ICE LENS ORIENTATION AROUND A CHILLED BURIED PIPE

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Abstract

Ice lens orientation was observed around a chilled buried pipe in a temperature-controlled facility. A comparison of the ice lens pattern to the isotherm pattern, in a section perpendicular to the pipe axis indicated that while the chilled pipe influences the ice lens orientation near the pipe, it is not the only factor controlling the ice lens pattern. Variations in soil density and the mechanical properties of the frozen soil also influence the ice lens pattern.

It appears that the heave consists of vertical and lateral components and that the displacement of the pipe is a result of the pipe being squeezed as well as being lifted by vertical heave generated directly below the pipe.

Résumé

On a observé l'orientation des lentilles de glace formées autour d'un conduit enterré et refroidi. L'arrangement des lentilles de glace le long d'un transect perpendiculaire au conduit est comparé aux isothermes. Il est montré que le conduit réfrigéré exerce un contrôle partiel sur l'orientation des lentilles de glace. Les variations de densité du sol et les propriétés mécaniques du sol gelé influencent aussi l'arrangement des lentilles de glace.

Il apparaît que le soulèvement gélival observé se compose de déplacements verticaux et horizontaux et que la distortion du conduit résulte de mouvements de compression latérale aussi bien que de soulèvement vertical directement sous le conduit.

Background

The Canada-France Pipeline-Ground Freezing study is being carried out in the controlled environment facility of the *Centre de Géomorphologie*, Caen France, under the auspices of *Centre National de la Recherche Scientifique*, *Laboratoire Central des Ponts et Chaussées*, and Energy Mines and Resources Canada. The freezing of soil in the facility, under known and controlled thermal, mechanical, hydrological and other conditions at a field scale has presented an unusual opportunity to investigate a central issue in studies of frost heave: The orientation of ice lenses and the direction and magnitude of the consequent stresses and displacements of soil. Whether for geotechnical considerations, or for the study of natural effects such as patterned ground, this is of fundamental importance.

Description of experimental facility

A pipe 18 m long and 273 mm in diameter is buried 30 cm below the surface in an 18 m by 8 m hall. Half the length of the pipe lies in silt and the other half in sand (fig. 1). A full description of the layout and all experiments being carried out is given elsewhere (Geotechnical Science Laboratories 1988, 1989). The water table was maintained at a depth of 90 cm below the surface, during the freezing of the ice lenses to be described. The freezing period lasted 468 days, during which the air temperature was maintained at a nominal -0.75 °C and the pipe at -5.25 °C. There were short-term fluctuations around these values.

Procedure for observing ice lenses

Cores of frozen soil, 10 cm in diameter, were obtained to examine the distribution and orientation of ice lenses. Coring was performed with a Sedidrill 100 (Seditech S.A.) — a prototype with a nitrogen-cooled auger, developed by the *Centre d'Expérimentation Routière* from that described in Van Vliet-Lanoe *et al.* (1987). A marker is inserted during coring so that the orientation of the core *in situ* is subsequently known. The silt was cored at three points at site 1 and at three points along a transect adjacent to the sand-silt transition (site 2) (fig. 1). The cores were kept in a frozen state and were cut in half lengthwise with a diamond saw to obtain a representative flat surface perpendicular to the pipe. The surface was then scraped with a knife to make the ice lenses visible.

Two pits approximately 1 m^2 in plan area and 60 cm deep were excavated next to the pipe. Pit 1 was located at site 1 within the silt and pit 2 located at site 2 was at the sand-silt transition (fig. 1).

