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**Synopsis**

As the mouth of the Kiku River flowing into the Sea of Ensyū always moves, being blockaded in some cases, due to the sand-drift in the sea and on the coast by monsoons in winter, the raised water level in the river mouth gives unfavorable effects to the upstream side of the river. Therefore, the control project to maintain the river mouth and prevent it from blockading is becoming a pending problem of the river. It is very difficult to solve this kind of problem satisfactorily, and it is necessary to start fundamental researches in order to obtain a clue to settle this problem. Thus, in this paper, we tackled the effect of sand storm on the coast by wind, that is, estimating the sand quantity moved by sand storm in a year based on the data of wind-velocity, -direction and rainfall, we discussed the effect of sand storm on the movement and blockade of the river mouth from the point of view of civil engineering.

## 1. Introduction

The Kiku River, which has a catchment basin of 157 sq.km and a planned maximum discharge of 660 $m^3/s$, flows into the Pacific Ocean across a belt of dune 1000∼2000 m wide on the coast of the Sea of Ensyū, as shown in Fig. 1, and is under the direct control of the Ministry of Construction. In general, rivers flowing into the sea across dunes or sand coasts where the sea is rough and the sand-drift violent, suffer more or less from the movement and blockade of their mouths, when the flow is gentle and discharge small. With the Kiku River, which is one of these rivers, the above mentioned properties are considered to be due partly to the sand storm on the coast by monsoons in winter in addition to the sand drift in the sea, judging from the fact that a dune develops on this coast and that the wind direction of monsoon is almost parallel to the beach line. In this paper, we will discuss the effect of sand storm on the coast, and the results obtained by the research on the sand drift in the sea will be reported in some future occasion.

First, discussing the existing studies on the sand drift by wind, we will make clear the various properties of the sand drift and then describe the results measured at the river mouth and the estimated sand quantity moved by sand storm in a year based on these results.

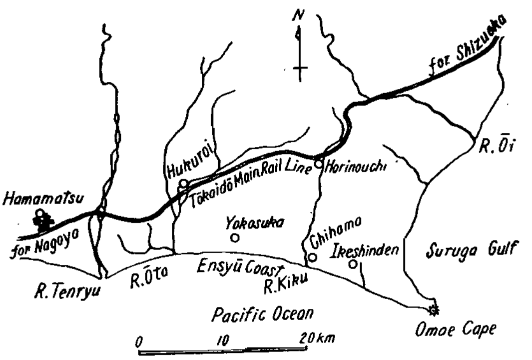


Fig. 1. Situation of the Kiku River.

## 2. Theory on the Sand Drift by Wind

### (1) Relation between frictional velocity in which sand grains begin to move, diameter of sand grains and beach slope

As the wind velocity increases gradually and becomes a certain value, sand grains begin to roll on the sand surface and move leeward, there being a number of experiments on the relation between this wind velocity and the diameter of the sand grain. But it is more convenient to investigate the relation between the critical frictional velocity $v_{*t}$ in which sand grains begin to move and the grain diameter $d$, as the wind velocity varies with the height. The frictional velocity $v_* = \sqrt{\tau_0/\rho}$ is one quantity which represents the intensity of wind, where $\tau_0$ is the shearing stress acting on sand surface and $\rho$ is the density of air. In Fig. 2 which represents the relation between the critical frictional velocity $v_{*t}$ and the square root of product $\sigma d$ of the grain diameter and its density, the experimental results by Chepil[1], Chigusa[2] and Akiba[3] are plotted. As shown in Fig. 2, in the region of $\sigma d > 0.5$, $v_{*t}$ is proportional to $\sqrt{\sigma d}$ and the following equation reduced by Bagnold[4] holds good.

$$v_{*t} = A\sqrt{(\sigma-\rho)gd/\rho},$$

where $A$ is a constant and $g$ is the gravity acceleration. Also the relation between $v_{*t}$ and $\sqrt{\sin(\varphi_0+\alpha)/\cos\varphi_0}$ is almost linear, as we can see in Fig. 3 and Fig. 4 which represent the relation between $v_{*t}$ and the slope angle $\alpha$ of the sand surface, where $\varphi_0$ is the repose angle of sand.

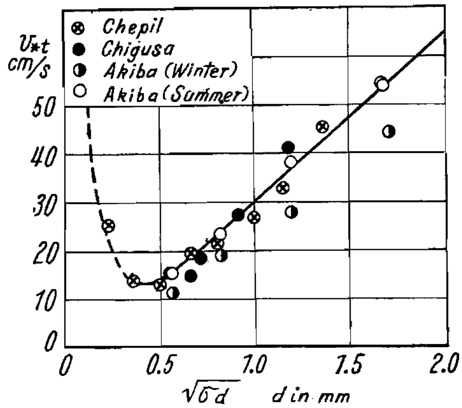



Fig. 2. Relation between $\sqrt{\sigma d}$ and $v_{*t}$.

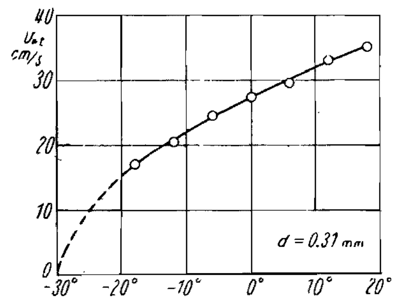



Fig. 3. Relation between $v_{*t}$ and $\alpha$.

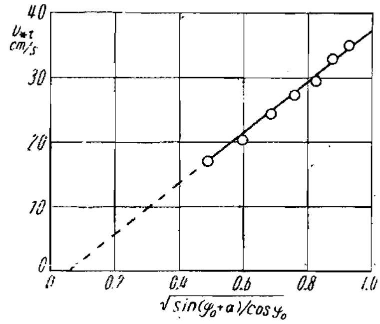



Fig. 4. Relation between $v_{*t}$ and $\sqrt{\sin(\varphi_0+\alpha)/\cos\varphi_0}$, in the case of $\varphi_0=30°$.

These relations can be reduced from the idea based on the air drag or the tractive force or the turbulence of air flow respectively, as follows.

1. *Idea based on the air drag.* This is a method to obtain the critical wind velocity, putting the air drag when the wind with velocity $u_1$ knocks against a sand grain on a sand surface equal to the sum of the maximum static frictional resistance of the grain and the component parallel to the surface of gravity force acting on the grain. When the diameter $d$ of the sand grain and the critical wind velocity are large, the relation

$$\frac{\pi}{6} d^3\sigma g(\tan\varphi_0\cos\alpha + \sin\alpha) = \frac{\rho}{8}\pi d^2 u_1^2 C_x$$

holds good, and therefore

$$u_1=\sqrt{4 \sin (\varphi_0+\alpha)\ g\sigma d/3 \cos \varphi_0 \rho C_x}, \quad \text{..................} (1)$$

where $C_x$ is the drag coefficient.

Since the vertical velocity distribution on sand surface is expressed by the equation

$$u=5.75\ v_* \log (30z/k)$$

and the value $k$ on flat sand surface may be assumed to be equal to the diameter of the sand grain, we obtain the equation

$$u_1=5.75\ v_* \log 30.$$

Therefore, from this equation and Eq. (1), the critical frictional velocity is given by

$$v_{*t}=A'\{\sin (\varphi_0+\alpha)/\cos \varphi_0\}^{1/2}\sqrt{g\sigma d/\rho}. \quad \text{..................} (2)$$

Putting $\alpha=0$ and considering the buoyancy of air in this equation, an equation of the same form as Bagnold's equation can be reduced.

2. *Idea based on the tractive force.* In this method, the shearing force acting on sand surface per grain of sand is considered to be equal to the sum of the maximum static frictional resistance of the grain and the component parallel to the surface of gravity force acting on the grain[5]. Now, if we consider the sand grains contained per unit volume of sand to be $N$ particles, $N=6\lambda/\pi d^3$, because the total volume of sand grains $\lambda$ is equal to $N\cdot\pi d^3/6$. On the other hand, since the number of wind-swept sand grains in a unit area of sand surface $n$ is considered to be equal to $N^{2/3}$, it becomes $n=(6\lambda/\pi)^{2/3}\cdot(1/d)^2$. Therefore, the frictional resistance acting on a grain of sand can be expressed by

$$\rho v_*^2/n=\rho(\pi/6\lambda)^{2/3}d^2 v_*^2$$

and equating this to $(\pi d^3\sigma g/6)\cdot(\tan \varphi_0 \cos \alpha+\sin \alpha)$, we obtain

$$v_{*t}=A''\{\sin (\varphi_0+\alpha)/\cos \varphi_0\}^{1/2}\sqrt{\sigma g d/\rho} \quad \text{..................} (3)$$

The above equation has the same form as Eq. (2).

