OBSERVATIONS AND SIGNIFICANCE OF INTERNAL PRESSURES IN FREEZING SOIL

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Abstract

The development of positive internal pressures accompanying soil freezing has been observed in experiments at laboratory and field scales. The measurements are explained in terms of the pressure developed as ice grows in the soil. Prior to freezing, the measured pressure is simply indicative of the weight of the overburden, but as the freezing front advances through the soil a characteristic evolution of pressure is observed. With the passage of the freezing front there is an abrupt rise in pressure to a peak value, after which it tends to gradually fall away. This pattern appears to be temperature-related. An explanation is proposed based upon thermodynamic and soil mechanical considerations.

Résumé

Des expériences sur le gel des sols réalisées à l'échelle du laboratoire et du terrain ont permis d'observer le développement de pressions internes positives. Les données sont interprétées en fonction de la croissance des lentilles de glace. Avant le passage du front de gel, la pression enregistrée correspond simplement au poids de la surcharge mais au fur et à mesure que le front de gel progresse dans le sol, on note une évolution caractéristique des pressions internes. Avec le passage du front du gel, la pression s'accroît subitement pour atteindre un sommet, elle tend ensuite à diminuer graduellement vers sa valeur initiale. Ce comportement est expliqué selon les points de vue de la thermodynamique et de la mécanique des sols.

Introduction

When ice forms in freezing soil, there is an increase in volume and/or pressure, the particular manifestation depending on the confining stresses on the soil. Although there have been numerous studies of frost heaving, most research has focused on the volume expansion associated with ice segregation and relatively few studies have measured the pressures developed. Furthermore, these studies have been mostly concerned with determining the so-called heaving pressure - i.e. "the pressure developed when a soil, frozen unidirectionally, is restrained (sic) from heaving" (Hoekstra et al. 1965). Such measurements are usually made with a load cell, mounted external to the soil against a reaction frame. Only a very few papers have reported the *internal* pressures developed within frozen soil (e.g. Tsytovich 1975 (p.142), Mackay 1980, Williams and Wood 1985, the latter at a small laboratory scale).

Edlefsen and Anderson (1943) were the first to outline, from a thermodynamic perspective, the ways in which changes in pressure arise from the freezing of water in soil. For example, if a soil were completely restrained from expanding (i.e. heaving), then the pressure on the ice (and water) would increase by 1 atmosphere per 0.007°C below zero. Such a dramatic result is not generally of practical concern, however, since under the natural conditions close to the earth's surface, some expansion of the soil is always possible. Where the confining stresses are small — as in the case of a thin layer of overburden — then the soil is able to expand easily, resulting typically, in the case of fine-grained frozen soil, in a highly segregated structure with discrete layers or lenses of ice. In this classic case, it is generally assumed that the pressure in the ice is simply that sufficient to displace the overlying load of the soil.

Assumptions concerning ice and water pressures in freezing soil are an integral part of physically-based frost heave models, serving to prescribe the flows of moisture that lead to ice accumulation. The present paper reports on observations of pressures which develop within freezing soil, made at both laboratory and field scales. The interpretation of the results which is proposed challenges conventional views of the state of pressure in freezing soils and the assumptions involved in frost heave models. The significance of the results in terms of soil freezing and frost heaving is discussed.

Ice and water pressures

Water in frozen soil is subject to several forces that lower its potential (pore pressure), creating a suction relative to bulk water. The matric potential, created by the capillary and adsorptive forces of the soil matrix, is the major component of soil water potential in frozen soil, and, regardless of the soil type, the water alongside the ice has a matric potential (P_i-P_w) that is proportional to the temperature depression below 0 °C. The relationship is described by the Clausius-Clapeyron equation:

$$(P_i - P_w) = -(T - T_o) L V_i / V_w T_o \qquad (1)$$

where T is the temperature (K), T_o the freezing point of pure free water (273.16K), L is the latent heat of fusion and V_i and V_w are the specific volumes of ice and water respectively. Equation (1) implies that a temperature gradient in frozen soil will cause a gradient of water pressure, although as Williams (1988) has pointed out, the equation can also be satisfied by a gradient in the ice pressure (in the opposite direction).

