BLOWN SAND ON BEACHES

by

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ABSTRACT

The blown sand transport rate and the vertical and shore-normal distributions of the wind speed were measured simultaneously on a windy beach. The sand transport rate was measured with conventional total quantity-type traps and with a large trap in the form of a trench. The vertical distribution of the wind speed was measured using an ultrasonic anemometer array consisting of six meters. The distribution of wind speed at a height of 1 m in a section normal to the shoreline was measured with five ultrasonic anemometers. A logarithmic law for the vertical distribution of the wind speed was satisfied, and the wind speed in the section normal to the shoreline was almost constant. The Kawamura and Bagnold formulae were found to predict well the sand transport rate. The trench trap and conventional traps gave empirical coefficients of 1.5 and 1.0, respectively, for the sand transport rate averaged over a section normal to the shoreline. The lower value determined with the conventional traps (1.0) is attributed to their inefficiency compared with the trench trap. In order to obtain data at high shear velocities, a wind tunnel experiment was carried out. This experiment showed that both the Kawamura and Bagnold formulae were valid in the range between 60 to 300 cm/s in the wind shear velocity. The empirical coefficient in the laboratory experiments was 1.0: the difference between the field result with the trench trap and the wind tunnel experiment is attributed to the fluctuations in natural wind.

1. INTRODUCTION AND OBJECTIVES

From the viewpoint of coastal zone management in Japan, up to about 30 years ago the prevention of river mouth closure and the protection of cultivated land from intruding blown sand were important subjects for agricultural civil and coastal engineers. At that time there were rich sandy beaches. However, characteristics of the coast have changed in this country since then. Flood control systems for inland rivers brought about new serious problems of coastal erosion, and engineers

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have become intensely occupied with this challenge. As a result, it seems that the topic of blown sand was left behind as a field of engineering interest. However, blown sand can be an important factor affecting beach change where a strong seasonal wind is predominant. In such situations, sand transport by wind should be included in the sand budget. Therefore, the authors initiated comprehensive field investigations and laboratory studies to establish calculation methods for the transport of sand by wind on beaches. As a first stage of this study, the main effort was concentrated on calculating the total sand volume transported through a section normal to the shoreline (Horikawa, Hotta, Kubota, and Harikai, 1981; Horikawa, Hotta, and Kubota, 1982a).

Several formulae for predicting the total sand transport rate by wind have been presented (O'Brien and Rindlaub, 1936; Chepil, 1945; Kawamura, 1951; Bagnold, 1954; Zingg, 1952; Kadib, 1966; Hsu, 1974). A characteristic of the above formulae, with the exception of Kadib's, is that the total sand transport rate is proportional to the third power of the shear velocity (i.e., the wind speed) at a certain height. A number of detailed discussions of the above formulae have been given (e.g., Horikawa and Shen, 1960; Nakamura, 1971; Phillips and Willetts, 1978). These studies indicate that the various predictive expression can give relatively good results if the empirical coefficients in the formulae can be determined with reasonable accuracy. The two formulae most commonly employed for estimating the total transported sand volume by wind, and for comparison and discussion of experimental results, are those of Bagnold and of Kawamura. They are

$$q = B\sqrt{\frac{d}{D}}\,\frac{\rho}{g}\,u_*^3 \qquad \text{Bagnold (1954)} \qquad (1)$$

$$q = K\,\frac{\rho}{g}\,(u_* - u_{*c})\,(u_* + u_{*c})^2 \qquad \text{Kawamura (1951)} \qquad (2)$$

where q is the sand transport rate (unit weight/unit time/unit width), u_* is the shear velocity, u_{*c} is the critical shear velocity of sand grain movement, ρ is the density of air, g is the acceleration of gravity, D is the standard sand grain diameter (0.25 mm), d is the sand grain diameter forming the sand bed, and B and K are nondimensional empirical coefficients.

2. FIELD OBSERVATION

Two field observations were carried out. The first was conducted between January 7 and January 12, 1981, and the second between January 7 and 17, 1982. The observation site was Yonezu Beach on the west side of the Tenryu River in the middle part of the main island of Japan (Fig. 1). During winter, sand is continually in motion at this site due to the strong seasonal wind from the west, blowing parallel to the shoreline. The sand grain size on this beach ranges between 0.1 to 0.8 mm, and its median diameter is 0.4 mm. The sand is well sorted. During the experiments, dune configurations 20 to 50 cm high and 20 to 30 m long existed on the beach normal to the shoreline and normal to the predominant direction of the wind.