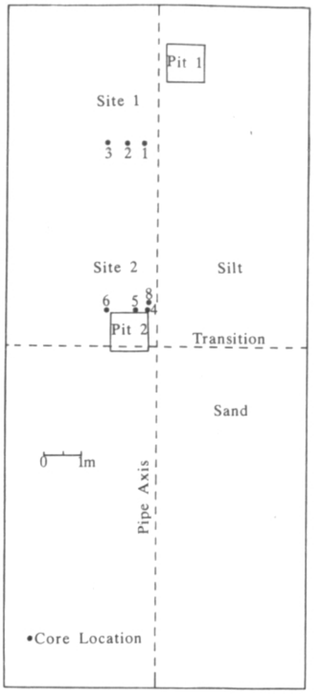

Figure 1. Experimental site and sampling locations.

The position and orientation of lenses in the cores and pits were mapped and the lens thickness and the distance between lenses were measured and recorded. The preferred orientation of lenses was determined by measuring the angle that lenses dipped from the horizontal and the direction of dip (i.e., toward or away from the pipe). Other characteristics of the lenses were noted including their shape (bent or straight) and continuity. Maps were carefully drawn, showing the distribution and orientation of ice lenses and all cores and pits were photographed.

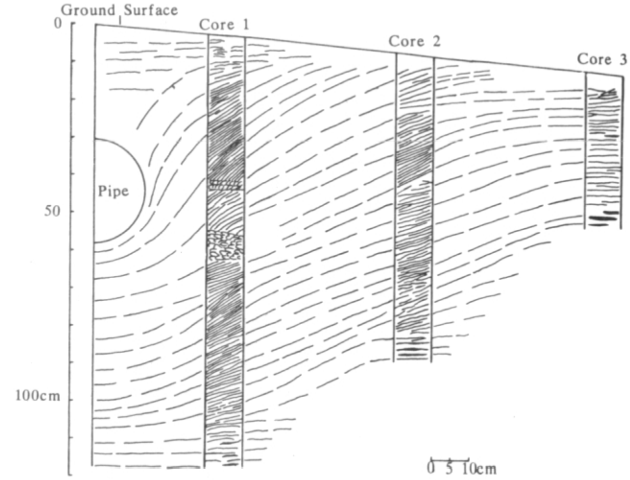

Figure 2. Ice lens pattern in the ground perpendicular to the pipe at site 1.

Description of ice lens orientation

The ice lens orientation in three cores from site 1 is shown in fig. 2. Ice lens orientation has been interpolated between the cores and extrapolated between core 1 and the pipe to produce a map which shows the ice lens orientation in the ground perpendicular to the pipe (fig. 2). Observations of ice lenses in pit 1 were used to aid interpolation and extrapolation. Descriptions of the vertical variation in ice lens orientation will be given first followed by a description of the lateral variation.

Ice lenses are found to be horizontal in the upper 10 cm of the ground 35 cm from the pipe (core 1). Below this the ice lenses dip toward the pipe at an angle that increases with depth to a maximum of 50° at 37 cm depth. Ice blades or

