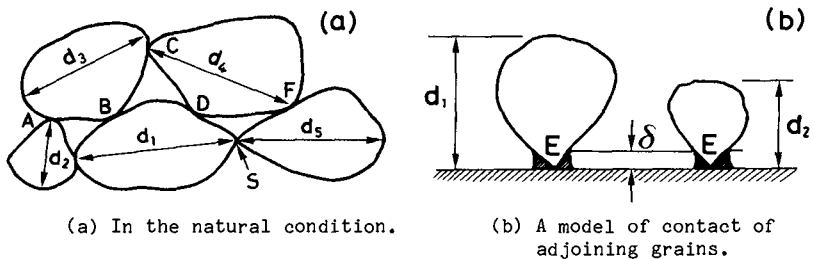


Fig. 3 Schematic diagram of the contact condition of sand grains.

IV SUMMARY OF INFORMATION AND DEVELOPMENT OF A HYPOTHESIS FOR BLOWN SAND ON A WET SAND SURFACE

From the literature survey, and from the fundamental experiments and field observations conducted in our work, much information concerning blown sand on a wet sand surface was obtained. The following gives a summary of the more important results:

- (1) The blown sand transport rate observed on a natural beach where a wet sand surface was exposed was almost the same as that measured on a dry sand surface (Kawata, 1950).
- (2) The water content of the blown sand caught by a trap and generated on a wet sand surface which contained about 9 % water content in the upper 10 cm of the surface was about 2.5 %. The empirical coefficient ranged from 0.065 to 0.116 if the Bagnold formula is assumed (Iwagaki, 1950).

- (3) The coefficient of the Bagnold formula was 0.25 on an open beach section and 0.0025 at a location behind a dune if the Bagnold formula is applicable (Aramaki, 1969).
- (4) With elapsed time, the sand transport rate decreased when the wind blew on a wet sand surface. The sand transport rate per 5 min with 0.5 % and 4.2 % water content on the surface was about 1/10 and 1/1000 of that on a dry surface (Nakashima, Sue and Nagasawa, 1973).
- (5) The sand transport rate observed on a wet sand surface with 6 % water content was almost the same as that on a dry sand surface when the wind speed at a height of 1 m was 15.8 m/s, even though it rained, (Nishikawa, Tanaka and Ikeda, 1975).
- (6) Within a few hours after rain stopped, the sand surface reached the air-dry condition when a strong wind blew (Nishikawa et al., 1975).
- (7) The sand transport rate suddenly increased when the water content of the surface sand became lower than 0.3 % and the rate of increase was proportional to the wind speed (Nishikawa et al., 1975).
- (8) There was a certain water content for which the sand transport rate suddenly decreased under a constant wind speed (Nakashima and Suematsu, 1976).

The above results were obtained from previous studies. From the our experimental study in a laboratory wind tunnel and a series of the field observations, we list:

- (9) When a constant wind speed (shear velocity of 42 cm/s) blew on the saturated sand surface,
 - (a) The blown sand on the surface with water content greater than 11 % was negligible, independent of the evaporation rate.
 - (b) The sand transport with a range of water content between 11 % and 6 % was a strong function of the evaporation rate, which was mainly controlled by the air conditions.
 - (c) The sand transport rate was high when the water content of the surface was below 6 %.
- (10) As soon as a rain stopped, blown sand was violently generated under recorded 10 minute-average wind speeds of about 15 m/s at a height of 5 m.
- (11) Within about 18 hr after a rain stopped, the sand volume accumulated in a trench was almost the same as that blown off a dry sand surface.
- (12) The sand volume blown off from a wet sand surface of about 3 or 4 % water content was the same as that trapped by a trench from a dry sand surface when the wind was strong, but the former was about

80 % of the latter when the wind was rather weak.

- (13) The blown sand dislodged from a wet sand surface with about 3 or 4 % of water content which moved downstream reached an equilibrium condition within about 10 m from the boundary where the sand was able to dislodge and the sand surface appeared to be dry. The water content of the flying sand grains was also lower than 1 %.

The above is the main information collected. By linking these fragments together, we become aware of three important matters with relation to the sand blown on a wet sand surface. That is,

- (1) The generation of blown sand on a wet sand surface will be strongly affected by the evaporation rate.
- (2) Concerning the water content, the sand transport rate on a wet sand surface is comparable to that on a dry sand surface when the water content of the surface is small. However, the transport rate decreases suddenly when the water content reaches a certain value.
- (3) Concerning the wind speed, the sand transport rate on a wet sand surface is low when wind speed is low. However, the transport rate becomes comparable to that on a dry sand surface when the wind speed is high even if the sand layer has water content of a few percent.

