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INSTRUMENTS AND METHODS

AN INEXPENSIVE TENSIOMETER FOR SNOW-MELT RESEARCH

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ABSTRACT. The construction and use of a rugged and easily installed tensiometer for use in snow hydrology is discussed. The tensiometer incorporates a short (380 mm) water manometer, adequate for the small range of capillary pressure in melting snow. The response of a row of tensiometers to the application of a dyed water pulse to the snow surface is compared to the resulting dye stain pattern. The lateral variation of flow in a snow-pack requires the use of many tensiometers to define the capillary pressure regime.

RÉSUMÉ. *Un tensiomètre peu coûteux pour les recherches sur la fusion de la neige.* On discute la construction et l'utilisation d'un tensiomètre simple et facile à monter pour les besoins de l'hydrologie nivale. Le tensiomètre comprend un court (380 mm) manomètre à eau, convenable pour l'étroite gamme des pressions capillaires dans la neige fondante. On a comparé la réponse d'une batterie de tensiomètres à l'injection d'une eau teintée à la surface de la neige avec le contour de la tache colorée qui en est résultée. La variation latérale de l'écoulement dans le manteau neigeux réclame l'usage de beaucoup de tensiomètres pour en définir le régime de pression capillaire.

ZUSAMMENFASSUNG. *Ein preiswerter Spannungsmesser für Schneeschmelzstudien.* Der Bau und Gebrauch eines einfachen und leicht installierbaren Spannungsmessers für die Schneehydrologie wird dargestellt. Der Spannungsmesser enthält ein kurzes (380 mm) Wassermanometer, das dem kleinen Bereich des kapillaren Druckes in schmelzendem Schnee angepasst ist. Die Reaktion einer Reihe von Spannungsmessern auf die Aufbringung eines Impulses mit gefärbtem Wasser auf die Schneeoberfläche wird mit dem entstehenden Farbfleckmuster verglichen. Die seitlichen Schwankungen des Flusses in einer Schneedecke erfordern den Einsatz vieler Spannungsmesser zur Bestimmung der Vertailung des kapillaren Druckes.

INTRODUCTION

The measurement of capillary pressure in melting snow-packs provides a new type of information to snow-melt research. Its potential in this regard was first shown by Colbeck (1976) who used an electronic transducer-type tensiometer. Wankiewicz (unpublished) employed arrays of water-manometer type tensiometers to investigate the mode of downward melt-water movement. The small scale of the tensiometer cup reveals the details of flow features in snow. The instrument can be designed to respond rapidly to unsteady flow. The construction and use of an inexpensive tensiometer which is rugged, lightweight, and easy to install in snow-packs at isolated sites is discussed below.

MEASUREMENT OF WATER PRESSURE IN SNOW

The snow-water pressure p_w can be measured relative to the ambient air pressure by means of a tensiometer.

$$p_w = P_w - P_a, \qquad (1)$$

where P_w and P_a are the absolute water and air pressures, respectively. A tensiometer is a water-filled porous cup connected to a manometer. When the tensiometer is placed in hydraulic contact with a porous medium, the gauge pressure of the water in the cup becomes equal to the pressure of the water in the porous medium once equilibrium has been established (Richards, 1965) and if the pressure of the water in the porous medium is above the bubbling pressure of the porous cup.

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The design of the tensiometer is shown in Figure 1. Figure 2 shows an array of instruments installed in the field. The rigid tube, inserted into a horizontal access hole, supports the porous cup at one end and the manometer at the other. A light-weight manometer can be used because the small range of water pressure in wet snow only requires a water manometer of short length. The design eliminates the need for a solid ground support for the manometer and facilitates the determination of the zero offset. These features are especially useful in deep, rapidly melting snow-packs.

To make the porous cups, 70 μm glass beads were closely packed in a steel mould by using a pneumatic vibrator, then heated to about 650°C in a furnace until the beads were fritted into a porous rigid block. The cylindrical cups were machined from the block of fritted glass beads. They were found to be impermeable to air for water pressures above about -10^4 N/m². The highly conductive cup greatly facilitates field installation, for the tensiometer can be filled in seconds by placing the cup into a container of water and drawing water into the system by applying suction at the air vent.

