CHAPTER 89

CHARACTERISTICS OF SALTATION OF SAND GRAINS BY WIND

Yoshito Tsuchiya

Professor of Coastal Engineering
Disaster Prevention Research Institute
Kyoto University

and

Yoshiaki Kawata

Postgraduate, Department of Civil Engineering
Kyoto University, Kyoto, Japan

ABSTRACT

Although the phenomenon of saltation of sand grains in a sand storm is very complicated, there exists the successive saltation defined by the authors. The height and distance of saltation of sand grains in successive saltation by wind are compared with the theory of successive saltation proposed by the authors. The concentration of sand grains and velocity profile in a saltation layer are theoretically investigated with the aid of the results of experiment.

INTRODUCTION

In sand storms, the sand grains on the bed are moved by aerodynamic forces due to wind. After rolling and sliding for a distance less than a grain diameter, the sand grains which are so massive as to fail to begin suspension come into collision with other sand grains and then begin jumping motion. Such a motion is considered as saltation in this paper. The most important aspect in the motion of saltating sand grains is that the grains move intermittently in contact with the uneven, movable sand bed. In establishing the law of sediment transport by wind, the mechanics of such a motion of sand grains should be developed.

In 1941, Bagnold made a comprehensive study of the sand transport by wind. About twenty years ago Kawamura(1951) proposed an excellent theory of sand movement by wind based on the equation of motion of a sand grain. Recently Owen(1964) also investigated the interaction between a turbulent wind and the motion of uniform saltating sand grains to discover the velocity profile in a saltation layer and the law of sediment transport. There are fruitful suggestions for establishing the mechanics but the distributions of saltation height of sand grains should be taken into account in the development. More recently the present authors have investigated the mechanics of saltation of sand grains by wind and proposed a theory of successive saltation based on the equation of motion of a sand grain and the dynamic characteristics of collision between a saltating sand grain and bed sand grains.

In this paper, experimental considerations of the height and distance of saltation of sand grains in the successive saltation are presented and a comparison between the theory of successive saltation and the experimental results is also described in comparison with the saltation of sand grains in water. Furthermore, the concentration of sand grains in a saltation layer is theoretically investigated based on the equations of sand movement and the stochastic approach to the distribution of saltation height of sand grains. An approach to discover the velocity profile in a saltation layer is presented with the aid of the momentum equation taking into consideration the bottom shear stress, the additional shear stress due to saltating sand grains and the Reynolds stress.

EXPERIMENTAL APPARATUS AND PROCEDURE

(1) Experimental Apparatus Experiments were carried out with a wind tunnel, 0.9 m wide, 11 m long and 0.39 m high. The tunnel was constructed of steel, but with both sides made of glass for observations. The velocity at the center of the section of tunnel is changed from 2 m/sec to 24 m/sec by a variator. The velocity measurements were made using a hot wire anemometer with a protecter of net. The characteristics of sand grains used in the experiment are shown in Table 1 with the experimental conditions carried out.

Table 1 Characteristics of sand grains used and experimental conditions carried out

(a) Fixed bed

No.	Dimeter of grains d cm	Kind of grains	Specific gravity σ/ρ_0	Density ratio σ/ρ	Shear velocity u_* cm/sec	Dimensionless tractive force (flow intensity) $u_*^2/(\sigma/\rho-1)gd$
1	0.225	sand grains	2.624	2235	97.9	0.0204
2	〃	〃	〃	〃	105.7	0.0227
3	〃	〃	〃	〃	119.0	0.0287
4	0.184	〃	2.523	2120	102.1	0.0273
5	〃	〃	〃	〃	114.8	0.0345
6	〃	〃	〃	〃	120.2	0.0378
7	〃	seeds	1.155	969	69.9	0.0280
8	〃	〃	〃	〃	83.3	0.0398
9	〃	〃	〃	981	67.8	0.0260
10	〃	〃	〃	〃	73.4	0.0305
11	〃	〃	〃	〃	82.4	0.0384
12	0.144	sand grains	2.474	2081	105.9	0.0382
13	〃	〃	〃	〃	122.0	0.0507
14	〃	seeds	1.155	981	76.9	0.0428
15	〃	〃	〃	〃	98.8	0.0706