3. *Idea based on the turbulence of air flow.* In this method, it is considered that, when the upward lift on a sand grain due to the turbulence of air flow in the vertical direction becomes a value balancing with the gravity force acting on the grain, the grain is kept in such a very movable condition that it may be moved by the action of a large mean velocity in the horizontal direction[6]. Now, if we consider the case of a horizontal sand surface, the upward lift due to the turbulence

of air flow can be expressed as $\frac{\partial p'}{\partial z} d\times\frac{1}{4}\pi d^2$, where $p'$ is the fluctuation of prersure and the $z$-axis is taken vertically upwards. Since this lift ought to balance with the gravity force acting on the sand grain, considering the buoyancy of air,

$$\frac{1}{4}\pi d^3 \frac{\partial p'}{\partial z}=\frac{\pi}{6}d^3(\sigma-\rho)g\,.$$

Furthermore, taking the statistical average of turbulent air flow, the following equation can be derived.

$$\sqrt{\overline{\left(\frac{\partial p'}{\partial z}\right)^2}}=\frac{2}{3}(\sigma-\rho)\,g \quad \text{.......................(4)}$$

If the relation for $p'$ is transfered into the relation for the velocity fluctuation $w'$ in the vertical direction by the application of Taylor's theory of isotropic turbulence, Eq. (4) becomes

$$\frac{2\left(\overline{w'^2}\right)^2}{\lambda^2}+\frac{1}{4}\left(\frac{\partial\,\overline{w'^2}}{\partial z}\right)^2=\left(\frac{2}{9B}\,\frac{\sigma-\rho}{\rho}\,g\right)^2, \quad \text{..............(5)}$$

where $\lambda$ is the diameter of the smallest eddies and $B$ is a constant near 1. Next, assuming $\sqrt{\overline{w'^2}}\infty\sqrt{\overline{u'^2}}$ and putting $\sqrt{\overline{w'^2}}=l_1\left|\frac{du}{dz}\right|$, the relation between $w'$ and $v_*$ becomes as follows.

$$\sqrt{\overline{w'^2}}=\frac{l_1}{l}\,v_*$$

If we put $l_1=\varepsilon z$ and assume that the mixing length $l$ and the diameter $\lambda$ of the smallest eddies may be expressed as parabolas of the higher order of $z$,

$$l=l_0\left\{1+\left(\frac{\varkappa}{l_0}z\right)^n\right\}^{1/n}, \qquad \lambda=\lambda_0\left\{1+\left(\frac{\beta}{\lambda_0}z\right)^n\right\}^{1/n},$$

where $\varepsilon$, $\varkappa$ and $\beta$ are constants near 1, 0.4 and 2 respectively in the case of a smooth wall, inserting these relations into Eq. (5) and assuming that the conditions for a sand grain are satisfied at $z=d$, the critical frictional velocity is given by the following equation.

$$v_{*t}=\sqrt{\frac{2}{9B}\,\frac{\sigma-\rho}{\rho}\,g}\Bigg/\frac{\varepsilon}{l_0}\left[\frac{2}{\lambda_0^2}\,d^4\left\{1+\left(\frac{\beta}{\lambda_0}d\right)^n\right\}^{-2/n}\left\{1+\left(\frac{\varkappa}{l_0}d\right)^n\right\}^{-4/n}\right.$$
$$\left.+\,d^2\left\{1+\left(\frac{\varkappa}{l_0}d\right)^n\right\}^{-4/n-2}\right]^{1/4} \quad \text{.....................(6)}$$

This equation becomes, in the case when diameters of sand grains are large, i.e., in the region of $(\varkappa/l_0)\, d \gg 1$ and $(\beta/\lambda_0)\, d \gg 1$,

$$v_{*t}=\sqrt{\frac{2}{9B}\,\frac{\sigma-\rho}{\rho}\,g}\;\frac{\varkappa}{\varepsilon}\sqrt{\frac{\beta}{\sqrt{2}}}\sqrt{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and in the case when diameters of sand grains are small, i.e., in the region of $(\varkappa/l_0)\, d \ll 1$ and $(\beta/\lambda_0)\, d \ll 1$,

$$v_{*t}=\sqrt{\frac{2}{9B}\,\frac{\sigma-\rho}{\rho}\,g}\;\frac{l_0}{\varepsilon}\,\frac{1}{\sqrt{d}}\,. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Eq. (7) shows that $v_{*t}$ is proportional to $\sqrt{d}$ in the case of large sand grains and also Eq. (8) shows that $v_{*t}$ is proportional to $1/\sqrt{d}$ in the case of small sand grains. Although this theory is based on various assumptions, the above obtained relations explain satisfactorily the experimental results shown in Fig. 2. The effects due to the slope of the sand surface, however, can not be explained.

Moreover, in Fig. 2, $v_{*t}$ based on the experimental results which Prof. Akiba obtained in winter is smaller than the other, but it seems to be owing to the fact that $\tan \varphi_0$ becomes small due to low humidity in winter.

## (2) Vertical distribution of quantity of drifting sand by wind

It is considered that there are no reasonable methods to treat this problem but the following two; that is, the one is to treat the sand grains as projectiles, neglecting wholly the turbulence of wind in spite of the certain effects it has on the sand drift when the diameter of dune sand is 0.2~0.3 mm, and the other is to use the coefficient of eddy viscosity as in the case of temperature or suspended silt in water, assuming that the sand grains are suspended in the air and their motion depends entirely on the turbulence of wind.

1. *Case when we regard the sand grains as projectiles.* Assuming that the distribution of the vertical velocity component $w_1$ of sand grains which jump out from the sand surface owing to the collision of saltant sand is expressed as Maxwell's distribution, Kawamura[6] derived the following equation for the vertical distribution of the drifting sand quantity, using the notation $q(z)$ for the total mass of sands passing through a unit area per unit time at the height $z$ in a steady state.

$$q(z)=2n_0\frac{\alpha V}{g}\exp\left[-\frac{1}{\pi}\,\frac{z}{h_0}\right], \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where $a=3\pi\mu d$, $\mu$ is the coefficient of viscosity, $n_0$ the number of sand grains jumping out from the sand surface per unit area in a unit time, $h_0$ the average value of the maximum height $h$ of the saltant path of grains and the wind velocity $V$ is assumed to be constant in the vertical direction. Afterward assuming the distribution of $e^{-\gamma w_1}$ type instead of Maxwell's distribution as the distribution of $w_1$, he obtained the following equation(7).

$$q(z)=G_0\left[2\sqrt{2}\,\lambda\left\{K_0(\xi)-\beta\sqrt{\frac{h_0}{g}}\,\xi K_1(\xi)\right\}\right.$$
$$\left.+\frac{1}{2}\,\frac{a\beta\sqrt{0.75h_0}}{g}\,\xi^2\left\{K_0(\xi)+K_2(\xi)\right\}\right], \quad \text{.........(10)}$$

where $\xi=\sqrt{\dfrac{2z}{h_0}}$, $\lambda=\dfrac{\bar{u}_1}{\sqrt{2gh_0}}$, $\beta=\dfrac{3\pi\mu d}{m}$,

and $V=a\sqrt{z}$ is assumed as the vertical distribution of the wind velocity, and $G_0$ is the mass of sand grains jumping out from the sand surface per unit area in a unit time, $\bar{u}_1$ the average value of the horizontal velocity components of sand grains jumping out from the sand surface, $m$ the mass of a sand grain, $a$ a constant, and $K_0$, $K_1$ and $K_2$ are Bessel functions of zero, first and second order respectively.

2. *Case when we regard the sand grains as being suspended in the air.* Taking $x$—axis in the direction of the main wind and $z$—axis vertically upward, the equation of motion of suspended sand grains is given by (8)

$$u_0\frac{\partial\varphi}{\partial x}=\frac{\partial}{\partial z}\left(\eta\frac{\partial\varphi}{\partial z}\right)+w_0\frac{\partial\varphi}{\partial z}, \quad \text{..................(11)}$$

where $\varphi$ is the mass of sand grains contained in a unit volume, $w_0$ the falling velocity of a sand grain, $u_0$ the mean velocity of a sand grain in the $x$—direction and $\eta$ the coefficient of eddy viscosity. Now assuming that $\eta$ is constant in the $z$—direction, Eq. (11) becomes

$$u_0\frac{\partial\varphi}{\partial x}=\eta\frac{\partial^2\varphi}{\partial z^2}+w_0\frac{\partial\varphi}{\partial z} \quad \text{........................(12)}$$

In the case of a steady state when $\varphi$ is constant in the $x$—direction, solving this equation with the conditions of $\varphi=\varphi_0$ at $z=0$ and $\varphi=0$ at $z=\infty$, gives

$$\varphi=\varphi_0\exp\left(-w_0z/\eta\right). \quad \text{..........................(13)}$$

Since $u_0$ may be assumed to be proportional to wind velocity $V$, using the proportional constant $c$, we have the equation

$$q(z)=c\varphi_0 V \exp\,(-w_0 z/\eta)\,. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

Eq. (9) and (14) show that the relation between log $q(z)$ and $z$ is linear. In Fig. 5 which represents the experimental results obtained by Kawamura, the full lines denote the theoretical results computed by Eq. (10), properly assuming the various factors in the equation. Although the theoretical results by Eq. (10) coincide with the experimental results satisfactorily, the equation is complicated and inconvenient to use. Since it may be considered that the relation between $\log q(z)$ and $z$ is almost linear from $z=5$ cm to $z=30$ cm, as shown in Fig. 5, Eq. (14) is applicable in computing the total quantity of drifting sand by wind per unit time per nnit breadth from the observed vertical distribution, as mentioned below. Above $z=30$ cm, the observed results deviate from the linear relation mentioned above and the quantity of drifting sand becomes larger than the theoretical value, which is a fact considered to be the result of assuming the wind velocity $V$ in the vertical direction as constant.

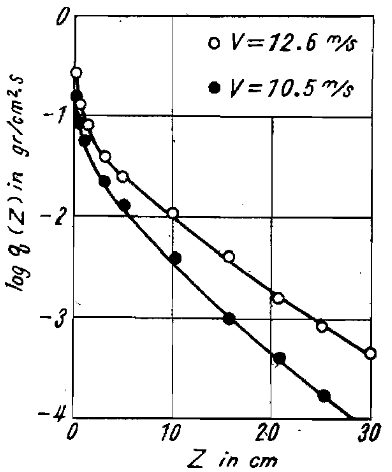


Fig. 5. Relation between $q(z)$ and $z$.

## (3) Relation between the mass of drifting sand by wind and the wind velocity

1. *Case when we regard the sand grains as projectiles.* The total mass $Q$ of drifting sand grains by wind passing through a unit breadth in a unit time from the sand surface to $z=\infty$ is given by

$$Q=m n_0 L\,,$$

where $m$ is the mass of a sand grain and $L$ the mean saltant distance of sand grains. Solving the equation of motion under the assumption that the saltant time of sand grains is short and $w_1$, $u_1$ are also small, Kawamura[5] obtained the following relations based on the theories of kinetic energy and momentum.

$$L=2aVw_1^2/mg^2, \quad w_1=kmgv_*/aV, \quad n_0=pv_*/2km,$$

hence
$$Q=k\frac{mg}{aV}\frac{\rho}{g}v_*^3=C\frac{\rho}{g}v_*^3, \quad \text{..................} (15)$$

where $k$ is a constant and the wind velocity $V$ above the sand surface is assumed to be always constant in the vertical direction, and therefore $C$ becomes a constant. This equation has the same form as Bagnold's equation.