Edlefsen and Anderson (1943, p.119) discuss two cases of interest in the application of equation (1) to freezing soils. These are:

i) The pressure on the ice remains constant while the pressure on the water falls by approximately 1 atmosphere per 0.1 °C below zero.
ii) The pressure on the water remains constant, while the pressure on the ice rises by approximately 1 atmosphere per 0.1 °C below zero.

Harlan (1973), for example, assumed that the ice pressure is everywhere constant in the soil, so that equation (1) could be used to relate P_w directly to the temperature (with due allowance for the effects of overburden pressure). According to Miller (1978), P_i will rise as ice grows in the soil, but only as much as needed to overcome the weight of overburden. Miller's model applies to cohesionless soils; in *cohesive* soils, P_i would need to be higher, since it must be sufficient to overcome the soil cohesion as well as the load. The presence of ice in soil imparts cohesion, so that this effect cannot be ignored in the soil freezing process. Gilpin (1982) refers to a pressure in the ice necessary to separate soil particles, and observations by Williams and Wood (1985) indicate that the ice pressure in freezing soil may be considerable.

Thus it is likely that neither of the two cases discussed above will apply strictly in nature. Usually, some part of the difference $(P_i - P_w)$ will be due to an increase in the ice pressure, as must be the case when frost heave occurs and overburden or some other resistance is overcome. Where the confining stresses on the soil are sufficient to resist expansion, then (very) large ice pressures arise (e.g. Hoekstra 1969). Recent observations on the nature of frost heaving suggest that some internal resistance will also always be present.

Continuing frost heave: rheological implications

For many years it was tacitly assumed that frost heaving involved only the formation of ice lenses at the boundary between the frozen and unfrozen soil. However, as Williams (1988) has pointed out, if the water phase is continuous right into the frozen ground (as is now generally acknowledged), then it is probable that some formation of ice lenses occurs within the frozen ground. Observations reported recently by Smith and Patterson (1989) imply that a considerable thickness of soil may be affected by moisture movement and ice accumulation during frost heaving and that vertical displacement of the soil involves *continuing* internal deformation of the frozen soil itself. Other authors (e.g. Penner and Goodrich, 1980; Yoneyama et al., 1983; Ohrai and Yamamoto, 1985) have reported on apparently similar observations. Gilpin (1980) implied that such heaving may be important over long periods of time.

The growth of ice bodies/lenses within frozen soil requires that the expansive work of frost heaving must take place against the resistance offered by the surrounding semi-rigid soil. This will involve deformation (creep) of the frozen soil, providing the pressures are high enough, the rate depending on the pressure the ice exerts and the creep properties of the soil, which are temperature dependent. Thus, while the ice pressure depends on the thermodynamic conditions (temperature and water pressure), in accordance with equation (1), the tendency for the pressure to approach thermodynamic equilibrium is influenced by the mechanical (creep) behaviour of the soil (see Wood 1986). Thus the ice pressure, and hence the water pressure (from equation 1), will depend on the interplay of thermodynamic and rheological factors.

Experimental methods

The development of internal pressures accompanying soil freezing was monitored using oil-filled (hydraulic) transducers (fig. 1). The sensor consists of a pneumatic piezometer, modified to measure total pressure by enclosing the end with a rubber bulb (about 3 cm3) which is clamped in place after being filled with silicon oil. Care is taken to avoid entrapment of air in the system. The sensor, which is about the size of a half-finger, incorporates a diaphragm by-pass valve and measurement is made by balancing the pressure acting on the diaphragm. The transducers were calibrated individually in a pressurized air chamber. No temperature dependence was found in the calibration.

