Pore-Water Pressures in Freezing and Thawing Fine-Grained Soils

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Abstract: Laboratory freezing tests were performed on laterally confined samples of lightly overconsolidated fine-grained soil exposed to one-dimensional freezing at a constant temperature gradient. Pore-water pressures and temperatures were measured at the perimeter of the specimens at various points along their height during freezing and thawing. Vertical heave and water inflow and outflow were also recorded in the sample. X-ray pictures were taken in order to correlate ice lens formation to the measured data. Of particular interest were occurrences of high pore-water pressures shortly after the freezing front had stabilized. Pore-water pressure peaks coincided typically with temperature peaks. Maximum negative pore-water pressures measured during freezing can be correlated to the compression observed in soft clay specimens subsequent to freezing and thawing, which is often called freeze-thaw consolidation. During early freezing, no heave was indicated in soft clay specimens even though numerous ice lenses had formed. No freeze-thaw-consolidation was recorded for stiff clay specimens with initial water contents near the plastic limit.

INTRODUCTION

Soft fine-grained soils, when exposed to freezing and thawing, will generally experience volume changes (Chamberlain and Gow 1979; Knutsson 1984), loss in shear strength (Graham and Au 1985) and sometimes alterations in their hydraulic conductivities (Chamberlain and Gow 1979; Wong and Haug 1991; Othman and Benson 1994). Such alterations of engineering properties during cyclic freezing and thawing are of practical significance for the design of engineering structures. For example, increases of permeability and compressibility, and loss in strength in clays at shallow depth due to cyclic freezing and thawing, are of importance for the design of clay liners, retention dikes, and other barriers in cold climates. Volume changes in soft clays subsequent to cyclic freezing and thawing are of importance for the performance of shallow structures based in freshly exposed soft clay deposits (e.g. in the case of highway cuts).

Even though considerable research has been carried out on freezing and thawing of fine-grained soils, quantitative correlations (so far) could not be established for changes in engineering properties subsequent to freezing and thawing, and soil types.

PREVIOUS RESEARCH ON FREEZING SOILS

In moist, frozen fine-grained soil, not all the water in its pores is solidified at temperatures below 0°C (Neresova and Tsytovich 1963). The amount of

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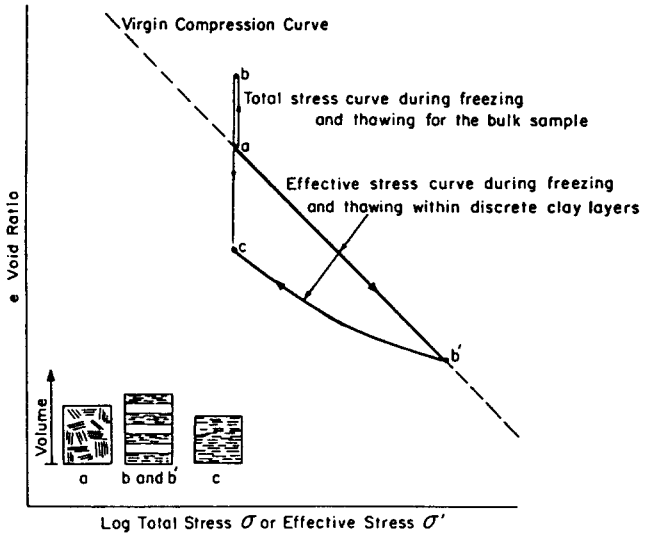

FIG. 1. Thaw-Consolidation Process [after Chamberlain and Gow (1979)]

unfrozen water depends on capillary and surface absorption effect (Anderson 1967; Konrad 1990), as well as on temperature, overburden pressure, pressure in water and ice phases, warming or cooling paths, and number of freeze-thaw cycles (Neresova and Tsytovich 1963; Williams 1964; Anderson and Tice 1973). The existence of unfrozen water implies that water transport may take place through frozen soil, which is of importance for the formation of ice lenses in freezing fine-grained soils. The rate of ice lens formation depends on the rate of heat loss and on the rate of water flow through the frozen soil, which again is related to the hydraulic gradient and the pore-water pressure difference (Loch 1979).

Chamberlain and Gow (1979) carried out a series of uniaxial, cyclic open-system freeze-thaw tests on soft, normally consolidated clay specimens at low stress levels and observed that the permeability and structure of the specimens was greatly changed by freezing and thawing. In all cases, freezing and thawing caused a reduction in void-ratio ("freeze-thaw consolidation") and an increase in vertical permeability. The process of freeze-thaw consolidation was explained qualitatively as illustrated in the void-ratio stress diagram shown in Fig. 1. For a soft clay sample exposed to freezing and thawing, total stress curves for the bulk sample (which includes clay and segregated ice) and effective stress curves for the clay only are shown, both starting at point "a" and ending up at point "c" where pore pressures are in equilibrium with the applied load. The total stress curve shows a volume increase during freezing for the bulk sample leading to point "b" and a volume decrease during thaw when excess water from the thawing of the ice lenses is extruded leading to point "c." Effective stress paths are related to the clay component and indicate, during freezing, an increase in effective stress and associated volume decreases leading to point "b." During thawing, the clay is unloaded in terms of effective stresses and accordingly expands, leading to point "c." The net result is a volume decrease designated by the distance "ac."