2. *Case when we regard the sand grains as being suspended in the air.* Integrating Eq. (14) from $z=0$ to $z=\infty$, the total mass of sand grains is given by

$$Q=c\varphi_0\eta V/w_0. \quad \text{..................................} (16)$$

Now, if the theory of the case when we regard the sand grains as projectiles is applied, $\varphi_0$ is expressed as

$$\varphi_0=2mn_0/w_1=2G_0/w_1 .$$

In the case when we regard the sand grains as being suspended in the air, it is not reasonable to consider the wind velocity to be always constant as in the case when we regard the sand grains as projectiles. Since in this case $V$ is proportional to $v_*$, $w_1$ becomes independent of the wind velocity, and from Kawamura's experiments[7]. $G_0$ is proportional to $V$, resulting in $\varphi_0$ becoming proportional to $V$. Furthermore, as the coefficient of eddy viscosity $\eta$ is also proportional to $V$[10][11], we can see that $Q\propto V^3$, that is, the total mass of drifting sand is proportional to the third power of the wind velocity. Thus, it becomes clear that a strong wind blowing a short time is more effective than a mild wind blowing a long time in moving sand grains.

### (4) Sand drift when the wind blows from the sea

Assuming that the sand grains are suspended in the air, we can treat the problem for the case when a sand drift begins from a beach line by applying the fundamental equation (12). As shown in Fig. 6, taking the beach line from which the sand drift begins as the original point, we assume that the initial and boundary conditions are given by

$$\left.\begin{array}{ll}\varphi=0 & \text{at } x=0,\\ \varphi=\varphi_0=\text{constant} & \text{at } z=0,\\ \varphi=0 & \text{at } z=\infty,\end{array}\right\} \quad \text{........................} (17)$$

Now dividing $\varphi$ into $\varphi_1$ and $\varphi_2$ and putting

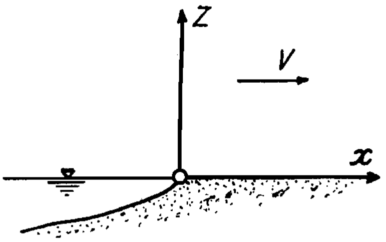



Fig. 6.

$$\varphi=\varphi_1-\varphi_2\,, \quad\dots\dots\dots\dots\dots\dots(18)$$

we consider as follows, that is, $\varphi_1$ which is independent of $x$ satisfies the equation

$$\eta\frac{\partial^2\varphi_1}{\partial z^2}+w_0\frac{\partial\varphi_1}{\partial z}=0\,, \quad\dots\dots\dots(19)$$

and the boundary conditions

$$\varphi_1=0 \text{ at } z=\infty, \quad \text{and} \quad \varphi_1=\varphi_0 \text{ at } z=0\,, \quad\dots\dots\dots\dots\dots(20)$$

and also $\varphi_2$ satisfies the equation

$$u_0\frac{\partial\varphi_2}{\partial x}=\eta\frac{\partial^2\varphi_2}{\partial x^2}+w_0\frac{\partial\varphi_2}{\partial z} \quad\dots\dots\dots\dots\dots\dots\dots\dots(21)$$

and the initial and boundary conditions

$$\left.\begin{array}{l}\varphi_2=\varphi_1 \quad \text{at} \quad x=0,\\ \varphi_2=0 \text{ at } z=0 \quad \text{and} \quad \varphi_2=0 \text{ at } z=\infty.\end{array}\right\} \quad\dots\dots\dots\dots\dots(22)$$

Then $\varphi_1$ which satisfies both Eq. (19) and Eq. (20) is given simply by

$$\varphi_1=\varphi_0 e^{-\frac{w_0}{\eta}z} \quad\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(23)$$

On the other hand, $\varphi_2$ which satisfies both Eq. (21) and Eq. (22) is obtained as follows, using Fourier integral.

$$\varphi_2=\frac{2\varphi_0}{\pi}e^{-\frac{w_0}{2\eta}z-\frac{w}{4u_0\eta}x}\int_0^\infty\frac{\xi}{\xi^2+(w_0/2\eta)^2}\sin\xi z\cdot e^{-\frac{\eta}{u_0}\xi^2 x}d\xi\,.\dots(24)$$

Therefore, from Eq. (18), (23) and (24), $\varphi$ becomes

$$\varphi=\varphi_0 e^{-\frac{w_0}{\eta}z}-\frac{2\varphi_0}{\sqrt{\pi}}e^{\frac{w_0}{2\eta}z}\int_0^{\sqrt{u_0 z}/2\sqrt{\eta x}}e^{-\frac{w_0^2z^2}{16\eta^2\zeta^2}-\zeta^2}d\zeta, \quad\dots\dots\dots(25)$$

where $\quad \zeta=\sqrt{u_0}z/2\sqrt{\eta x}.$

If $x$ is converged to $\infty$ in Eq. (25), then Eq. (13) will be obtained.

1. The mass of sand grains moving through a section per unit time per unit width is given by

$$Q=u_0\int_0^\infty\varphi\,dz=\frac{u_0\eta\varphi_0}{w_0}F_1(\zeta')\,, \quad\dots\dots\dots\dots\dots\dots\dots\dots(26)$$

where

$$F_1(\zeta')=\operatorname{erf}(\zeta')-2\zeta'^2\{1-\operatorname{erf}(\zeta')\}+\frac{2}{\sqrt{\pi}}\zeta' e^{-\zeta'^2},\ \zeta'=\frac{w_0\sqrt{x}}{2\sqrt{u_0\eta}} \quad \ldots.(27)$$

If $x$ is converted to $\infty$ in Eq. (26), it becomes

$$Q=u_0\eta\varphi_0/w_0,$$

which is the same equation as Eq. (16) when $u_0$ is assumed to be proportional to wind velocity $V$.

2. The mass of sand grains scoured per unit time per unit area of sand surface becomes as

$$-\left|\eta\frac{\partial\varphi}{\partial z}+w_0\varphi\right|_{z=0}=\varphi_0 w_0 F_2(\zeta'), \quad \ldots\ldots(28)$$

where
$$F_2(\zeta')=\frac{1}{2}\left\{\frac{1}{\sqrt{\pi}\zeta'}e^{-\zeta'^2}-1+\operatorname{erf}(\zeta')\right\}. \quad \ldots\ldots(29)$$

3. The mass of sand grains scoured from the beach line to a certain section per unit time per unit width of sand surface is obtained as follows, integrating Eq. (28) from 0 to $x$.

$$Q=\frac{u_0\eta\varphi_0}{w_0}F_1(\zeta'), \quad \ldots\ldots(30)$$

which coincides entirely with Eq. (26), as it ought to. Fig. 7 represents the relations between $F_1(\zeta')$, $F_2(\zeta')$ and $\zeta'$

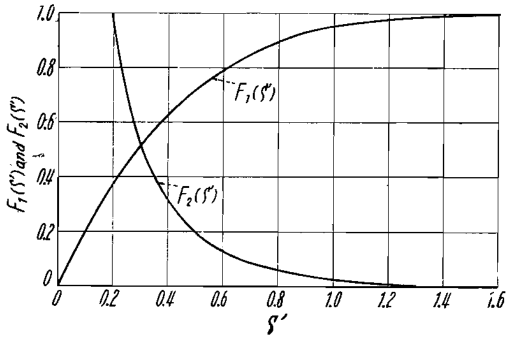


Fig. 7. Relation between $F_1(\zeta')$, $F_2(\zeta')$ and $\zeta'$.

Now if we assume that $w_0=2$ m/s (the value for the case of $d=0.2\sim0.25$ mm), $\eta=2\cdot10^3$ cm²/s, $u_0=10$ m/s and $x=4$ m, it becomes $\zeta'=1.414$, and $F_1(1.414)=0.99$ and $F_2(1.414)=0.004$ are obtained. This fact means that the mass of sand grains moving through a unit width at $x=4$ m in a unit time is 99% of the mass of moving sand grains in a steady state independent of $x$ and also the mass of sand grains scoured per unit area of sand surface at $x=4$ m in a unit time is 0.4% of $\varphi_0 w_0$. From the above computed results, we can conclude that the scouring of the sand surface is limited to the neighbourhood of the beach line. This conclusion gives a solution to the question of from where the enormous volume of sand grains in a dune is transported.

### (5) Sand drift when the sand grains flying over the sand surface drop into the water

This case can also be analysed mathematically by applying Eq. (12), as mentioned above. If we take the water edge as the original point, as shown in Fig. 8, the initial and boundary conditions will be given by

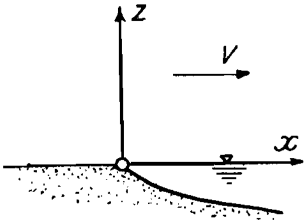



Fig. 8.

$$\left.\begin{aligned} &\varphi=\varphi_0\, e^{-\frac{w_0}{\eta}z} \quad \text{at } x=0, \\ &\eta\frac{\partial\varphi}{\partial z}=0 \quad \text{at } z=0, \\ &\varphi=0 \quad \text{at } z=\infty. \end{aligned}\right\} \cdots\cdots (31)$$

The second condition in Eq. (31) shows that the sand grains which drop into the water never jump out from the water surface again. Now transferring $\varphi$ into $\theta$ by the equation

$$\frac{\partial\varphi}{\partial z}=\theta, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (32)$$

Eq. (12) and (31) become respectively

$$u_0\frac{\partial\theta}{\partial x}=\eta\frac{\partial^2\theta}{\partial z^2}+w_0\frac{\partial\theta}{\partial z} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (33)$$

$$\left.\begin{aligned} &\theta=-\frac{w_0}{\eta}\varphi_0\, e^{-\frac{w_0}{\eta}z} \quad \text{at } x=0, \\ &\theta=0 \quad \text{at } z=0, \quad \text{and} \quad \varphi=0 \quad \text{at } z=\infty. \end{aligned}\right\} \cdots\cdots\cdots\cdots (34)$$

As the solution satisfying these conditions, the following is obtained similar to Eq. (35).

