**Mechanical conditions of snow erosion**
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# PREFACE

Snowdrifts can be a major source of disruption in the operation of transportation services and a general nuisance in the normal wintertime activity of a community. Such drifts are formed whenever a wind, strong enough to transport horizontally a significant amount of snow, encounters an obstacle which forces it to deposit some of this snow. The usual approach taken in defending an area or structure against snowdrifting has been to locate the structure properly so that the drift problem will be a minimum and to erect obstacles, such as snow fences, to control where the snow will be deposited. The approach taken in the development of these defences has been largely empirical. Attention has been directed primarily to the character of the air flow with little attention being given to the material transported. In some circumstances, it would be an advantage to have a more complete defence against snowdrifting than is now available. In their attempts to develop this defence, engineers are giving more consideration to the theoretical aspects of the problem and in particular to the relationships between the air flow and the snow being transported.

It is one of the responsibilities of the Snow and Ice Section of the Division of Building Research to collect and make available information required for the solution of snow and ice problems. The present paper, translated from the Russian, is a contribution to the theory of snowdrifting. This paper will give to the reader an appreciation of some of the factors to be considered in the theoretical description of blowing snow and its deposition as snowdrifts.

The paper was translated by Mr. D.A. Sinclair of the Translations Section of the National Research Council Library, to whom the Division of Building Research wishes to record its thanks.

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## THE MECHANICAL CONDITIONS OF SNOW EROSION

### Summary

Formulae are developed for the critical wind speed for the start of snow erosion, using the theory of dimensions.

One of the most important questions in the theory of snow deposits is the explanation of the conditions underlying the start of snow erosion. We explain these conditions using the methods of the theory of dimensions.

Let us construct the differential equation for the motion of a particle in a liquid, considering the particle as a material point:

$$m\left(\bar{\tau}\frac{dv}{dt}+\bar{n}\frac{v^2}{R}\right)=\bar{b}mw+\bar{i}f, \tag{1}$$

where m - mass of the particle;

v - scalar value of its speed;

f - force exerted on the particle by the liquid;

R - radius of curvature of the particle motion;

$$w=g\left(1-\frac{\rho}{\lambda}\right), \tag{2}$$

τ - unit vectors of tangent and normal force;

b - unit vertical vector;

i - arbitrary unit vector;

g - acceleration due to gravity;

ρ - mass density of liquid;

λ - mass density of particles.

Converting to the non-dimensional form (ref. 4, equation 1), we obtain:

$$\frac{d^3\lambda v^2}{l}M\left(\bar{\tau}\frac{dv}{dT}+\bar{n}\frac{v^2}{L}\right)=\bar{b}\,d^3\lambda g\left(1-\frac{\rho}{\lambda}\right)WM+ifF,$$

where l - a given linear dimension of the flow;

d - linear dimension of the particle.

Dividing the two sides of the equation by $d^3\lambda g\left(1-\frac{\rho}{\lambda}\right)$, we obtain in the right-hand part of the non-dimensional combination:

$$K_1=\frac{f}{d^3g(\lambda-\rho)}, \tag{3}$$

where the force f is an unknown quantity.

For a preliminary estimate of the value f we make use of N.E. Zhukovskii's theory of elliptical vortices(3).

Considering the part of the flow near the ground, N.E. Zhukovskii assumed the existence in this section of elliptical vortices playing a principal role in the process of creation of the turbulent pulsations resulting in the suspension of the granular materials. This was confirmed in the later experiments of G. Dzhil'bert, L. Prandtl and others (ref. 2, page 18). On the basis of these experiments the pattern of this process is represented in the following form (see Fig. 1)*.

An elliptical vortex A is formed in the part of the turbulent flow near the ground and sucks in particles situated along the surface 1 - 1. These vortex formations are unstable. They form, increase in size and disintegrate giving place to new ones.

On disintegration the ground ("bottom") vortices eject a mass of liquid M saturated with particles from their hind part.

In its general form the flow function of the elliptical vortex field, according to V.N. Goncharov (ref. 2, page 20), is:

$$\psi = \frac{в v_3}{n+1}\left(\frac{x_1^{n+1}}{a^{n+1}} + \frac{x_2^{n+1}}{в^{n+1}}\right), \tag{4}$$

where a,b - maximum semiaxes of the vortex core (Fig. 1);

$v_3$ - velocity at the point B.

n - a factor which according to N.E. Zhukovskii is equal to one and according to V.N. Goncharov equal to two.