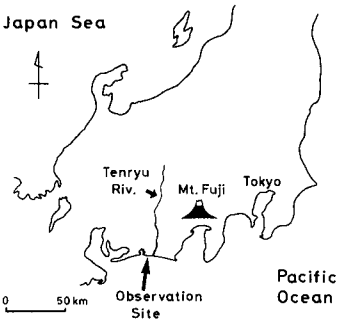

Fig. 1 Location map of the site.

2.1 Experiment Background

The wind speed was measured by an anemometer array consisting of six ultrasonic Doppler shift-type anemometers (Photo 1). An ultrasonic anemometer has the distinguishing merit that the wind speed can be measured precisely at high frequency, because the ultrasonic beam is emitted at 10 Hz. However, this instrument has a drawback for the present application. Data can be lost if a flying sand grain intersects a beam or hits the emitting probe. Therefore, this instrument is not suitable for measuring the wind speed near the beach surface where high concentrations of blown sand can appear. The lowest elevation used for the wind speed measurement was 10 cm. At this elevation noise sometimes appeared, but the frequency of occurrence was small and the noise could be excluded in the computer analysis.

Two kind of traps were used for measurement of the blown sand transport rate. One was a conventional total quantity-type trap and the other was a trench trap. The former was patterned after the traps used by Horikawa and Shen (1960), with some modifications based on field experience. Photo 2 shows a trap in operation. The mouth of the trap was 10 cm by 200 cm. In Photo 2, it is seen that local scour did not take place around the trap. Normally, local scour will appear around an object. Because of this, irregular trapping of the blown sand occurs during progress of the scour. To prevent the generation of scour, several procedures were attempted. We finally succeeded by spraying water around the trap during its setting. The sprayed surface resists erosion and no scour takes place. For the first few minutes, dried sand grains transported from upstream adhere to the wetted surface. Thereafter, a dry sand surface with no scour forms (as seen in Photo 2).

The other trap used for measurement of the blown sand transport rate is a trench-type trap. The idea of such a trap was suggested from previous studies. It is commonly known that the travel distance of a sand grain in saltation or in suspension is in the range of a few centimeters to a few meters. The experiment by Ishihara and Iwagaki (1952) showed that 97% of the total blown sand from upstream fell within 4 m of the waterline in the case of a pond or a stream. Iwagaki (1950) also reported that by utilizing the above information and constructing a

Photo 1 Ultrasonic anemometer array.

Photo 2 Total quantity type trap.

stream a few meters wide, cultivated land could be protected from intruding blown sand. This measure was implemented at Tottory beach in Japan. From the preceding results, the authors concluded that the entire quantity of blown sand could be trapped by a trench of width more than a few meters. A trench trap 8 m wide, 1 m deep, and 50 m long was therefore used.

Photo 3 shows the trench in the first observation: (a) at the beginning of the observation, and (b) at the same location after four days. The photo shows the upstream side slope, and indicates that the slope advanced while maintaining the rest angle of the dry sand. We can estimate the total amount of blown sand trapped by the trench given the width of the accumulated sand and the depth of the trench.

(a) Beginning of the observation. (b) End of the observation.

Photo 3 Trench trap.

2.2 Experiment Procedure

Figure 2 shows the beach profile and the arrangement of the instrumentation for the first observation. Symbols A to F indicate positions of the total quantity traps (arranged across a section normal to the shoreline). The open squares indicate locations where the vertical distribution of the wind speed was measured. Together with measurements of the vertical wind speed distribution at each position on the beach, blown sand was collected by the total quantity traps on January 8, 9 and 10, 1981. The sampling period for the transport rate was 10 minutes.

Survey poles with measurement scales were installed in the trench at 1-m intervals in the direction of the wind, and at 2-m intervals in the direction normal to the wind (See Photo 3). The change in the sand surface was measured from differences in distance from the tops of the poles to the sand surface. Measurement of the sand surface change in the trench was carried out around 9:00 am and 5:00 pm from January 8 to January 12.

Figure 3 shows the beach profile and the arrangement of the instruments for the second observation. Letters A to F give positions of the total quantity traps. Numbers 3 to 7 give the positions of the anemometers. While measuring the wind speed distribution continuously, the distribution of the sand transport by wind in a section normal to the shoreline was measured by total quantity traps on January 13 and 14, 1982. As in the first observation, the sampling period was ten minutes.