$$\theta=-\frac{w_0}{\eta}\frac{2\varphi_0}{\sqrt{\pi}}\, e^{-\frac{w_0}{2\eta}z}\int_0^{\sqrt{u_0 z}/2\sqrt{\eta x}} e^{-\frac{w_0^2 z^2}{16\eta^2\zeta^2}-\zeta^2}\, d\zeta \cdots\cdots\cdots (35)$$

Transforming $\theta$ inversely into $\varphi$ by the relation

$$\varphi=-\int_0^\infty \theta(z+\rho,\ x)\, d\rho,$$

Eq. (35) becomes as follows.

$$\varphi=\frac{4}{\sqrt{\pi}}\varphi_0\, e^{-\frac{w_0}{2\eta}z}\int_0^{\sqrt{u_0 z}/2\sqrt{\eta x}} e^{-\frac{w_0^2 z^2}{16\eta^2\zeta^2}-\zeta^2}\, d\zeta$$

$$+2\varphi_0\left\{1-\mathrm{erf}\left(\frac{\sqrt{u_0}z}{2\sqrt{\eta x}}+\frac{w_0\sqrt{x}}{2\sqrt{u_0\eta}}\right)\right\}$$

$$+\frac{w_0^2\varphi_0}{2u_0\eta}\int_0^x\left\{1-\mathrm{erf}\left(\frac{\sqrt{u_0}\,z}{2\sqrt{\eta x}}+\frac{w_0\sqrt{x}}{2\sqrt{u_0\eta}}\right)\right\}dx-\varphi_0 e^{-\frac{w_0}{\eta}z} \quad \ldots\ldots(36)$$

1. The mass of sand grains dropping into the water surface per unit time per unit area is given by

$$w_0\varphi_{z=0}=w_0\varphi_0 f_1(\zeta')\,, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(37)$$

where $$f_1(\zeta')=\{1-\mathrm{erf}\,(\zeta')\}\,(1+2\zeta'^2)-\frac{2\zeta'}{\sqrt{\pi}}\,e^{-\zeta'^2}\,. \quad \ldots\ldots\ldots\ldots(38)$$

2. The mass of sand grains dropping into the water surface from the water edge to a certain section per unit time per unit width of the surface is obtained as follows.

$$Q=\int_0^x w_0\varphi_{z=0}dx=\frac{u_0\eta\varphi_0}{w_0}f_2(\zeta')\,, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(39)$$

where $$f_2(\zeta')=\mathrm{erf}\,(\zeta')+4\,\zeta'^2\{1-\mathrm{erf}\,(\zeta')\}\,(1+\zeta'^2)$$

$$-4\,\zeta'^2\,\frac{e^{-\zeta'^2}}{\sqrt{\pi}}\left(\zeta'+\frac{1}{2\zeta'}\right) \quad \ldots\ldots\ldots\ldots\ldots(40)$$

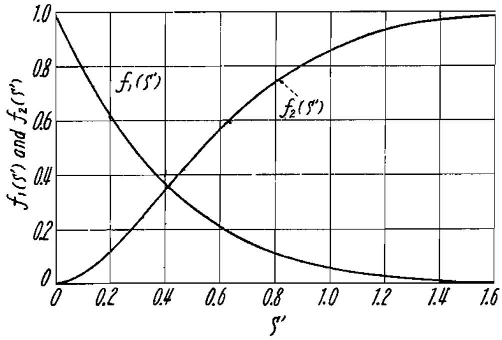


Fig. 9. Relation between $f_1(\zeta')$, $f_2(\zeta')$ and $\zeta'$.

Fig. 9 represents the relation between $f_1(\zeta')$, $f_2(\zeta')$ and $\zeta'$ If $w_0=2$ m/s, $\eta=2\cdot10^3$ cm$^2$/s, $u_0=10$ m/s and $x=4$ m as assumed before, then $f_1(1.414)=0.012$ and $f_2(1.414)=0.97$. Therefore we see that the mass of sand grains dropping into the water surface at $x=4$ m per unit area per unit time is 1.2% of the mass $\varphi_0 w_0$ at the water edge, and also the mass of sand grains dropping into the water surface from the water edge to $x=4$ m per unit width per unit time is 97% of the mass $u_0\eta\varphi_0/w_0$ of sand grains moving through the section at the water edge. From the above computed results, we come to the conclusion that the saltant sand grains mostly drop into the water surface near the water edge. A project based on the above mentioned properties of sand grains was applied to the Kawachi River, Tottori Prefecture, long ago, and the farm land is being protected from the landward movement of sand drift by wind. Moreover this theory is applicable in tackling the problem of the dropping of salt contained in sea wind which is harmful to the crops and trees on the land near the sea, and also in explaining the experimental results of Uchida[13]

## 3. The Coast near the Kiku River Mouth where Sand Drifts by Wind

The topography near the mouth of the Kiku River as surveyed in August, 1950 and 1951 where the mean tidal level of Tokyo Bay is

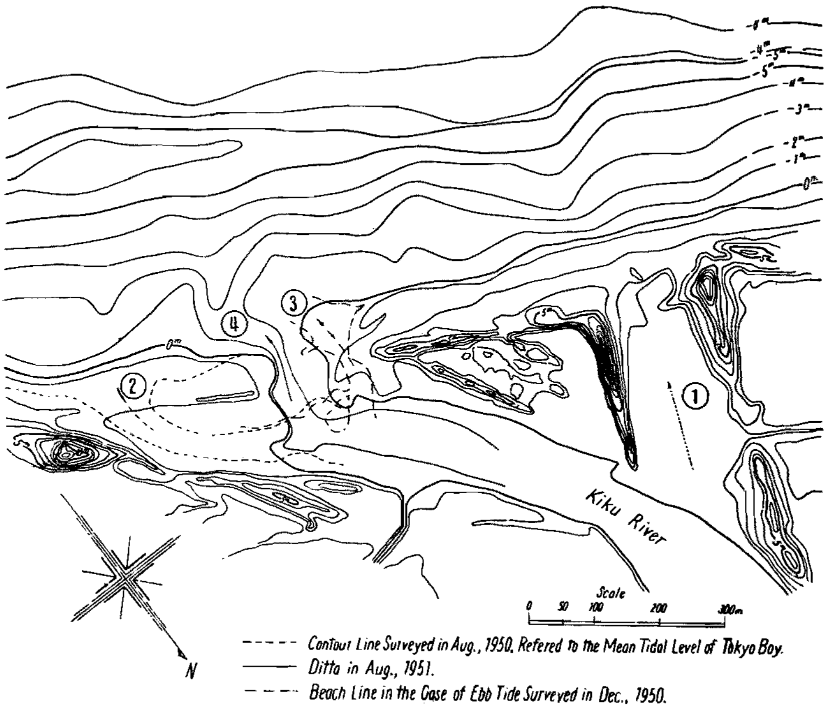



Fig. 10. Topographical map near the Kiku River mouth.

taken as the datum plane of leveling, is represented in Fig. 10. In this figure the beach line at ebb tide surveyed in Dec., 1950 are also shown. Although the river mouth curved westwards long ago, the mouth was transfered artificially into a straight water course (1) about 10 years ago, as shown in Fig. 10. But after that, due to this mouth becoming blockaded, the water course changed naturally into course ②, little by little. The water course near ③, newly excavated after the blockade of the mouth ② in Sept., 1950, is now changing eastwards and the position ④ represents the mouth surveyed in August, 1951.

By the afforestation and sand hedges, this belt of sand dune is now being fixed, except for about 100 m from the beach line which is inclined 25° to the direction from east to west as shown in Fig. 10. Since the direction of the strong wind which is the monsoon in winter is almost W. at Omaezaki and W.N.W. (or N.W. in some cases) at the Kiku River mouth as mentioned below, the sand quantity moving landwards by wind is small, the main part moving from west to east parallel to the beach line. Therefore, the scale of the sand dune near the Kiku River mouth is small, compared with that at Tottori where the monsoon blows from the sea to the land at almost right angle to the beach line. Consequently, at the Kiku River mouth, the sand drift on the coast by wind is caused mainly by the transportation of sand grains along the beach line from west to east, rather than the formation of sand dune.

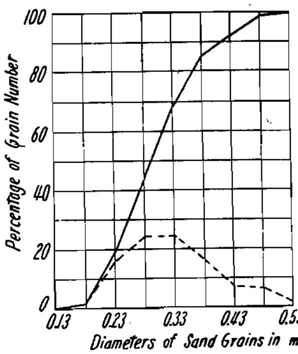


Fig. 11. Distribution curve of the diameters of sand grains on the coast.

The distribution curve of the diameters of sand grains on this coast, shown in Fig. 11, is not the weight distribution, but the grain number distribution which was obtained by the microscopic measurement of the diameters of 107 sand grains taken arbitraly from the coast. Although the grain diameter in an ordinary sand dune is 0.2∼0.3 mm, the mean diameter on this coast is 0.33 mm, and the value of $v_*$ when the grain begins to move is 25∼30 cm/s which corresponds to the wind velocity of about 6 m/s at the height of 1 m.

## 4. The Wind at the Coast of Ensyū Sea

### (1) Data at the Omaezaki Weather Station

It has already been mentioned that the sand grains become easy to jump out of the sand surface at low humidity. As shown in Fig. 12 which represents the monthly mean humidity in 1950 at the Omaezaki Weather Station about 16 km E.S.E. from the Kiku River mouth, humidity is low in Dec., Jan., Feb. and March. Both this fact and the strong monsoon in winter are the causes of violent sand drift by wind on this coast. Regarding the data of wind velocity and direction, a self-recording meter was established in the forest near the Kiku River mouth in

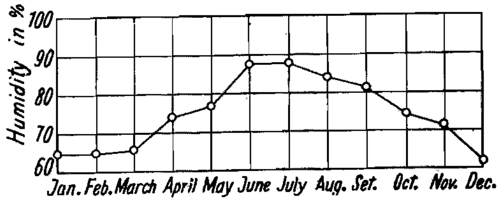



Fig. 12. Monthly mean humidity at Omaezaki. (Jan.~Dec., 1950)

August, 1950, but owing to some trouble in the meter there are some blancks in the data. Moreover as mentioned below, the wind velocity at the coast near the beach line where sand drifts by wind was of a closer value to that observed at the Omaezaki Weather Station than to that meaured by the self-recording meter in this forest. Therefore, we will now describe the data at Omaezaki.