The stress in any material cannot be measured directly but must be determined by measuring the strain of an (elastic) inclusion embedded in the medium. Cox and Johnson (1983) discuss the considerations involved in

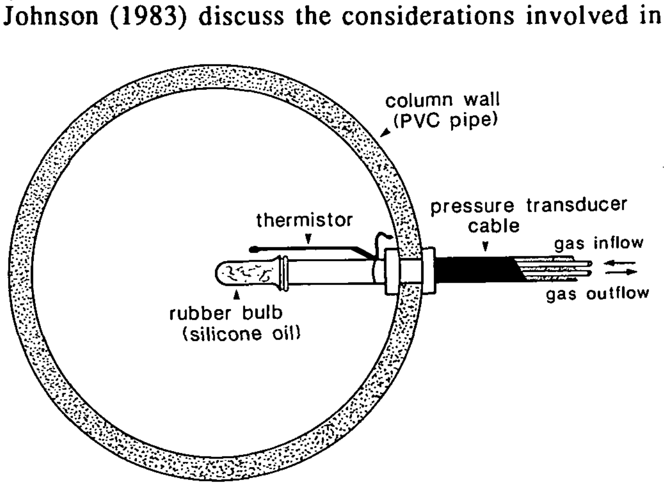

Figure 1. Top view of soil column assembly.

measuring internal stresses; in particular, if the elastic modulus of the sensor is different from that of the enclosing medium, the sensor will change the local stress field. The transducer design employed in the present experiments follows a similar principle to that used by Williams and Wood (1985), who argue (p. 414) that their device is activated by the growth of ice adjacent to it and hence that it indicates the ice pressure.

Laboratory experiment

Six pressure transducers were spaced in a profile throughout a soil column, 20 cm in diameter and 90 cm high, containing Manchester (New Hampshire) silt, a soil well known to be susceptible to heave. The oil-filled rubber bulb was mounted on a rigid plastic cylinder which protruded into the middle of the column (fig. 2); a thermistor was attached to each. These were placed at 15, 25, 35, 45, 55, and 65 cm depth, as the column was being filled. Thermistors were also placed at the base of the silt and on the top surface, in contact with a metal cooling plate. The soil was compacted manually in 6 cm layers; for compaction, the soil material was first prepared to a water content of about 5% by mass. After compacting a layer, the surface was raked before further material was added.

The column was insulated to minimize radial heat flow, and placed inside a controlled temperature chamber at 1 °C. The soil was provided with free access to de-ionized water, via a reservoir connected to a burette (fig. 2), with a constant head equal to the height of the column. The column was left for one week in order to reach saturation and thermal equilibrium.

Uni-directional freezing was imposed from the top surface by circulating glycol from a controlled temperature bath through a cooling plate. The silt surface temperature was gradually stepped down to -7.5 °C over the first 150 hours and the experiment was continued for a further 450 hours. Water intake during freezing was measured from the burette and surface heave was measured by means of a dial gauge.

Field scale experiment

The development of internal soil pressures has also been monitored as part of a field-scale experiment conducted at a controlled environment facility in Caen, France. This experiment comprises a study of ground freezing around a refrigerated pipeline which traverses two soils; one of the soils (Caen silt) is prone to frost heave. The soil pit is 8 m wide by 18 m long, and can be filled to a depth of about 2 m.

Pressure transducers of the same design were installed in a vertical profile beneath the pipe, at 80, 100, 120 and 140–cm depths below the surface, and at three locations along the pipe (fig. 3). Results from the two silt sites are discussed here. Further details of the experiment may be found in Smith et al. (1985), Geotechnical Science Laboratories (1986, 1988).