Even though the process of freeze-thaw consolidation and the rate and

magnitude of ice lens formation in freezing, fine-grained soils depends on magnitude and distribution of pore-water pressures, pore-water pressures in freezing soils were not measured by Chamberlain and Gow (1979), nor in subsequent investigations. Therefore, a test program was initiated in which pore-water pressures and their distribution in a freezing, fine-grained soil were measured together with temperature, water intake, and heave.

LABORATORY TESTING

Unidirectional freezing tests (Eigenbrod et al. 1991) were carried out at a constant temperature difference between the top and bottom of the specimen. Freezing was induced to cylindrical soil specimens from the bottom upward to minimize side friction (Konrad and Morgenstern 1982). The bottom end was exposed to a temperature below freezing while the top end was kept at a temperature above freezing, and the samples were insulated against lateral heat flux. During freezing, pore-water pressures and temperatures were measured at the perimeter of each soil specimen along its height. Further, water intake, expulsion, and vertical movements at the top of the specimen were recorded. Equipment and instrumentation used for this setup is shown in Fig. 2.

Soil samples of a 70 mm length and a 46 mm diameter were contained in a teflon coated plastic cylinder. Along the inside of the cylinder, 11 filter rings of 3 mm width were arranged 4 mm apart, which was consisted of a porous plastic filter material. Each filter ring was connected to a 0.1 mm inside diameter stainless steel needle, which via plastic tubing was jointed to a pressure transducer of ±0.01 kPa accuracy. Filter rings, steel needles, and connecting tubes were filled with 50% alcohol to allow pore-water pressure measurements during freezing conditions. The purpose of the filter rings was not only to prevent clogging of the steel needles with fines from the soil sample, but also to measure pore-water pressures at a given level along the

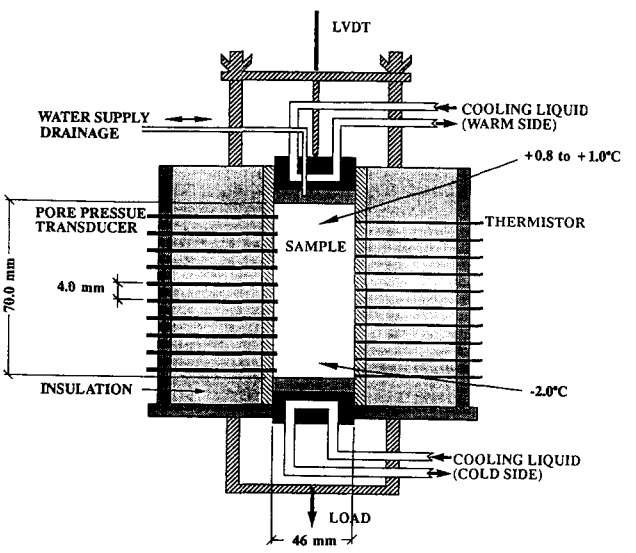

FIG. 2. Experimental Setup for Freezing Soil with Measurement of Pore-Water Pressures, Temperatures, and Vertical Movements

perimeter of the soil specimen. Calibration tests (Eigenbrod 1994) indicated that negative pore-water pressures of up to −25 kPa could be measured with this arrangement. Maximum positive pore-water pressures were governed by the specification of pressure transducers. In this case, the upper limit was 100 kPa. In the spaces between the filter rings, 11 thermocouples were arranged within the plastic cylinder walls 7 mm apart and 0.5 mm away from the inside surface. All thermocouples were calibrated to ±0.001°C. The samples were allowed to drain during placement and during consolidation at top and bottom. During freezing, however, the lower drainage was closed-off. Thus, drainage occurred during freezing and thawing only at the top against a specified back pressure. Water in and outflow was measured by the weight change of a water container, which was connected via tubing to the sample. This setup for measuring volume changes was easily affected by disturbances and probably did not always provide reliable data. Therefore, water in and outflow data will not be reported in this paper.

Vertical movements were measured at the top cap with a linear variable differential transducer (LVDT) with an accuracy of ±0.002 mm.

An automatic data acquisition system was used to read the instruments at 1 s intervals and to record 2 min averages of these readings. Top and bottom caps were connected to separate cooling units, while testing was carried out in a temperature controlled climate room. Water contents, taken prior to and after completion of freezing and thawing, provided additional information to the volume changes during testing.

The soil tested was a clayey silt of low plasticity with the following index properties: liquid limit = 30%; plastic limit = 16%; passing No. 200 sieve (0.08 mm) = 90%; clay size = 18.5%. A total of four specimens were tested. The first test, however, was of preliminary nature and is of limited value for the final evaluation.