The trenches were dug as sbown in Fig. 3. The sand transport rate was measured at the most-upstream trench, TC. Tbe region S between the two downstream trenches TB and TA was used in an attempt to check the sand budget. The trench TB stops the blown sand from the upstream side, while the downstream trench TA collects the blown sand originating from region S. If we know the total sand volume which moved from region S, we can compare this amount with that collected in trench TA. To determine the total sand volume moved from region S, small steel pipes 12 mm in diameter and 1 m in length were hammered into the surface

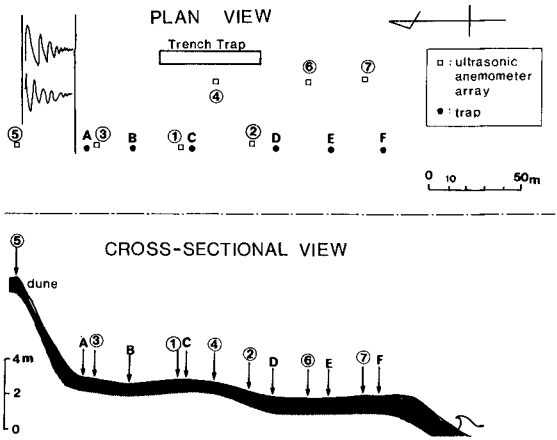

Fig. 2 Beach profile of the site and arrangement of instrumentation (first observation).

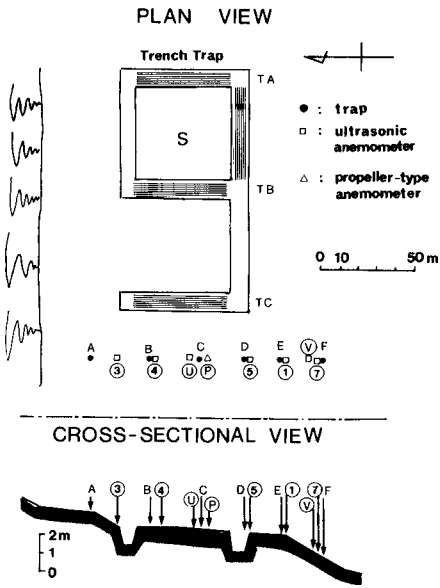

Fig. 3 Beach profile of the site and arrangement of instrumentation (second observation).

to form a grid with a 2 m by 2 m mesh. The distance between TB and TA was 50 m. A width of 50 m was choosen for the measurement. A total of 676 pipes were installed.

The region between TC and TB was used in an experiment of the drying process of the sand surface. Details of this experiment have been described elsewhere (Horikawa, Hotta, and Kubota, 1982b).

The circled letters U and V indicate the positions where the vertical distribution of the wind speed was measured on January 15 and 16, 1982. The ultrasonic anemometer has been rather recently developed. To discuss and compare results of our field observations relative to previous studies, one needs to know the characteristic difference, if any, between the ultrasonic anemometer and conventional anemometers such as the propeller-type, cap-type and so on. For this purpose, the wind speed at a height of 5 m was measured with a propeller-type anemometer at position P in Fig. 3. The statistical characteristics and 10-min averages of the two types of instruments were found to be essentially the same. The wind speed was recorded on an open-wheel recorder for both experiments, and the data were averaged in intervals of 10 minutes.

3. RESULTS

3.1 Sand Characteristics

The grain size distribution and the median diameter of the sand are important parameters governing the blown sand transport. Table 1 gives examples of the median diameter and the uniformity coefficient based on sieve tests of the sand trapped by the total quantity traps in the first observation. Here d_{50} is the median diameter, and the uniformity coefficient is $U_c = d_{60}/d_{10}$. In Table 1 is also given the median diameter (0.4 mm) and uniformity coefficient (1.75) of the surface layer sand to about 0.5 cm in depth, which was removed from the neighborhood of point C on January 10, 1981

Table 1 Median diameter of blown sand and uniformity coefficient.

Location (Fig. 2)	10 Jan 81		9 Jan 81		8 Jan 81	
	d_{50}	U_c	d_{50}	U_c	d_{50}	U_c
A	0.31	1.50	0.25	1.47	0.27	1.58
B	0.31	1.50	0.27	1.50	0.28	1.55
C	0.31	1.52	0.28	1.58	0.27	1.50
D	0.30	1.45	0.28	1.50	0.28	1.48
E	0.32	1.62	0.27	1.58	0.28	1.50
F	0.26	1.61	0.25	1.53	0.24	1.44
surface	0.4	1.75				
u_*	37.6 (cm/s)		39.5 (cm/s)		30.0 (cm/s)	

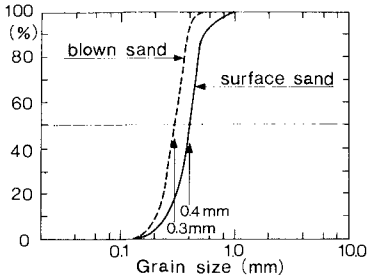

Fig. 4 Grain size accumulation curves of blown sand and surface sand.