We determine the pressure of the internal contour A'BAB' due to the suction of particles entering the zone of influence of the vortex.

Let us take the Navier-Stokes equation:

$$\frac{\partial v_i}{\partial t} + v_k \frac{\partial v_i}{\partial x_k} = S_i + \frac{1}{\rho}\frac{\partial \tau_{ik}}{\partial x_k} - \frac{1}{\rho}\frac{\partial P}{\partial x_i}, \tag{5}$$

where i,k - 1,2,3...are indices over which summations are carried out;

t - time;

$S_i$ - components of the external forces;

$\rho$ - mass density of liquid;

P - pressure;

$\tau_{ik}$ - viscous stress tensor.

For the sake of simplicity we assume that in the given interval of time 0 - t the field is stationary. For the two-dimensional stationary vortex equation (5) has the form:

$$\left.\begin{aligned} v_{x_1}\frac{\partial v_{x_1}}{\partial x_1} + v_{x_2}\frac{\partial v_{x_1}}{\partial x_2} &= -\frac{1}{\rho}\frac{\partial P}{\partial x_1} + \nu\left(\frac{\partial^2 v_{x_1}}{\partial x_1^2} + \frac{\partial^2 v_{x_1}}{\partial x_2^2}\right) \\ v_{x_1}\frac{\partial v_{x_2}}{\partial x_1} + v_{x_2}\frac{\partial v_{x_2}}{\partial x_2} &= -g - \frac{1}{\rho}\frac{\partial P}{\partial x_2} + \nu\left(\frac{\partial^2 v_{x_2}}{\partial x^2} + \frac{\partial^2 v_{x_2}}{\partial x_2^2}\right) \end{aligned}\right\}, \tag{6}$$

where $\nu$ - kinematic coefficient of viscosity.

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* This scheme must be regarded as only an approximate mechanical model. A more accurate representation of the process is given by the methods of statistical physics.

According to equation (4) we have:

$$v_{x_1} = \frac{\partial \psi}{\partial x_2} = v_3 \frac{x_2^n}{b^n}$$

$$v_{x_2} = -\frac{\partial \psi}{\partial x_1} = -v_3 \frac{x_1^n b}{a^{n+1}}$$

$$\frac{\partial v_{x_2}}{\partial x_1} = -v_3 \frac{b n x_1^{n-1}}{a^{n+1}}$$

$$\frac{\partial v_{x_1}}{\partial x_2} = v_3 \frac{n x_2^{n-1}}{b^n}$$

$$\frac{\partial^2 v_{x_1}}{\partial x_2^2} = v_3 \frac{n(n-1) x_2^{n-1}}{b^n}$$

$$\frac{\partial^2 v_{x_2}}{\partial x_1^2} = -v_3 \frac{b n (n-1) x_1^{n-2}}{a^{n+1}} .$$

Substituting these expressions in (6), multiplying the first equation (6) by $dx_1$, and the second equation (6) by $dx_2$ and combining them we get:

$$-v_3^2 \frac{n}{a^{n+1} b^{n-1}} \left( x_1^n x_2^{n-1} dx_1 + x_2^n x_1^{n-1} dx_2 \right) = -g dx_2 - \frac{1}{\rho} dP + \nu v_3 \left[ \frac{n(n-1) x_2^{n-2}}{b^n} dx_1 - \frac{b n (n-1) x_1^{n-2}}{a^{n+1}} dx_2 \right]$$

After integration we have:

$$-v^2 \frac{I_2}{\rho} = \frac{I_0}{\rho} - \frac{P}{\rho} + v_3 \frac{I_1}{\rho} + c$$

where $I_0 = -g x_2 \rho$

$$I_1 = \rho \nu n (n-1) b x_1 x_2 \left( \frac{x_2^{n-3}}{b^{n+1}} - \frac{x_1^{n-3}}{a^{n+1}} \right)$$

$$I_2 = \frac{\rho n x_1^{n-1} x_2^{n-1}}{(n+1) a^{n+1} b^{n-1}} \left( x_1^2 + x_2^2 \right).$$

At the point A (a, 0) (Fig. 1) let the pressure be $P_0$. The pressure difference (suction) within the contour ABA'B is then written:

$$P_0 - P = -\left( I_0 + I_1 v_3 + I_2 v_3^2 \right).$$

Hence the suction is equal to the sum of three terms, one of which depends on the square of the forward velocity, the second is proportioned to the same velocity and the third (piezometric term) is not dependent on the velocity.