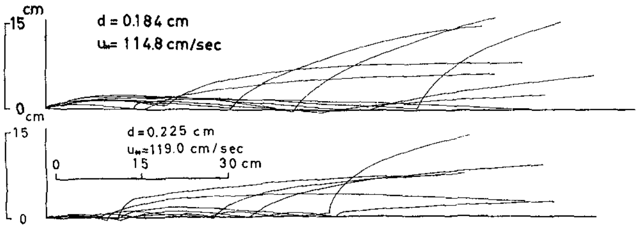
(b) Movable bed

No.	d cm	σ/ρ_0	σ/ρ	u_*cm/sec	$u_*^2/(\sigma/\rho-1)gd$
1	0.225	2.528	2172	112.2	0.0262
2	〃	〃	〃	113.0	0.0267
3	〃	〃	〃	116.5	0.0286
4	0.184	2.550	〃	101.7	0.0266
5	〃	〃	〃	105.9	0.0287
6	〃	〃	〃	113.0	0.0326
7	0.144	2.528	2158	90.2	0.0267
8	〃	〃	〃	96.6	0.0307
9	〃	〃	〃	104.3	0.0358

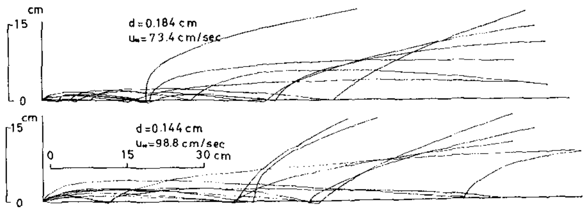
(2) Experimental Procedure In the experiment in the case of fixed bed, the sand grains were uniformly coated on the tunnel bed. In the case of movable bed the sand grains were spread over the tunnel bed with a 2 cm thickness. After the sand bed was leveled, each run was started with the wind velocity shown in Table 1. The saltating sand grains in both the cases of fixed and movable beds were photographed with a Miliken high speed cine camera. The analysis of the trajectory of a saltating sand grain and the concentration of sand grains in a saltation layer were made with a film motion analyzer.

CHARACTERISTICS OF SALTATION

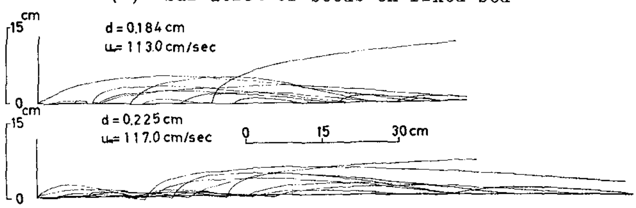
(1) Trajectory of Saltating Sand Grains Fig. 1 shows some examples of the trajectories of saltating sand grains in a saltation layer. It was concluded from the observation through the film motion analyzer that there



(a) Saltation of sand grains on fixed bed



(b) Saltation of seeds on fixed bed



(c) Saltation of sand grains on movable bed
Fig. 1 Trajectories of grains in saltation layer in cases of fixed and movable beds

exists similar seven elementary phenomena in the saltation as those in a water stream, such as the stationary state of a sand grain, the beginning of motion due to hydrodynamic forces, the beginning of motion due to collision, the saltation, the collision among saltating sand grains, the rebound and the stop of saltation. Since the momentum of a successively saltating sand grain increases generally with order of saltation, the saltating sand grain often makes one more sand grains start to saltation. Because of the fact the mechanism of collision between saltating sand grains and bed sand grains is very important to consider the mechanics of sand transport by wind.

(2) Height and Distance of Saltation in Successive Saltation In the previous paper, the authors presented a theory of successive saltation of sand grains. The main formulations firstly can be summerized as follows. Based on the equation of motion of a sand grain, the vertical and horizontal velocities of saltation can be written approximately as

$$\left.\begin{array}{l} \bar{W} = \pm a_1\sqrt{\bar{H}-\eta}\ ,\ \bar{U} = \bar{U}_0 + a_1(\sqrt{\bar{H}} \mp \sqrt{\bar{H}-\eta})\{(\bar{u}-\bar{U}_0)/K\}^2 \\ \bar{W} = W/u^*,\ \bar{U} = U/u^*,\ \eta = z/d\ ,\ K^2 = (4/3)\{(\sigma/\rho-1)gd/u^{*2}\}(1/C_D) \\ a_1^2 = K^2\{(3/2)C_D/(\sigma/\rho+1/2)\} \end{array}\right\} \qquad (1)$$

in which u* is the shear velocity, W the vertical velocity of a sand grain, W_0 the initial one, U the horizontal velocity, U_0 the initial one, d the grain diameter, σ/ρ the specific gravity, g the acceleration of gravity, C_D the drag coefficient and z the coordinate.