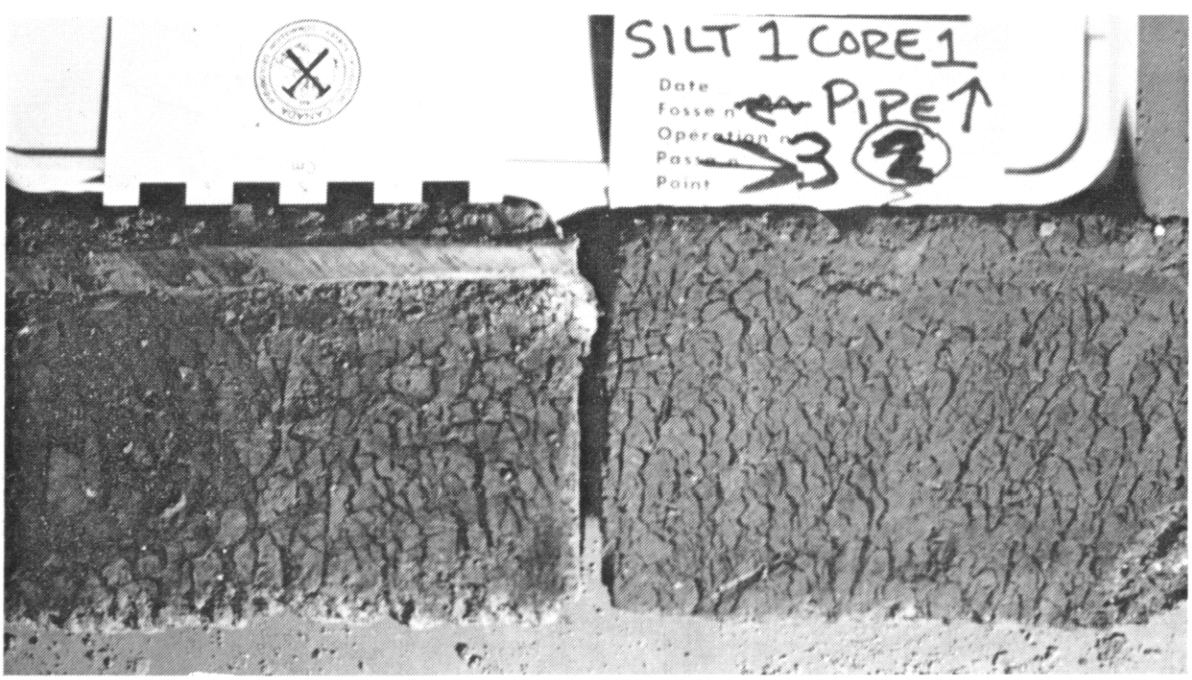

Figure 3. Ice blades next to the pipe at site 1, 50 to 80 cm below the surface. The pipe is on the left side of the photograph.

reticulate ice veins (fig. 3) with no preferred orientation appear to be present between 37 and 42 cm depth. Ice lenses dip 40° to 50° toward the pipe between 42 and 54 cm below the surface. Interconnected vertical and horizontal ice blades are present at a depth of 55 to 62 cm. Ice lenses dip toward the pipe at an angle which increases from 15° to 40° from a depth of 62 to 70 cm. The dip angle then decreases with depth and ice lenses are found to be horizontal at a depth of 104 cm and remain horizontal throughout the rest of the segregated ice zone which ends at a depth of 114 cm.

At a distance of 83 cm from the pipe (core 2) the ice lenses dip toward the pipe at an angle of approximately 30° in the upper 62 cm of the ground. Ice lenses dip at an angle of 15° to 23° between a depth of 62 and 75 cm and are found to be horizontal in the remainder of the frozen zone which extends to a depth of 83 cm. Ice lenses are generally found to be horizontal throughout the frozen zone at a distance of 135 cm from the pipe (core 3).

Ice lenses are found to be horizontal in the upper part of the ground at distances greater than 1 m from the pipe. Ice lenses gradually dip toward the pipe at an increasing angle as the pipe is approached. Extrapolation of data suggests that ice lenses would be vertical next to the pipe but it is possible that ice blades with no preferred orientation, similar to those found in core 1, would be present instead. Ice lenses dip toward the pipe in the lower part of the frozen zone but probably become horizontal under the pipe. Ice lenses are horizontal at all points at the bottom of the frozen zone and the depth of the last ice lens decreases with distance from the pipe. Data from core 1 and pit 1 suggest that ice lenses are horizontal above the pipe. The ice lenses do not appear to show any curvature around the top of the pipe in contrast to the situation beneath the pipe.

The same general pattern of ice lenses was observed in the two pits and in the cores at site 2, as in the cores at site 1, but there was a different pattern 30 cm below the surface (fig. 4). At this depth there is a straight lens which is horizontal near the pipe and gently slopes away from the pipe as distance from the pipe increases. This lens is conspicuous because those above it dip toward the pipe and exhibit some irregular curvature. Below the horizontal lens there is a band approximately 6 cm thick containing horizontal lenses and a few lenses that dip toward or away from the pipe. A horizontal lens marks the bottom of this zone. This zone becomes narrower with distance from the pipe and ends at a distance of 110 cm from the pipe in pit 1. Lenses below this section dip toward the pipe. A similar pattern is assumed to occur along the length of the pipe in the silt and probably occurs at site 1 but was not observed because it was located between cores 1 and 2.