The result obtained serves as a basis for the adoption of the following working hypothesis:

Force f in expression (3) is equal to the sum of three terms, one of which is proportional to the square of the forward velocity of the flow near the ground, the second directly proportional to the same velocity and the third is independent of the velocity.

The basic factors influencing the value of f are (the dimensional formulae are shown in the square brackets: F - force, L - length, T - time):

Mass density of liquid $\rho[FL^{-4}T^{2}]$

Viscosity of liquid $\mu[FL^{-2}T]$

Mean forward velocity of flow $v[LT^{-1}]$

Acceleration due to gravity in the liquid $w[LT^{-2}]$

Size of particle $d[L]$

According to the theory of dimensions:

$$f = \sum_{o}^{\infty} a_i \rho^{z_1} d^{z_2} w^{z_3} \mu^{z_4} v^{z_5},$$

where $\alpha_1$ - non-dimensional constance.

We now construct the dimensional equation:

$$[F]^1 = [FL^{-4}T^2]^{z_1}[L]^{z_2}[LT^{-2}]^{z_3}[FL^{-2}T]^{z_4}[LT^{-1}]^{z_5}$$

$$z_1 + z_4 = 1$$

$$-4z_1 + z_2 + z_3 - 2z_4 + z_5 = 0$$

$$2z_1 - 2z_3 + z_4 - z_5 = 0$$

whence:

$$z_1 = 1 - z_4$$

$$z_2 = 3 - \frac{3}{2}z_4 - \frac{1}{2}z_5$$

$$z_3 = 1 - \frac{z_4}{2} - \frac{z_5}{2}.$$

Hence:

$$f = \rho d^3 w \sum_{o}^{\infty} a_i \left(\frac{\mu}{\rho d^{3/2} w^{1/2}}\right)^{z_4}\left(\frac{v}{d^{1/2} w^{1/2}}\right)^{z_5}.$$

Assuming $z_4 = \frac{1}{2}(3 - i)$ and $z_5 = 2 - i$, we obtain the first three terms of the sum in full conformity with the working hypothesis formulated above:

$$f = \rho d^3 w\left[\alpha_0\frac{v^2}{dw} + \alpha_1\frac{\nu v}{d^2 w} + \alpha_2\frac{\nu}{d^{3/2} w^{1/2}}\right]. \tag{7}$$

Substituting (7) in (3), we have:

$$K_1 = \frac{\alpha_0 v^2 + \alpha_1\frac{\nu v}{d} + \alpha_2\frac{\nu g^{1/2}\left(1 - \frac{\rho}{\lambda}\right)^{1/2}}{d^{1/2}}}{dg\left(\frac{\lambda}{\rho} - 1\right)}. \tag{8}$$

Or, after introduction of the constants $K_2 = \frac{K_1}{\alpha_o}$

$$\beta_0 = \frac{\alpha_1}{\alpha_o}, \qquad \beta_1 = \frac{\alpha_2}{\alpha_0}:$$

$$K_2 = \frac{v^2 + \beta_0\frac{\nu v}{d} + \beta_1\frac{\nu g^{1/2}\left(1 - \frac{\rho}{\lambda}\right)^{1/2}}{d^{1/2}}}{dg\left(\frac{\lambda}{\rho} - 1\right)}.$$

Let v be the mean velocity for the layer of the flow at a height equal to unity (1 m). Taking the distribution of velocities near the ground according to S.A. Sapozhnikov[6]:

$$v^{y} = v_1\left(1 - \frac{lgy}{lg\delta}\right), \tag{9}$$

where $v_y$ - wind speed at the height y

$v_1$ - wind speed at a height of 1 m

$\delta$ - linear characteristic of roughness.

We determine the mean velocity in the layer from 0 to y:

$$v_{y\,mean} = v_1 \cdot \frac{1}{y-\delta}\int_{\delta}^{y}\left(1 - \frac{lgy}{lg\delta}\right)dy =$$

$$= \frac{v_1}{y-\delta}\left|y - \frac{lge}{lg\delta}\left(ylny - y\right)\right|_{\delta}^{y} =$$

$$= \frac{v_1}{y-\delta}\left[y\left(1 - \frac{lgy}{lg\delta}\right) + \left(y - \delta\right)\frac{lge}{lg\delta}\right].$$

Because of the small value of $\delta$, $y \cong y - \delta$.