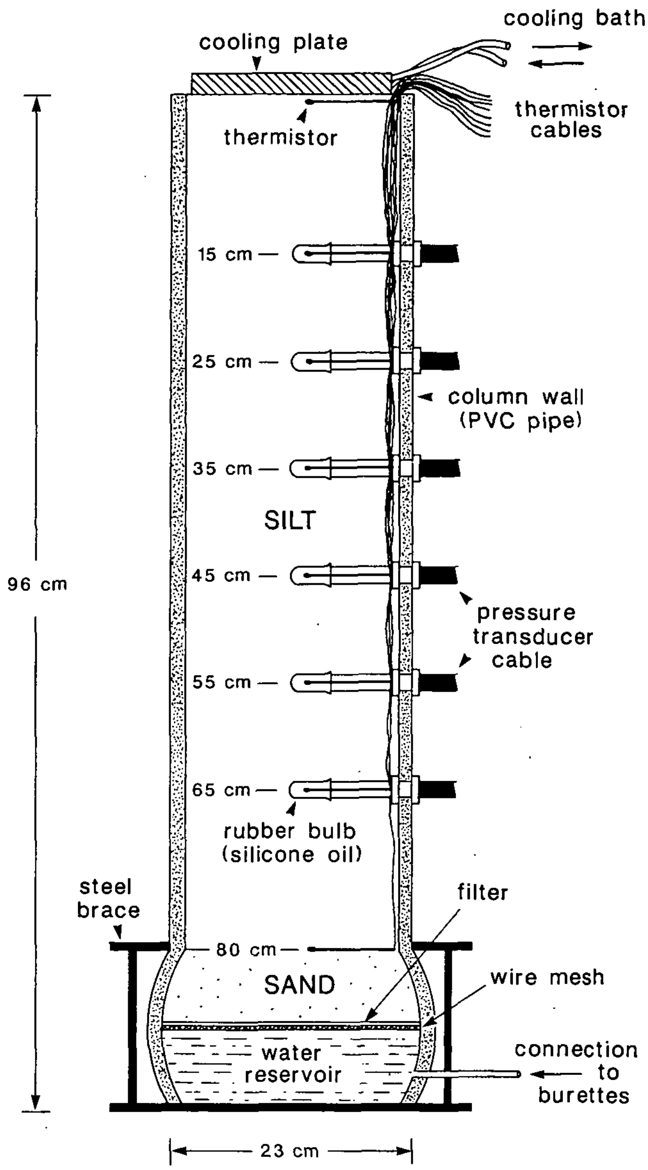

Figure 2. Schematic diagram of soil column experiment.

Results

Pressure values, in all cases, are given as the change since time zero, to remove the effects of overburden, and residual pressures which may arise during sensor assembly. These initial values varied between 5 and 9 kPa. In all cases, the depth mentioned refers to the initial placement of the sensor.

Figure 4 shows the evolution of pressure and temperature in the laboratory soil column; since the freezing front did not reach the first pressure transducer until about 240 hours into the experiment, readings prior to 150 hours have been omitted. The Figure shows that at each depth, in turn, the pressure shows a slight rise with the approach of the freezing front, an abrupt rise with the passage of the front, and a gradual fall as cooling of the soil progresses. In each case, the abrupt rise coincides with the passage of the freezing isotherm (fig. 4).