Since the quantity of sand drift is nearly proportional to the third power of the wind velocity as mentioned above, the large wind velocity comes into question in discussing the quantity of sand drift. Thus we will first discuss the data on large wind velocity. In Fig. 13 which represents the frequency of the daily mean maximum wind velocity for 10 minutes, the thick line represents the sum of the wind frequency of S.S.W., S.W.~N.N.W. and N. directions which means distinguishing the left side of the water course in the river mouth from the right side. Thus we can see that the wind of a large velocity has the direction of S.S.W., S.W. ~N.N.W., N. and belongs to the right side of the river

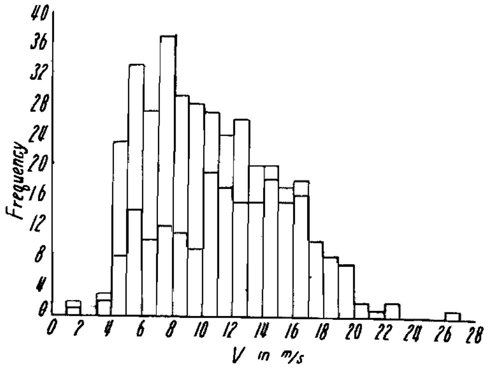



Fig. 13. Frequency of the daily mean maximum wind velocity for 10 minutes in 1950

mouth, and also presuppose that a much larger quantity of sand grains drops into the river mouth from the right side bank than from the left side bank. In Fig. 14, the wind direction diagram of the daily mean maximum wind velocity for 10 minutes is represented, distinguishing that for April~Sept. from that for Oct.~March, and we can see that the strong wind of W. prevails especially in Oct.~March. Refering to Fig. 15 which represents the wind velocity diagram, the mean velocity of the south wind is large, but as shown in Fig. 14, its frequency is very small, so that it is out of question.

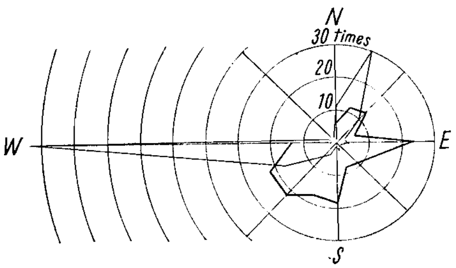



Fig. 14. Wind direction diagram of the daily mean maximum velocity for 10 minutes in 1950.

In Fig. 14 and 15,
Thick line; for April~Sept.
Fine line; for Oct.~March

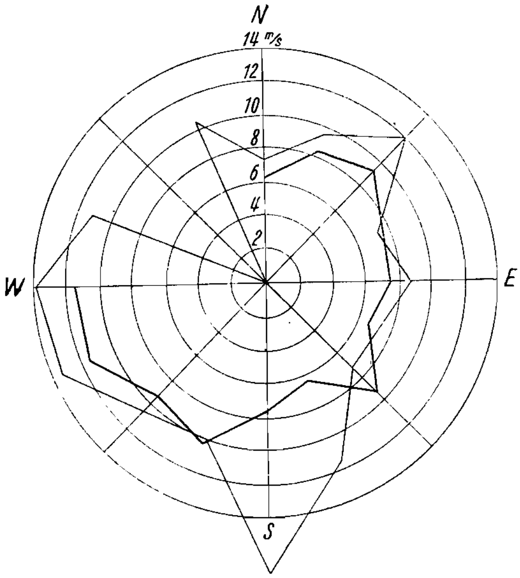



Fig. 15. Wind velocity diagram of the daily mean maximum velocity for 10 minutes in 1950.

In Fig. 16 which represents the wind direction diagram based on the data observed at 6, 12, 18 and 24 o'clock daily, the part painted black is that for the wind of a velocity greater than 6 m/s when the sand grains begin to move. According to this wind diagram, we can see that, as for the wind of a velocity greater than 6 m/s, the west wind is by far the most frequent in Dec., Jan., Feb. and March and in other months there are various wind directions without any distinguished one and the frequencies are all small.

With regard to strong wind, a comparison of the date at the Omaezaki Weather Station with that of the self-recording meter situated near the Kiku River mouth shows that the wind directions are not the same, the wind direction at the river mouth always being W.N.W. (or N.W. in some cases) when the wind direction is west at Omaezaki. Therefore, when the wind direction is west at Omaezaki, the wind blows almost parallel to the beach line at the coast near the Kiku River mouth (cf Fig. 26).

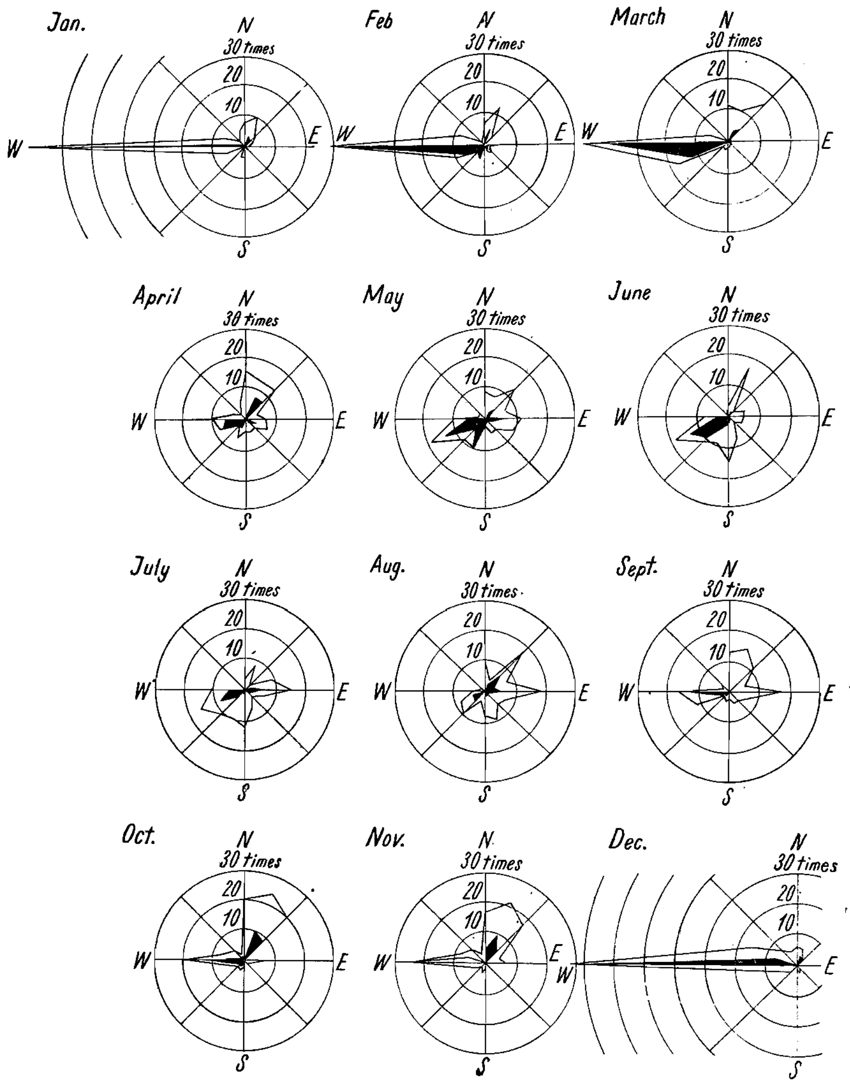



Fig. 16. Wind direction diagram based on the data observed four times daily in 1950.

## (2) Fluctuation and frequency of the wind velocity at the Kiku River mouth

In Fig. 17, we represent the fluctuation and frequency of the wind velocity near the Kiku River mouth, which were obtained by measuring them with the calibration curve between wind velocity and generating current measured by a propeller type anemometer using a midget-generator. In this figure, the intensity of turbulence is the value of the standard deviation of wind velocities $\sigma=\sqrt{\Sigma f_i(u_i-\bar{u})^2/N}$ divided by the mean velocity $\bar{u}$, where $\bar{u}$ is the arithmetical average of the observed

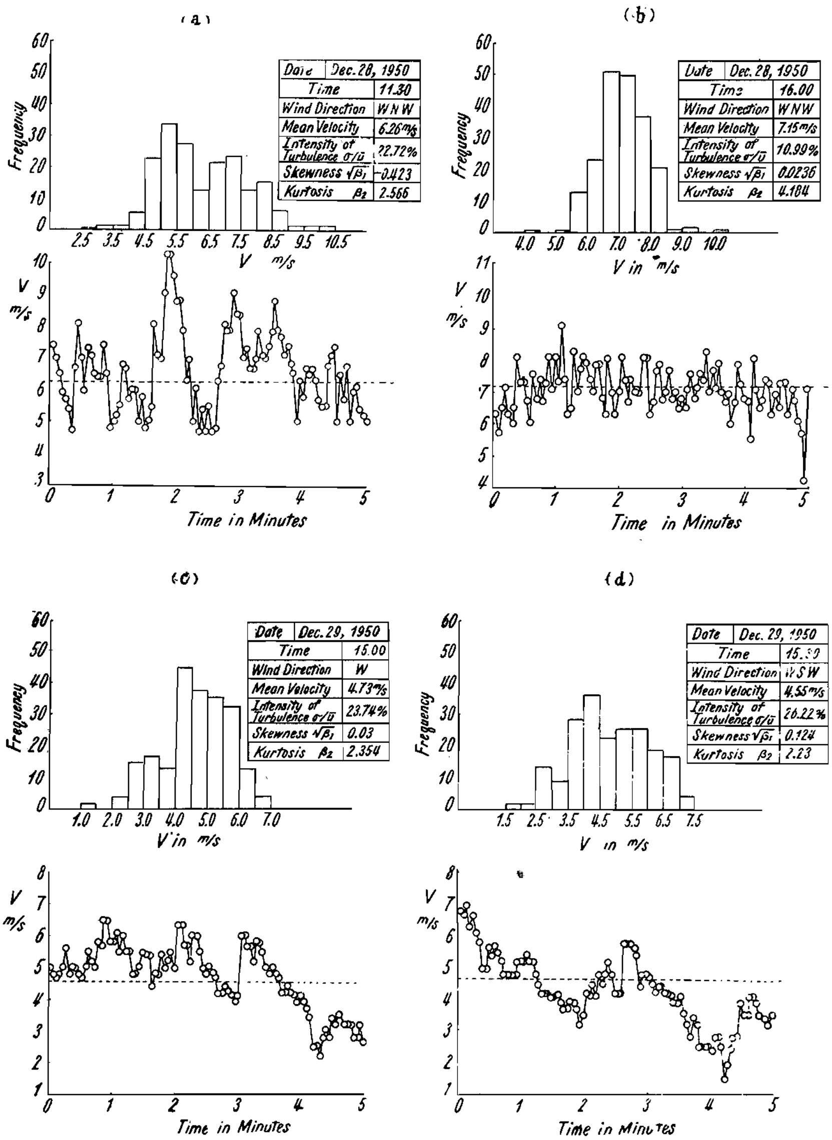



Fig. 17. Fluctuation and frequency of the wind velocity at the Kiku River mouth.