Therefore:

$$v_{y\,mean} \cong v_1\left(1 + \frac{lg\frac{e}{g}}{lg\delta}\right) \tag{10}$$

(e - basic Napier logarithm (e = 2.718...)).

Employing formula (10) we determine, after a simple transformation, $v_{1\,mean}$, expressing this value in terms of $v_1$ and $v_y$:

$$v_{1\,mean} = v_1\left(1 + \frac{lge}{lg\delta}\right) \tag{11}$$

$$v_{1\,mean} = \frac{v_{y\,mean}}{1 - \frac{lgy}{lge\delta}}. \tag{12}$$

The initial period of motion of heavy macroparticles in liquid or gaseous medium is characterized by three velocities:

(1) v' - critical or "non-moving" velocity at which complete absence of particle motion is assured;

(2) v" - threshold velocity, i.e. velocity at which separate particles begin to break away from the surface and to be displaced;

(3) v‴ - upper critical velocity, i.e. velocity at which mass motion of particles begins.

For the case of sand in water ("sand + water") the following relations between these velocities have been established (ref. 7, page 443):

$$v'' = 1.2\ v';\ v''' = 1.56\ v'. \tag{13}$$

If $K_2$, $\beta_0$ and $\beta_1$ have been determined from the conditions of non-motion of surface particles, then in formula (8) we shall have v = v'.

Let us assume that the parameters $K_2$, $\beta_0$ and $\beta_1$ determined in this manner are constant, independently of the character of the medium in which the particles are moving. To verify this supposition we may take two very different media such as water and air.

We employed the existing experimental value v' for the case of "sand + water". Calculations showed that the following numerical values for the parameters of formula (8) corresponded closely to this value:

$$K_2 \approx 3{,}5$$
$$\beta_1 \approx -550$$
$$\beta_0 \approx 0.$$

The linear characteristic of the roughness $\delta$ was calculated according to V.N. Goncharov's data (ref. 2, pages 46-48) for the velocity distribution in depth as indicated in Fig. 2. On the average log $\delta$ = -4.75* (broken line in Fig. 2).

For sand we have taken $\lambda = 276 \cdot 10^3 \frac{g\ sec^2}{m^4}$. For water at a temperature 15°C, $\rho = 102 \cdot 10^3 \frac{g\ sec^2}{m^4}$, $\nu = 1.14 \cdot 10^{-6}$ m²/sec. Acceleration due to gravity $g = 9.8$ m/sec².

In Fig. 3 we give the curve $v_{0.1\ mean} = f(d)$, constructed according to formulae (8) and (12). This figure reveals the meaning of the critical velocity determined by V.N. Goncharov (ref. 2, page 158) for quartz particles of an average size of 0.35 - 39.3 and reduced to a flow depth of 0.1 m. In addition, we have plotted the data of Dzhalstrom (ref. 9, page 160) on quartz particles of very small size.

The value $v_{0.1\ mean}$ for small particles is due to the increased influence of the viscosity of the medium and also to the increase in their specific areas, which increases the cohesion between minute particles, inhibiting their removal from the surface of the ground or snow cover.

Substituting the above cited values $K_2$, $\beta_1$ and $\beta_0$ in formula (8) we find:

$$v_1' = \sqrt{E_1 d + \frac{E_2}{\sqrt{d}}}, \qquad (14)$$

where

$$E_1 = 3{,}5g\left(\frac{\lambda}{\rho} - 1\right)$$
$$E_2 = 550\,\nu\sqrt{g\left(1 - \frac{\rho}{\lambda}\right)}.$$

Differentiating the right-hand part of (14) with respect to d and putting the result equal to zero, we obtain the condition of minimum $v'_{mean}$.

$$d' = \left(\frac{E_2}{2E_1}\right)^{2/3}. \qquad (15)$$

At this value of d the critical velocity is a minimum. For velocity smaller than $v'_{min}$ there will be no removal of particles (erosion), as though

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* Strictly speaking the roughness $\delta$ depends on the sizes d of the particles forming the bed of the flow and on log $\delta$, as can be determined from the slope of the dotted lines in Fig. 3, and varies from -4 to -5.3.

there were no particles of small dimensions.