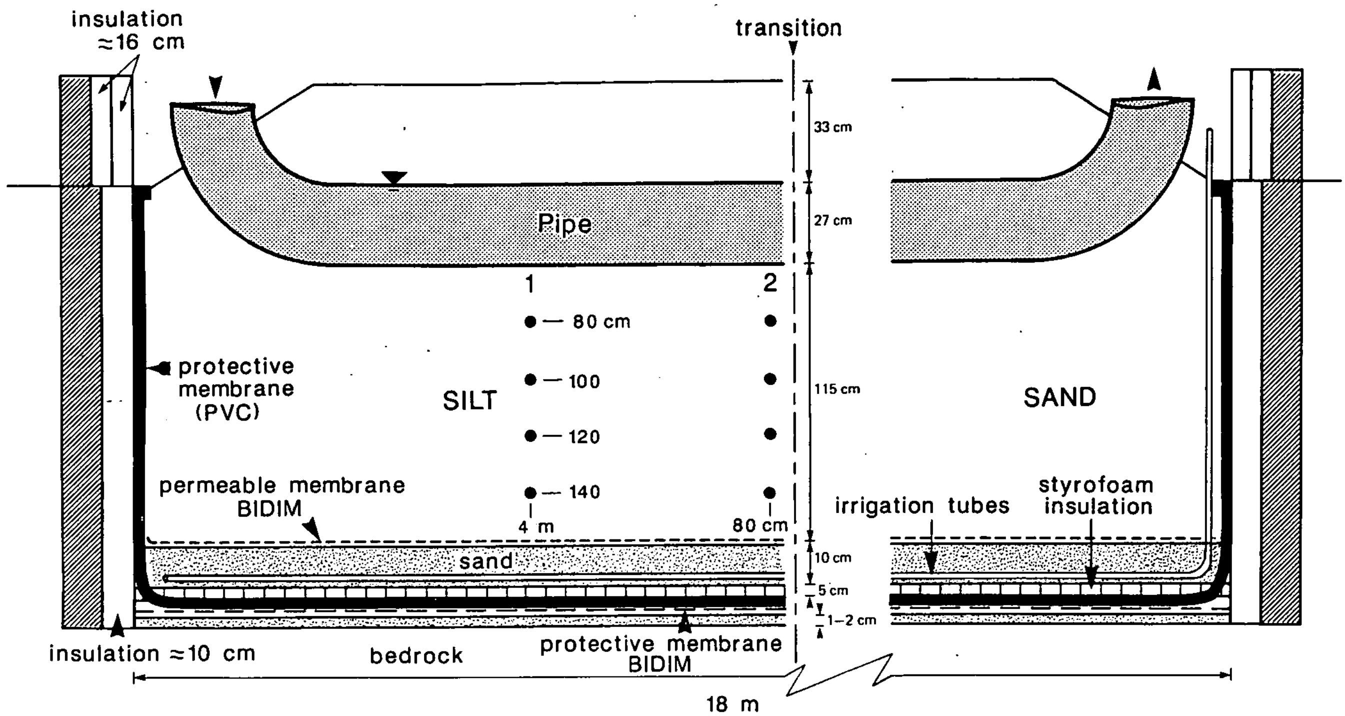

Figure 3. Longitudinal cross-section of the Caen experiment.

It is presumed that the initial rise in pressure, prior to the passage of the freezing front, represents a reaction stress in response to the growth of ice in the adjacent freezing soil above. The vertical displacement of the soil associated with this is resisted by friction between the soil and the sidewall of the column; the pressures measured at this stage suggest a frictional stress of about 40 to 50 kPa (fig. 4).

With the passage of the freezing front past the transducer, the pressure rises more rapidly. While the transducer measures a total stress (i.e. the weight of the soil plus the pressure of the pore contents), the only possible explanation for an increase in pressure is the growth of ice in the soil (refer to equation 1). Therefore, the pressure measured must give some indication of the ice pressure locally within the soil. With this assumption in mind, the rise in pressure which is observed can be explained by the effect of decreasing temperature on the ice pressure, as the frost line advances beyond the transducer (see equation 1).

However, as stated previously, thermodynamic conditions are not the sole determinant of the ice pressure in the soil. For, as internal pressure develops, the soil matrix becomes stressed and deformation (in the form of creep, most likely) is induced. As stress relaxation occurs in the soil, ice pressure will decrease; this causes a disequilibrium in the thermodynamic conditions, and, as a result, some water will tend to freeze causing a rise in the ice pressure and further stress in the soil. This interactive process will continue, contingent upon a supply of water into the frozen soil via liquid films, and the necessary flow of heat. However, as the soil continues to cool, the hydraulic conductivity decreases and water migration (i.e. ice accumulation) will decline to a rate insufficient to offset the relaxation of stresses due to creep. Thus, after reaching a peak, the pressure gradually falls away.

