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Some features of ice drilling technology by a drill on a hoisting cable

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Abstract: Ice core drilling is optimized by analyzing the main factors that influence the drilling time. These factors are the depth of the bore-hole, power of the driving motor of the winch, mean speed of lowering and hoisting, speed of penetration, penetration per run and time of surface operations. One of the major characteristics which influences the drilling time is the mean travel speed. This paper presents the equations for calculation of the mean travels speed depending on the depth of drilling and other factors.

The influence of the main factors on the total time is analyzed. The mean travels speed is a more significant factor than penetration per run. The influence of the power of the winch driving motor is similar to that of the mean travel speed. Determination of the optimal values of factors allow optimization of deep ice drilling accounting for the features of drilling.

The most effective way to analyze the material composition and dynamics of ice masses deposited in polar regions is drilling of bore-holes with complete recovery of the cores. One of the major characteristics which influence drilling time and power input is the mean travel speed (ν_f), to determine which it is necessary to know the law of drill movement during lowering and hoisting (Bobin *et al*., 1988; Vasiliev and Kudryashov, 1993). Generally the differential equation of drill movement in a bore-hole is:

$$m\frac{d\nu}{dt}=F-G'-P_h-G_c', \tag{1}$$

where m is the mass of the moving drill, kg; ν is the speed of drill movement, m/s; t is the travel time of the drill, s; F is the force on the hook, N; G' and G_c' are respectively the weight of the drill and weight of the hoisting cable in liquid, N; P_h is force of hydraulic resistance, N.

For conditions of ice drilling by core drills on the hoisting cable the left side of eq. (1) is rather small. Since $m^*(d\nu/dt)\approx 0$, we have:

$$F=G'+P_h+G_c'. \tag{2}$$

The weight of the drill and weight of the cable in liquid can be calculated from:

$$G'=G\left(\frac{\rho}{\rho_d}\right), \tag{3}$$

$$G_c'=H\gamma_c', \tag{4}$$

where ρ_d is the mean density of drill material, kg/m^3; G is the weight of the drill in air, kg; ρ is the bore-hole liquid density, kg/m^3; H is the bore-hole depth, m; and γ_c' is the weight of one meter of cable in liquid, N/m.

The force of hydraulic resistance during movement of the drill is determined from (Vasiliev and Kudryashov, 1993)

$$P_h = \beta_1 \nu^{1.75}, \tag{5}$$

where

$$\beta_1 = 4.62 \cdot 10^{-3}\left(1.05 + 26\frac{\delta}{d}\right)\left[1 + 1.63\left(\frac{\delta}{d}\right)^{1.14}\right]^2 \nu^{0.25}\rho l d^{3.75}\delta^{-3}\left(1 + \frac{\delta}{d}\right)^{-1.75}, \tag{6}$$

where δ is the radial clearance between the surface of the drill and walls of the bore-hole, m; d is the diameter of the drill, m; l is the length of the drill, m; and ν is the coefficient of kinematic viscosity of the bore-hole fluid, m^2/s.

During hoisting the force F in eq. (2) can be determined from the following equation:

$$F = \frac{N'}{\nu}, \tag{7}$$

where N' is the power of the winch, motor taking into account the coefficient of performance, W.

Having substituted (3), (4), (5) and (7) into eq. (2), we obtain:

$$N' = (G' + H\gamma_c')\nu + \beta_1 \nu^{2.75}. \tag{8}$$

The mean hoisting speed of the drill from depth H to the surface can be determined using integral calculus. But concerning speed eq. (8) is transcendental, so we solve it relative to depth H:

$$H = H(\nu) = \frac{1}{\gamma_c'}\left(\frac{N'}{\nu} - \beta_1 \nu^{1.75} - G'\right). \tag{9}$$

It is possible to write the following equation:

$$H_i \nu_{mi} = H_i \nu_{0i} + \int_{\nu_{0i}}^{\nu_{fi}} H(\nu) d\nu, \tag{10}$$

where ν_{mi}, ν_{0i} and ν_{fi} accordingly mean, initial and final hoisting speed in run number i, m/s.