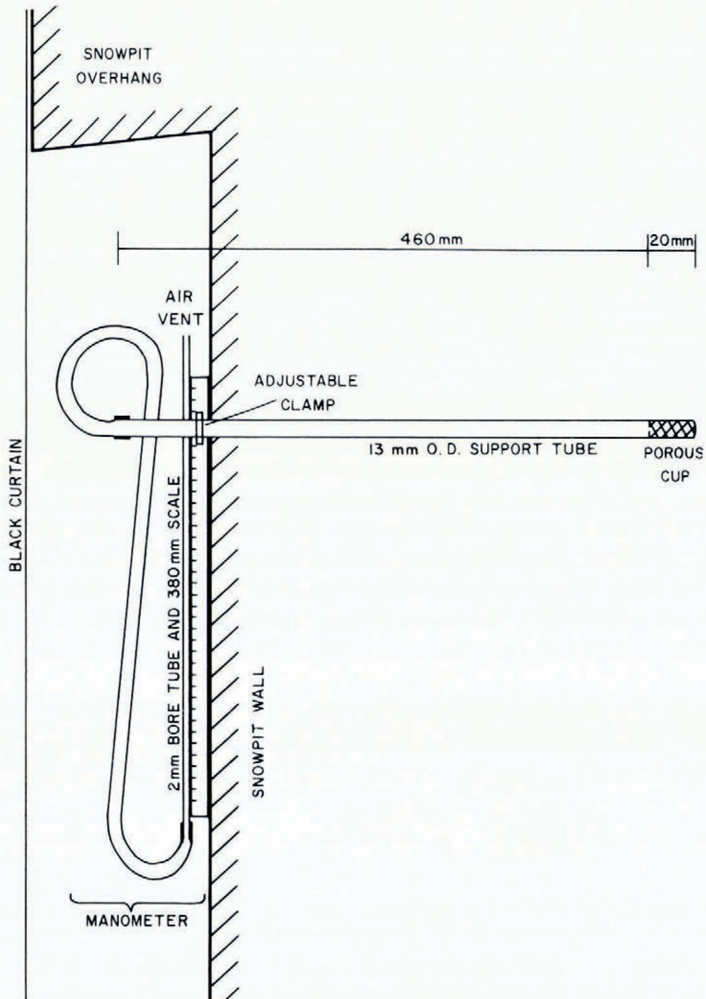

Fig. 1. Diagram of a tensiometer inserted into an access hole horizontally drilled into the snow-pit wall.

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Fig. 2. *A row of tensiometers installed in a melting snow-pack. One tensiometer in each group of five is installed about 50 mm higher than the others so that vertical pressure gradients can be measured. A metre stick is on the lower right (12 July 1974).*

The transparent connecting tubes consist of the 13 mm O.D. acrylic support tube, a flexible Tygon tube, and short air-tight rubber connections. The manometer hangs from the support tube by means of a clamp. The water manometer is a glass capillary tube, wired to a scale. The large (2 ± 0.25 mm) bore of the capillary tube facilitates removal of air bubbles by means of a thin wire. This bore produces a capillary rise of (15 ± 2 mm) in the capillary tube, so 15 mm was subtracted from the manometer readings. The tensiometers were installed into horizontally drilled access holes in the snow-pit wall. The wall was covered with polystyrene boards to reduce nocturnal radiation from the manometers and exposed connecting tubes.

The use of a water manometer limits the response of the instrument to changes in snow-water pressure because of the time required for the manometer water to enter or leave the porous cup. The cup response time t_T has been defined to be $1/KQ$ (Richards, 1949), where K is the cup conductance, and Q is the gauge sensitivity. The gauge sensitivity is the pressure change (expressed as a head of water) per unit volume of water transferred to or from the tensiometer. For the manometer that was used in the present study, the gauge sensitivity was 0.318 mm change in manometer reading per cubic millimetre of water transferred across the tensiometer cup. It was measured by immersing the porous cup in a container of water and timing the approach of the manometer reading h_c to its equilibrium value h_I; according to Klute and Gardner (1962):

$$\frac{h_c - h_I}{h_0 - h_I} = \exp(-t/t_T), \tag{2}$$

where h_0 is the initial manometer reading. The tensiometers have cup response times in water ranging from 1.3 to 12 s with a median value of 3.0 s.