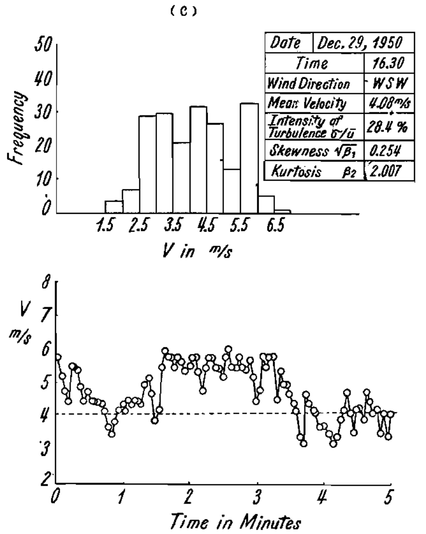


Fig. 17.

value $u_i$ obtained by measuring every three seconds for 10 minutes at the height of about 1 m above the beach line, $f_i$ the frequency of the value $u_i$ and $N$ the number of all observed values. The skewness $\sqrt{\beta_1}$ is given by

$$\sqrt{\beta_1}=\frac{1}{N}\Sigma f_i(u_i-\bar{u})^3/\sigma^3,$$

which must become zero in the case of a symmetrical distribution. Furthermore, the kurtosis is given by

$$\beta_2=\frac{1}{N}\Sigma f_i(u_i-\bar{u})^4/\sigma^4,$$

which is a coefficient becoming 3 in the case of Gaussian normal distribution. Since the quantity of sand drift by wind is measured by the quantity entering a sand collector in a certain time and also since it is proportional to the third power of the wind velocity, the intensity of turbulence naturally has an influence on that quantity. That is to say, it may be thought that the larger the intensity of turbulence is, the larger the quantity of drifting sand by wind is, even if the wind velocities are the same.

As shown in Fig. 17, the intensity of turbulence is smallest in the case of (b), and comparing its wind diagram of velocity fluctuation with those in other cases, we see that the period of fluctuation is small in the case of (b) but with the cases of the four other examples there is a period of several minutes. Therefore, it may be considered that there are two kinds of wind blowing from the sea directly, one which has the intensity of turbulence of about 10% and the other of 20～25%. The same fact was ascertained in our observation at Ajiro Harbour, Tottori Prefecture, some time ago, but the value observed by Prof. Kawata using the same type anemometer at Ikeshinden coast of Ensyū Sea was about 10% and the one of 20～25% was not obtained. In this way, even when the velocity is the same, different results for the quantity of sand drift by wind may be obtained, because it is possible for the intensity of turbulence to be different.

# 5. Measurement of the Quantity of Drifting Sand

## (1) Vertical distribution of the quantity of drifting sand by wind

The sand collector which catches the saltant sand grains may be divided into two kinds, the total quantity type and the distribution type. In order to measure its vertical distribution, we used the sand collector of the distribution type as shown in Fig. 18. Besides this there are various other sand collectors of this type, but they all measure a quantity less than the actual value and the real quantity of drifting sand can

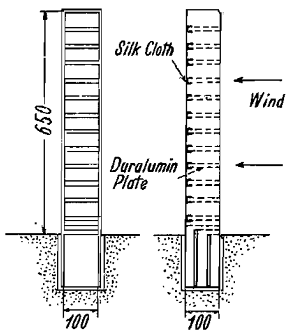



Fig. 18. Sand collector., (vertical direction)

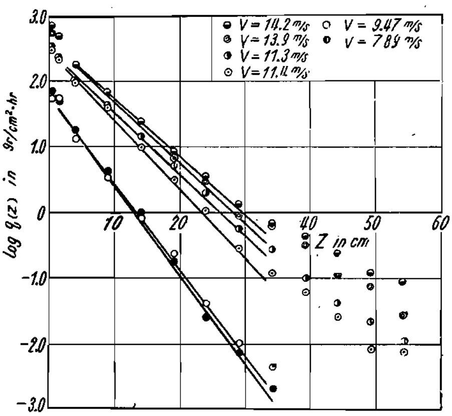



Fig. 19. Vertical distribution of the quantity of drifting sand by wind.

not be grasped. Moreover Chepil experimented by a method using a vacuum pump, but the one as shown in Fig. 18 is simple and convenient. Refering to Fig. 19 which represents our results obtained at the Kiku River mouth, Eq. (10) holds good strictly as mentioned above, but we can say that there exists a linear relation between $\log q(z)$ and $z$ except for the part under several cm and above 30 cm from the sand surface and that Eq. (14) holds fairly good in the region above mentioned.

## (2) Horizontal distribution of the quantity of drifting sand by wind

Using sand collectors as shown in Fig. 20, we can measure the horizontal distribution of the quantity of drifting sand, as in the case when the saltant sand grains on the coast drop into the water surface. The sand collectors shown in Fig. 20(a), which is named box type, has

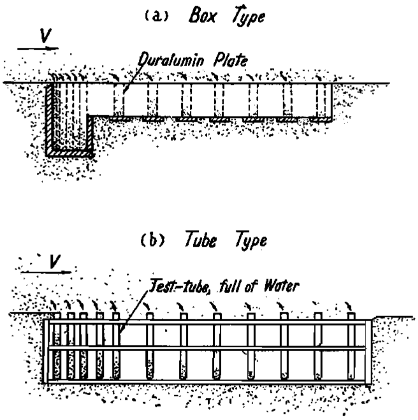
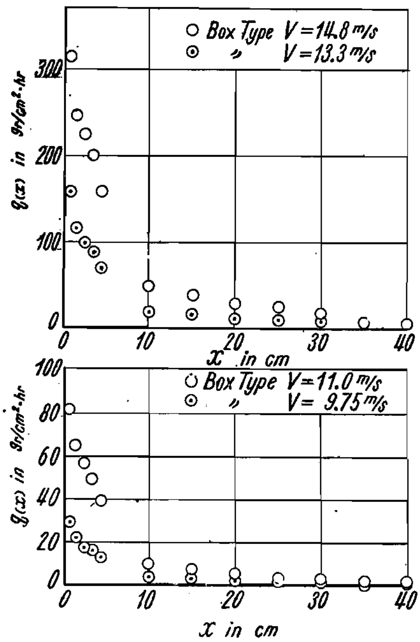



Fig. 20. Sand collector.
(horizontal direction)

a width of 5 cm and a length of 42 cm and is divided into compartments with duralumin plates. The one shown in Fig. 20(b), which is named tube type, has many test tubes standing side by side which are full of water so that the sand grains dropping into the tubes will not jump out again.

In Fig. 21 which represents the results obtained by these sand collectors, there is only an example of the result obtained by the collector of the tube type, which agrees well with that by the collector of the box type in the region of $x > 10$ cm, but the former is considerably small compared with the latter in the region of $x < 5$ cm. This may be considered as due to the fact that the sand collector of the tube type does not catch the real quantity of drifting sand, because a large quantity of sand grains can not drop into the tubes as the entrances become blockaded with wet grains.



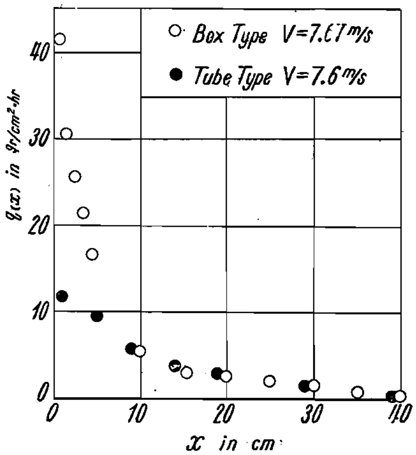




Fig. 21. Relation between $q(x)$ and $x$.

Refering to Fig. 22 which represents the relation between the wind velocity and $q_x$ at $x=10$ cm in the case of sand collector of the box type and $x=9$ cm in the case of the tube type, it is possible to presume that the almost real quantity can be obtained when the wind velocity is small because $q_x$ must become zero in general when the velocity is $5\sim6$ m/s, and that the sand collector of the box type catches only a quantity much smaller than the real one when the wind velocily becomes large.

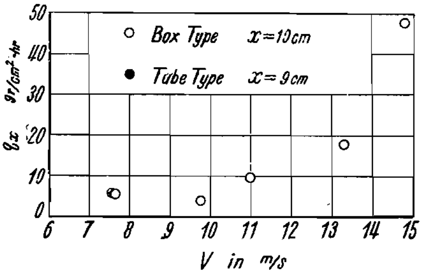



Fig. 22. Relation between $q_x$ and wind velocity.

