Journal of Glaciology, Vol. 7, No. 51, 1968

INSTRUMENTS AND METHODS

A BUOYANCY-STABILIZED HOT-POINT DRILL FOR GLACIER STUDIES

By HALDOR W. C. AAMOT

(U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, U.S.A.)

ABSTRACT. Hot-point drills are practical for producing holes in glaciers for ice-thickness and temperature measurements, as well as other glaciological studies. Buoyancy stabilization assures a vertical attitude of the drill and a plumb hole. This is achieved by designing a drill with a heavy hot point and a light upper section which is buoyant in the surrounding melt water. The buoyant force is less than the weight of the drill in air but its rectifying moment about the fulcrum (the tip) is greater than the tilting moment of the drill weight. Two methods to prevent refreezing of the melt water are proposed in order to permit drilling in cold ice and to assure continued access to the hole.

RÉSUMÉ. *Foreuse à pointe chaude stabilisée par la poussée hydrostatique pour l'étude des glaciers.* Les foreuses à pointe chaude sont pratiques pour faire dans les glaciers des trous servant à la mesure de l'épaisseur de la glace et de sa température, ainsi que pour d'autres études glaciologiques. La stabilisation par poussée hydrostatique confère au foret une position verticale et produit un trou rectiligne vertical. Le foret doit avoir en bas une pointe chaude lourde et l'extrémité supérieure assez légère pour flotter dans l'eau de fonte ambiante. La poussée hydrostatique est moindre que le poids du foret dans l'air, mais le moment redresseur par rapport à la pointe est plus grand que le moment dû au poids de l'engin. On propose deux méthodes pour empêcher l'eau de fonte de se congeler afin de permettre le forage dans la glace froide et pour garantir l'accès permanent au trou de forage.

ZUSAMMENFASSUNG. *Ein durch Auftrieb stabilisierter Bohrer mit Schmelzspitze für Gletscheruntersuchungen.* Bohrer mit Schmelzspitze eignen sich zur Herstellung von Löchern in Gletschern zur Eisdicken- und Temperaturmessung, sowie für andere glaziologische Untersuchungen. Die Auftriebsstabilisierung sichert den senkrechten Lauf des Bohrers und ein lotrechtes Bohrloch. Sie wird durch Konstruktion eines Bohrers mit schwerer Schmelzspitze und leichtem Oberteil erreicht, der einen Auftrieb im umgebenden Schmelzwasser erfährt. Die Auftriebskraft ist zwar geringer als das Gewicht des Bohrers in Luft, aber ihr Richtmoment um die Spitze ist grösser als das Kippmoment des Bohrergewichts. Um in kaltem Eis bohren und das Bohrloch immer zugänglich halten zu können, werden zwei Methoden zur Verhinderung des Wiedergefrierens von Schmelzwasser vorgeschlagen.

INTRODUCTION

The glaciologist in the field has a need for a practical drill to penetrate mountain glaciers for ice-thickness measurements and other possible uses of the hole. The principle of an electrically powered, cable-suspended hot-point drill appears as a most effective solution. LaChapelle (1963) reported on such a development. A cable-suspended drill, however, requires a means of positive attitude stabilization if a plumb hole is to be assured for depths of 100 m and greater (Philberth, 1966; Aamot, 1967[b]).

The purpose of the project reported in this paper was to develop a small practical drill capable of producing such plumb holes. The ice is considered nearly temperate so that refreezing of the melt water is not a problem during drilling.

This paper describes the drill with its buoyancy-stabilization feature as proposed by the author. Methods of drilling in cold ice are suggested. The performance of several prototypes in the field and the results obtained by Mellor and Keeler are reported. Such drills, of any desired diameter, can produce plumb holes for ice-thickness measurement and continued access for lowering instrument packages and mechanical devices.

BUOYANCY STABILIZATION

The drill is completely immersed in melt water while penetrating the ice. It has a heavy tip (the hot point), which is heated to produce melt penetration, and a light upper end (the buoyancy section), whose upward force keeps the drill erect. The drill is always heavier than water so that it rests on its tip. This contact force S (Fig. 1) is necessary for effective melt penetration. Consequently, the buoyant force B must be less than the weight of the drill in air (W). Nevertheless, the drill is positively erect and plumb when the rectifying moment (buoyant force times distance of the center of buoyancy from the tip) is greater than the tilting moment (weight of the drill times distance of the center of gravity from the tip).

