Report for 2004AK29B: Infiltration in Coarse Soil and Formation of Infiltration Ice

There are no reported publications resulting from this project.

Report Follows

Investigation of the Formation of Pore Ice in Coarse Grained Soils

Overview

Numerous studies of ice formation in soils are focused on fine-grained soils freezing in closed or open systems mainly in attempt to describe frost heave impact on structures. While the characteristics of the accumulation of ice in fine grain soil have been thoroughly studied, the formation of ice in coarse grain soil has not been investigated. Freezing of fine grain soils is accompanied by movement of water to the freezing front and formation of stratified ice layers. Such temperature gradient induced soil-water migration is not the case for coarse-grained soils with small amount of fines (soil particles with diameters less than 0.075mm). Also, differing water retention characteristics in comparison to fine grain soil and mechanisms of moisture transfer suggest that the nature of pore ice formation in coarse grain soil is different than in fine grain soil. Understanding the nature of ice formation in this type of soil and the soil characteristics that control the depth at which the pore space becomes saturated with ice is important to assessment and cleanup of contaminated coarse grained soil to include naturally deposited soils as well as engineered soils such as the base coarse of air strips, roadways, and gravel foundations in northern, alpine, and Arctic climates. In addition, others are investigating the use of permeable reactive barriers to control the migration of surface and subsurface contamination in cold climates. Design of these barriers requires an understanding of where ice is likely to form in the pore space and if preferential channels for flow will form due to the presence of ice. Furthermore, in the area of geotechnical engineering, knowledge of pore ice formation in coarse graded base soil materials is required to reduce the impact of roadway weakening during thawing. As accumulated ice near the top of base soils directly underneath the paved surface thaws high pore water pressures reduce the strength of base soils causing failures in the paved surface.

Drainage of liquids through frozen soils is limited by the formation and presence of ice in the porous matrix in comparison to similar unfrozen soil. As water added to the soil by rain events or by melting snow drains through frozen soil, a fraction of the water will be retained in pore space and eventually freeze. Ultimately, with repeated infiltration of water, pore space will become saturated with ice restricting any additional infiltration of water. The infiltration of other liquids such as non-aqueous phase liquids (for example petroleum) accidentally released to the ground surface will also be impacted by the presence of ice in the pore space. Proper assessment and cleanup of these impacted regions first requires a better understanding of how pore ice changes the characteristics of porous media. The overall objective of this project was to quantify the factors controlling the formation of pore ice in coarse grained soil.

Laboratory Methodology

The infiltration studies were conducted in a walk-in cold room to ensure a homogeneous temperature distribution through the columns. The columns were constructed of acrylic to facilitate a visual interpretation of the results. The mesh at the bottom of the column has a screen size of 1.5mm. The setup is shown in Figure 1.

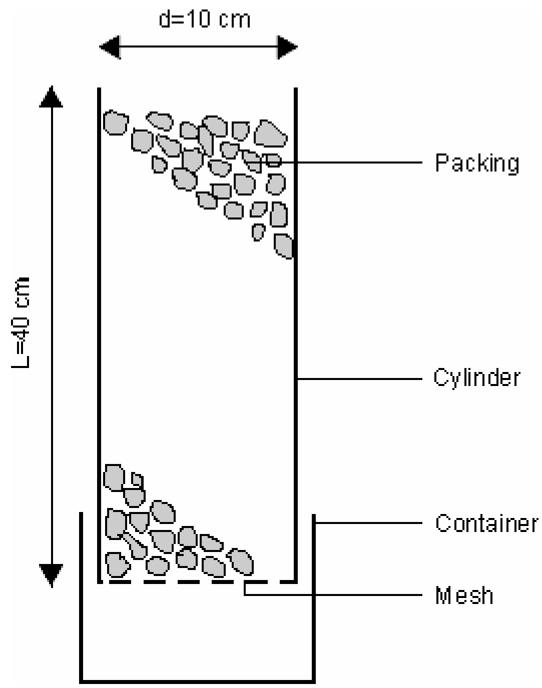

Figure 1: Experimental setup of the column studies

In each test, melt water at 0^{o}C was introduced at the top of the column and allowed to infiltrate and freeze. If the water made it all the way through the column, the permeant was collected in a container and allowed to freeze before the next introduction of melt water was made. To decrease the possibility of inducing a convective current in the column melt water was left in the container below the column and allowed to freeze before the next introduction of melt water. Between each introduction of melt water the column and the container was weighed to establish the partitioning of the permeant. The whole setup was also enclosed in a loose plastic wrapping to minimize the amount of sublimation of ice out of the column. The parameters tested in the column studies were the soil gradation, temperature, volume of water added by infiltration, compaction, and initial soil moisture content and the layout of the tests are shown in Table 1.