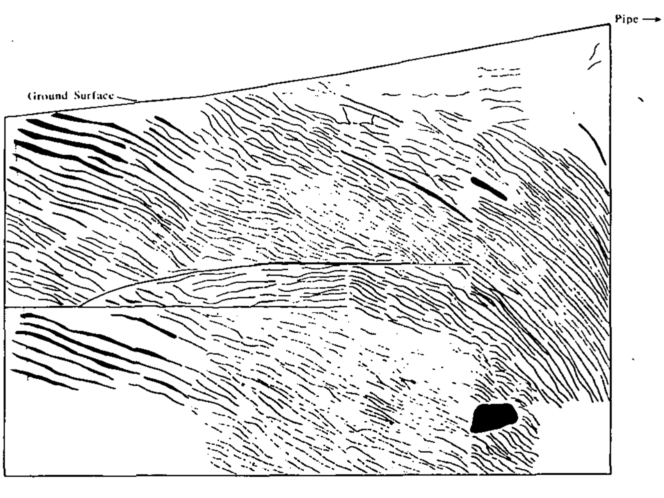

Figure 4. Ice lens pattern in a section perpendicular to the pipe in pit 1.

Discussion

Relationship between ice lens orientation and isotherm pattern

It can be seen in fig. 2 that the ice lenses curve around the pipe. It is often assumed that ice lenses will form perpendicular to the direction of heat flow or in other words parallel to the isotherms (Carlson and Nixon 1988, National Research Council 1984, Shumskii 1964 and Taber 1930). Fig. 5 shows the isotherm pattern in a section perpendicular to the pipe at site 1, 323 days after start of freeze cycle. The isotherms curve around the pipe and become horizontal at distance from the pipe. There is some similarity between the pattern of the ice lenses and the isotherms. Both the isotherms and ice lenses dip toward the pipe and become steep next to the pipe but the isotherms and ice lenses are not parallel. Thus, the pipe as a heat sink clearly influences the ice lens pattern near the pipe, but the thermal configuration is not the only factor controlling ice lens orientation. At distances greater than 1 m from the pipe the vertical heat flow component is more important and the ice lenses are found to be horizontal.

It is necessary to examine the isotherm pattern at the time a particular ice lens formed to determine the

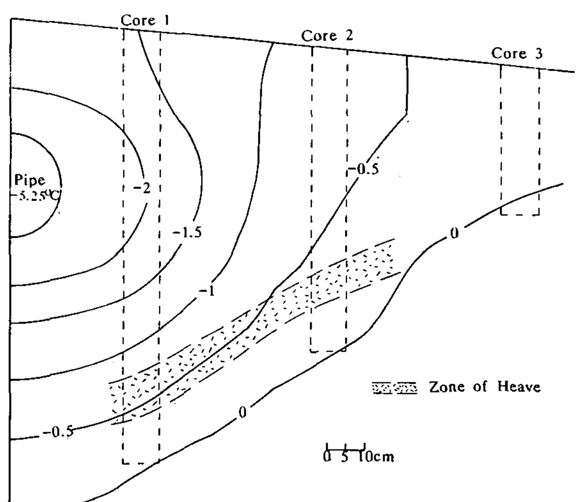

Figure 5. Isotherm pattern in section perpendicular to the pipe at site 1 on day 323 of the freeze cycle. Temperatures are in °C.