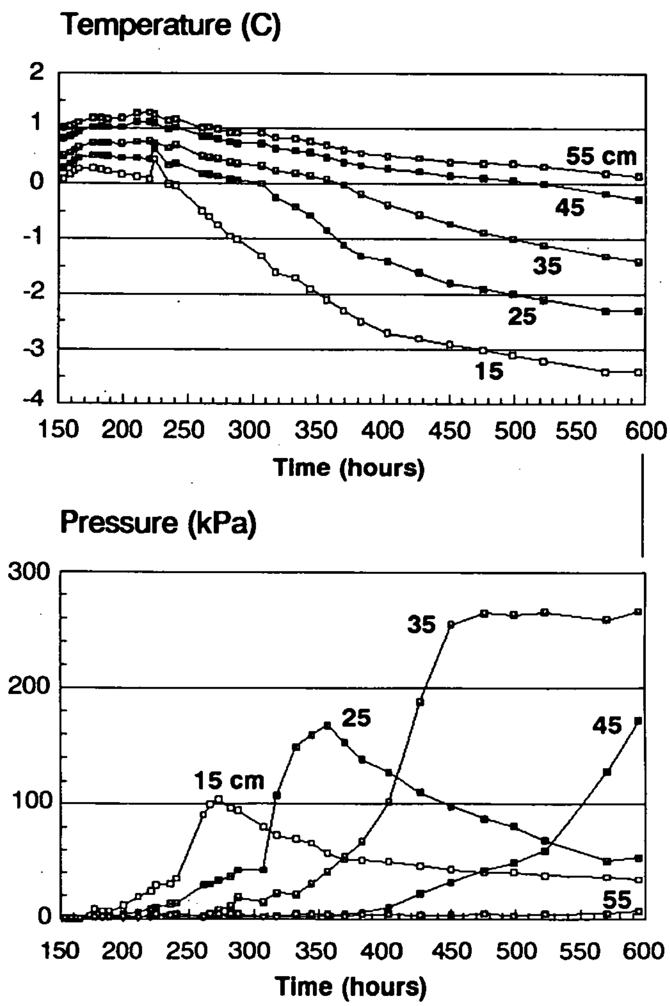

Figure 4. Temperature and pressure data, soil column experiment.

The pattern of pressure decrease depicted in Figure 4 resembles a typical relaxation phenomenon, as implied by the above discussion. If, on the contrary, some kind of stick-and-slip process were involved along the column wall, the pressure pattern should exhibit abrupt changes (singularities), which it does not. Also, the surface heave record should show similar abrupt changes, which it does not (fig. 5). In fact, the slight increase in heave rate at about 350 hours coincides with an increase of pressure at 25 cm depth. Nevertheless, future experiments should investigate the nature of shear at the column wall and the effects of the boundary on the stress field in the centre of the column.

In the case of the 35-cm depth, however, the pressure does not decay with time but levels off. This seems to imply that the processes of stress generation and stress relaxation maintain a balance. This could be achieved by the continued growth of even very small quantities of ice adjacent to the transducer. This further implies, however, that sufficient water is able to migrate through the frozen soil to this level, even though the temperature fell to -1.4 °C by the end of the experiment.

The peak pressure that is reached depends on the balance between the hydrologic and thermal properties of the soil (i.e. the flow of water and heat) and the rheological properties of the soil which control stress relaxation. According to the results of Zhu and Carbee (1987, pp.22-31), the creep resistance of frozen silt in the temperature range 0 to -0.5 °C is likely less than about 250 kPa, for the duration of stress involved in the present experiment. Thus the creep properties of the soil apparently place a more immediate control on the ice pressure than the thermodynamic conditions. For each transducer, the maximum pressure reached corresponds to a temperature of about -0.6 °C to -0.8 °C.

Another feature of Figure 4 is an increase in the peak pressure with depth. This could be explained by the fact that as the average temperature of the frozen part of the soil column falls with time, its overall creep resistance increases, and higher ice pressures may be sustained. Additionally, it may be that the rigid plastic mount for the bulbs acts to reinforce the soil somewhat, and that as more of them become frozen in, the resistance to vertical displacement is increased above that of sidewall friction alone. In a future experiment, "free floating" transducers will be used.

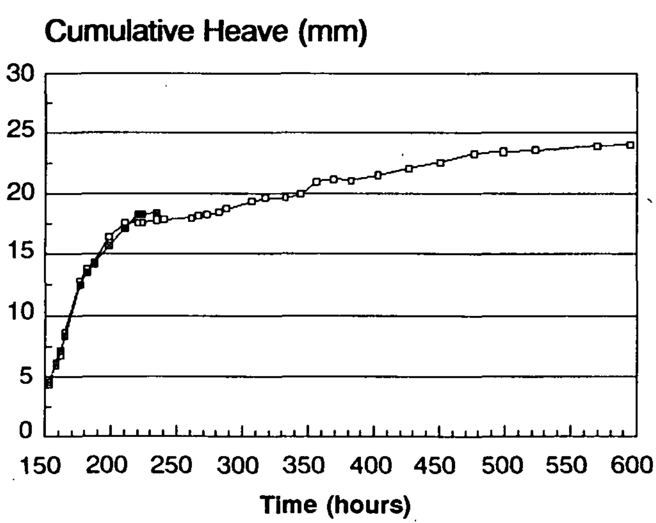

Figure 5. Cumulative heave, soil column experiment (note that heave values after 250 hours are based on calculation using water inflow measurements, since the dial gauge malfunctioned after that time; both sets of data are shown up to 250 hours.).

