STEADINESS OF GRANULAR MATERIALS ON ICE-COATED ROAD SURFACE

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1. Abstract

In practice of operation of roads in northern countries the influence of a climate and intensive atmospheric precipitations can result in a complete icing of pavements. There are a lot of cases of serious traffic accidents with heavy consequences due to the loss of cohesion with the road and uncontrollability of automobiles. Therefore quick restitution of cohesive qualities of the wheel with the ice surface is an actual problem. Even more important is the forming of a rough layer from ice and stone fines at the moment of ice nucleation on the pavement. The frictional material melts well into snow cover, but on an ice layer the separate grains in a cold state do not cohere with ice and are promptly thrown out of the roadway. There exist a technology of distribution of hot stone fines into snow-ice cover or on ice. (Sweden. Materials of X^{th} Winter Road Congress, 1998). Melting of ice and the subsequent freezing of separate particles of stone fines ensures their fastening and creating of a rough mat.

However, to advance this technology it is necessary to answer the following questions:

- Under what conditions will the grains of different shape have the best resistance in an ice substrate against ejection by wheels of automobiles?
- What size of grains is expedient for applying? What is the minimal depth of their freezing-in? And in what amount should they be dispersed onto the pavement?

The answers to these questions are necessary to ensure the road safety at a winter icing of pavements.

The present paper considers stability conditions of granular materials of different shape, frozen in ice, when they are subject to impact of vertical and horizontal loadings from wheeled vehicles. It shows, that to ensure proper cohesion of wheels with the surface of road, covered with ice, the determinate sizes of fractions of granular materials and determinate mass on an area unit are required. It is determined in the paper, that the minimal depth of freezing of a spherical or pyramidal grain should make not less than 0.6 of its height, what ensures its steadiness from turning or overturning. The grains with a diameter of 12 mm, frozen into ice, ensure traveling of 30 trucks with a loading on an axis of 100 kN, but fine grains with a diameter of 4-6 mm – only 10 trucks. An ice stratum with the grains, frozen in in one row, does not split up, if mass of grains of natural rock makes from 0.5 up to 1.6 kg/м^2.

2. Full-paper

The answers to these questions can be obtained with the help of physical modeling of behavior of a grain, which is frozen in an ice substrate, and which is subjected to a vertical and a horizontal force and their impulses. Then we can derive equations of steadiness and resolve them under real boundary conditions. In this connection we shall make a series of assumptions: the mineral grains are elastic, weightless and have smooth surfaces. The shapes of grains are a ball, a pyramid and arbitrary. It is obvious, that the best steadiness belongs to the pyramid inscribed in a ball with a diameter d;

the worst steadiness belongs to the ball. The arbitrary (casual) shape of grains occupies an intermediate position. Each grain is subject to action of reiterated impulses of normal and tangential forces being a concentration and constituents of impulses of slanting stresses from wheel loading. Each grain is deepened in a layer of ice substrate, characterized by tearing strength, compression strength and width $0 \le hn \le d$. The strength of grains is incommensurably higher than the strength of substrate, and the deformability is incommensurably lower. Therefore the loss of steadiness occurs only as a result of tearing of a grain off the ice substrate, its rotational displacement etc. without its fracture.

The load, which affects a grain, results from a concentration of an evenly distributed load q_x and τ_y on a platform for a ball grain - $\frac{\pi d^2}{4}$, and for a pyramid grain with equal-sized facets - $\frac{d^2}{2}$. Of course, this condition is acceptable only when grains are in contact with each other, i.e. in a close-packed arrangement in one layer. Therefore for a ball:

$$P = q_x \cdot \frac{\pi d^2}{4}, Q = \tau_y \cdot \frac{\pi d^2}{4}, \quad (1)$$