The response time of a tensiometer to step changes in capillary pressure within a porous medium depends on whether the exchange of water between the porous medium and the cup is limited by the conductance of the cup, as above, or by that of the medium (Klute and Gardner, 1962). The effect of the cup, given by Equation (2), with a 3 s response time would result in the tensiometer requiring 3.6 s to record 70% of a step change in capillary pressure. When the conductivity of the porous medium limits the transfer of water, the response for long cylindrical cups with an initial cup pressure h_0 suddenly inserted into a porous medium with capillary pressure h_1 is given approximately by (Klute and Gardner, 1962)

$$\frac{h_c - h_1}{h_0 - h_1} \approx \frac{1}{4\pi KQLt} \qquad \text{for } \frac{h_c - h_1}{h_0 - h_1} < 0.3, \tag{3}$$

in which K is the hydraulic conductivity of the medium (assumed constant during the test) and L is the length of the cup. Equation (3) is taken as a crude approximation for the response time for the stubby cups described in this report. For $L = 20$ mm, 70% recovery will take place in the same time (3.6 s) given by Equation (2) as long as K is 12×10^{-6} m s^{-1}. For gravity drainage in a steadily melting snow-pack, K is equal to the melt rate. Hence at normal melt rates, the response time would be limited by the snow conductance (Equation (3)). For a higher percentage of recovery, the effect of flux on the recovery time is even more important because of the more slowly varying time function in Equation (3) compared with that in Equation (2). The times required for 70% response are listed in Table I for different values of K.

TABLE I. TENSIOMETER TIME LAG FOR 70% RESPONSE TO A STEP CHANGE

Snow hydraulic conductivity m s^{-1}	*Cup response in water by Equation (2) and experiment* s	*Estimate of snow response from Equation (3)* s
10×10^{-6}	3.6	4.2
1×10^{-6}	3.6	42
100×10^{-9}	3.6	420
10×10^{-9}	3.6	4 200
1×10^{-9}	3.6	42 000

FIELD ERRORS IN TENSIOMETER MEASUREMENTS

The snow-water pressure p_w is given by the equation:

$$p_w = \rho_w g(h_M - h_R + h_z), \tag{4}$$

where h_M is the manometer reading, h_R is the capillary rise for the bore of the capillary tubing used in the manometer (in the present case $h_R = 15$ mm $= 0.015$ m), h_z is a zero offset, ρ_w is the density of water (1 000 kg/m^3), and g is the acceleration due to gravity (9.8 m/s^2). In this equation, if the values of h_M, h_R, and h_z are in millimetres, a factor of 10^{-3} appears on the right-hand side to give p_w in newtons per square metre.

The zero offset is the height of the manometer scale zero above the cylindrical axis of the cup. A zero offset is introduced to the extent that the tensiometer access hole is not drilled horizontally. The error can be systematic if caused by deflection of the drill by sloping ice sheets; on the other hand, random errors resulting from lack of precision in levelling the drill during boring of the access hole will produce statistically a mean h_z of zero. The standard deviation of h_z for tensiometer installation during the writers' experiments in ripe snow was measured to be $\sigma = \pm 8$ mm.

When the flow rate in the snow-pack was steady, the manometer readings were steady to within the error in the manometer scale (± 1 mm). Progressive melt-back of the snow-pit wall can result in bending of the exposed portion of the support tube under the weight of the manometer while the rest of the tube is held firmly in the snow. Periodic measurement of this "droop" allowed corrections to this time-varying contribution to h_z to within an error of $\sigma = \pm 2$ mm.

PRESSURE RESPONSE TO DYED WATER INPUTS

The use of tensiometers in studying the downward melt-water flow in snow is demonstrated in an experiment conducted on 12 July 1974. A row of 25 tensiometers was installed in groups of 5 in a melting snow-pack of density 580 kg/m³ at a site 1 200 m a.s.l. on Mt Seymour in the Coast Mountains of British Columbia. For demonstration purposes the snow surface was irrigated at many times the normal melt rate. Rhodamine WT was diluted to a concentration of about 1.5×10^{-5} parts by weight and sprinkled over an area of about $1\text{ m}\times3\text{ m}$ of the snow surface directly above the tensiometer array, at a rate of $20\times10^{-6}\text{ m s}^{-1}$ for about 300 s. Since all but one of the 25 tensiometers responded to the irrigation, it can be concluded that dye penetrated to almost all parts of the instrumented layer. The response of the tensiometers in the third and fourth groups (from the left in Figure 2) is shown in Figure 3. The pressures shown are not corrected for any static zero error which probably