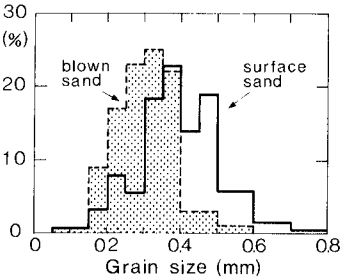

Fig. 5 Grain size distribution of blown sand and surface sand.

Figure 4 shows the particle size accumulation curves of the surface sand and a sample of the trapped sand at point C on January 10 (as listed in Table 1). Figure 5 shows the sand grain size distribution of both sand samples. The median diameter of the trapped blown sand is about 0.3 mm and the uniformity coefficient is around 1.5 (well sorted). Both the median diameter and the uniformity coefficient of the trapped sand are smaller than those of the surface sand. Larger grain sizes in the blown sand are seen to be limited in number (Fig. 4). It is therefore a difficult problem to determine the median diameter which represents the blown sand.

3.2 Wind Speed Distributions

To calculate the blown sand transport by Eqs. (1) and (2), the shear velocity u_* as an external force must be given. The shear velocity can be obtained as the gradient of a straight line on semilog paper, if the logarithmic law for the vertical distribution of wind speed is valid. That is,

$$u = 5.75\, u_* \log_{10} \frac{z}{z_o} \tag{3}$$

where u is the wind speed at a height z, the roughness of the sand surface is z_o, and u_* is the shear velocity. Equation (3) holds under the condition that the wind speed is not sufficiently large to move the sand grains. However, the distribution of the wind speed will be affected by the moving sand grains if the wind speed is greater than the critical wind speed and sand grains begin to move. Then Eq. (3) should be replaced by

$$u = 5.75\, u_* \log_{10} \frac{z}{z'} + u' \tag{4}$$

where (z', u') defines the "focal point" according to Bagnold (1954). Therefore, on semilog paper, all lines expressing the vertical distribution of wind speed converge to the focal point.

Figure 6(a) shows examples of the vertical distribution of wind speed observed on January 7 and 8 in the first observation. We can conclude that Eq. (4) is satisfied. Equation (4) was also satisfied at other observation points on the flat portion of the beach, except in the vicinity of a coastal dune located parallel to the shoreline.

The focal point observed in the first observation ranged between $u' = 130$ to 250 cm/s, and $z' = 0.11$ to 0.3 cm. Zingg (1952) suggested the following empirical equations for the focal point:

$$u' = 20\ d \quad \text{(mile/hr)} \tag{5}$$

$$z' = 10\ d \quad \text{(mm)} \tag{6}$$

Here d is the diameter of the sand in mm. We shall compare the observed results with Zingg's equations. If the diameter of the sand grains is taken as 0.4 mm (the median diameter of the sand bed), then

$$u' = 8.8 \cdot 10^2\ d = 358 \text{ cm/s} \quad \text{and} \quad z' = 10 \cdot 0.4 = 0.4 \text{ cm}$$

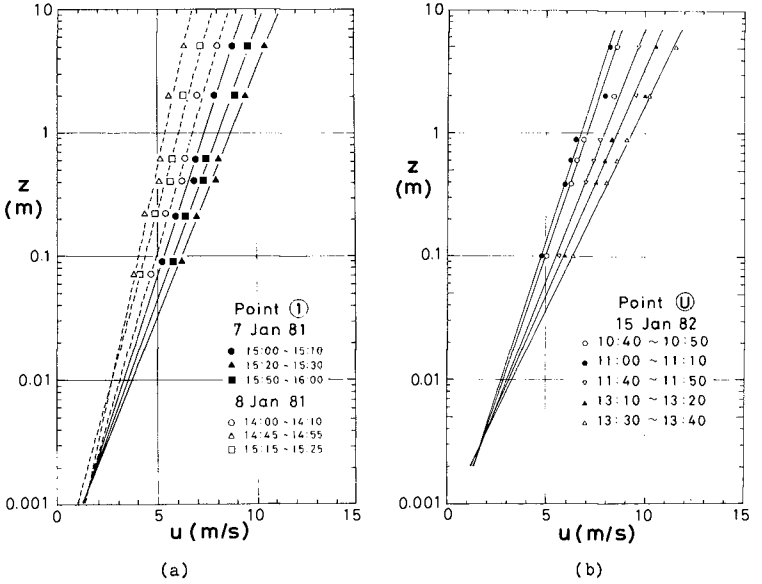

Fig. 6 Examples of vertical distribution of wind speed.