Table 1: Test schedule

Test	Soil Type	Temperature
A	Gravel (large –100% passing 25mm)/dry	-10 ^{o}C
B	Gravel (pea –100% passing 6.25mm)/dry	-10 ^{o}C
C	Graded surface course /dry /compacted	Room Temperature
D	Graded surface course /dry /compacted	-2 ^{o}C, -5 ^{o}C
E	Graded surface course /dry /uncompacted	-10 ^{o}C
F	Graded surface course with fines (< 75µm) removed /dry /compacted	-5 ^{o}C
G	Graded surface course /initial moisture contents of 0%, 4.5% and 9% /compacted	-5 ^{o}C

Results and Discussion

The results from the tests can best be described in a series of figures. A description of how ice forms in a poorly graded soil (singular grain size) as opposed to a well graded material is provided in Figure 2. In well graded material, the existence of small dimensioned pore space created by the presence of varied sized soil grains creates dead end pores as water is retained in these spaces by capillary forces freezes. The result of the creation of dead end pores is ice saturation in the top few centimeters of the column. Conversely, a poorly graded coarse grained soil will have relatively larger dimensions pore space resulting in drainage of the melt water until the latent heat is lost or there is a change in soil gradation. An additional factor contributing to blockage of draining melt water is air entrapment in the near ice saturated pore space. The existence of these often large volumes of entrapped air is shown in Figure 3.

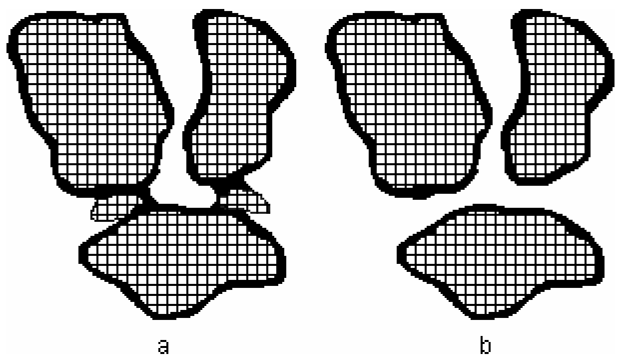

Figure 2: Comparison of pore ice formation in coarse grained soils with (a) and without (b) the presence of smaller particles. Cross hatched areas represent soil grains and the solid areas represent water held by capillary forces. The scenario shown in (a) represents the creation of a dead-end pore with minimal pore ice content in comparison to the scenario shown in (b) where pore channels remain open to flow. Further additions of water to the pore space shown in (a) will result in the pore becoming either filled with ice or entrapped air.

Figure 3: Large volumes of entrapped air form because of dead end pores

In poorly graded soil or in relatively large dimensioned pore spaces, melt water rapidly freezes to soil grain surfaces changing the pore dimensions of the coarse grained soil. Eventually pores become blocked as the pore dimensions are reduced such that melt water can be retained by capillary forces. This process is illustrated in Figure 4.

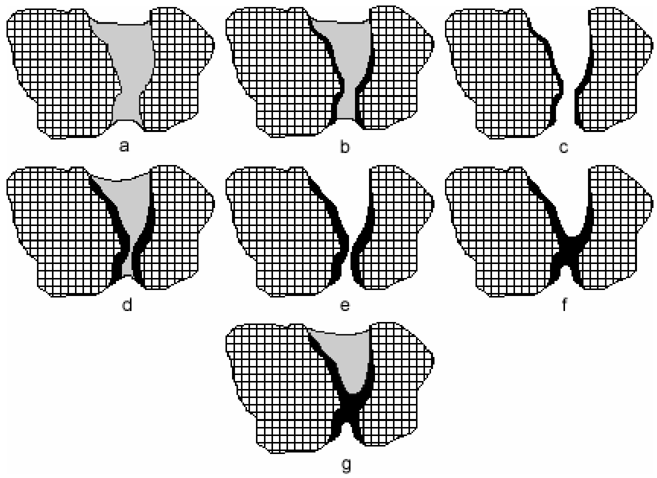

Figure 4: The hypothetical freezing of coarse grained soils from infiltration of melt water. In (a) the pore is filled with fluid, the fluid rapid freezes to the pore walls (b) and then drains (c). Successive infiltration causes additional freezing to the pore walls (d) and (e) until the pore has been closed off (f). Thus the pore-throat has become a dead end (g).