relationship between the heat flow direction and ice lens orientation. Magnetic heave measurement devices developed from the concept of Mackay and Leslie (1987) were used to determine when a particular soil layer starts to heave, that is, when ice lenses start to grow in that layer (Geotechnical Science Laboratories 1988, Smith and Patterson 1989). The heave data indicates that heave was occurring in the layer shown in fig. 5 on day 323 of the freeze cycle (Geotechnical Science Laboratories 1989). A comparison of the isotherms and ice lenses for this layer shows that the isotherms dip toward the pipe at a steeper angle than the ice lenses. At core 1 ice lenses dip at an angle of 25° to 30° while the isotherms dip at approximately 40°. Ice lenses and isotherms at core 2 dip at angles of 30° and 77° respectively. A preliminary examination of isotherm patterns at earlier points in the freeze cycle also indicates that the ice lenses and isotherms are not parallel. These results indicate that other factors such as the resistance of the frozen soil to deformation are also important in determining ice lens orientation. It is probable that ice lenses tend towards perpendicularity to the direction of least resistance. The resistance is a function of the soil properties and the mechanical configuration of the ground and pipe. However, the fact that the ice lenses are oriented around the pipe also demonstrates that the direction of least resistance (towards the ground surface) is not the sole factor.

It is important to note that when heave started in the layer shown in fig. 5, heave continued to occur in the frozen soil above this layer (Geotechnical Science Laboratories 1989). Ice lenses therefore were still forming in the frozen soil as the direction of heat flow changed. It is possible that the orientation of the ice lenses changes or that deformation occurs as the freezing front progresses. This possibility needs to be examined in more detail.

The existence of the distinct ice lens pattern observed in the pits and at site 2 (fig. 4) also indicates that the heat flow direction is not the only factor controlling the ice lens pattern. The abrupt change in ice lens orientation (centre of fig. 4) does not coincide with a similar change in the isotherm pattern at that depth. The layer in question is at the level of the pipe and when the pipe was being installed, equipment and people on the ground surface along the pipe caused some additional compaction of the soil (Dumoulin *et al.* 1987). Lithic discontinuities or stratification of sediment can influence the location of ice lenses (Van Vliet-Lanoe 1985) through local changes in hydraulic conductivity and porosity. In stratified sediment ice lensing will generally follow the bedding whereas in uncompacted sediments the location of ice lenses will be influenced by the orientation of the thermal gradient. Carlson and Nixon (1988) concluded from observations of horizontal ice lenses around a buried pipe at a Calgary test site that ice lens orientation is controlled by stratigraphic factors rather than heat flow direction. Textural changes in material of silt to clay at the Calgary site were thought to be responsible for the horizontal lenses.

The straight ice lens which is horizontal near the pipe and gently dips away from the pipe with distance from the pipe could be following the top of the compacted layer and the horizontal lens 6 cm below this could be following the bottom of the compacted layer. Abrupt changes in soil density therefore appear to cause abrupt changes in the ice lens pattern.

The soil used in the experiment was remoulded soil which had not been frozen prior to the installation of the pipe. Under natural conditions, freezing of the soil could establish a stratigraphy (following from ice lens formation, consolidation and thaw) before pipe installation. The ice lens pattern that develops after pipe installation would be superimposed on that which developed under natural freezing conditions.

The ice blades or veins observed next to the pipe, described earlier by Van Vliet-Lanoe *et al.* (1985), have a pattern similar to that described by Mackay (1974). It can be seen from figure 3 that the ice surrounds aggregates which were observed to be compacted and hard. These veins have no preferred orientation and their pattern is not parallel to the isotherm pattern. Mackay (1974) found reticulate ice veins in lake and marine clays in northern Canada in which ice surrounded clay blocks. The blocks were free of visible ice lenses and were overconsolidated and released little water when thawed. Mackay proposed that reticulate ice veins grow in preference to ice lenses because of restrictions on the flow of water which is a requirement for ice lens formation. Water drawn from the frozen and unfrozen soil causes a shrinkage of the clay. Large suctions are created by an advancing freezing front and this will create high effective stress in the unfrozen soil below resulting in consolidation and cracking if there is no access to water (McRoberts and Nixon 1975). The water which fills the cracks and freezes will be obtained from the consolidation of soil. The growth of veins is favoured by a steep temperature gradient and low permeability in structureless soils. The veins observed at the experimental site were likely formed by cracking in association with consolidation because they are found next to the pipe where temperature gradients would be steep and the soil would freeze quickly (Dupas and Van Vliet-Lanoe 1988, Van Vliet Lanoe *et al.* 1985). Water flow to this location would thus be limited.