The samples were cut with a tube sampler from a block that had been consolidated from a slurry. For the first two tests (No.s 1 and 2), consolidation occurred under its own weight. For the subsequent tests 3 and 4, the specimens were consolidated under a surcharge of 50 kPa in order to obtain stiffer and less sensitive specimens. Thus, the water contents of the specimen at the beginning of testing were around 44% for tests 1 and 2, and 20% for tests 3 and 4. The specimens were then extruded into the test container previously described. To allow dissipation of pore-water pressures and closure of voids, which might have developed during transfer of the specimen to the container, the samples were consolidated again in the test container at a room temperature of 20°C under a surcharge of 50 kPa against a back pressure of 20 kPa. After primary consolidation was complete, the room temperature was lowered to +5°C, and the sample was allowed to rebound under a reduced vertical pressure (generally 30 kPa) and a reduced back pressure of 10 kPa before freezing was initiated.

Even though all four tests demonstrated similar patterns, primarily data from test 2 will be presented in this paper as due to the high initial water content of the sample, ice lens formation, pore-water pressure fluctuations, and volume changes were the most pronounced.

Freezing was induced by lowering the temperature at the bottom plate to below freezing temperatures (−2.0°C) and holding the top-plate slightly above freezing (+1.2°C), while the room temperature was set approximately equal to the top-plate throughout the test, permitting the establishment of a stable freezing front in the test specimen. The freezing front was stabilized for all three tests approximately 15 to 20 h after freezing was initiated. After pore pressures in the specimen seemed stabilized, the test was terminated,

TABLE 1. Characteristic Test Data of Test No. 2

Parameter (1)	Consolidation (2)	Freezing (3)	Thawing (4)
Time, h	163	1,970	451
Total surcharge, kPa	50/30	30	30
Back pressure, kPa	20/10	10	10
Top temperature, °C	+18.0 +8.0 +2.0	+0.08 +1.0	+10.0
Bottom temperature, °C	+18.0 +2.0 +1.0	−2.0	2.0 +1.0
Vertical movement, mm	−2.2	+2.5	−0.36
[Result]	[Settlement]	[Heave]	[Settlement]

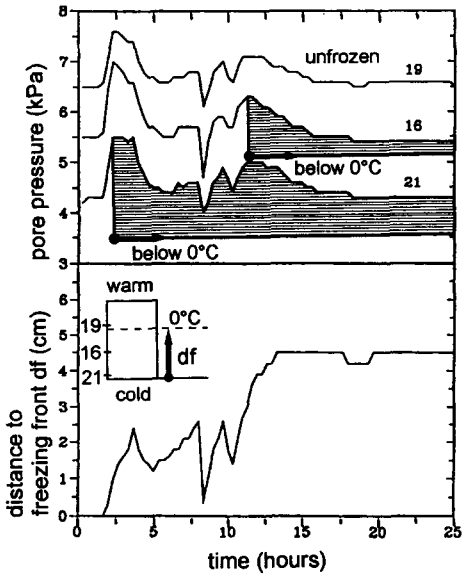

FIG. 3. Frost Penetration Rate at Constant Temperature Gradient and Related Pore-Water Pressures for Test 2

and thawing was induced by raising the temperature at the top to +10°C, while keeping the bottom temperature in a first stage at −2.0°C. For test No. 2, this occurred after 3,000 h or 130 d. In a second thawing stage, the bottom temperature was raised to +1.0°C.

X-ray photographs were taken with a portable 200 KV X-ray generator during freezing at regular intervals in order to correlate formation of ice lenses with the development of pore-water pressures, temperatures, water intake, and volume changes.

For additional information, characteristic data of test 2 is summarized in Table 1.

TEST RESULTS

The results of test 2 are summarized in Figs. 3–6 and for tests 3 and 4 in Figs. 7–9. The position of the freezing front is expressed in terms of the distance of the 0°C isotherm from the base of the specimen as defined in Figs. 3 and 4 for test 2. It is apparent in Fig. 3 that the freezing front is