Gradation changes from fine grained soil to coarse grained soils are of interest due to the development of capillary breaks and the restriction of further water drainage through the soil horizon. In a frozen soil, ice will form in the soil above the capillary break. This effect was seeing in our test as water was retained in the mesh openings at the bottom of the column as shown in Figure 5.

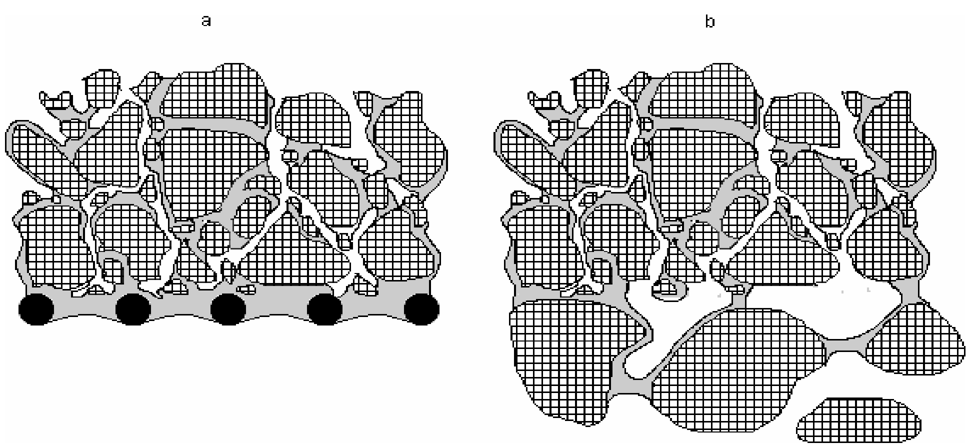

Figure 5: Water held by a capillary break freezes at the interface. In (a) the laboratory experiment is shown were water is infiltrated at the top, advances to the capillary break and is unable to pass as the pressure head is not great enough to infiltrate the pore space below. The water freezes at this point and subsequent additions of melt water will pond on top of the impermeable layer. This can be likened to the real world situation in (b) were a gradation change takes place, as in the case of a surface course on top of a base course.

Compaction also plays a very important role in ice formation; this relationship is summarized in Figure 6.

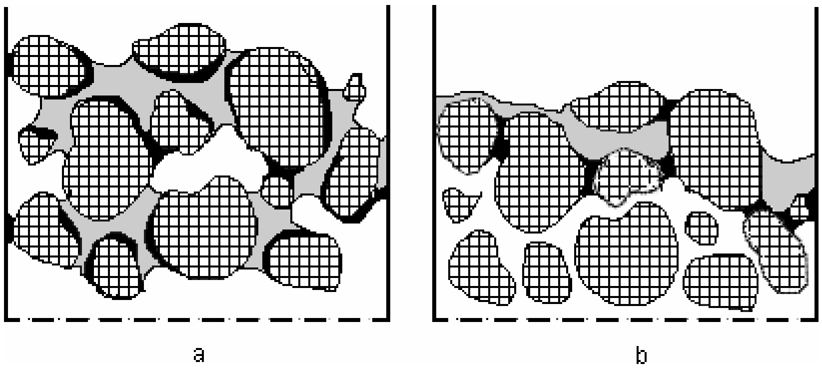

Figure 6: In compacted sample in (b) the pore throats have become much smaller than those in (a). The rapid freezing process described previously occur much more readily and therefore the impermeable layer forms higher up in the sample.

Conclusions

The freezing mechanism of infiltration ice is an important issue with regards to engineered coarse grained soils. Infiltrated melt water rapid freezes to the soil grain boundaries, decreasing the pore throat diameter and increasing the resistance to flow. The addition of relatively finer particles (not necessarily clay and silt) to a coarse grained soil also decrease the average pore throat diameter and drastically changes the location of the initial impermeable ice layer. The sub-zero temperature of the soil does not greatly affect the freezing rate or the location of the ice layer, as the latent heat of water is orders of magnitude higher than its specific heat. The compaction of the soil also affects the formation of the ice layer. In compacted soils the small particles are forced in between the bigger particles, decreasing the average pore throat diameter. The initial frozen moisture content greatly influences the pore space available for flow.

The application of this theoretical work can be shown in engineered coarse grained porous media such as permeable reactive barriers (PRBs) and road beds. In permeable reactive barriers care should be taken to reduce the possibility of flow channeling, which would reduce the effectiveness of the PRB. Moreover, the possibility of a capillary break between the engineered barrier soil and the surrounding soil should be reduced. Such a break would also allow water to freeze at the PRB boundary and further reduce its efficiency. In road beds the fine material in the surface coarse is largely responsible for the retention of water and the subsequent problems with rutting and thaw settlement.