The height and distance of saltation of a sand grain can approximately be given respectively as

$$\left.\begin{array}{l} \bar{H}\,(=H/d) = (\bar{W}_0/a_1)^2 \\ \bar{L}\,(=L/d) = 4\bar{U}_0\bar{W}_0/a_1^2 \end{array}\right\} \qquad (2)$$

And the relationships between the velocity components just before and after the collision of a saltating sand grain with bed ones can be expressed aproximately as

$$\bar{U}_0 = e\bar{U}_1\ ,\ \bar{W}_0 = e(b_1\bar{U}_1 + b_2\bar{W}_1)/\{b_3 + b_1(\bar{W}_1/\bar{U}_1)\} \qquad (3)$$

in which $b_1 = (1+e)\tan\gamma$, $b_2 = 1-e\tan^2\gamma$, $b_3 = \tan^2\gamma - e$, e is the rebound coefficient of a sand grain and γ a parameter expressing the bed condition.

In the successive saltation in which the initial velocity of a sand grain holds constant, the height and distance of saltation can be given approximately as

$$\left.\begin{array}{l} \bar{H} = \{(1/2)\lambda\{(1+e)-\sqrt{(1-e)^2+2(1-e)/\lambda(\bar{u}/K)^2}\}(\bar{u}/a_1)\}^2 \\ \bar{L} = \lambda\{[(1+e)-\sqrt{(1-e)^2+2(1-e)/\lambda(\bar{u}/K)^2}](\bar{u}/a_1)\}^2,\quad \lambda = 4\bar{H}/\bar{L} \end{array}\right\} \qquad (4)$$

respectively. The density functions for the distributions of height and distance of saltation can be formulated respectively as

$$\left.\begin{array}{l} f_1(\bar{H}) = (1/2\sqrt{2\pi})(1/\varepsilon\sqrt{\bar{H}\bar{H}_m})\exp\{-(\sqrt{\bar{H}}-\sqrt{\bar{H}_m})^2/2\varepsilon^2\bar{H}_m\} \\ f_2(\bar{L}) = (1/2\sqrt{2\pi})(1/\varepsilon\sqrt{\bar{L}\bar{L}_m})\exp\{-(\sqrt{\bar{L}}-\sqrt{\bar{L}_m})^2/2\varepsilon^2\bar{L}_m\} \end{array}\right\} \qquad (5)$$

in which H_m is the mean value of saltation height, L_m the mean value of saltation distance and ε the standard deviation. Using the above relationships, the height and distance of saltation of a sand grain in the successive saltation can be calculated based on the results of experiment of the empirical constants in the theoretical formulations. Fig. 2 shows changes of the parameters characterizing the sand bed condition which are the empirical constants in the theory with order of saltation in the cases of fixed and movable beds. Although the data shown in the figure are fairly scattering, it is seen that the angle of departure of a sand grain at the moment of beginning of movement β and the ratio of the height to the distance of saltation have a tendency to somewhat increase with order of saltation. The trend of decrease in the rebound coefficient may suggest the possibility of loss of momentum of a saltating sand grain due to bottom friction and the movability of the bed sand grains at the moment of collision.

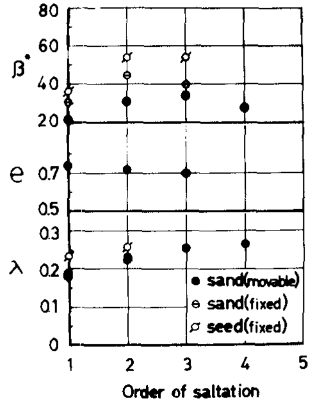


Fig. 2 Changes of parameters characterizing sand bed conditions with order of saltation

Fig. 3 shows an example of changes of the height and distance of saltation of a sand grain with order of saltation in comparison between the theoretical curves calculated by the above theory and the results of experiment in which the solid line indicates the result calculated by Eqs. (2) and (3) using the height and distance of saltation in the first saltation and the dimensionless representative velocity in the saltation layer $\tilde{u} = 20$, and the broken line the similar one but the value of $\tilde{u}$ is used as the velocity corresponding to the saltation height in each saltation. The height and distance of saltation of a saltating sand grain more radically increase with order of saltation than those in a water stream, since the rebound coefficient of a saltating sand grain in air is usually compared to be large with the one in water. It is concluded from the comparison that the theoretical curves for the height and distance of saltation in the successive saltation are in good agreement with the experimental values and that the height and distance of saltation become constant nearly at sixth order of saltation.

Fig. 4 describes a comparison between the theoretical curves for the stationary saltation in which the initial velocity of a saltating sand grain holds constant and the experimental values of height and distance of saltation obtained using sand grains and seeds on the fixed or movable bed, including the data in sediment transport in water obtained by the authors. A similar comparison has been presented in the previous paper but the figure is misdrawn. It is seen from the figure that the effect of the rebound coefficient of a saltating sand grain is very significant to estimate the height and distance of saltation. It is seemed that the height and distance of saltation approach to the theoretical curves for the stationary saltation if the successive saltation is continued.