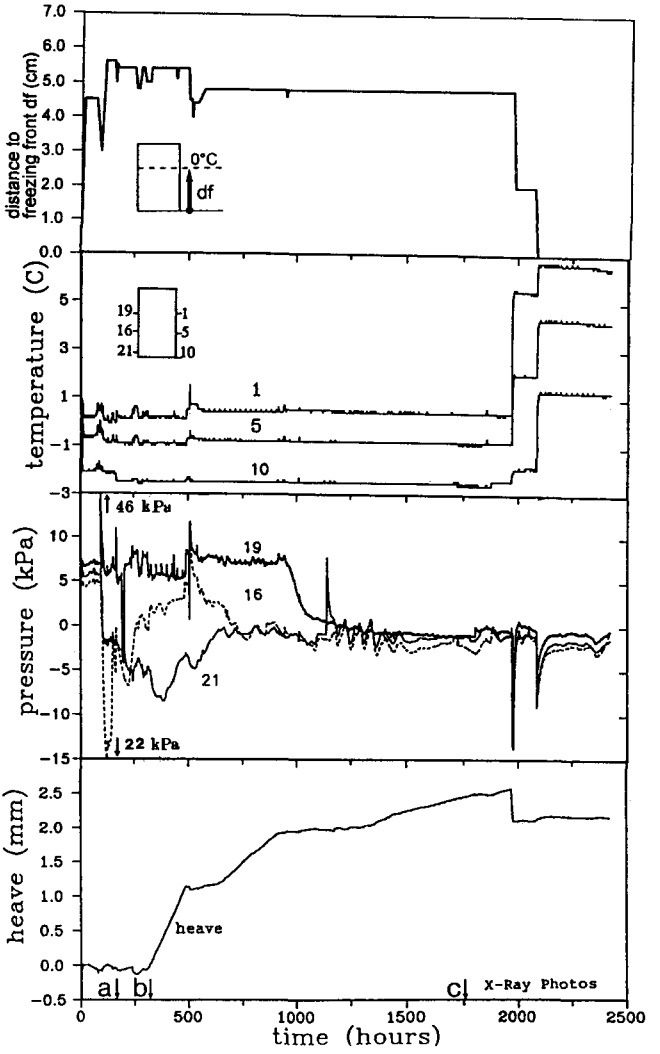

FIG. 4. Temperatures, Pore-Water Pressures, and Vertical Movements of Sample-Top versus Time for Test 2

advancing in a rather irregular way. The various advances and retreats appear to be directly related to the pore-water pressure development, also shown on this graph. Pore-water pressure increases were typically associated with temperature increases. This interaction is also recognized in Fig. 4 where the position of the freezing front, pore-water pressures, temperature readings for typical points, and heave at the top of the sample are plotted versus time. It should be noted that a slight increase of the top-plate temperature by 0.3°C took place due to malfunctioning of the respective cooling unit after 500 h of freezing. Subsequent to this event, the new temperature setting was kept constant until the end of the freezing period.

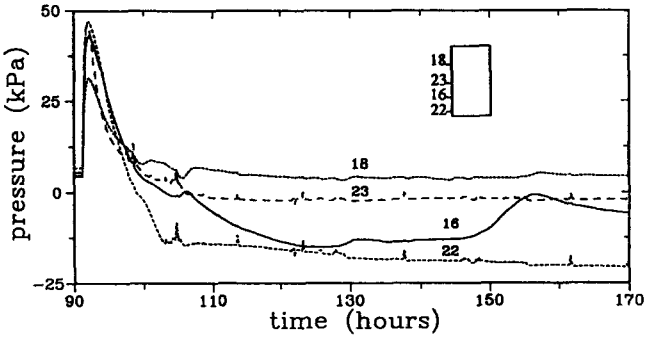

FIG. 5. Maximum Pore-Water Pressures during Freezing for Test 2

Similar interactions between temperatures and pore-water pressures are recognized for tests 3 and 4 as shown in Figs. 7 and 8, respectively. Test 3 was severely interrupted for a period of one month after 1,600 h of freezing due to failure of the cooling unit.

Maximum pore-water pressure variations occurred during the initial freezing stage after 120 h of freezing (test 2) with maximum and minimum values of +46 kPa and −22 kPa, respectively. After about 300 h before the start of heave, pore-water pressure fluctuations were considerably less (between +12 kPa and −10 kPa). Details of the time period, during which maximum and minimum pore pressures occurred, are shown for test 2 in Fig. 5.

Pore-water pressure fluctuations observed for tests 3 and 4 (see Figs. 7 and 8) show maximum and minimum values of +18 kPa and −21 kPa for test 3, and +18 kPa and −19 kPa for test 4, after approximately 20 h of freezing.

During thawing, pore-water pressures for all measuring points dropped suddenly as the temperatures increased, but rebounded back to almost the same values as prior to thaw in tests 2, 3, and 4 well below the back pressure of 10 kPa that had been applied in all three tests.

Heave in test 2 started after 300 h of freezing, subsequent to initially fluctuating small movements, occurring at variable rates during the freezing stage. A total heave of 2.5 mm was recorded during freezing, and 0.4 mm settlement during thaw. Almost no heave was observed during freezing in tests 3 and 4.

In test 2, the water content decreased from initially 44% (prior to consolidation) to 21% at the end of the freeze-thaw test. The water content of the specimen subsequent to consolidation and prior to freezing was not measured directly but was estimated to around 30% on the basis of the compressibility of normal consolidated clays (Azzouz et al. 1976). The water contents for specimens 3 and 4 increased slightly from about 20% at the beginning to 22% at the end of the tests.