If d is 0.3 mm, the median diameter of the trapped blown sand, then

$u' = 264$ cm/s and $z' = 0.3$ cm.

For the first observation, Zingg's formulae agree with the upper limits from the field measurements.

In the second observation, the vertical distribution of wind speed was observed on January 14 and 15 (Fig 6(b)). Equation (4) was satisfied, but the focal point took on somewhat different values from the first observation. That is, u' was around 220 cm/s, and z' was around 0.6 cm, about twice that of the first observation. The value $z' = 0.6$ cm is somewhat larger than that predicted by Zingg's equation. To evaluate the utility of Zingg's equations, further observations are needed.

Another way to determine the shear velocity is to establish a relationship between the shear velocity and the wind speed at some specified elevation. Horikawa and Shen (1960) gave the following equations to calculate the shear velocity from the wind speed at heights of 1 m and 4.465 m. They are

$$u_* = 0.0690\, u_{100} - 18.4 \quad \text{(cm/s)} \tag{7}$$

$$u_* = 0.0548\, u_{446.5} - 14.7 \quad \text{(cm/s)} \tag{8}$$

Here u_{100} and $u_{446.5}$ are the wind speed at heights of 100 cm and 446.5 cm respectively. These equations are based on four assumptions; 1) Eq. (4), 2) Zingg's empirical formulae for the focal point, 3) the diameter of sand grain is 0.3 mm, and 4) the Karman constant is equal to 0.4. Assuming the same conditions, but directly inserting the measured average focal point ($u' = 200$ cm/s and $z' = 0.20$ cm), we obtain the following two equations:

$$u_* = 0.0644\, u_{100} - 12.9 \quad \text{(cm/s)} \tag{9}$$

$$u_* = 0.0511\, u_{500} - 10.2 \quad \text{(cm/s)} \tag{10}$$

Thus the shear velocity can be calculated from the wind speed at heights of 1 m and 5 m. Figure 7 shows a comparison of the shear velocity given by Eqs. (9) and (10) with the field data. The equations are seem to provide a good prediction.

Figure 8 shows an example of the ten-minute average wind speed at a height of 1 m across a section normal to the shoreline in the second observation. The data show that the wind speed was almost constant on the beach surface. Therefore, we can assume that the shear velocity acting on the sand surface was also constant.

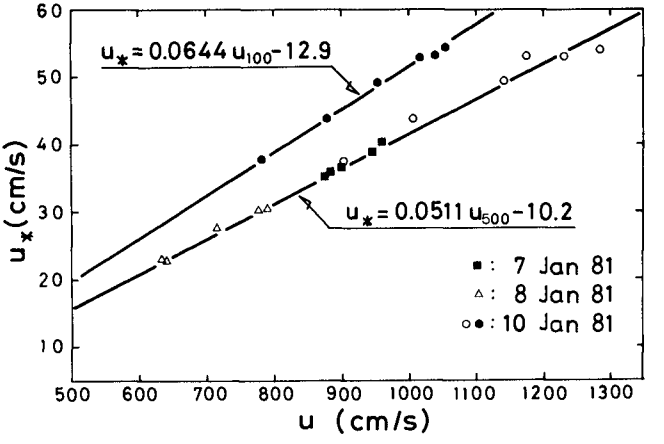

Fig. 7 Relationship between shear velocity and wind speed at heights of 1 m and 5 m.

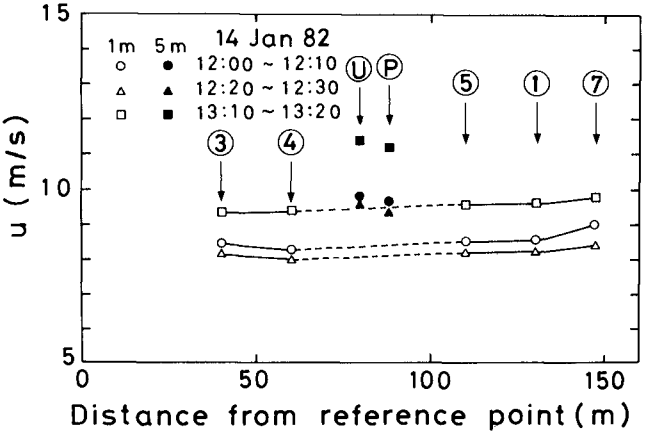

Fig. 8 Wind speed distribution at 1 m height in a section normal to the shoreline.