If we know the values of $w_0$, $u_0$, $\eta$ and $\varphi_0$ in Eq. (37) and (38), the relation between $q(x)$ and $x$ can be computed. Nevertheless, as $\varphi_0$ can not be obtained by measurement, there is no method in practice but to compare the theoretical results with the measured results by means of the ratio between $q_x$ and $q_{x=a}$. That is to say, using the relation

$$\frac{q_x}{q_{x=a}}=\frac{f_1(\zeta')}{f_1(\zeta_a')}, \quad \zeta_a'=\frac{w_0\sqrt{a}}{2\sqrt{u_0\eta}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(41)$$

only a qualitative comparison is possible. In this way, in Fig. 23 which represents the relation between $q_x/q_{x=a}$ and $x$ where $a=10$ cm in the case of the box type and $x=9$ cm in the case of the tube type, the real lines are the theoretical curves computed by Eq. (41), assuming that $w_0=4.3$ m/s since $d=0.33$ mm and that $u_0$ is equal to the wind velocity $V$. Moreover, we adopted here the value of $\eta$ obtained from Fig. 24 which represents the relation between $\eta$ and $V$ obtained by Eq. (14) refering to the slope of the real line in Fig. 19. Since $V$ is proportional to $v_*$, it is seen that a linear relation between $\eta$ and $V$ or $v_*$ exists as shown in Fig. 24, even if we are based on the assumption that the sand grains are suspended in the air[10][11].

As seen in Fig. 23, the results measured coincide satisfactorily with the theoretical values in the region of $x \geq 10$ cm, but the larger the wind velocity is, the larger the former are than the latter in the region of $x<10$ cm, i.e., small valves of $x$. This seems to be due to the fact that the sand grains moved in the condition of surface creep are added and also that $q_x$ decreases rapidly along $x$—direction, because instead of being constant in the vertical direction $u_0$ becomes much smaller and $\eta$ also becomes smaller near the sand surface. But the qualitative agreement

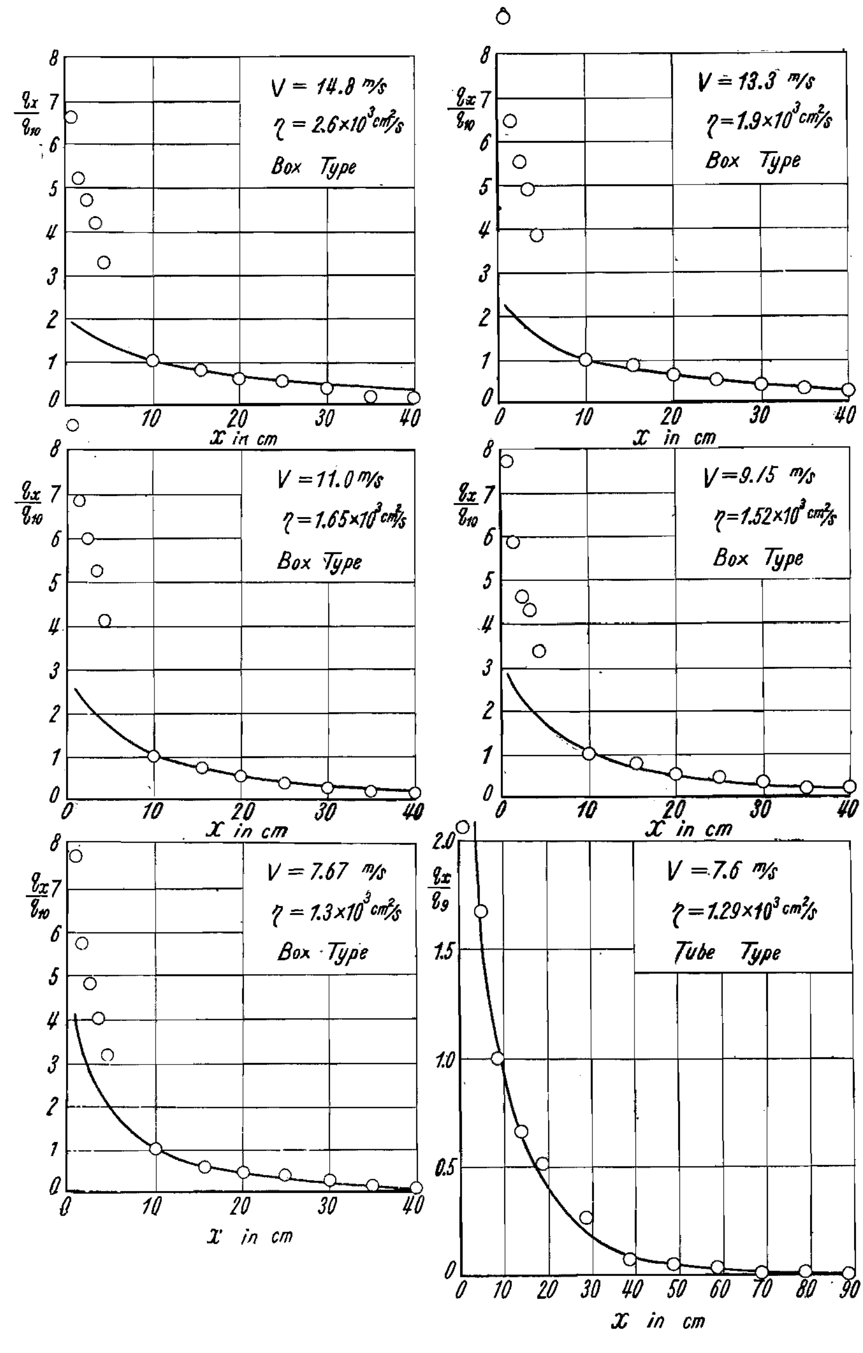



Fig. 23. Relation between $q_x/q_{x=a}$ and $x$.

is satisfactory except in the region of the small values of $x$. These points mean that the relation between $\log q(z)$ and $z$ is not strictly linear.

In this way, as the main part of the drifting sand drops into the water surface in the region of the small values of $x$, actually the quantity dropping on per unit area per unit time is smaller than 1.2% of $\varphi_0 w_0$ and also that dropping on per unit width per unit time is larger than 97% of $u_0 \eta \varphi_0 / w_0$, both of which are the values obtained by the theoretical computation in (5) of chapter 2.

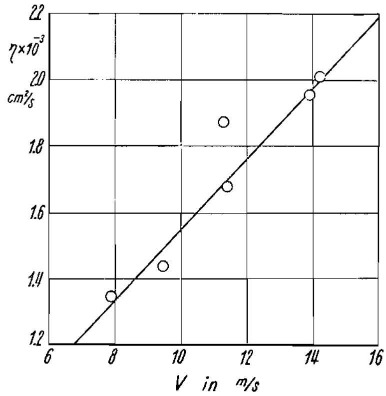


Fig. 24. Relation between $\eta$ and $V$.

### (3) Relation between the wind velocity and the quantity of drifting sand

There are two methods to measure the quantity of drifting sand in a certain wind velocity, that is, the one is to use a sand collector of the total quantity type which catches the total quantity of drifting sand, and the other is to measure the vertical distribution $q(z)$ of the quantity by a sand collector of the distribution type as shown in Fig. 18 and obtain the total quantity, integrating $q(z)$ under the assumption of the linear relation between $\log q(z)$ and $z$ above $z > 2$ cm. Comparing the total quantities obtained by these two sand collectors some time ago at Ajiro Harbour, Tottori Prefecture, we ascertained that the quantity by the distribution type was about twice that by the total quantity type[14]. Therefore, in the case of the Kiku River mouth, we obtained the total quantity of drfting sand, using a sand collector of the distribution type. As shown in Fig. 25 which represents the experimental results by the authors and Prof. Kawata, the results seem to be scattered considerably. This fact is due to the intensity of turbulence being different even with the same wind velocity, the plotted points in the figure being based on the data by various sand collectors and also the magnitude of $v_*$ varying with the place of observation even in the same wind velocity, but it can be said the quantity of drifting sand is proportional to the third power of the wind velocity as shown in the theoretical results. Even in the case of wet sand surface due to rain, it seems that the quantity of drifting sand is proportional, as well, to the third power of the wind velocity in the region of the large velocity.

In this way, using the equation expressed by Bagnold, the relation between the equantity of drifting sand $Q$ and the wind velocity $V$ is given in general by

$$Q = 7.1 \times 10^{-3} C (V-4)^3 , \quad \ldots\ldots\ldots\ldots (42)$$

where $Q$ is in ton/m·day, $V$ in m/s and $C$ is a constant. Refering to Fig. 25 in which the real lines represent the relations corresponding

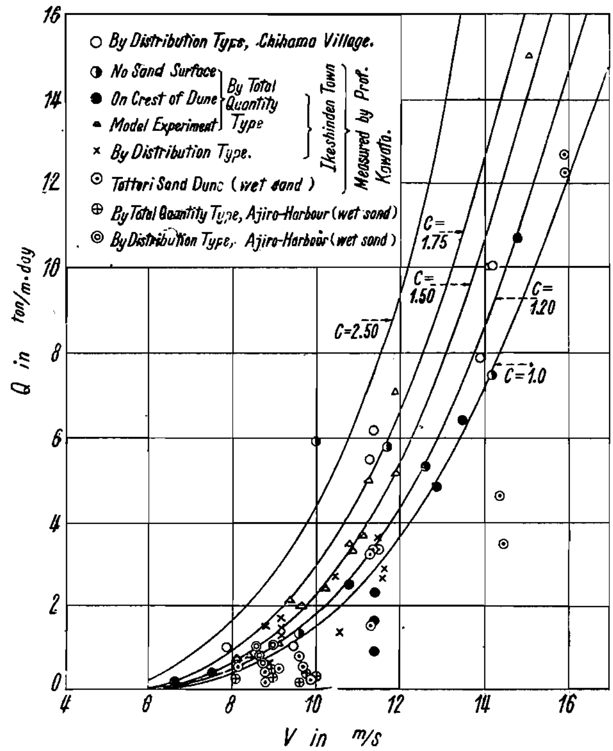



Fig. 25. Relation between the wind velocity and the quantity of drifting sand.

various values of $C$, it may be taken $C = 1.50$ for dry sand considering the case of large wind velocity, and $C = 1.20$ for wet sand, although we have only the data for wet sand at Tottori sand dune and Ajiro Harbour because it is very rare for a strong wind to blow on a rainy day at the coast near the Kiku River mouth.