And for a pyramid:

$$P = q_x \cdot \frac{d^2}{4}, Q = \tau_y \cdot \frac{d^2}{4} \quad (2)$$

The actual values q_x and τ_y can reach for passenger cars 0,15 - 0,2 mPa and 0,05 - 0,1 mPa, and for lorries 0,6 - 0,65 mPa and 0,2 - 0,3 mPa. The duration of action of concentrated loadings P and Q is equal to time when a wheel passes with velocity V the route equal to the length of its contact with the tread, i.e. $\frac{B_k}{\nu}$. Therefore impulses of normal and tangential forces will make for a globe grain:

$$j_p = q_x \cdot \frac{\pi d^2}{4} \cdot \frac{B_k}{V}, \quad (3)$$

$$j_Q = \tau_y \cdot \frac{\pi d^2}{4} \cdot \frac{B_k}{V}. \quad (4)$$

And for a pyramid grain:

$$j_p = q_x \cdot \frac{d^2}{4} \cdot \frac{B_k}{V}, \quad (5)$$

$$j_Q = \tau_y \cdot \frac{d^2}{4} \cdot \frac{B_k}{V}. \quad (6)$$

The combined impulses of forces operate aslant to a horizontal axis under the angle $\gamma \ge 0^0$ ($tg\,\gamma = \frac{Q}{P}$), and in a mode of deceleration on length B_k and τ_y can reverse.

On a pyramidal grain the impulses of forces act on its vertex according to the formulas 3 and 4, but on a ball grain the tangential impulse of forces will act below the upper point of the ball at a distance equal to $\frac{W}{2}$. W is defined from a proposition about the pressing of a stiff ball in elastic half-space according to the formula:

$$W = \sqrt[3]{\frac{9}{8} \cdot \frac{P^2 (1 - \mu_0^2)^2}{d E_0^2}}, \quad (7)$$

where E_0 and μ_0 are elastic modulus and Poisson's coefficient of elastic half-space (material of a pneumatic wheel) consequently. If a series of spherical grains with the diameter d_l has at least one grain with the diameter *d*, on its surface from above force *P* is distributed on a globe segment of radius $\frac{B_0}{2}$, equal:

$$\frac{B_0}{2} = \sqrt[3]{\frac{3}{8} \cdot \frac{Pd(1-\mu_0)^2}{E_0}}. \qquad (8)$$

It is obvious, that at the distance *r* from the center of application of the load *P* the pneumatic wheel will touch the surface of a ball of a smaller diameter *d*, which will be determined from the following condition:

$$d\text{-}d_1 = W_r. \qquad (9)$$

The depth of pressing of a stiff ball grain in gum of the tire at the distance *r* from center of the load application will be determined from the proposition of loading of linearly-deformable half-space:

$$W_r = W\frac{2}{\pi}\arcsin\frac{B}{2r}. \qquad (10)$$

Implementing condition (9) by iterations we shall get the relative magnification of a load on a grain $\frac{P^*}{P}$ depending on d/d_1, what illustrates concentration of forces on a grain of a greater diameter.

Dependence of Relative Concentration of Forces on Grains of Various Sizes

Table 1

d, cm	*d_1, cm*	*d/d_1*	*d/d_1*	*r, cm*	*P^*/P*
1,2	0,4	3	0,8	1,58	6,93
	0,8	1,5	0,4	1,0	2,77
	1,2	1,0	0	0,6	1,0
0,8	0,4	2,0	0,4	0,77	3,71
	0,8	1,0	0	0,4	1,0
0,6	0,4	1,5	0,2	0,49	267
	0,6	1,0	0	0,3	1,0