3.3 Sand Transport Rate

(1) Conventional trap

Figure 9 shows the distribution of the blown sand transport rate in a section normal to the shoreline on the first observation. Figure 10 shows a plot of the sand transport rate against the shear velocity at the measurement point C obtained from vertical distribution of wind speed measured simultaneously at the same point. In this figure, the curves calculated by the Bagnold and Kawamura formulae with empirical coefficients of 1.0 and 2.0 are also drawn. It is clear that both the Bagnold and Kawamura formulae agree well with the field data if the empirical coefficients are chosen to be about 1.0.

Figure 11 shows the sand transport rate distribution during the period in which the wind speed distribution was measured on the second observation. The sand transport rate was not constant in the section, although we had inferred that the shear velocity was constant on the beach (last paragraph of Subsection 3.2). We carefully observed the sand surface to resolve this problem. The surface consisted of a dune configuration about 30 to 50 cm high and about 15 to 20 m long. The dried sand layer was thick at the crest and thin at the trough. Sand was actively blown at the crest but not at the trough. We finally realized that the quantity of sand caught by the trap was dependent on the location of the trap. That is, a large amount of blown sand was trapped if a crest was located in front of the trap, whereas the amount collected was small behind a trough.

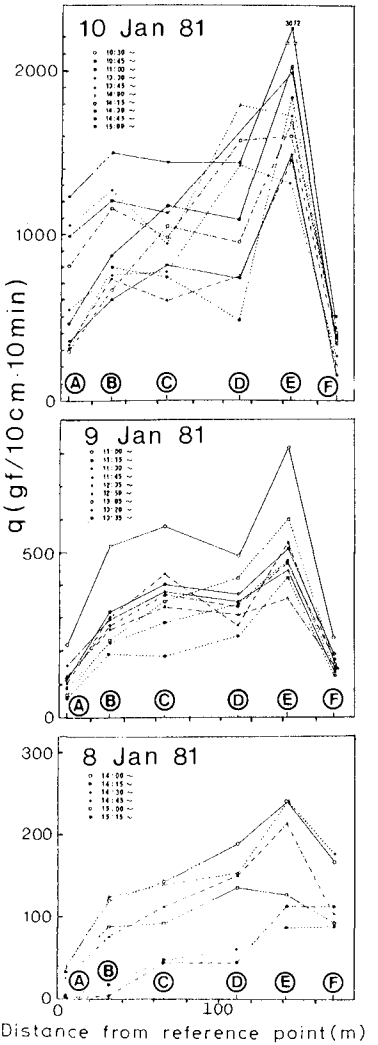

Fig. 9 Blown sand transport rate distribution in a section normal to the shoreline (first observation).

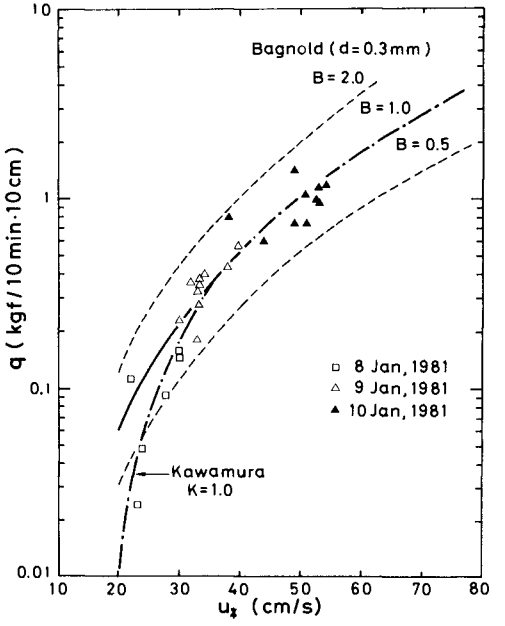

Fig. 10 Blown sand transport rate at point C (first observation).

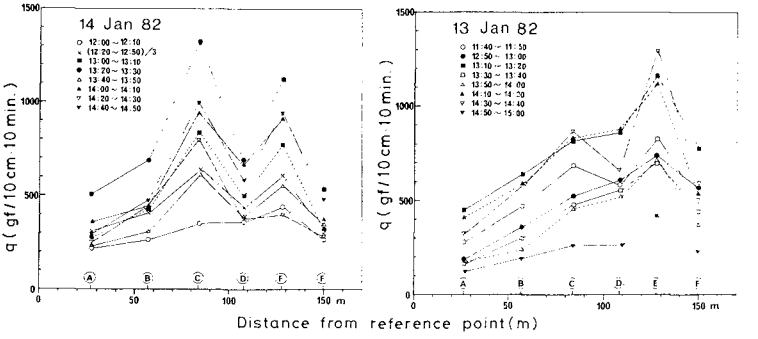

Fig. 11 Blown sand transport rate distribution in a section normal to the shoreline (second observation).