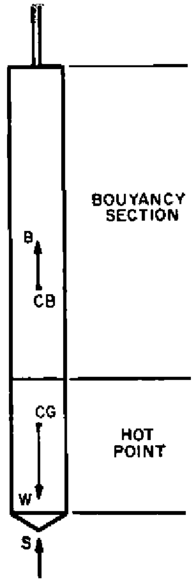

Fig. 1. The buoyancy-stabilized drill stands vertical on its tip, the hot point, when immersed in water. The center of buoyancy, CB, *is above the center of gravity,* CG. *The leverage of the buoyant force B (equal to the weight of the displaced water) keeps the drill erect. The contact force of the hot point on the ice, S, is equal to the weight of the drill in air, W, less B.*

For analysis, the drill will be considered a prismatic (cylindrical) body. The hot point is of a homogeneous heavy material such as copper. The buoyancy section is a hollow and sealed tube, e.g. of a laminated plastic. The following nomenclature is defined: l_1 is length of hot point; l_2 is length of buoyancy section; W_1 is weight of hot point before immersion; W_2 is weight of buoyancy section before immersion; ρ_1 is density of hot point; ρ_2 is density of buoyancy section; and ρ_3 is density of water or other fluid.

The required length of the buoyancy section will now be determined. For equilibrium conditions, the sum of the moments in Figure 2 is zero:

$$\frac{l_1}{2}W_1+\left(l_1+\frac{l_2}{2}\right)W_2-\left(\frac{l_1+l_2}{2}\right)B=0, \tag{1}$$

$$\left(\frac{l_2}{l_1}\right)^2\left(\frac{\rho_2-\rho_3}{2}\right)+\left(\frac{l_2}{l_1}\right)(\rho_2-\rho_3)+\left(\frac{\rho_1-\rho_3}{2}\right)=0,$$

$$\frac{l_2}{l_1}=\frac{-(\rho_2-\rho_3)\pm\{(\rho_2-\rho_3)^2-(\rho_2-\rho_3)(\rho_1-\rho_3)\}^{1/2}}{(\rho_2-\rho_3)},$$

$$\frac{l_2}{l_1}=-1+\left\{1-\left(\frac{\rho_1-\rho_3}{\rho_2-\rho_3}\right)\right\}^{1/2}. \tag{2}$$

The following values are selected for the solution of a practical example:

$$\rho_1=8.0\ \mathrm{Mg/m^3}\qquad \rho_2=0.1\ \mathrm{Mg/m^3}\qquad \rho_1=1.0\ \mathrm{Mg/m^3},$$

$$\frac{l_2}{l_1} = +1.96 \quad \text{or} \quad -3.96. \tag{3}$$

The negative value is not applicable. For positive stability, the length of the buoyancy section must be greater than 1.96 times the length of the hot point:

$$l_2 > 1.96 l_1. \tag{4}$$

The magnitude of the buoyant force at equilibrium is:

$$\frac{B}{W} = \frac{(l_1 + l_2)\,\rho_3}{l_1\,\rho_1 + l_2\,\rho_2} = 0.361. \tag{5}$$

For positive stability

$$B > 0.361\,W. \tag{6}$$

The resulting contact force with the ice is

$$S < 0.639W.$$

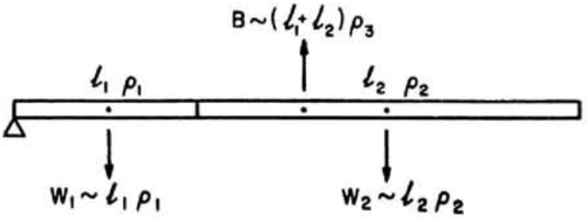

Fig. 2. When the rectifying moment of the buoyant force about the pivot point is greater than the sum of the tilting moments of the various parts, the drill assumes a vertical attitude.

It is desirable to maintain a large contact force with the ice to achieve efficient melt penetration. The designer has little control over ρ_1 and ρ_3 but ρ_2 can be kept to the smallest practical value, thus keeping l_2 and B small. The buoyancy section can be made from a sealed thin-wall tube. The hydrostatic pressure which tends to collapse the tube is not great at the ice depths encountered in mountain glaciers and thus permits a very light-weight design. The cable should be as light as possible to reduce the disturbing effect on the drill stability and to preserve the operator's feel of the cable tension.

Description of the Drill and Field-test Results

The design used for the first drills tested in Alaska is illustrated in Figure 3. The solid copper hot point has a relatively great length to achieve a large contact pressure of the tip with the ice. The cartridge heating element is heated only in the lower half. It is completely soldered into the copper with tin-lead solder for effective heat transfer. The buoyancy section consists of a tube of laminated plastic (glass cloth with epoxy resin). It is bonded and sealed against the hot point and the cap with connector with an epoxy resin adhesive. The cable connection is with a push-on connector to permit recovery at least of the cable if the drill cannot be retrieved.

For power transmission a 100 m length of RG 58 A/U coaxial cable is suitable. The resistance of the cable is about 5 Ω, the heater resistance is 50 Ω, the generator voltage is 117 V a.c. and the power requirement about 250 W. The diameter of the hot point is 2.03 cm and the drill length about 50 cm.