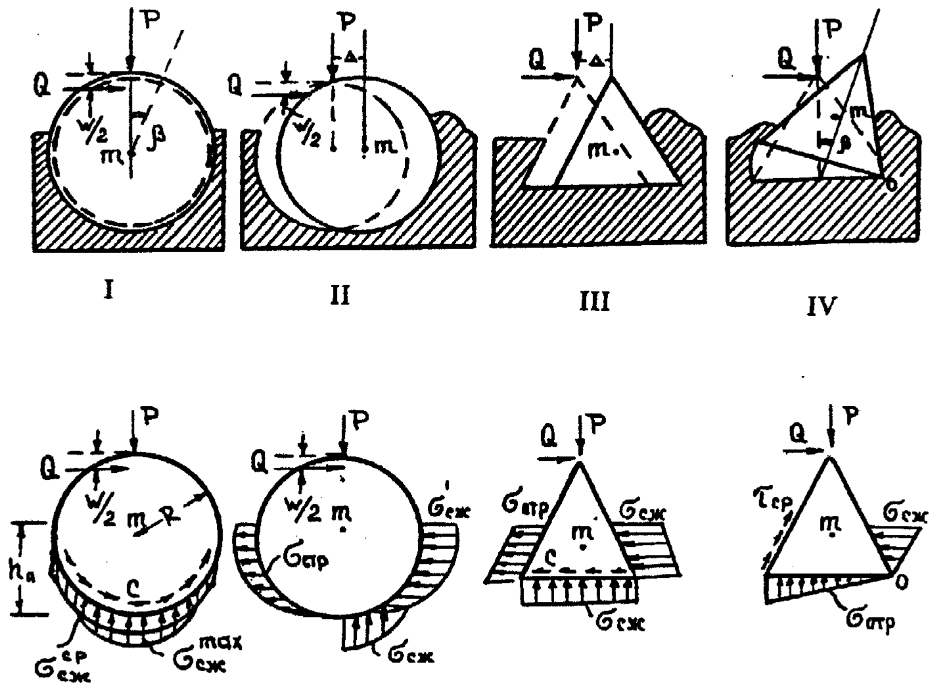

Fig. 1: Schemes of Loss of Steadiness and Their Corresponding Loading Diagram
I - Rotational Displacement of a Ball in a Substrate with Slippage;
II - Horizontal Bias of a Ball;
III - Horizontal Bias of a Pyramid;
IV - Rotational Displacement of a Pyramid Concerning the Edge of Its Basis.

Now we shall consider the basic probable schemes of loss of steadiness of grains in an ice substrate (fig. 1) and their corresponding loading diagrams. Obviously, if the shearing strength of a material of a substrate is low, the scheme I will be probable for a ball. If the compression and tearing strength is low, the schemes II and III will be appropriate for a ball and a pyramid. And if the tearing strength is low, and compression strength is high, the pyramid grain is likely to have scheme IV. The steadiness for the different schemes of its loss is characterized by value of coefficient of steadiness margin, which represents the relation of the moments of retaining and tilting forces, or forces retaining a grain in an ice substrate to displacing forces. The mathematical models of coefficients of steadiness margin are given in tab. 2.

Table 2

Shape of a grain	Scheme of loss of steadiness	Mathematical model of safety factor of steadiness
Ball	Rotational displacement of a ball in a substrate with slippage	$K_3 = \frac{R_{shearing} \cdot \pi hn(2d - hn)d}{Q(d - w)}$ 11
Ball	Horizontal bias of a ball	$K_3 = \frac{[R_{compr.} + R_{tensile}]\pi d \cdot hn(2d - hn)}{2Q(d - w)}$ 12
Pyramid	Horizontal bias of a pyramid	$K_3 = \frac{4Q}{2hn \cdot d \cdot \sqrt{3(R_{compr.} + R_{tensile}) + 3d^2 \cdot R_{shea.}}}$ …..13

Shape of a grain	Scheme of loss of steadiness	Mathematical model of safety factor of steadiness
Pyramid	Rotational displacement of a pyramid around an edge of the basis	$K_3 = \frac{3Q}{[2hn \cdot \sqrt{3(R_{s.} + R_{comr.}) + 3d \cdot R_{tens/}} - P\sqrt{3}]}$ …..14

If $K_3 > 1$, the steadiness is ensured. If $K_3 \leq 1$, the steadiness is the least or absent. Let's assume, in calculations q_x*=0,6 mPa,* τ_y*=0,3 mPa,* E_0*=9450 mPa,* μ_0*=0,34*[**]*, d=0,4; 0,6; 0,8; 1,0 and 1,2 cm*, compression, tensile, shearing and bending strengths of ice at temperature 0 ÷ -2° C are 1,6 mPa, 1,0 mPa, 0,6 mPa and 0,4 mPa accordingly.[**]

The results of calculations of coefficient of a steadiness margin, given in fig. 2 and 3 allow making the following conclusions:

1. For a grain of a spherical shape the loss of steadiness is most probable by rotational displacement in a substrate of ice, and for a pyramidal shape – by rotational displacement around an edge of the basis.
2. Freezing-in of grains of any shape in an ice substrate on depth of 0,6 ÷ 0,8 of their diameters quadruplicates the steadiness.
3. The pyramidal and spherical grains with a diameter of 12 mm, immersed in ice on depth up to 7 ÷ 8 mm, withstand 25 ÷ 30 calculated automobile axes (up to 100 kN on an axis), and the grains with a diameter of 4 ÷ 6 mm withstand only 2 ÷ 10 axes.
4. The consumption of stone grains, which are immersed in ice and ensure the traffic and preservation of an ice stratum from crushing, should be for fraction sizes of 1,2; 1,0; 0,6 and 0,4 cm not less than 1,6; 1,0; 0,8 and 0,5 kg/m^2 respectively.

The above-mentioned conclusions should be taken into account to advance the Swedish technology of ensuring an emergency road safety on ice-coated surfaces.

[**] Bogoroditsky V.V and others. Physics of freshwater ice. – Leningrad: Hydrometeoizdat, 1971.

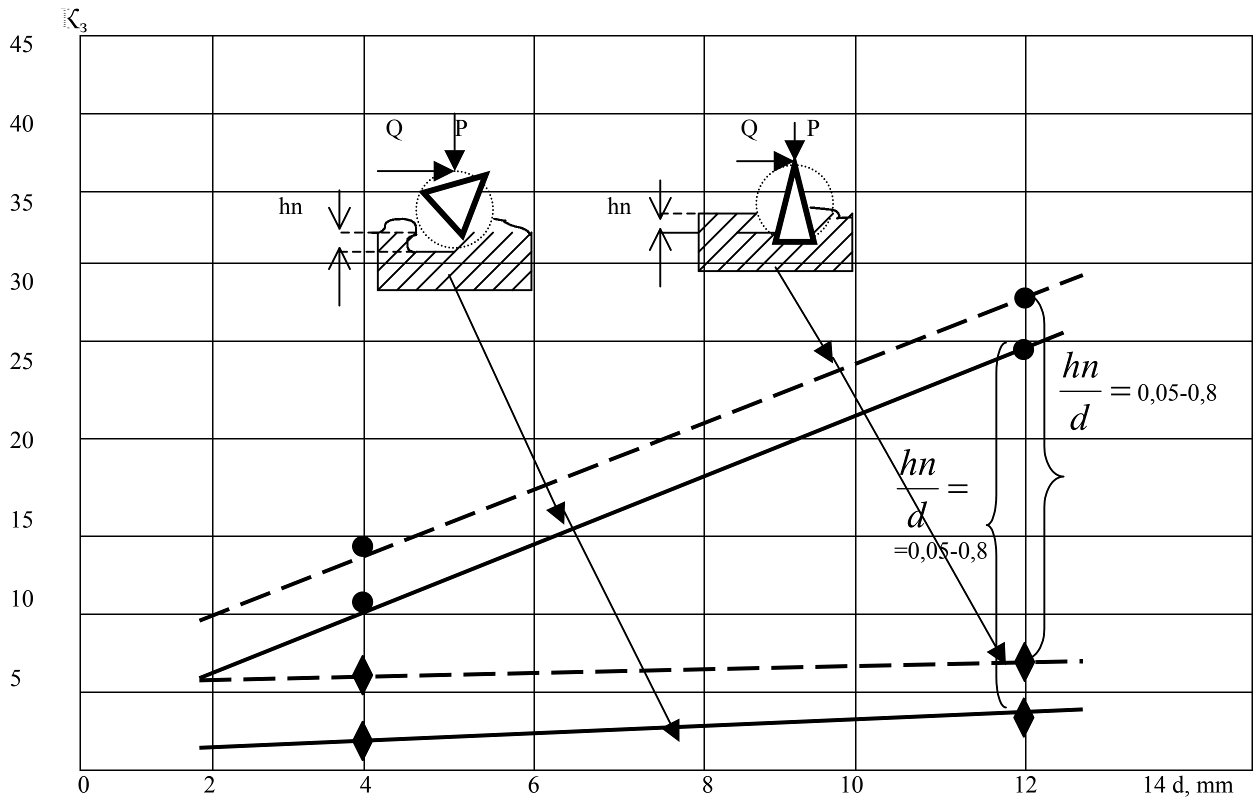

Fig.2: Dependence of Coefficient of Steadiness Margin of Pyramidal Grains in an Ice Substrate on a Diameter of a Ball.