We found that the sand was not actively blown on the landward side of the beach which had been covered by dirt deposited by a storm. There was also very little sand blown in areas of dense coastal vegetation (e.g., measurement point A). We therefore can expect that a plot of the transport rate measured by point sampling against the shear velocity will show great scatter. However, for engineering purposes, it is more important to evaluate the average sand transport than to evaluate the local transport.

Figure 12 shows the average transport rate in the section A to F for the two observations. The shear velocity was calculated from the vertical distribution of wind speed for the first observation, and from Eq. (9) for the second observation. Both the Kawamura formula and the Bagnold formula agree well with the data when the empirical coefficient is 1.0. The Kawamura formula gives a particulary good result for the sand transport under shear velocities lower than 33 cm/s because it accounts for the critical shear, as was pointed out by Horikawa and Shen (1960).

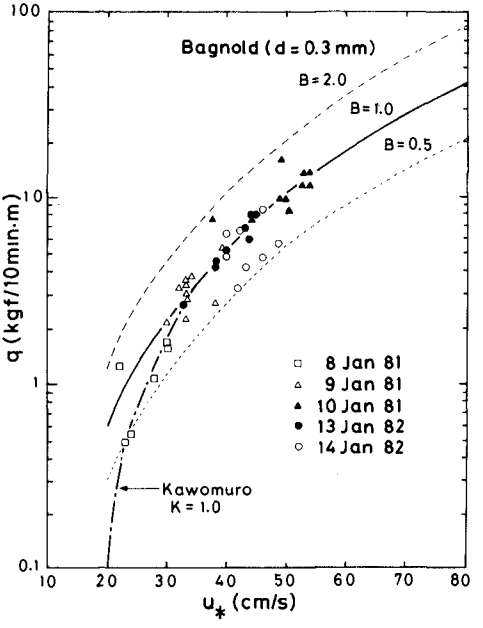

Fig. 12 Average sand transport rate (both observations).

(2) Trench trap

In Table 2, columns 1 to 3 list the times when sand was effectively blown, and the accumulated sand volume during the respective period. The measured sand volumes in the second observation were almost the same for trenches TC and TA (Fig. 3). The fourth column in Table 2 shows accumulated sand weights calculated assuming the dry sand has a weight density of 1650 kgf/m^3. The fifth and sixth columns indicate the estimated blown sand volume using Eqs. (1) and (2) for the transport rate, and (9) and (10) for the shear velocity. In the estimation, the following parameters were assumed: an empirical coefficient of 1.0 in the Bagnold and Kawamura formulae; a sand grain diameter of 0.3 mm in the Bagnold formula; u_{*c} of 20 cm/s in the Kawamura formula, and finally $\rho/g = 1.25 \cdot 10^{-6}$ (gf·s^2/cm^4).

The last two columns show the ratio of the measured blown sand volume to the estimated volume. The measured volume from the trench is greater than the estimated volume, about 1.25 (1.5) times the estimated amount for the first (second) observation. It is not clear why this difference appears, although it is reasonable to attribute it to experimental error. In Subsection 3.3 (1), it was found that the empirical coefficients for both formulae based on measurements by the conventional trap have a value of about 1.0. The difference in results most likely is due to the lower efficiency of the conventional traps. From this consideration, the efficiency of the conventionl trap is given by the reciprocal of the ratio of the measured sand volume to the estimated volume. The range in efficiency is about 0.65 to 0.8.

Accordingly, we conclude that the empirical coefficients for Eqs. (1) and (2) should be about 1.5.

Table 2 Blown sand measured by trench trap.

Date	Time	Observed sand volume		Estimated sond volume		Ratio of observed to estimated vol.	
		(m^3/m)	(Kgf/m)	Bagnold	Kawamura	Bagnold	Kawamura
1981							
Jan. 9	9:00 ~ 16:00	0.071	117	102	92	1.15	1.27
10	9:00 ~ 15:15	0.314	518	425	452	1.22	1.15
11	9:00 ~ 15:40	0.171	282	218	222	1.29	1.27
12	9:00 ~ 15:00	0.186	306	222	232	1.37	1.33
1982 Jan. 13, 9:00 ~ Jan. 14, 17:00		0.60	990	661	641	1.50	1.54

Now we will discuss the sand budget for region S and trench TA in the second observation. The sand volume blown off region S was about 1 m^3 per unit width in the period when effective blown sand took place, as listed in Table 2. If the weight density of the sand is 1650 kgf/m^3, the weight of sand blown off the region per unit width is 1650 kgf/m. This value is much larger than that caught in trench TA (or TC, Table 2). If this value is correct, it implies that trench TA did not stop the entire volume of blown sand from upstream. However, we observed

that only a very small volume of blown sand in suspension crossed over the trench. Therefore, it seems that the overestimation of the sand volume blown off region S was due to insufficient accuracy in the measurement of the sand surface change with the rods.