Messrs Malcolm Mellor and Charles M. Keeler used five drills for ice-thickness measurements in Alaska on 21 and 22 August 1967. Their work was on an east-facing tributary to Black Rapids Glacier south of Fort Greely (located about lat. 63° 25′ N., long. 146° 10′ W.). The elevation was about 1 500 m (5 000 ft). There was surface melt-water run-off on the glacier.

The first and second holes were 51 and 53 m, respectively. The third hole reached an empty cavity at a depth of 22 m; the drill made contact again with solid material at 60 m. The fourth hole was started near the third and reached a depth of 62 m. On the fifth hole the drill froze in place at 10 m after having been stopped overnight.

The pentration rate was about 5 m/h. The efficiency, based on a minimum melt-penetration power requirement $P_M = 12.1va^2(79.71+0.5T)$W, is about 61 per cent. Typical values are between 60 and 70 per cent. T is ice temperature below the freezing point (°C); a is the radius of the hot point (cm); v is the rate of penetration (cm/s); (see also Aamot, 1967[a]).

None of the drills were recovered but the cable was pulled back out of each hole. The subsurface ice temperature could not be measured in the water-filled holes but the temperatures in the "winter cold wave" a few meters below the surface were probably several degrees below the freezing point.

Fig. 3. This buoyancy-stabilized drill has a solid copper hot point with electric-resistance heating element and uses a laminated plastic tube for the buoyancy section. The diameter at the hot point is 2.03 cm, the overall length about 50 cm. The penetration rate is about 5 m/h with an input of 250 W.

DRILLING IN COLD ICE

Cold ice presents a special problem. The melt water refreezes at a rate directly proportional to the temperature difference between the original ice temperature and the freezing point. The drill itself functions equally well while penetrating fast enough but before any great depth can be reached the cable becomes anchored in the refrozen melt water which constricts and finally closes the hole beginning near the top and following the drill. Refreezing must be prevented.

The freezing point of the melt water can be lowered by adding a suitable amount of ethylene glycol. The antifreeze mixture keeps the hole open. The glycol is suitably fed through a flexible tube which follows the drill into the hole to assure uniform mixing over the length of the hole. This is the least expensive approach.

The melt water can also be removed from the hole by pumping or by displacement. Pumping is not as practical as it may seem at first because a submersible pump must be used and the flow lines must be prevented from freezing. An immiscible non-freezing liquid with a density greater than water, such as trichlorethylene, will lift the water out of the hole very effectively. The drill works efficiently under this solvent and the water rises in small droplets. Tests are still necessary to determine whether the water will rise in a deep hole without wetting and freezing to the hole walls, causing them to build up and constrict the hole gradually, or whether problems due to slushing occur. If the water freezes into ice droplets, these will then rise more reliably and their removal at the surface is relatively easy. The material cost of this approach is greater than the antifreeze method.

By preventing hole closure due to refreezing the drill can probably be recovered. In that case the cost of the antifreeze or the solvent will be offset, at least in part.

CONCLUSIONS AND APPLICATIONS

The cable-suspended hot-point drill is capable of penetrating glaciers and producing vertical holes reaching beyond the limits of hand augers to depths of 100 m and more. In temperate ice the drill can be retracted by the cable. In slightly colder ice similar depths can be reached without special measures to prevent refreezing providing the drill speed is sufficient; recovery is not possible. Very few glaciers are really temperate. Therefore, the drill is considered expendable and the design is simple to keep the price low.

In cold ice refreezing must be prevented. Access to the hole and probably even the recovery of the drill are thus assured as long as ice movement does not produce large deformations. Pipe casing, inserted into the hole, can assure access for a long time, even following significant ice movement.

The drill permits first of all an effective measure of ice thickness. A temperature measurement may be of interest immediately following. In a plain melt-water filled hole the temperature sensors must be left to freeze in place. In a hole filled with a non-freezing liquid the temperature relaxes much quicker because less heat has to be dissipated in the ice, and the cooling curve and final ice temperature are obtained sooner than if there is refreezing.

An open hole (filled with antifreeze or a solvent), especially if it is cased, permits other glaciological measurements and studies, such as ice movement with an inclinometer or acoustic and dielectric properties with instrument packages inside the glacier.

MS. received 6 February 1968

REFERENCES

Aamot, H. W. C. 1967[a]. Heat transfer and performance analysis of a thermal probe for glaciers. *U.S. Cold Regions Research and Engineering Laboratory. Technical Report* 194.

Aamot, H. W. C. 1967[b]. Instruments and methods. Pendulum steering for thermal probes in glaciers. *Journal of Glaciology*, Vol. 6, No. 48, p. 935–38.

LaChapelle, E. R. 1963. Instruments and methods. A simple thermal ice drill. *Journal of Glaciology*, Vol. 4, No. 35, p. 637–42.

Philberth, K. 1966. Sur la stabilisation de la course d'une sonde thermique. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* (Paris), Sér. B, Tom. 262, No. 6, p. 456–59.