Hence,

$$\nu_{mi} = \frac{H_i \nu_{0i} + \int_{\nu_{0i}}^{\nu_{fi}} H(\nu) d\nu}{H_i}, \tag{11}$$

where

$$\int_{\nu_{0i}}^{\nu_{fi}} H(\nu) d\nu = \frac{1}{\gamma_c'}\left(N' \ln \nu - \frac{\beta_1}{2.75}\nu^{2.75} - G'\nu\right)\Bigg|_{\nu_{0i}}^{\nu_{fi}}. \tag{12}$$

Limits of integrating ν_0 and ν_f we can determine from eq. (8).

If $H = H_i$

$$N' = (G' + H_i\gamma_c')\nu_{0i} + \beta \nu_{0i}^{2.75}. \tag{13}$$

If $H=0$

$$N'=G'\nu_{fi}+\beta_1\nu_{fi}^{2.75}. \tag{14}$$

Having substituted (12) in (11), we obtain the equation for the mean hoisting speed of the drill from depth H:

$$\nu_{mi}=\nu_{0i}+\frac{1}{H_i\gamma_c'}[\mathrm{N}'(\ln\nu_{fi}-\ln\nu_{0i})+(\nu_{0i}^{2.75}-\nu_{fi}^{2.75})+G'(\nu_{0i}-\nu_{fi})]. \tag{15}$$

During lowering of the drill in the bore-hole the forces P_h and G' action the drill; hence eq. (2) will be:

$$P_h-G'=0. \tag{16}$$

Taking account of (5) gives the equation for the lowering speed of the drill.

$$\nu_{di}=\left(\frac{G'}{\beta_1}\right)^{0.57}. \tag{17}$$

Knowing the mean speed of lowering and hoisting during a run, it is possible to determine the mean travel speed:

$$\nu_{ti}=\frac{2H_i+h}{T_{di}+T_{ai}}, \tag{18}$$

where ν_{ti} is the mean travel speed in run number i, m/s; T_{di}, T_{ai} is the time of lowering and hoisting of the drill in run number i, s; and h is the penetration per run, m.

Neglecting h, as $2H\gg h$, we obtain:

$$\nu_{ti}=\frac{2H_i}{T_{di}+T_{ai}}=\frac{2}{T_{di}/H_i+T_{ai}/H_i}=\frac{2}{1/\nu_{di}+1/\nu_{ai}}. \tag{19}$$

The mean travel speed for a run is a function of bore-hole depth: $\nu_t=\nu(H)$. Therefore mean travel speed for the total drilling time of the bore-hole can be determined using a theorem of mean integral calculus

$$\nu_t=\frac{\int_{H_0}^{H_f}\nu(H)dH}{H_f-H_0}. \tag{20}$$

During experimental drilling on Vavilov glacier on Severnaya Zemlya, the time of lowering and hoisting was measured (Bobin *et al.*, 1988). The difference between experimental and calculated speeds of lowering and hoisting of the drill KEMS-112 at values of radial clearance from 0.002 to 0.014 m does not exceed 11%.

From analysis of eq. (19) we conclude that the increase of travel speed for one run and for the total drilling time of the bore-hole is not effective in case of increase of one speed (speed of lowering or speed of hoisting) only, because $\nu_{di}\to\infty$ as $\nu_{ai}\to 2\nu_{fi}$, and *vice versa*. Hence, simultaneous increase of ν_{di} and ν_{ai} is necessary. This is possible due to the decrease of force of hydraulic resistance, the value of which depends on the radial clearance (Vasiliev and Kudryashov, 1993).

The decrease of hoisting time due to increasing of hoisting speed requires increase of winch driving motor power.

Let's look at the influence of radial clearance and power of the winch driving motor on mean travel speed during deep drilling to 4000 m depth at Vostok station (East Antarctica) by an electromechanical drill KEMS-112 with the following characteristics (Kudryashov *et al.*, 1994): $d=0.108$ m; $l=13$ m; $G'=1800$ N; $\nu=3\cdot10^{-6}$ m²/s; $\rho=825$ kg/m³; $\gamma'=7.54$ N/m; $\eta=0.75$ (η is coefficient of performance of the winch driving motor).

Experience in deep ice drilling demonstrates that for secure drilling the travel speed of drill movement in a bore-hole, especially during lowering, should be limited. In deep drilling it is possible to choose the maximum speed of $\nu_{max}=1$ m/s. At constant power of the winch driving motor, the speed of drill movement in some intervals can exceed 1 m/s. Hence, limitation of hoisting speed is possible due to decrease of winch driving motor power. This will work at below nominal power.