The results from the large-scale experiment in Caen (figs. 6 and 7) are similar in some ways to those above, although in no case does the pressure seem to relax after the peak is reached. Thermistor data from adjacent locations are also shown in the figures. However, it should be noted that the thermistor strings are progressively moved up with the soil as it heaves, while the pressure devices are not (at least until they are frozen in). Thus there is no exact correspondence between the temperature data and the pressure data, with the discrepancy increasing with the depth. At the end of the experiment, the total heave at site 1 was about 20 cm and at site 2, 13 cm. Thus the thermistor labelled "120" in figure 6 would actually have been about 20 cm above the pressure transducer "120" by the end of the experiment; at site 2, the difference was 13 cm.

Once again it is seen that as the freezing front approaches the pressure rises, with the increase becoming

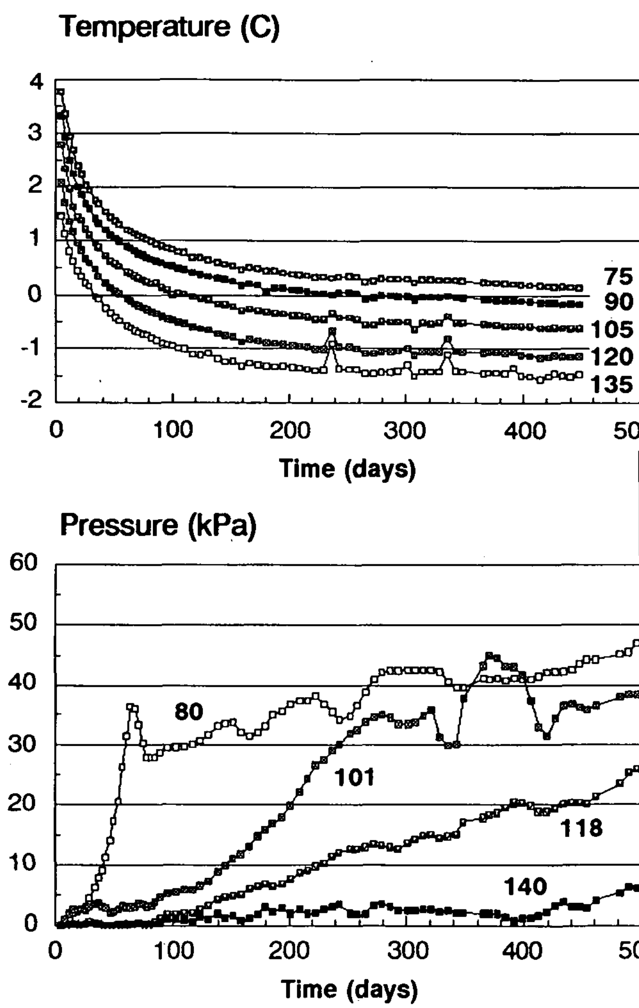

Figure 6. Temperature and pressure data, Site 1, Caen experiment.

more abrupt as the freezing front passes through. An apparent exception to this, at both the 120-cm depths can be explained as follows. At site 1, where the rise is more-or-less steady with no abrupt change, the freezing front never actually reaches the "120" pressure transducer; its temperature is closer to that of the "135" thermistor, or slightly warmer. At site 2, on the other hand, there is an abrupt rise in pressure at around 310 days; again, this is consistent with the fact that the temperature there would lie somewhere between the "120" and "135" thermistors.