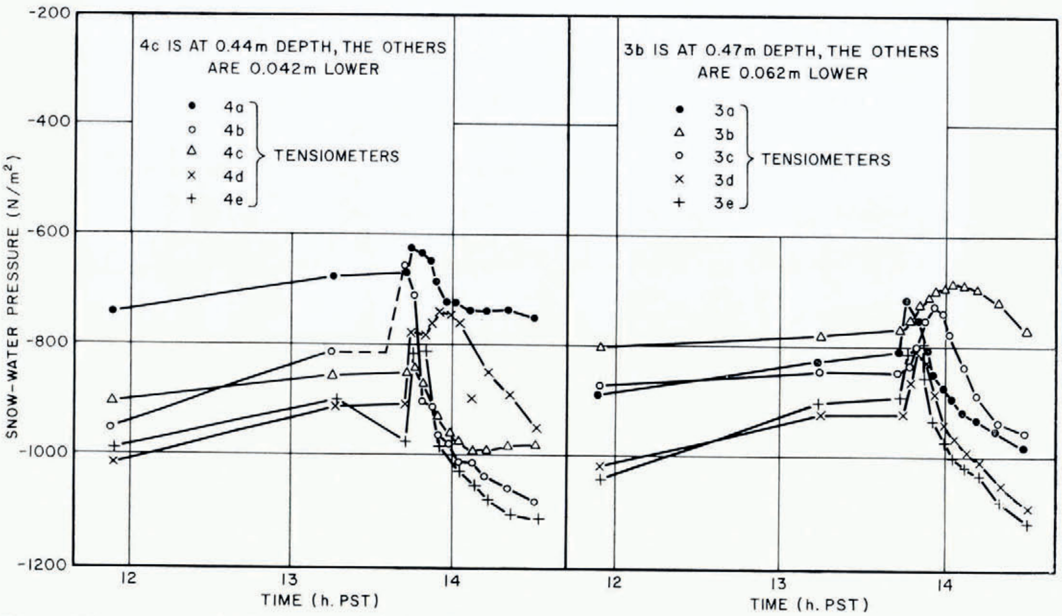

Fig. 3. Water-pressure changes in snow following the application of dyed water to the snow surface between 13.36 h and 13.41 h on 12 July 1974. These values are for the third and fourth groups of tensiometers from the left of Figure 2.

explains part of the scatter in the absolute values among cups placed at the same level. Note that the range in arrival times for the wetting fronts and the range in the drainage wave shapes are real since the zero error is constant with time. A fingering-type flow passed through the instrumented layer.

Also note that while the flux in the snow following drainage of the applied water would be expected to return to the original natural melt value, the snow water pressures are much lower afterwards. This would be explained by hysteresis in the hydraulic conductivity–capillary pressure relation for snow, in common with other types of porous media. These details of water flow would not be revealed by melt pans which produce only an integrated response in both space and time.

After drainage of the applied pulse, a section of the snow was cut open to reveal the stain pattern produced by dyed water retained by the snow. Detailed comparison of each tensiometer's pressure curve and the dye patterns at that location is inconclusive, possibly because of the difficulty of localizing the cut section to better than a few centimetres of the vertical plan through the tensiometer cups. A fingering dye pattern characterizes the right three-quarters of the photograph (Fig. 4).

Fig. 4. Dye-stain pattern in a cut section at 15.00 h 12 July 1974. The tensiometers had been removed and the cup locations tagged with beans prior to exposing the section. Compare with Figure 3.

The general absence of "blurring" of the dye fingers in the photograph, taken over an hour after the pulse passed the tensiometer level, suggests that the dye has stained real structures with a larger permanent liquid-water content than that of the bulk of the snow-pack. In fact, cohesive yet permeable "glands" of icy appearance up to 10 mm in diameter were found in the same snow layer, 3.5 m away. The presence of a network of highly conducting glands could explain the fingering type of flow observed with the tensiometers.