The values of $E_1$ and $E_2$ (for d expressed in mm) are derived for various media and particles and are given in Table I.

The values of d' and $v'_{min}$ calculated according to formulae (14) and (15) are given in Table II.

The curves of $v'_1 = f(d)$ for the cases "air + sand" and "air + soil particles" (see Fig. 4) are derived from the data of Table I and II and formulae (11) and (14). They agree well with the experimental data of M.A. Sokolov (ref. 1, page 204) and Chepil and Mailn[10], confirming our assumption about the constancy of the parameters $K_2$ and $\beta_1$. Similar curves have been constructed also for "air + snow".

According to G.D. Rikhter's data (ref. 5, page 29) snow is not blown away at wind speeds of less than 2 m/sec, regardless of the state of the snow cover or the size of the snow particles. This corresponds to the value of $v'_{1\,min}$ = 1.93 m/sec in Table II.

According to the data of A.A. Komarov, a collaborator of TEI ZSFAN*, at a mean snow particle size of approximately 0.5 mm snow is not transported at speeds v of less than 3 m/sec, corresponding to the broken line curves in Fig. 4.

The mass transport of drifting snow particles of approximately 0.5 mm in diameter in the absence of previous thawing begins, according to formulae (13) and (14), at upper wind speeds $v''' = 2.68 \cdot 1.56 \approx 4.2$ m/sec, assuming that equation (13) applies to the snow and the wind flow. According to the data of A.Kh. Khrgian[8], TsNII MPS** and TEI ZSFAN, the transport of snow really beings at wind speeds of $v_1 = 4 - 4.5$ m/sec.

After thawing and refreezing of the surface crystals ("regelation") and wind packing of the surface of the snow cover, the latter becomes covered by a so-called "crust" which possesses greater resistance to erosion. The value $v_1'''$ under these conditions increases to 10 m/sec and more[5].

The degree of resistance to erosion depends on the value of the snow cohesion.

If the snow is somewhat brittle, then the value of the adhesion depends, as was indicated above, on the size of the snow particles. This can be determined by representing the phenomenon as follows (see Fig. 5).

Let us consider three cubic particles $a_1$, $a_2$ and $a_3$ of side d.

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** Central Scientific Research Institute, Ministry of Transport.

Particles $a_1$ and $a_3$ are on a given plane while $a_2$ is raised to a plane at the height $\frac{d}{2}$. The distance between the particles is d.

If there were no resistance to the fall of particle $a_2$ it would fall towards the surface at a rate $v_H = \sqrt{wd}$. However, surface viscous forces

$$\tau_0 = \mu \frac{v_H}{d}\ g/m^2$$

oppose this motion.

Substituting $v_H = \sqrt{wd}$ we obtain

$$\tau_0 = \mu \frac{v_H}{d} = \mu \sqrt{\frac{w}{d}}. \tag{16}$$

The third term of formula (8) in the numerator of the right-hand side can easily be expressed in terms of $\tau_0$

$$\beta_1 \frac{\nu w^{1/2}}{d^{1/2}} = \beta_1 \frac{\mu}{\rho} \sqrt{\frac{w}{d}} = \beta_1 \frac{\tau_0}{\rho}.$$

This is the physical interpretation of the third term of equation 8. In the general case this term is equal to $\frac{\beta_1}{\rho}\tau$, where $\tau > \tau_0$ for a packed or frozen snow cover.

Comparisons of the conditions at the start of erosion of various granular materials in various media give the basis for deriving a first approximation to the correct formula for determining the critical speed $v'_1$. It will have the form

$$v'_1 = \frac{\sqrt{K_2 dg\left(\frac{\lambda}{\rho} - 1\right) - \beta_1 \frac{\tau}{\rho}}}{1 + \frac{\lg e}{\lg \delta}}.$$

From what has been said the following conclusions may be drawn:

(1) The phenomenon of erosion of loose snow is a particular case of the erosion of various granular materials in water and in air and depends on the same parameters.

(2) The larger the values of $\delta$, d and $\tau$ the greater will be the critical velocity of the air flow required to initiate snow erosion at ground level. Therefore the measures to be taken to prevent erosion must consider the following: (a) the roughness of the snow surface, (b) the diameter of the surface particles, (c) the adhesion between the surface particles.

In pursuance of the considerations presented in this paper additional experimental material is required for further development of the theoretical conclusions.