The boundary values of radial clearance for which the instantaneous speed of hoisting in separate intervals of the bore-hole exceeds 1 m/s, depending on the winch driving motor power, are the following: 30 kW 4 mm; 20 kW 4.5 mm; 10 kW 6 mm and 5 kW 10 mm. In the last case, limitation on hoisting speed occurs at any power of the winch driving motor. The analysis of results shows that these limitations of hoisting speed brings some changes to the dependence of mean travel speed on the radial clearance and power of the winch driving motor.

The solid curves (Fig. 1a) correspond to the case with limitations of the hoisting speed, while dotted lines correspond to the case without limitations. At values of radial clearance below boundary values the full lines and stroke lines at the same power are merged to one line.

At the limiting travel speed, curves which correspond to powers of 20 and 30 kW practically merge in one line. In Fig. 1b the curves of mean travel speed versus power of the winch driving motor in the range of radial clearance from 0.002 up to 0.01 m are shown.

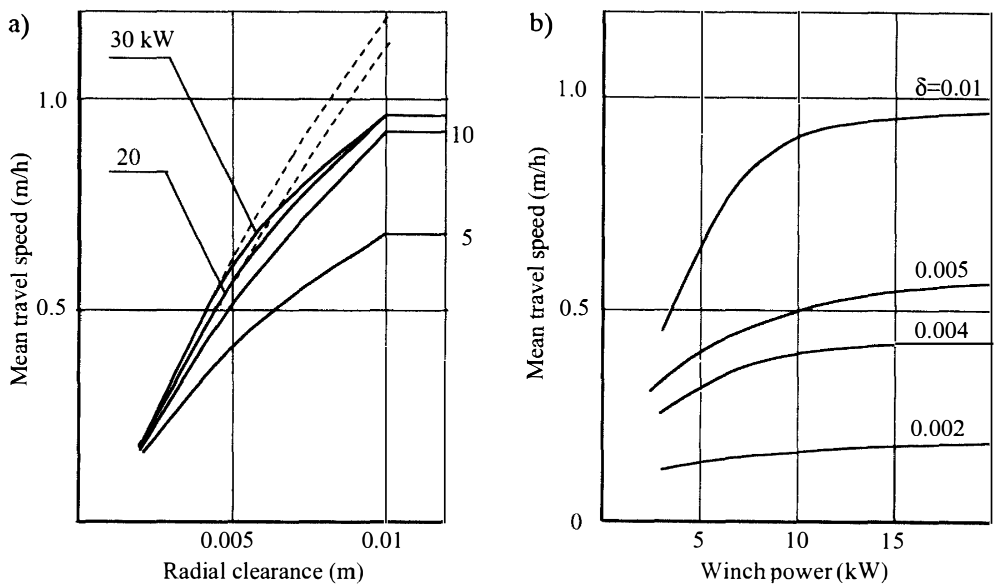

Fig. 1. The mean travel speed versus:
a: radial clearance (Solid lines—at $\nu_{max}=1$ m/s; Dashed lines—without limitation of hoisting speed); b: winch driving motor power.

It is obvious that increase of power of the driving motor to more than 15 kW is not effective, because it brings growth of the mean travel speed of not more than 3%. The range of mean travel speed at bore-holes with depths more than 1000 m is from 0.5 up to 1.0 m/s (Bobin *et al.*, 1988). Then the range of radial clearance corresponding to these speeds will be from 0.005 to 0.01 m at driving motor power of more than 10 kW.

Increase of the radial clearance promotes the growth of the mean travel speed, and at the same time causes increase of the bottom space and, hence, the amount of ice chips. Increase of the quantity of ice chips is will reduce the drill penetration per run. The increase of the bottom space at constant power of drill driving motor will reduce the mechanical rate of penetration.

Thus, the value of the radial clearance affects the drilling characteristics; specifically mean travel speed and mechanical rate of penetration. To estimate the influence of the radial clearance on the overall drilling time to depth H, we can use the following equation (Bobin *et al.*, 1988):

$$T=\frac{H^2-H_0^2}{h\nu_t}+\frac{H-H_0}{h}T_s+\frac{H+H_0}{\nu_m}, \tag{21}$$

where T is the bore-hole drilling time, h; H is the depth of bore-hole, m; H_0 is the initial depth of the bore-hole, m; $h=h(\delta)$ is penetration per run, m; $\nu_t=\nu(\delta, N)$ is mean travel speed m/h; T_s is time of surface operation per run, h; $\nu_m=\nu(\delta)$ is mechanical rate of penetration, m/h.

