The Frost Behavior of Soils
II. Horizontal Sorting

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Laboratory experiments have been performed with a special "closed-system" side freezing cabinet in which completely saturated soil samples were subjected to alternate freeze-thaw cycles without surcharge. A vertical or nearly vertical freeze-thaw plane was obtained in the side freezing cabinet. The soil used was a straight-graded noncohesive material with 14 percent finer than the No. 200 (0.074 mm) mesh sieve. According to existing criteria, the soil would be classified as nonfrost susceptible.

All experiments were run for 22 cycles. Freezing was at rates of 30, 33, and 42 mm per hr. The initial dry density was approximately constant for each test at 1.8 gr per cc or 112.4 pcf.

The tests under saturated conditions showed an over-all increase in volume during the cycles, but the movement of particles away from the freezing front caused a noticeable loss of volume close to the cooling plate. The rate of movement of the fraction finer than 0.074 mm for the closed-system condition was in the order of 0.05 percent per cycle. Differences in fines (finer than the 0.074 mm fraction) concentration between cold and warm faces after 22 cycles show 3.4 percent for the unwashed and 0.9 percent for the washed sample. Lines connecting equal amounts of like particle sizes have a tendency to be vertical at low rates of freeze and become inclined at higher rates of freezing.

The phenomenon of vertical and horizontal sorting is considered a problem of volume change. Volume changes produced by a sieving action without freezing and thawing show that the volume change produced by the sorting of a straight-graded sample is a function of the uniformity coefficient.

The active layer in the permafrost shows vertical sorting whenever horizontal sorting is encountered and sorting occurs in soils with and without particles finer than 0.02 mm. Because vertical sorting is produced by freezing and thawing from the top and horizontal sorting by freezing from the sides, it is expected that vertical and horizontal sorting should be found in seasonally frozen soils besides the permafrost regions where the soil freezes from the top and sides.

A general principle of sorting is presented: When freezing from the top, fine particles migrate downward away from the cooling front and this movement is facilitated by gravity and pore space left by the freezing action. When freezing from the bottom up, the vertical sorting is increased by (a) fines migrating upward in front of the freezing plane, and (b) fines coming down in the unfrozen part. For the side freezing, gravitational forces cause a parabolic path of the migrating particles. A heterogeneous soil with or without particles finer than 0.02 mm has a natural tendency to become vertically and horizontally sorted if it is frozen from the top, the bottom, or the sides. As in the case of vertical sorting, this principle implies that a well-graded gravelly soil, with or without fines, will be sorted whenever subjected to a sufficient number of

freeze-thaw cycles. Although such a soil may not form ice lenses during the first freeze-thaw cycle, the chance for such a formation will increase during the subsequent cycles as more fines segregate.

It is recommended that particle migration caused by side freeze-thaw cycles be studied for engineering application in certain types of construction.

•LABORATORY experiments and field data reported in Part I (1) show that "vertical sorting" of particles of different sizes is produced by a horizontal freeze-thaw plane moving from the bottom up or from the top down in the soil layer. Vertical sorting is defined as a segregation of coarse particles at the top and fine particles at the bottom of the freeze-thaw layer. Results of the study on horizontal sorting produced by a vertical freezing plane are presented here.

The freeze-thaw plane may vary from the horizontal to the vertical depending on two conditions: (a) the change of the uniformity coefficient over short horizontal distances and (b) the arrival of large particles at the soil surface by vertical sorting. If the uniformity coefficient (C_u D_{60}/D_{10}) increases from the two ends of a certain vertical plane to a maximum at the center, volume changes directly related to C_u will occur. The mound created by the greater volume change will produce a freezing direction normal to the slope of the mound. Large particles rising to the surface of the mound by vertical sorting will gravitate down the slope, leaving a center of fine material surrounded by coarse particles. In the case of large particles brought to the surface by vertical sorting, the freeze-thaw plane will follow the contour of the stone. As stones have a higher thermal conductivity than the surrounding material, the particles adjacent to the stones are subjected to a side freezing component.

This report deals with the effects of a vertical freeze-thaw plane moving laterally in heterogeneous and skip-graded mixtures. The results of laboratory data are used to explain one type of sorting in nature. In the cold regions of the earth, the soil surface is characterized by the formation of areas of fine particles surrounded by coarser ones, called "horizontal sorting." Since the beginning of the Twentieth Century, the problem has attracted the attention of scientists, and, by 1927, 21 theories had been proposed to explain the origin of ground sorting (2, p. 182). Hundreds of papers have been published in different countries expanding on various theories and findings on the subject.

The problem of sorting is complex. A necessary step is to isolate the main factors responsible for the segregation of particles. Because this is a complicated matter, an appropriate approach to the solution is through experimental work in the field and laboratory where controlled conditions can show the effect of the different variables of frost behavior. USA SIPRE (CRREL) has been experimenting with the problem of soil sorting since 1955.