To explain the above phenomena for the blown sand on a wet sand surface, the following mechanism will be considered. When the sand layer is moist, the threshold shear velocity increases and should be given by an appropriate function of water content in the sand layer. The blown sand on a wet sand surface will then be generated under the same conditions as on a dry sand surface when the shear velocity exceeds the threshold shear velocity. However, even at a condition lower than the threshold shear velocity, sand will be blown when the evaporation rate, controlled by weather conditions, is high, since with a high evaporation rate the sand surface will rapidly dry and the threshold shear velocity of grains on the surface will become lower than that of the underlying sand layer. In this case, the transport rate at a given position depends on the evaporation rate.

The above can be expressed by modifying the Kawamura formula. Thus we write,

$$q = K \frac{\rho_a}{g} (u_* + u_{*cw})^2 (u_* - u_{*cw}) \quad (9)$$

$$u_{*cw} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} g d} + 7.5 w I_w$$

$$0.0 < w < 8.0 (\%), 0.2 \text{ mm} < d < 0.8 \text{ mm} \quad (10)$$

where u_{*cw} is the threshold shear velocity on a wet sand surface and an appropriate function of the water content, and I_w is an appropriate function of the evaporation rate. The coefficient I_w has the value 1.0 when the shear velocity exceeds the threshold shear velocity on a wet sand surface and takes a value ranging from 0.0 to 1.0 depending on the

evaporation rate when the shear velocity is higher than the threshold shear velocity on a dry surface but lower than that on a wet surface. This condition is schematically described in Fig. 4. For example, the transport q_{w_s} in a case when I_w becomes meaningful is calculated by substituting u'_{*cw} into Eq. 9 and u'_{*cw} is an apparent threshold shear velocity given by Eq. 10 taking a value of I_w between 0.0 and 1.0 depending on the evaporation rate. It is considered that I_w is a coefficient which converts the drying speed of the wet sand surface by evaporation and a lowering of u_{*cw} , e.g., to u'_{*cw} . The coefficient I_w will be discussed further in Section VI.

The next task is to examine the sand transport rate on a wet sand surface when the shear velocity exceeds the threshold shear velocity on a wet surface.

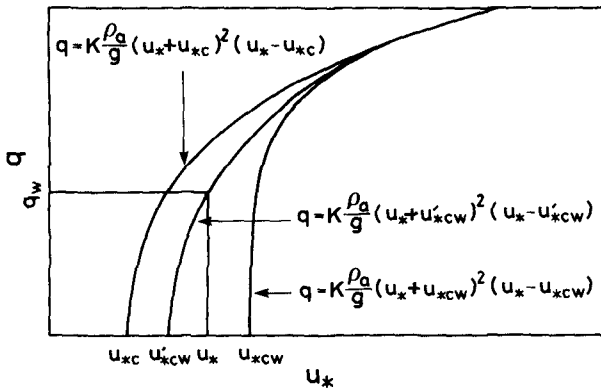


Fig. 4 Schematic explanation of the point at which the coefficient I_w becomes important.

V EXPERIMENT FOR THE SAND TRANSPORT RATE ON A WET SAND SURFACE UNDER HIGH SHEAR VELOCITY

5.1 Purpose

A hypothesis for the blown sand on a wet sand surface was given in Section IV. To examine this hypothesis, an experiment on a wet sand surface under high shear velocity was carried out. The results are described here.

5.2 Facilities (Wind tunnel and Anemometers)

Experiments were carried out using a blowoff type wind tunnel which was specially designed for studying blown sand at the Central Research Institute of Electric Power Industry. The wind tunnel has a test section 110 cm high, 100 cm wide and 20 m long. The bottom is tapered with a gradient of 1/10 at both ends and the cross section of the tunnel

is 100 x 100 cm on which sand can be placed to a thickness of 10 cm. A side wall of glass allows visual observation of the tunnel interior. The wind speed is variable from 3 to 30 m/s, controlled by the frequency of the rotary fan. A sand collecting chamber lies on the end opposite the blower.

For the wind speed measurement, a hot-film anemometer array consisting of four probes and one ultrasonic anemometer was used. The vertical distribution of the wind speed was measured at a location 16 m from the upstream end of the test section in the tunnel. The elevations at which the wind speed measurements were usually made were 5, 10, 20, 30 and 40 cm above the sand surface. These elevations were sometimes changed when some of the anemometers malfunctioned.