X-ray photographs of test specimen 2 are shown in Fig. 6 for three different time stages during freezing with the respective pore-water pressure profiles. The soil between the ice lenses appears in a dark tone when they are clearly lighter. The position of the ice lenses, with respect to the thermistor locations, can be recognized. For time stages a and b, ice lenses, during early freezing, are shown about 3 d apart, whereas time stage c indicates ice lenses after three months of freezing subsequent to a slight increase in temperature. It seems that the ice lenses are not equally distributed over the cross-section of the sample. They appear more intense on the right side near the locations of the thermistor gauges.

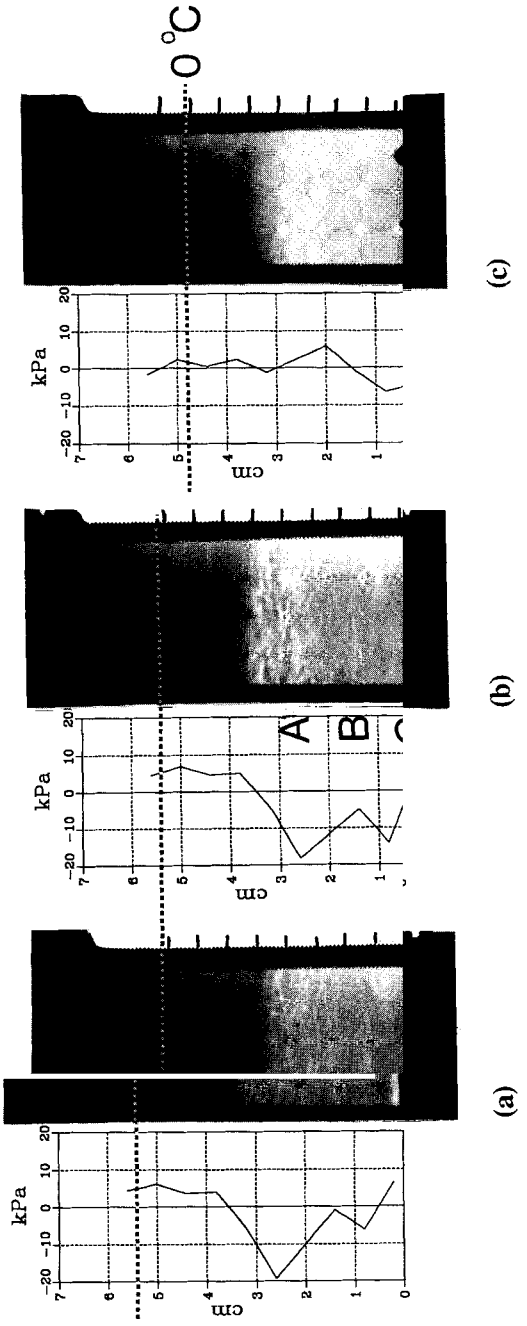

FIG. 6. X-Ray Photographs of Freezing Soil Sample 2 at Three Different Time Stages with Respective Pore-Water Pressure Profiles: (a) Initial Time Stage; (b) 3 Days Later; (c) 3 Months Later

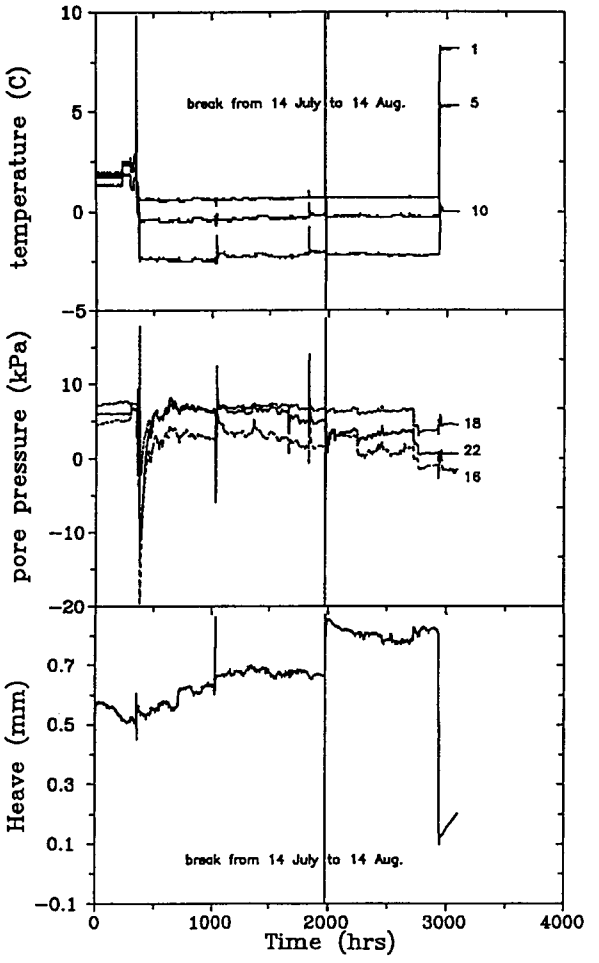

FIG. 7. Temperatures, Pore-Water Pressures, and Vertical Movements versus Time for Test 3