## 6. Estimation of the Annual Quantity of Drifting Sand

In order to analyse the effect of sand storm on the movement and blockade of the Kiku River mouth, it is very necessary to know the annual quantity of sand grains moving by the sand storm and dropping into the water surface at the river mouth. The annual quantity of drifting sand can be estimated from the data of wind velocity and direction, time of the day when rainfall begins and ceases and rainfall intensity etc. In Fig. 26 which represents the variation diagram of the wind velocity and direction based on the data measured by self-recording meters situated at the Omaezaki Weather Station and the Kiku River mouth, the plotted points are the wind velocities measured at the coast near the river mouth where the sand grains drift by wind. As shown in Fig. 26, the wind velocity on this coast approximates to that observed at the Omaezaki Weather Station rather than that measured by the self-recording meter situated near the Kiku River mouth, and therefore we estimated the quantity of drifting sand based on the data at Omaezaki, according to Eq. (42) where the wind velocity was assumed to be the average valve of those observed every three hours. At this coast a strong wind rarely blows on a rainy day, but the question is how to treat the rainfall.

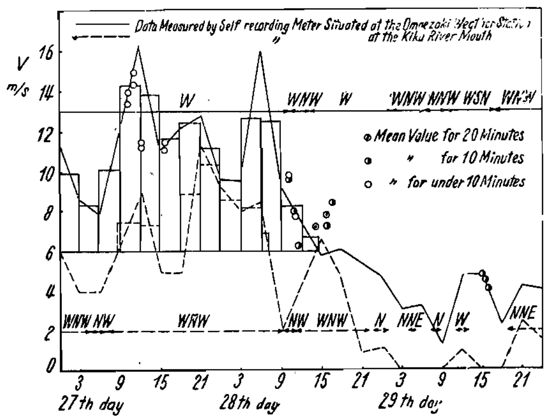



Fig. 26. Variation diagram of the wind velocity and direction. (velocities are plotted every three hours)

When a strong wind blows on the wet sand surface after a rainfall, the moisture of the sand surface evaporates, and just when its moisture content becomes a certain value, the sand grains begin to jump out from the surface. Refering to Akiba's experiment[16], the relation between the moisture content $\alpha$ of the sand surface and the critical wind velocity $V_t$ and also the relation between the time interval $T$ from the time the wind begins to blow to the time the sand grains begin to move and the wind velocity $V$ in this case are given by

$$V_t = 100\,a u + b, \quad \cdots\cdots (43)$$

$$V = \frac{K_1'}{T} + K_2, \quad \cdots\cdots (44)$$

where $a$, $b$, $K_1$ and $K_2$ are constants respectively. When the initial moisture content is $20\sim30\%$, the time interval is about 2 hours and 1.5 hours in the cases of $V=8$ m/s and 10 m/s respectively.

According to the experimental results above mentioned, we estimated the monthly quantity of drifting sand by wind in a year per unit width. In this case, we used the following three assumptions based on the above experiment by Akiba, that is, the first one is that the sand grains do not jump out when the intensity of rainfall is larger than 1 mm/hr, the second one that the sand grains begin to move just when the rainfall ceases and the quantity of drifting sand is computed by Eq. (42) using $C=1.20$, and the third one that the sand surface becomes dry after 3 hours from the time when the rainfall ceases and the quantity of drifting sand is also computed by Eq. (42) using $C=1.50$. Since the quantity of drifting sand depend upon several factors as the property of the sand grains, the intensity and duration of the rainfall, the wind velocity etc., it is not rational to decide the necessary assumptions uniquely, but in this case the three assumptions above mentioned were practically used.

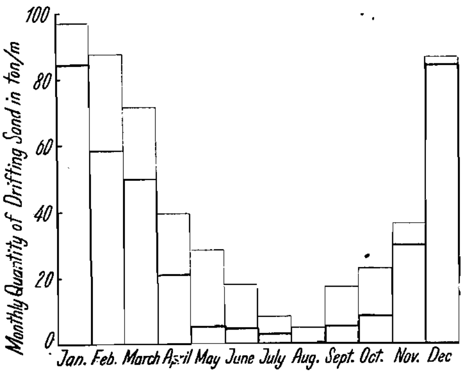


Fig. 27. Monthly quantity of drifting sand by wind in a year.

Refering to Fig. 27 which represents the monthly quantity of drifting sand by wind in a year per unit width, the quantity is very large in Dec., Jan., Feb. and March, but least in July and August. These properties are the same as those at the coast of Tottori Prefecture, but the tendency at the Kiku River mouth that the quantity is very large in winter due to the small effect of rain and snow is remarkable. The thick line drawn in Fig. 27 represents the quantity of drifting sand by the west wind.

Refering to the following table, which represents the estimated quantity of drifting sand by wind in a year arranged according to wind direction, we can see that the quantity due to the west wind is by far the greatest and holds 68.5% of the annual total quantity. In the table, the wind directions are divided into two groups of left and right, refering to the direction of water course at the Kiku River mouth, and the estimated quantity due to each wind direction belonging to the left bank side is shown in the left column and that to the right bank side in the right column. Therefore, the quantity of drifting sand by wind which drops into the water surface from the right bank side becomes 92.5% of the annual total quantity.

Estimated quantity of drifting sand by wind in a year arranged according to wind direction. (unit: ton/m)

| left bank side of the river mouth | | right bank side of the river mouth | |
|---|---|---|---|
| wind direction | estimated quantity | wind direction | estimated quantity |
| N. N. E. | 10.2 | S. S. W. | 28.1 |
| N. E. | 16.4 | S. W. | 22.8 |
| E. N. E. | 1.5 | W. S. W. | 65.7 |
| E. | 3.1 | W. | 354.1 |
| E. S E. | 0.5 | W. N. W. | 7.1 |
| S. E. | 0.5 | N. W. | 0.2 |
| S. S. E. | 0.9 | N. N. W. | 0.1 |
| S. | 5.2 | N. | 0.8 |
| sum | 38.2 | sum | 478.8 |

(wind direction is the one at Omaezaki)

The actual quantity of sand dropping into the water surface at the Kiku River mouth must be obtained, summing up the quantity described in the above table multiplied by the width of each wind direction. Since there are many sand hedges on the coast and the river mouth is moving, it is difficult to estimate accurately the quantity of sand dropping into the water surface at the river mouth, but considering that the W.– and W.S.W.– winds (these being the wind directions at Omaezaki, it is assumed that these become W.N.W. and W. respectively at the river mouth as shown in Fig. 26) give the most distinguished effect on the quantity and the breadth of the coast where sand drifts is about 100 m, the annual total quantity becomes about 41,000 ton which corresponds to about 33,000 $m^3$, assuming the apparent specific gravity of sand to be 1.25. Thus we can conclude that this quantity of sand drops into the water surface at the Kiku River mouth from the right bank side.

## 7. Conclusion

We can extract the following points from the above description.

1. The frictional velocity in which the sand grain begins to move is proportional to $\sqrt{\sin(\varphi_0+\alpha)/\cos\varphi_0}$, and also to $\sqrt{\sigma d}$ in the region of $\sigma d > 0.5$.

2. In the case of a horizontal sand surface, the frictional velocity

$v_{*t}$ is 25~30 cm/s and the wind velocity at the height of 1 m corresponding to this value of $v_{*t}$ is about 6 m/s.

3. The vertical distribution of the quantity of drifting sand by wind is given by Eq. (10) strictly, but there exists a linear relation between $\log q(z)$ and $z$ except near the sand surface and $z > 30$ cm. Thereby the main parts of the quantity of drifting sand are moving in the region of several cm above the sand surface.

4. The quantity of drifting sand by wind is proportional to $v_*^3$ or the third power of the wind velocity.

5. When the wind is blowing towards the land from the sea and the drifting of sand grains begins from the beach line, the scouring is limited near the beach line on the coast.

6. When the sand grains moving towards the sea from the land drop into the water surface, the greater part of the drifting sand drops into the water surface near the water edge.

7. The distinguished movement of sand grains near the Kiku River mouth is limited to the coast near the beach line and the sand grains are moving nearly parallel to this beach line from west to east.

8. The winds of large velocity belong to the right bank side of the Kiku River mouth and the quantity dropping into the water surface of the river mouth from the right bank side is very larger than that from the left bank side.

9. The intensity of turbulence of the monsoon in winter is divided into two kinds, the one being about 10% and the other 20~25%.

10. The experimeneal distribution of the quantity of drifting sand in the horizontal direction coincides well qualitatively with the theoretical distribution by our theory except in the region of small values of $x$.

11. According to the estimated monthly quantity of drifting sand by wind, the quantity is very large in Dec., Jan., Feb. and March and least in July and August.

12. The annual quantity of drifting sand due to the west wind holds 68.5% of the annal total quantity.

13. The annual quantity of drifting sand dropping into the water surface from the right bank side holds 92.5% of the annual total quantity.

14. The estimated annual quantity of drifting sand dropping into the water surface at the Kiku River mouth becomes about 33,000 m$^3$, assuming the breadth of the water edge from which the sand grains drop into the water surface to be about 100 m.

The following is considered from the conclusions above mentioned, Following the periodical movement of sea water due to tide, the sand grains dropping into the water surface at the river mouth are transported to the upper and down streams, that is to say, at flood-tide they are moved to the upper stream and deposited at places where the river breadth enlarges, and contrarily at ebb-tide they are carried out of the river mouth by the flushing water and become the source of the sand drift in the sea. Since even the sand grains depositing at the upper stream will be carried out into the sea in the case of flood, it may be considered that the sand grains dropping into the water surface at the river mouth are all transported into the sea and become the source of sand drift in the sea. Moreover, the fact that most of the drifting sand grains drop into the water surface near the water edge making the west bank side of the river mouth become shallow is considered to help the river mouth to move eastwards. Although the distinguished cause of the river mouth moving is not yet known, it is certain that the sand drift by wind on the coast is helping it to move eastwards.

It is a problem of sand drift in the sea what courses of movement the annual quantity of about 33,000 $m^3$ of drifting sand carried out into the sea takes, and we will make a report on this problem in relation with the blockade of the river mouth at another opportunity.

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