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Table I

| Average and large particles | $\lambda\ \frac{g\ sec}{m^4}$ | $\rho\ \frac{g\ sec^2}{m^4}$ | $\nu\ \frac{m^2}{sec}$ | $E_1$ | $E_2$ |
|---|---|---|---|---|---|
| Water + sand t° = 15°..... | $276 \cdot 10^3$ | $102 \cdot 10^3$ | $1.14 \cdot 10^{-6}$ | 0.0584 | 0.0495 |
| Air + sand............... | $276 \cdot 10^3$ | 123 | $15 \cdot 10^{-6}$ | 77 | 0.82 |
| Air + soil particles, t° = 20°, pressure 760 mm..... | $160 \cdot 10^3$ | | | 47 | |
| Air + snow, t° = -10°, pressure 760 mm.......... | $40 \cdot 10^3$ [1] | 137 | $12.1 \cdot 10^{-6}$ | 10 | 0.658 |

Table II

| Medium and large particles | log δ | $d'_{mm}$ | $v'_{min}$ |
|---|---|---|---|
| Water + sand......... | -4.75 | 0.56 | $v_{0.1\,mean\,min} = 0.24$ m/sec |
| Air + sand........... | -4.68 [2] | 0.035 | $v'_{1\,min} = 2.92$ m/sec |
| Air + soil particles. | -3.12 [3] | 0.03 | $v'_{1\,min} = 2.88$ m/sec |
| Air + snow........... | -4.85 [4] | 0.1 | $v'_{1\,min} = 1.93$ m/sec |

1) Density of flakes related to mean according to Nakaiya (granular and dendritic) and according to the data of Prof. A.D. Zamorskii.

2) According to Bagnold. See Fig. 2 and ref. 10.

3) According to Chepil and Milne. Fig. 2 and ref. 10.

4) See author's paper on "Vertical distribution of solid flux in a snow-wind flow" in this collection. (NRC TT-999).