CONCENTRATION OF SAND GRAINS IN A SALTATION LAYER

The saltation layer is formed when the shear velocity due to wind action much exceeds the initial value for sand movement. The concentration of sand grains is defined as the mass of saltating sand grains per unit volume in a saltation layer. In order to investigate the concentration of sand grains, Kawamura's approach can be applied on the basis of the characteristics of saltation of sand grains described already.

Consider the concentration of sand grains at any order of saltation. The concentration of sand grains having the saltation height between H and H + dH, $\psi_H dH$ can be written as

$$\psi_H dH = 2G_0 f_1(H)\, dH/W \qquad (6)$$

in which G_0 is the mass of sand grains emitting from unit area of the bed per unit time. Integration of Eq. (6) using Eqs. (1) and (5) gives an expression for the concentration of sand grains at the distance from the bed as

$$C(\eta) = (\hat{G}_0/\sqrt{2\pi}\, a_1 \varepsilon/\hat{H}_m)\int_\eta^\infty (1/\sqrt{\hat{H}(\hat{H}-\eta)})\exp\{-(\sqrt{\hat{H}}-\sqrt{\hat{H}_m})^2/2\varepsilon^2\hat{H}_m\}\, d\hat{H} \qquad (7)$$

in which

$$C(\eta) = \psi(z)/\sigma, \quad \psi(z) = \int_z^\infty \psi_H\, dH, \quad \hat{G}_0 = G_0/\sigma u^*$$

Therefore, if partition of number of saltating sand grains at any order of saltation is estimated, the concentration of sand grains in a saltation layer can be calculated by summing up the concentration function for every order of saltation. Fig. 5 shows an experimental result for the change of succession ratio of saltation. Using the result of Fig. 5, the concentration of sand grains can be calculated as shown in Fig. 6. It is concluded from the figure that the theoretical concentration curve is in good agreement with the results of experiment and that the concentration of sand grains does not decreases exponentially.

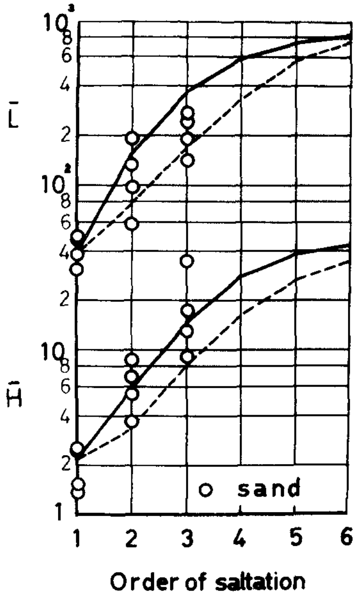


Fig. 3 Changes of height and distance of saltation of sand grain with order of saltation

VELOCITY PROFILE IN A SALTATION LAYER

Since the momentum transfer in a saltation layer occurs due to action of saltating sand grains, changes in the velocity profile in the layer take place. The shear stresses due to wind and saltating sand grains are considered to be composed with the Reynolds stress by wind and the additional shear stress due to saltating sand grains. From the point of view the shear stress can be expressed as