In all three pictures, the 0°C isotherm is clearly above the visible ice surface. The majority of the ice lenses are approximately parallel to the freezing front. There are, however, several ice-wedge-like features that intersect the horizontal ice lenses at almost 90° angles. These ice wedges are concentrated in areas of higher ice content. Comparing time stage a and b with each other, it is apparent that during a time period of 3 d, the zone of visible ice moved towards the freezing front by about 6 mm, and that the number and size of ice lenses had increased considerably. However, the size of the mineral soil portions had decreased from stage a to b. At both time stages a and b, the total volume changes of the frozen soil specimen were almost zero. A significant increase of ice content is apparent from time stages a and b to c. The boundary of the visible ice zone in stage c is more diffuse than in the earlier stages.

Correlating the pore-water pressure profiles with the appropriate X-ray

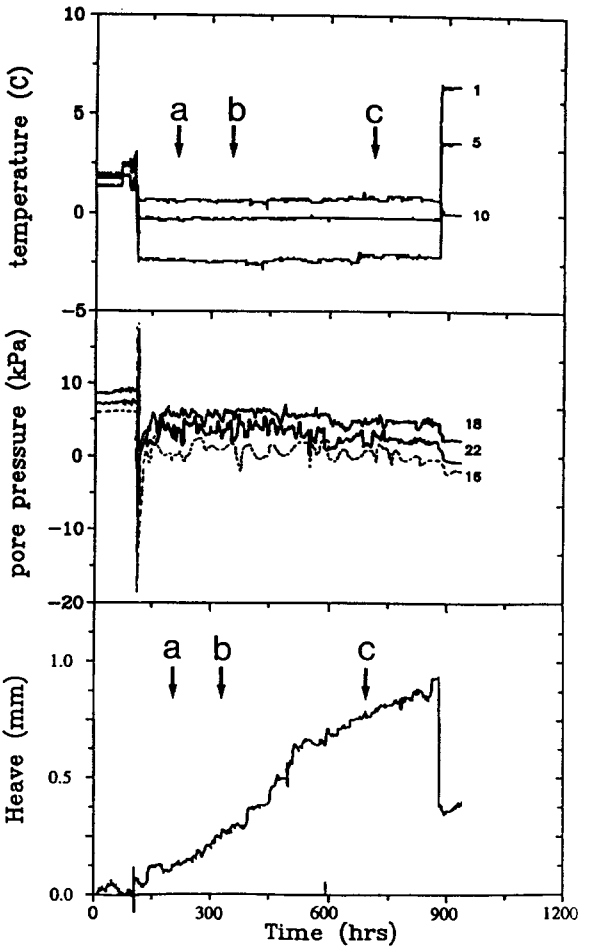

FIG. 8. Temperatures, Pore-Water Pressures, and Vertical Movements versus Time for Test 4

photos in Fig. 6 indicates that pore-water pressures are more negative in the zones of preferred ice lens formation. Positive pore-water pressures occur near the ice lenses at the very bottom (location c) as well as in the zone above the visible ice front. No obvious change of pore-water pressure across the 0°C isotherm is indicated. However, a distinct decrease in pore-water pressure is apparent in the frozen fringe just above the zone of visible ice.

X-ray photographs of test specimens 3 and 4 demonstrated that ice lens formation was much less pronounced than in specimen 2. Fig. 9 shows X-ray photographs of soil sample 4 at two different time stages with respective pore-water pressure profiles.

ANALYSIS

Measurement of pore-water pressures during freezing of soft clays indicated considerable fluctuations. The variations of pore-water pressures appear