The output of the wind speed was recorded on a pen chart recorder with six channels, because a constant wind speed was applied. The wind speed was directly read from the chart. The shear velocity was calculated from the vertical distribution of the wind speed by Eq. 11.

$$u_* = (u_{10} - u_1)/5.75 \quad (11)$$

The sand used in the experiment was taken from Yonezu Beach, the site of our field investigations. The sand was well sorted with a median diameter of 0.3 mm and a uniformity coefficient of approximately 1.7.

5.3 Procedure

Sand was spread over the test section of the 20-m long tunnel. The sand surface was carefully flattened and water was gently applied without disturbing the surface until about one-third of the sand layer from the surface was wet. Then, in a period ranging from 10 to 25 days, the sand layer was left to dry until it reached a certain specified water content. The experiment was carried out when the overall sand layer achieved the suitable water content. On the sand surface, partially dried and dried portions of the surface appeared here and there in the tunnel. In this case, a preliminary burst of strong wind at the beginning of the experiment was applied and the dried sand layer on the surface was blown off. Then the experiment was executed.

For measuring the water content of the sand surface, 5-mm samples of sand were scraped from the surface. Immediately after scraping, the samples were weighed and dried and the water content was calculated. Four samples were scraped, two from the upstream side of the tunnel and two from the downstream side. Sampling was done before and after a run and an average value of the eight samples was employed for defining the water content of that run.

The most difficult procedure of the experiment was to achieve a certain specified water content over the sand bed. The tunnel is constructed out of doors. One side of the tunnel is directly exposed to the outside. The sand bed is strongly affected by the weather, such as the sunlight through the glass wall, the local wind flow passing the mouth and end opening of the tunnel, and shading of the tunnel roof by trees. In order to prepare a sand bed of constant water content, many

attempts by trial and error had to be made. In the end, we could not succeed in establishing a reliable method of making a sand bed of constant water content. However, the experiment runs were carried out only under conditions of constant water content of the sand bed.

5.4 Experiment results and discussion

Figure 5 shows an example of the vertical distribution of the wind speed obtained on a wet sand surface for a constant water content of the sand bed. Figure 5 shows that the logarithmic law for the vertical distribution of wind speed was satisfied on the wet sand surface when blown sand was generated. The focal point is given by $z' = 0.5$ cm and $u' = 300$ cm/s and this value is of the same order as that for a dry sand surface. The difference is judged to be within experimental error.

Figure 6 shows the sand transport rate on a wet sand surface. Data for which the average water contents of the bed at the upstream side and downstream side of the tunnel before and after a run differed by more than $\pm 1.0\%$ were not plotted in Fig. 6.

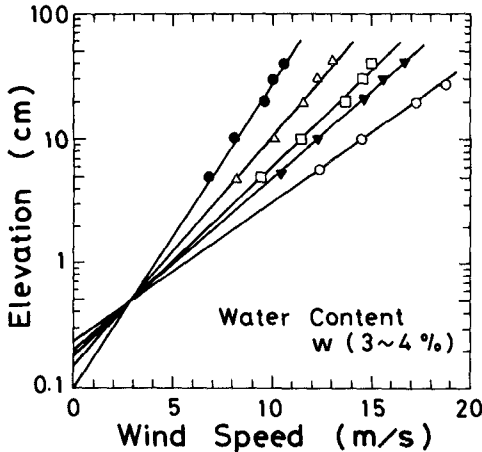


Fig. 5 Example of the vertical distribution of wind speed on a wet sand surface.

The experimental results shown in Fig. 6 for the sand transport rate agree fairly well with Eq. 9 for the values $K = 1.0$ and $I_w = 1.0$ when Eq. 10 is substituted into Eq. 9, although the data at high water content were limited. The shortage of data in the high water content range is due to the difficulty in preparing a bed of constant water content. A considerable scatter in the data is recognized in the low shear velocity region. This may depend not only on experiment error and unsuitability of Eqs. 8 or 10, but also on the rate of evaporation.

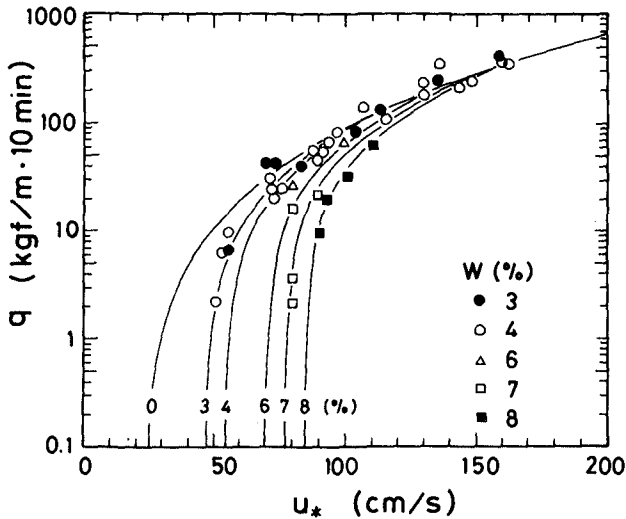


Fig. 6 Sand transport rate under high shear velocity on a wet sand surface.