$$\tau = \tau_w + \tau_s \qquad (8)$$

in which τ is the total shear stress, τ_w the Reynolds stress by wind and τ_s

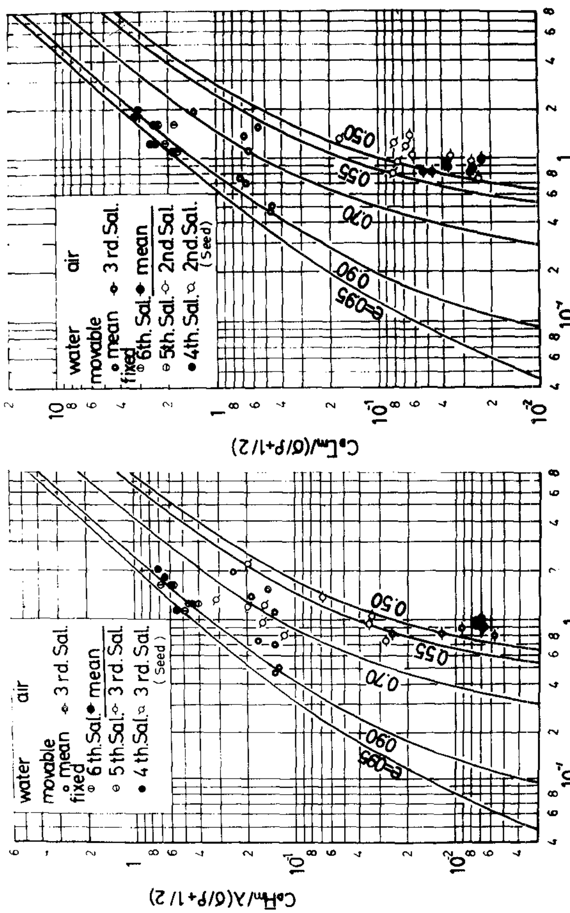


Fig. 4 Comparison between theoretical curves of height and distance of saltation of sand grain in stationary saltation and experimental values

the additional shear stress due to saltating sand grains. It is assumed that the additional shear stress is proportional to the mean value of the product of horizontal and vertical velocities of sand grains $\langle UW \rangle$ which is written as

$$\langle UW \rangle = \int_0^\infty UW f_1(H)\, dH \tag{9}$$

based on the momentum transfer theory. Eq. (8) can finally be written as

$$\tau = \rho\{1-\psi(z)/\sigma\}\ell^2(du/dz)^2 - \psi(z)\langle UW \rangle \tag{10}$$

in which ℓ is the mixing length assumed to be $\varkappa z$ and u the wind velocity. Integration of Eq. (10) using Eqs. (1), (5) and (7) can approximately be made. It is concluded from some results of computation of

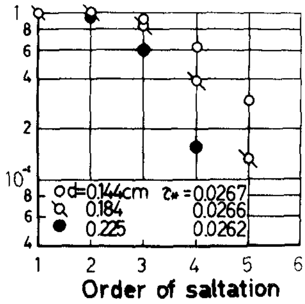


Fig. 5 Succession ratio of saltation of sand grains with order of saltation

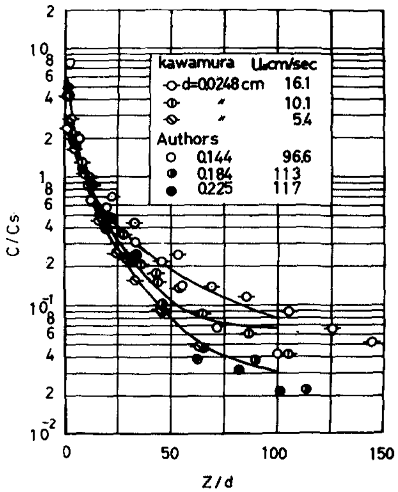


Fig. 6 Comparison between theoretical curves of concentration of sand grains in saltation layer and experimental values

Eq. (10) that the defect in velocity profiles in a saltation layer increases with the increase of the bottom shear stress due to wind action or the height of saltation of sand grains. Since a basic experiment of velocity profiles in a saltation layer has been carried out, comparison between the theoretical velocity profile and the result of experiment will be presented in the next paper.

CONCLUSIONS

Based on the detailed experiments on the successive saltation of sand grains by wind, an applicability of the theory of successive saltation is mainly considered in connection with the saltation by water. The main results obtained can be summerized as follows.

It was concluded that changes of the height and distance of saltation of sand grains with order of saltation are in good agreement with the theoretical curves and that the height and distance of saltation approach the stationary ones nearly at sixth order of saltation. The theoretical relationships of stationary saltation are applicable to express the characteristics of saltation of sand grains both in air and in water. The concentration of sand grains in a saltation layer can be theoretically formulated using the characteristics of saltation. In addition, an attempt to derive the velocity profile in a saltation layer is presented based on the momentum transfer theory taking into consideration the additional shear stress due to saltating sand grains.

REFERENCES

Bagnold, R. A. (1941). The physics of blown sand and desert dunes: Methuen & Co. Ltd., London.

Kawamura, R. (1951). Study of sand movement by wind: Report Tech. Res. Inst., Univ. of Tokyo, Vol. 5, pp. 95-112(in Japanese).

Owen, P. R. (1964). Saltation of uniform grains in air: Jour. Fluid Mech., Vol. 20, Part 2, pp. 225-242.

Tsuchiya, Y. (1969). Mechanics of the successive saltation of a sand particle on a granular bed in a turbulent stream: Bull. Dis. Pre. Res. Inst., Kyoto Univ., Vol. 19, Part 1, No. 152, pp. 31-44.

Tsuchiya, Y. (1970). Successive saltation of a sand grain by wind: Proc. Twelfth Conf. Coastal Engg., Vol. 1, pp. 1417-1427.