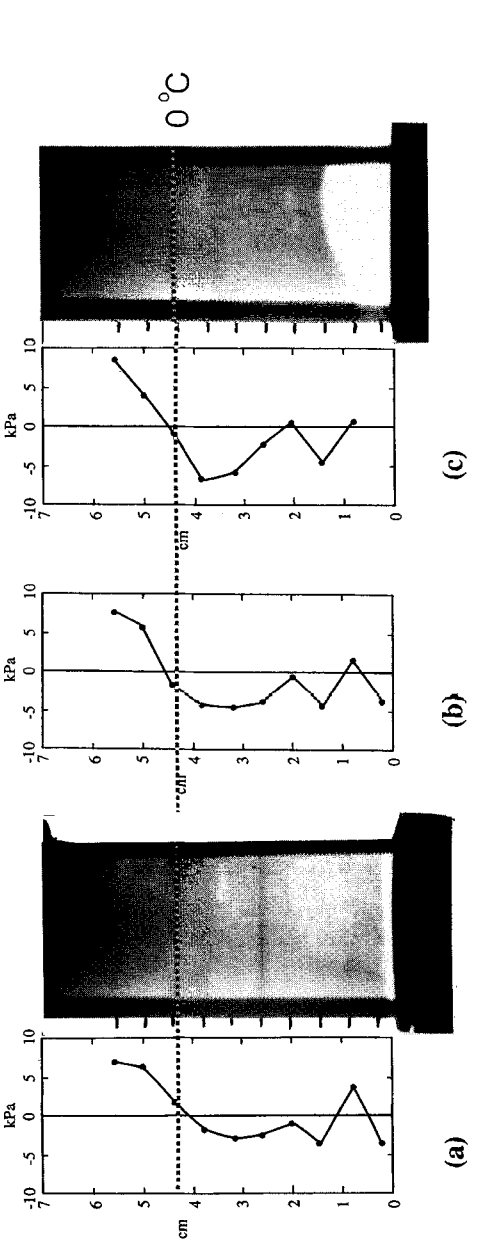

FIG. 9. X-Ray Photographs of Soil Sample 4 at Two Different Time Stages with Respective Pore Water Pressure Profiles

almost cyclic over a given time period (between 100 and 400 h, or 1,100 and 1,600 h in test 2). Similar cyclic pore pressure variations with maximum amplitudes of less than 5 kPa had been observed in the field during freezing of slightly overconsolidated clays at shallow depths (Eigenbrod 1993).

Pore-water pressure increases were typically associated with temperature increases (see Figs. 3 and 4), which during otherwise steady freezing conditions can be related to increased formation of ice crystals. Temperature spikes reflect the increased formation of ice lenses. Associated pore-water pressure increases carried the effective stresses towards zero, a necessary condition for the formation of ice lenses (Miller 1978). Fast growing ice lenses that expand into unfrozen soil portions exert pressure onto the unfrozen pore water. As a result, the pore-water pressures continue to increase, which in turn promotes suction towards the growing ice lens in the adjacent unfrozen soil portions. Thus, the initial increasing pore-water pressures decrease, and eventually, negative pore-water pressures develop. Decrease in pore-water pressures causes an increase in effective stress and thus, compression of the soil. The increased availability of water due to compression of the soil again leads to pore-water pressure increases. Associated decreases in effective stresses accelerate formation of ice lenses and cause suction towards the growing ice lenses and thus once more a decrease in pore-water pressures. A cyclic pattern of pore-water pressures, and water in and outflow also develops.

The amplitudes of the pore-water pressure fluctuations are largest during the early stages of freezing, probably due to the large quantities of water that are available during compression of the initially soft soil. As the soil portions approach their final compression, less water is accessible and the amplitudes of pore-water fluctuations decrease. The fluctuations become zero as soon as the ice lenses discontinue to grow and no further heave occurs.

The development of maximum and minimum pore-water pressures during the initial stages of freezing indicates that at that time, the soil between the ice lenses experiences maximum loading and unloading in terms of effective stresses. It can be visualized that the volume increases due to formation of ice lenses and the volume decreases due to compression of the clay from increased effective stresses are balanced, resulting in zero net heave, as was observed during the initial freezing stages of sample 2. This behavior is also apparent from the X-ray photographs shown in Fig. 6. At time stage a, ice lenses occupy a much smaller volume and soil portions a much larger volume than at time state b, while for both time stages, the total volume changes of the frozen soil specimen is almost zero. When the clay does not compress any further, heave, as a result of the continuing formation of ice lenses, becomes apparent.

During freezing, consolidation of the clay specimen is reflected by the change of water content from approximately 30% (prior to freezing) to 21% after completion of the test. This change in water content is equivalent to a compression of 9%. This compression of 9% is related to a stress change in the order of 30 kPa, if the compressibility of normal consolidated clays is considered (Azzouz et al. 1976). This calculated pressure change is very close to the measured maximal drop in pore-water pressure of 32 kPa from the level of the back pressure. According to the Clapeyron Equation, maximum negative pore-water pressures at the water-ice interface must be much larger (Konrad 1989). Therefore, it must be concluded that the measured pore-water pressures, although obtained at relatively distinct points, are not the maximum values, but constitute averages for larger areas within the soil specimen, which appear to govern the resultant overall volume changes. Similarly, it

can be concluded that the measured maximum positive pore-water pressures are averages for larger areas, and the actually occurring maximum values are considerably higher.

The measured net heave of 2 mm after thaw (for sample 2) appears erroneous, indicating that during thaw, the loading cap got stuck to the sides of the test container and was not in contact with the specimen.

The suggestion that most of the compression of the clay occurs during the initial stages of freezing is confirmed by observations from cyclic freeze-thaw tests in which the net deformations after each freeze-thaw cycle were almost independent from the length of freezing stages, as long as the freezing periods were long enough to permit some heaving to occur (K. D. Eigenbrod, in press, 1996).

The observation of growing ice lenses behind the freezing front in the X-ray photographs, as well as the development of negative and positive pore pressure behind the freezing front, suggests that water movements toward the growing ice lenses occurs on the warm side of the ice lenses through the frozen fringe and on the cold side of lenses from consolidating clay layers.