(3) Laboratory experiment

Measurements of the sand transport by wind obtained from this field study were limited to rather low shear velocities as seen in Fig. (11). The maximum shear velocity obtained in our field observations was around 60 cm/s. If we evaluate the wind strength at the height of 5 m, a shear velocity of 60 cm/s is equivalent to a wind speed of around 12 to 13 m/s for a ten-minute average, and around 18 to 20 m/s for a momentary maximum wind speed. It often happens that the wind speed is higher than the above values. It was, however, difficult for us to wait for such a condition to occur during the field investigation because of economic considerations. Therefore, we conducted a simple laboratory experiment on the sand transport rate by wind under a high wind speed. The results are now briefly described.

The experiments were carried out using a blowoff-type wind tunnel specially designed for studying blown sand. The wind tunnel is 1.1 m high, 1 m wide, and 20 m long. The bottom is tapered with a gradient of 1/10 at both ends. The cross section of the tunnel on which sand can be placed to a thickness of 10 cm is 1 m by 1 m. The wind speed can be varied from 3 to 30 m/s. The wind speed was measured by an array of four hot-film anemometers. The experimental facility is described by Horikawa, Hotta, and Kubota (1982b).

Sand from Yonezu beach (site of the field study) was used in the experiments. The vertical distribution of wind speed was measured, and the shear velocity was calculated from the distribution. The anemometers were placed 1, 5, 10, and 20 cm from the sand surface. Equation (4) was satisfied in this experiment, although the wind speed at the 1-cm height deviated somewhat from the straight line formed by the other measurement points (when the shear velocity was higher than around 180 cm/s). The sand passing the downstream end of the test section was considered to be the sand transported by wind. The time interval for applying the wind varied from two minutes to ten minutes, depending on the speed. Figure 13 shows that the Kawamura and Bagnold formulae agree well with the experimental results even at high shear velocities, with the empirical coefficient determined to be about 1.0.

4. DISCUSSION AND CONCLUSIONS

From results of the field study, we concluded that the empirical coefficient for the Bagnold and Kawamura formulae should be about 1.5. However, the laboratory experiments with high shear velocities indicate that the these coefficients should be about 1.0. Horikawa and Shen (1960) also found that the coefficient in the Kawamura formula is approximately 1.0 from their laboratory experiments using well-sorted sand of medium diameter 0.2 mm.

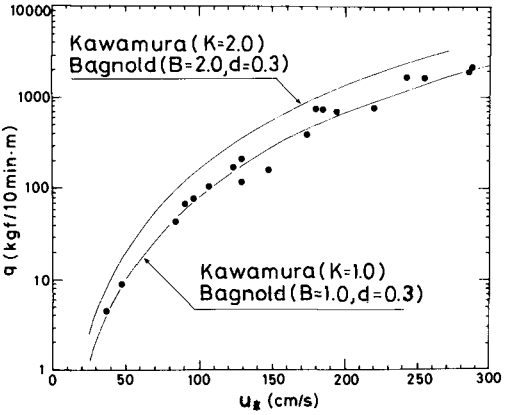

Fig. 13 Blown sand transport rate at high shear velocities.

The coefficients based on the field data are therefore larger than those obtained from the laboratory experiments. This may be due to a difference in characteristics between natural wind and latoratory wind. Usually a constant wind speed is maintained in laboratory experiments. However, the speed of natural wind varies, and a ten-minute average is ordinarily used in correlations. The blown sand transport rate is proportional to the third power of the wind speed, or of the shear velocity. A short interval of high speed wind is then efffectively equivalent to a longer interval of constant lower wind speed.

The value of 1.5 for the empirical coefficients in the Bagnold and Kawamura formulae found in the second field experiments fortuitously agrees with the result of Bagnold from laboratory experiments using well-sorted sand with median diameter of 0.25 mm. The reliability of the coefficient is increased by this field study. We consider both of the Bagnold and Kawamura formulae valid to estimate the total sand transport rate by wind. Both are equivalent at high shear velocities, but the Kawamura formula is recommended for low shear velocities.

Finally, we mention the fact that the total sand transport rate is strongly affected by the moisture in the sand layer. However, we have just begun to study this effect. An intense effort is necessary to clarify the role of moisture in the sand layer.

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