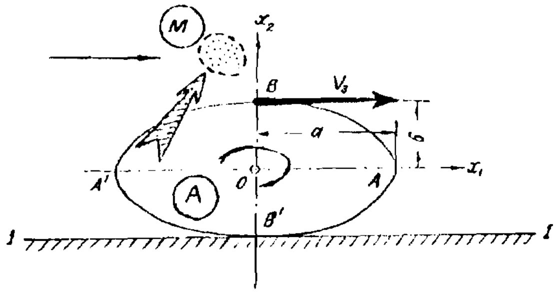


Fig. 1

Diagram of analytical vortex
at the ground

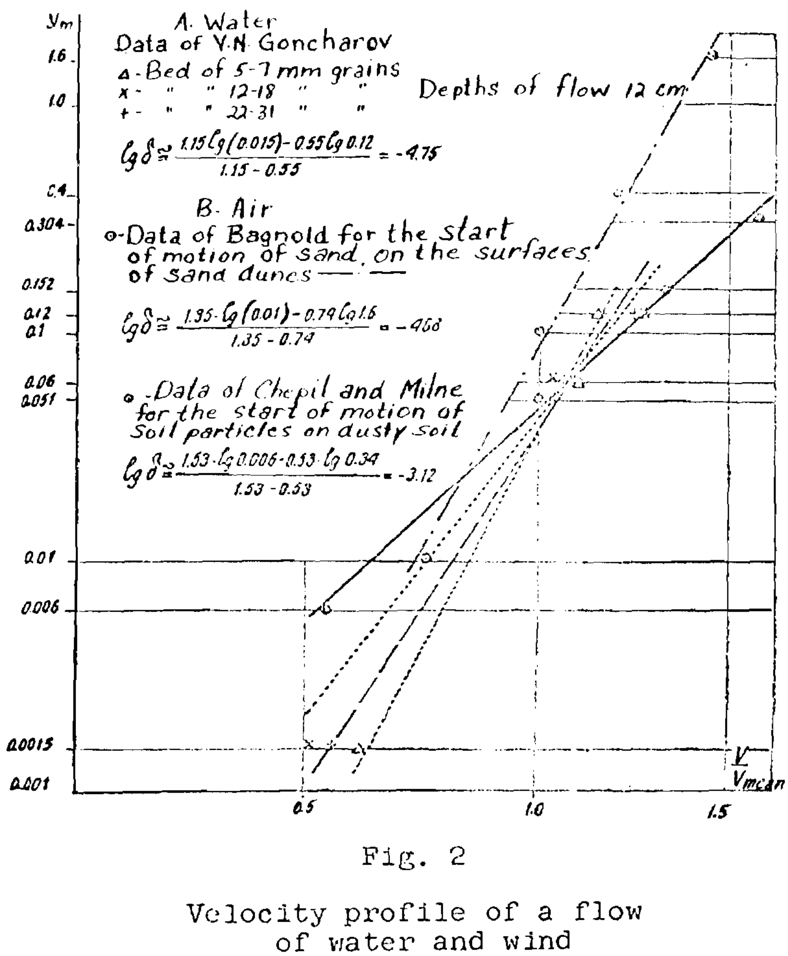


Fig. 2

Velocity profile of a flow
of water and wind

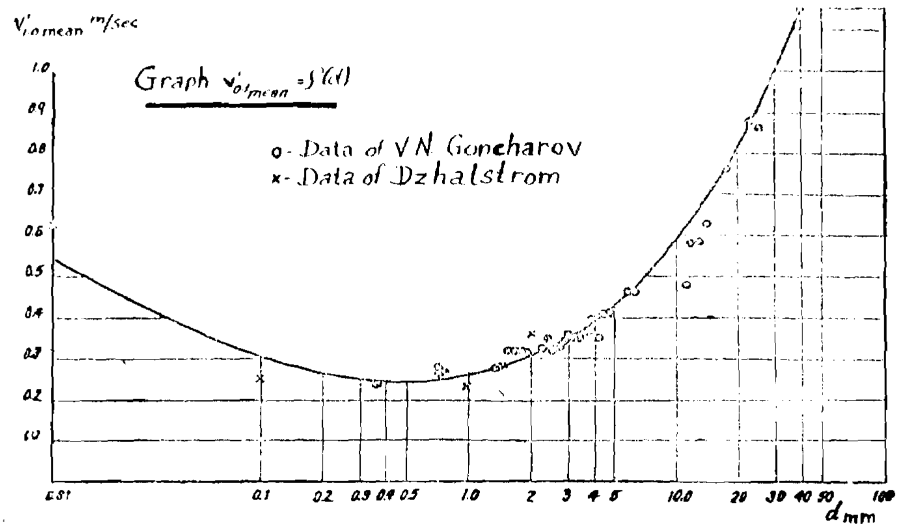


Fig. 3

Graph of the function v' = f(d) for the case of "sand + water"

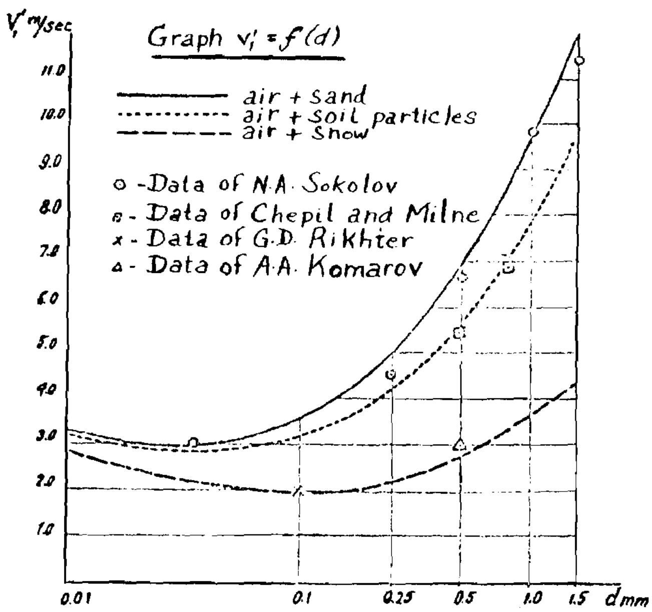


Fig. 4

Graph of the function $v'_1 = f(d)$ for the case of motion of heavy particles in a flow of air

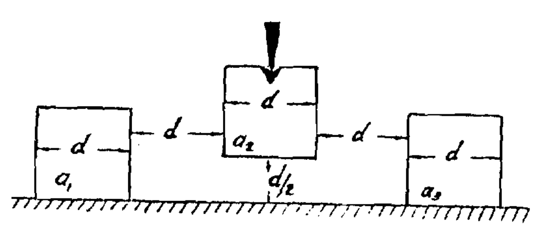


Fig. 5

Diagram for the derivation of formula (16)