The water that accumulated in the ice lenses partly originated from both the consolidating soil and from water that had been drawn into the specimen from the outside. The finding that much of the water contributing to ice lenses originates from within the consolidating clay sample is in agreement with observations from other researchers (Othman and Benson 1994), who noted that ice lenses can form in clays frozen in a closed system with no external water supply.

In specimens 3 and 4 with initial water contents of around 20%, much thinner ice lenses developed as compared to specimen 2 with an initial water content of around 40%. For the same specimens, practically no decreases in water content were measured after freezing and thawing, indicating that no freeze-thaw consolidation had taken place. The thin ice lenses that had formed must have developed primarily from water drawn from the outside through the frozen fringe.

Little or no volume changes were observed subsequent to freezing and thawing for specimens with initial water contents near the plastic limit. This agrees with data reported by Knutsson (1984) for several Swedish clays that had been exposed to cyclic freezing and thawing.

Differences in pore-water pressures measured across the frozen fringe between the 0°C isotherm and the visible ice front were consistently very small ranging between +1 and −2 kPa, which is consistent with observed water in and outflow. Accordingly, the hydraulic gradient across the frozen fringe (of around 18 mm width) is rather low. Assuming that the water inflow observed at the top of the specimen is correct for time stages a and b in Figs. 4 and 6 and approximately the same as in the frozen fringe, the average hydraulic conductivity of the frozen fringe K_f is directly calculated using Darcy's law (Konrad and Morgenstern 1980)

$$K_f = v/i \tag{1}$$

where v = flow velocity; and i = hydraulic gradient across the frozen fringe.

For conditions a and b shown on the X-ray photographs of specimen 2 with a flow velocity of 3 to 12×10^{-6} cm/s, the hydraulic conductivity of the frozen fringe K_f was evaluated to approximately 2 to 8×10^{-9} m/s. This value is about one tenth of the permeability of the unfrozen soil. Similar decreases in permeability had been reported by Horiguchi and Miller (1983) for silty soils during a temperature drop from 0°C to −0.3°C.

The sudden drop in pore-water pressures during thaw, which was apparent in all four tests, is surprising even though a similar behavior had been previously observed in a different type of freezing test (Eibenbrod and Burak 1989). It can be explained only by a sudden drop in ice pressure, associated with a sudden decrease in specific volume as ice changes into liquid water. It must also be assumed that air voids in the ice lenses permitted dissipation of pore-water pressures. The rise in pore-water pressures is not very dramatic and may be explained by a higher permeability of the fissured soil in its thawed condition, which permitted drainage of water and dissipation of pore-water pressures at the same rate as the ice lenses thawed. Increases in permeability, subsequent to cyclic freezing and thawing, were reported by Chamberlain and Gow (1985); Wong and Haug (1991) for soft, normally consolidated clays; and Othman and Benson (1994) for compacted natural clay specimens.

CONCLUSION

Experimental results obtained in freezing tests with constant temperature gradients demonstrated the following:

- During freezing of soft, fine-grained soils, cyclic pore-water pressure changes occurred with maximum values during the initial phases of freezing, shortly after the freezing front had stabilized.
- Maximum positive pore-water pressures were approximately equal to the overburden pressure.
- Maximum negative pore-water pressure changes can be correlated to net volume changes of the soils subsequent to freezing and thawing.
- Pore pressure peaks were always associated with temperature increases. Temperature increases during otherwise steady freezing conditions are related to the increased formation of ice crystals. At the same time, it is indicated that pore-water pressure peaks were sufficiently large in order to reduce the effective stresses to zero, which is necessary for the formation of ice lenses.
- During the initial stages of freezing, no net volume changes were recorded even though considerable ice lenses had formed. This suggests that volume increases due to the formation of ice lenses were balanced by volume decreases due to compression of the clay as a result of high negative pore pressure changes and the associated increases in effective stresses. The water that accumulates in the ice lenses during freezing of soft clays partly originates from consolidating soil and partly from water drawn into the specimen from the outside through the frozen fringe.
- For test specimens with initial water contents at or near the plastic limit, water contents did not decrease during freezing and thawing, indicating that "freeze-thaw consolidation" did not occur.

Of practical significance for the performance of engineering structures in winter are the high positive water pressures that were observed particularly during the early freezing stage: pore-water pressures between 20 and 40 kPa are equivalent to the total overburden pressures existing in subgrades below pavements and indicate that the subgrade soil has little strength, at this point in time.

It is also important to recognize that structures on soft clays will experience

permanent settlements if the foundation soil is affected by freezing and thawing. Little or no permanent settlements occur if the soils are stiff with water contents at or below the plastic limit.

Research continues to explain in more detail volume and permeability changes of soft clays during freezing and thawing in order to identify quantitative correlations with soil parameters.

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