The results of calculations using eq. (21) at $T_s=0.25h$ (Bobin *et al.*, 1988) are shown in Fig. 2. These calculations were done for two cases: first, drilling with limitation of maximum speed of drill movement to 1 m/s, and second, without limitation. In the case of drilling with limitation of travel speed of the increasing of the radial space up to 10 mm

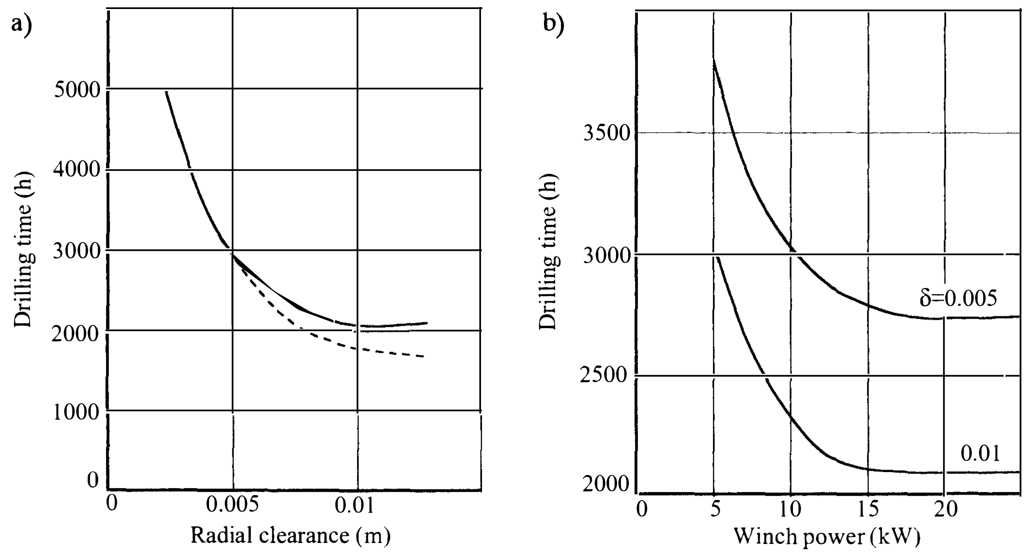

Fig. 2. Drilling-time of bore-hole versus: a: radial clearance at $\nu_m=20$ m/h (Solid line—with limitation of travel speed at $\nu_t=1$ m/s; Dashed line—without limitation of travel speed); b: winch driving motor power at $\nu_m=20$ m/h with limitation of travel speed at $\nu_t=1$ m/s.

promotes the decrease of bore-hole drilling time, despite the decrease of penetration per run (see Fig. 2). Hence, the mean travel speed is a more significant factor than penetration per run. Increase of the radial clearance to more than 10 mm increases the drilling time, in connection with the limitation of the maximum travel speed. Without this limitation beginning from $\delta = 0.0045$ m the curve is shown as a broken line. This curve has a minimum at a radial clearance of near 0.02 m, but this value has no practical significance.

The effect of winch driving motor power on the bore-hole drilling time (see Fig. 2b), is similar to the effect of the mean travel speed. Increasing of driving motor power to more than 15 kW has no practical significance because it decreases the bore-hole drilling time not more than 1%. This conclusion holds for all radial clearances, from 0.005 to 0.01 m, that are used in ice drilling.

Analytical equations for the speed of drill movement in a bore-hole filled by fluid can be used to solve problems of optimization of ice deep drilling, accounting for the features and conditions of drilling.

References

Bobin, N.E., Vasiliev, N.I., Kudryashov, B.B., Stepanov, G.K. and Talalay, P.G. (1988): Mechanical bore-hole drilling in ice. Uchebnoe posobie. L.: Izdatelstvo Leningradskiy gorni institut (Leningrad Mining Institute), 1-90 (in Russian).

Kudryashov, B.B., Vasiliev, N.I. and Talalay, P.G. (1994): KEMS-112 electromechanical ice core drill. Mem. Natl Inst. Polar Res., Spec. Issue, **49**, 138-152.

Vasiliev, N.I. and Kudryashov, B.B. (1993): Hydraulic resistance to movement of a drill suspended on a cable in a bore-hole at travel. Zapiski SPGGI (St.-P. Mining Institute). 136, St-Petersburg, S 14-20 (in Russian).

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