The experiment was repeated on 30 July 1974 at another level in the snow-pack. The pressure curves in Figure 5 show the response of the middle two groups of tensiometers to the 8 min application of dyed water at a rate of 20×10^{-6} m s^{-1} to the snow surface. This time the tensiometers in each group responded similarly in respect to arrival times and drainage wave shapes although differences remained between the different groups. The similar response among tensiometers in each group indicates the absence of fingering-type flow at this level. The resultant dye-stain pattern shown in Figure 6 suggests concentrations of the flow into zones about 500 mm across within which the flow is uniform and vertically directed. This concentration is thought to be produced by the ice sheets at the top of the section.

Summary

The use of a tensiometer in a snow-pack requires special attention to the following four points: First, the tensiometer must be used only in a wet snow-pack and care must be taken to prevent freezing of the exposed manometer. Secondly, the height of the porous cup relative to the manometer scale zero (the zero offset) should be accurately known, a task made more difficult by melting of the snow surface and snow-pit walls. Third, the lateral variation in flow

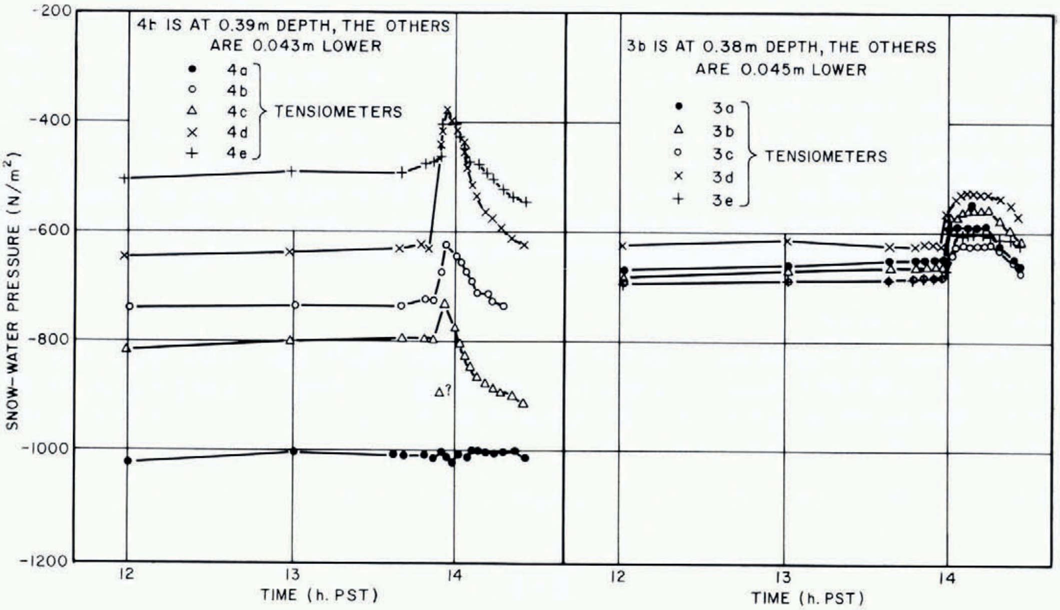

Fig. 5. Water-pressure changes in snow following the application of dyed water to the snow surface between 13.47 h and 13.55 h on 30 July 1974. The values are for the centre groups of tensiometers located by holes in Figure 6.

Fig. 6. Dye-stain pattern in a cut section at 15.00 h 30 July 1974. A metre stick is on the left. The lysimeters located below the line of tensiometer holes were used to measure flux.

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requires the use of many tensiometers if the mean snow-water pressure of a layer is required. Finally, short-wave radiation penetrating the snow from the access snow-pit must be minimized so as to produce an insignificant change in snow properties in the vicinity of the porous cup.

Tensiometers can be used in the field to reveal the flow pattern and the water-pressure response of snow to inputs of water at the surface. The instruments are light in weight and can be installed within minutes into a snow-pit wall. Snow-melt events can be monitored by their pressure effects. Large numbers of these inexpensive instruments can be deployed to investigate the effects of vegetation cover, topography, and ice sheets on melt rate and run-off. Tensiometers could be used to determine the extent of fingering-type flow at normal melt rates within snow-packs and their effect on melt-wave travel times. An interesting research need is to define the relation between snow water pressure and snow-melt rate.

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