Heave direction

It is generally accepted that the heave generated by the formation of a particular ice lens occurs in a direction perpendicular to the lens. The general pattern of ice lenses has been drawn in fig. 6 with arrows representing the heave direction.

The ice blades were excluded when fig. 6 was produced. It is difficult to determine the heave direction in the part of the soil containing the ice veins since they show no preferred orientation. Heave in these layers however, may be insignificant compared to that in the rest of the frozen section since there is no net addition of water to this area of the soil. Mackay (1974) suggests that if ice veins derive all their water from the adjacent soil blocks then the net heave would be approximately 9 % of the volume of water in the ice veins. This would be equivalent to the expansion associated with the freezing of pore water and would not result in the formation of excess ice as is the case in the frozen soil containing ice lenses.

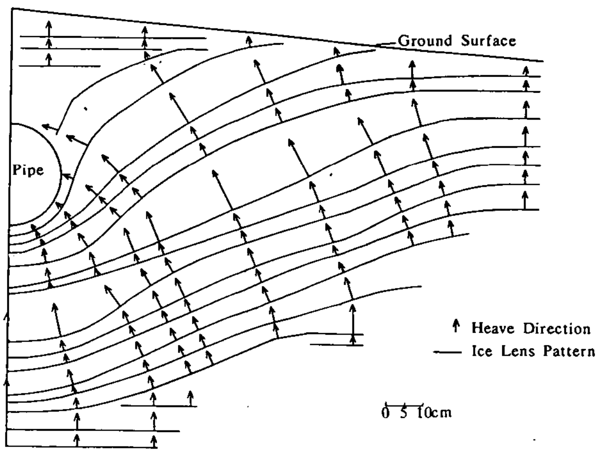

Figure 6. Direction of heave at site 1.

Our data suggests that heave occurs in a vertical direction directly below the pipe (fig. 6) because ice lenses are horizontal. Heave is also vertical near the bottom of the frozen zone and at distances greater than 1 m from the pipe. Closer to the pipe however, the heave is directed toward the pipe so that there is a horizontal as well as a vertical component to heave. As distance from the pipe increases the vertical component of heave becomes more important.

These results show a complex pattern of heave and suggest that the displacement of the pipe is not simply due to the pipe being lifted up by a force acting in a vertical direction. If one assumes that a similar pattern of heave exists on both sides of the pipe, it appears that the pipe is being squeezed as ice lenses grow around the pipe. These forces directed toward the pipe which consist of a horizontal component as well as a vertical one would also cause a displacement of the pipe. The displacement of the pipe therefore would not just be due to the vertical heave generated directly below the pipe.

Summary

Observations of ice lens clearly show that the chilled pipe influences the ice lens orientation near the pipe but it is not the only factor which controls the ice lens pattern. The mechanical conditions and properties of the frozen soil and abrupt changes in soil density apparently are also important in determining ice lens orientation.

The heave that occurs during freezing in a complex situation such as the present one, consists of vertical and horizontal components. The pattern of heave indicates that the displacement of the pipe is a result of the pipe being squeezed from the sides as well as being lifted by vertical heave generated below the pipe.

Acknowledgements

The assistance of B. Van Vliet-Lanoe and her advice to Sharon Smith during a month-long stay on site, is greatly appreciated. A. Dupas, B. Dumoulin, O. Jean and T.L. White provided much help with the excavations, coring and sample retrieval.

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