We conclude that sand will be blown off of a wet sand surface as well as off a dry sand surface when the shear velocity exceeds the threshold shear velocity under a certain water content of the sand surface, although the upper limit of the water content could not be determined from the present experiments.

VI FURTHER CONSIDERATION ON THE FACTOR I_w AND THE THRESHOLD SHEAR VELOCITY ON A WET SAND SURFACE

The coefficient I_w will become meaningful when the shear velocity falls below the threshold shear velocity on a wet sand surface but is higher than that on a dry sand surface.

Considering I_w further, I_w is related to the sand transport rate from the upstream area and the water content of the sand surface, i.e., the threshold shear velocity. As described in Section IV, the sand dislodged from a wet sand surface rapidly loses its adhering water when blown downstream and the transporting sand volume increases (the sand transport rate becomes larger with downstream distance from the generation area). At a certain location under consideration, this transported sand volume from the upstream must be added to that which will be generated at that location by the evaporation rate. Thus the distance from the boundary from which the blown sand will be generated to the particular location enters into the determination of I_w . Furthermore, the sand blown off the downstream affects the water content, i.e., the threshold shear velocity on a wet sand surface. Eventually I_w and the water content on the wet sand surface become

interconnected. However, the relationship between I_w and the water content of the sand surface cannot be determined analytically because they are related to each other in a complicated way. Therefore, we have to search for approximate expressions for I_w and the water content of the surface after a rainfall.

VII CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDIES

The important conclusions obtained from this study for the calculation of the sand transport on a wet sand surface are:

1. The threshold wind speed and the threshold shear velocity obtained in previous experiments differed considerably due to differences in experimental methods and the definition of the critical condition. It was difficult to decide which of the results were valid. No acceptable equations could be found for the prediction of the threshold shear velocity on a wet sand surface.

However, using those experimental results which were judged to be reasonable among the various experiments, an empirical equation predicting the threshold shear velocity was obtained (Eq. 8).

2. The sand transport rate will be given by Eqs. 9 and 10.

This equation should be applicable for water contents lower than 8 % on a wet sand surface.

3. The blown sand dislodged from a wet sand surface of 3 or 4 % water content rapidly lost its adhering water. Within about 10 m from the boundary where the sand was generated, the dislodged sand achieved the air-dry condition and the sand transport rate reached equilibrium.

Therefore, no experiment on sand transport may be made on a wet sand surface if there is a distance greater than 10 m at the upstream from the position for which the blown sand would be calculated, and if the water content of the same surface is lower than 4 %.

4. Whether it is raining or not, effective blown sand will be generated if the water content of the sand surface is relatively low or if the wind is strong.

5. In the field, the sand surface may rapidly achieve the air-dry condition due to a high evaporation rate, percolation to the underground and dried sand blown from upstream. In addition, after a rain stops, the sand volume trapped in a trench trap within 18 hr was comparable to the volume trapped corresponding to a dry sand surface.

Therefore, special consideration to rainfall may not be necessary for beaches such as Yonezu Beach where a series of field observation was carried out by the authors, and where blown sand is usually generated under fine weather and only occasionally under rain.

The above are the main conclusions obtained from this study concerning the topic of blown sand on a wet surface. Many other characteristics of blown sand on a wet sand surface were revealed, but

they were not deemed suitable for a quantitative discussion. An intensive effort should be made to investigate the characteristics of blown sand on a wet sand surface.

In particular, the following subjects should be studied.

1. How deep is the sand layer wetted by a rainfall? What relationships are there between the water content, amount of rainfall, median grain diameter and the sand diameter distribution?
2. What processes are involved in the drying of the sand surface? What are the roles of air temperature, humidity, wind speed and solar radiation? Is it possible to predict the water content of the surface at a given time after a rainfall?
3. What is the functional form of I_w ?
4. Is it possible to improve the equation for the threshold shear velocity, Eq. 8?

To solve the above problems, systematic field observations and well-controlled laboratory experiments are needed. In particular, it is recommended to perform field observations on a rainy beach such as a beach facing to the Japan Sea in winter. For the above studies, the development of new electronic instruments for the rapid measurement of the water content in the sand layer, for the continuous measurement of the blown sand rate, and for the exact measurement of the threshold wind speed are necessary.

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