Compared to the laboratory experiment, the following differences may be noted:

- A distinct peak, as in the case of figure 4, is not readily apparent, but rather the pressures tend to level off, with little indication of relaxation.
- The variations are somewhat more irregular, although this may be due in some part to vagaries in the measurement system employed.
- The values are lower overall, but with values at site 2 being higher than site 1. At the latter, the pipe (and hence soil) are largely unrestrained from heaving, whereas towards the transition zone, the uplift resistance becomes greater.

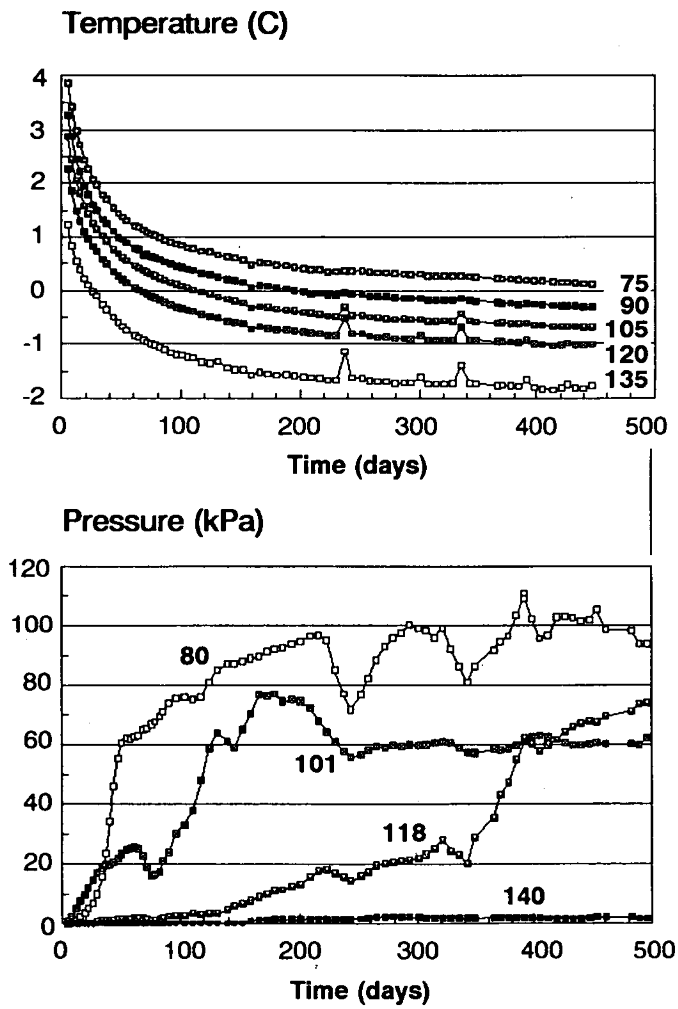

Figure 7. Temperature and pressure data, Site 2, Caen experiment.

The lower overall values, compared to the soil column experiment, may be due to the difference in soil type. Although both are silts, the Caen silt has a significantly higher natural salinity, with higher unfrozen water contents. This lowers the creep resistance at any temperature and may explain the lower measured pressures. Additionally, the higher unfrozen water contents lead to higher hydraulic conductivities, which might explain the maintenance of pressures with time, as determined by continued water migration (see above).

Concluding remarks

This paper has reported on measurements of the internal pressures that arise during soil freezing, observed in both laboratory and field-scale experiments. While there are some differences between the two sets of data, there are also clear similarities. It is acknowledged that the experimental data are rather limited, and that, consequently, the explanations offered are still speculative.

The experimental results are interpreted in a thermodynamic-rheological context (see Wood 1986), in which the ice pressure is regarded as both a partial pressure of the water in the ice phase (a thermodynamic perspective) and as an internal stress acting to deform the soil (a rheological perspective). Consequently, the ice (and water) pressures are modified by the rheological properties of the soil. The variations which arise in P_i, under the influence of these factors, act to determine the pattern of P_w throughout the soil, the migration of water into the freezing soil and ultimately the rate of heaving. Thus, the frost heave process depends on a complex interaction of thermodynamic conditions and the rheological behaviour of the soil. This perspective introduces additional complications into modelling the frost heave process. Little work has been done yet to unify these views in a single model, although the reader is referred to Shen and Ladanyi (1987) and Lundin (1989).

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