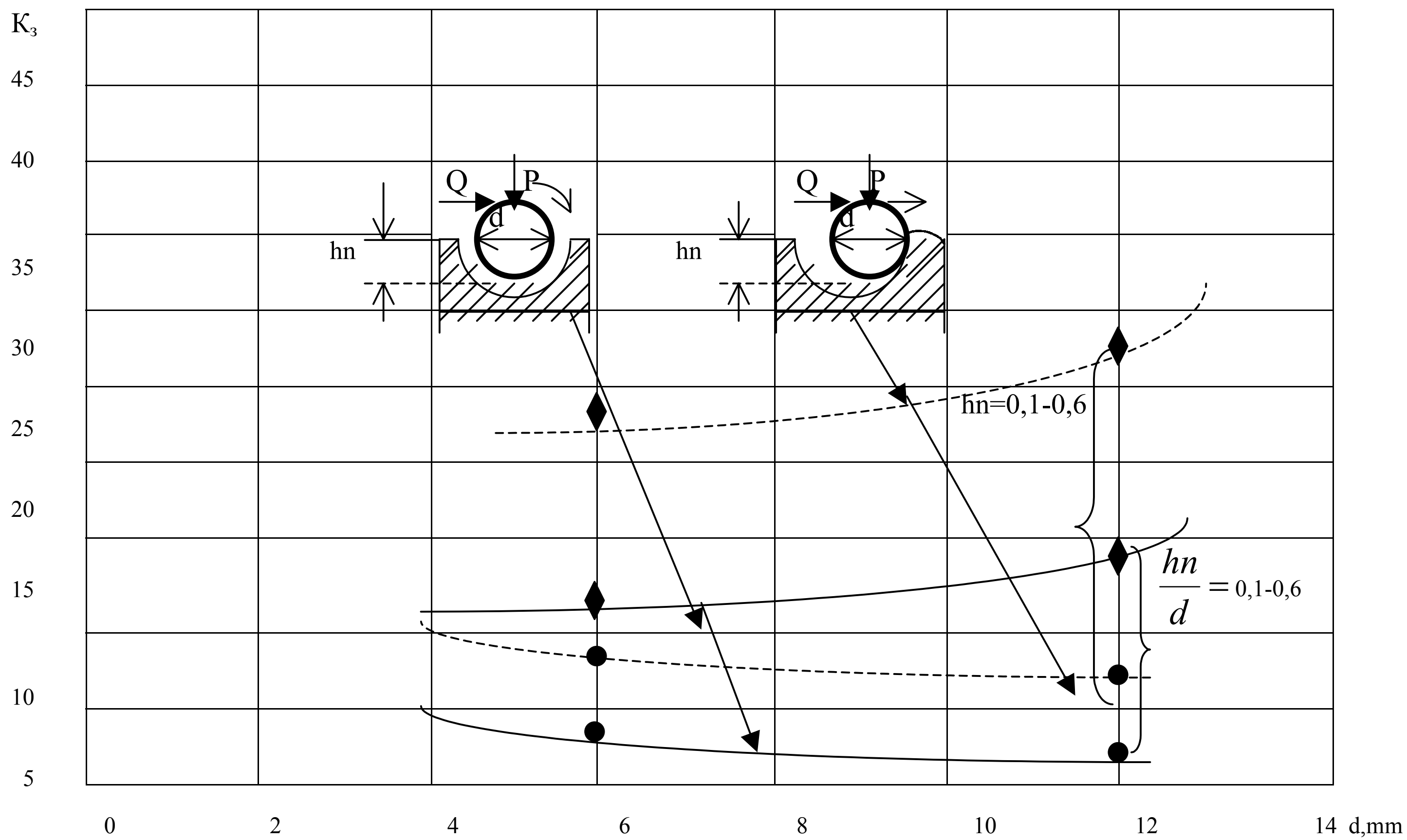

Fig.3: Dependence of coefficient of steadiness margin of spherical grains in an ice substrate on a diameter of a ball.