One type of sorting is purely mechanical and is produced by gravitation of particles into depressions. The type of sorted feature depends on the geometric pattern of the soil depressions, according to field and laboratory studies at CRREL. Sorting is produced by wind and rain in desiccation cracks (3) and by differential melting of ice under various thicknesses of gravel (4). However, the melting of glacier ice under a layer of heterogeneous material or the collapse of permafrost due to melting of ice masses cause a more or less rounded irregular pattern (4).

A second type of sorting is produced by cyclic freeze-thaw. The sorting effects of a horizontal freeze-thaw plane has been already reported (1). The present report on the effects of a vertical freeze-thaw plane should be considered as an extension of the previous one on vertical sorting. In the conclusions the results of both papers are brought together.

LABORATORY EXPERIMENTAL DATA

Experimental Procedure

In Part I of this report (1) it was demonstrated that, when a soil is subjected to a cyclic freeze-thaw action in a horizontal plane, coarse particles will move up and fines

will move down. When a large particle reaches the surface and remains partially embedded, it will create a change in the freeze-thaw condition because its thermal conductivity is greater than the surrounding material. The soil adjacent to the larger particle will freeze more quickly and the freeze-thaw plane will be parallel to any point on the stone. Therefore, the freeze-thaw plane will vary from a horizontal to a vertical position depending on the point in question. For that reason, it is necessary to understand the effects of a vertical freeze-thaw plane in heterogeneous and nonheterogeneous materials.

Materials Used for Experiments.—The two types of material used in the experiments had straight and discontinuous gradation (Fig. 1). Three samples were prepared in the laboratory: Sample a-5-2 had a straight gradation with 14 percent crushed quartz particles (Silicrete) finer than No. 200 sieve. Samples X-1 and X-2 were mixtures of two ranges of particle sizes. Sample X-1 contained 66 percent (between 7.93 and 10.0 mm) and 34 percent (between 0.71 and 1.00 mm). Sample X-2 contained 71 percent (between 7.93 and 10.0 mm) and 29 percent (between 0.037 and 0.074 mm) (Silicrete). Samples a-5-2 and X-1 are located in the so-called never-frost heaving moraine soils of Beskow (5, p. 125).

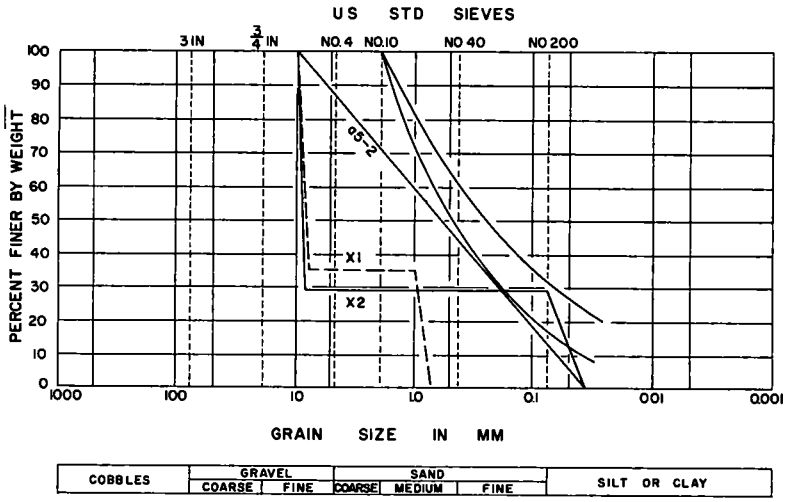

Figure 1. Samples a-5-2, X_1, and X_2, compared with the frost susceptibility limiting curves of Beskow (solid heavy lines).

Before the cyclic tests were performed, the samples were compacted to a dry density of approximately 1.8 g per cu cm (112.4 pcf). A small rubber piston was used for compaction so as not to crush the grains. A lucite plate was placed at the top of the soil sample as a bearing surface for a dial gage installed to measure soil heave. The tests were carried out under saturated conditions; water was added every five cycles to maintain saturation. In this closed system, no overburden pressure was applied.

Apparatus and Experimental Control.—The apparatus for this side-freezing experiment was a square box with a cross-section 15 by 15 cm constructed from 2-in. plywood (Fig. 2). The bottom and sides of the freezing cabinet were treated with shellac to make them watertight. A vertical freeze-thaw plane was obtained by placing two aluminum plates connected by five 1-in. diameter aluminum cylinders against the side of the cabinet. A heating tape was placed in the side of the cabinet opposite the cooling surface to control the freezing rate. By regulating the voltage drop across the heating tape, freezing rates varying from 2 to 42 mm per hr could be obtained. Most of the

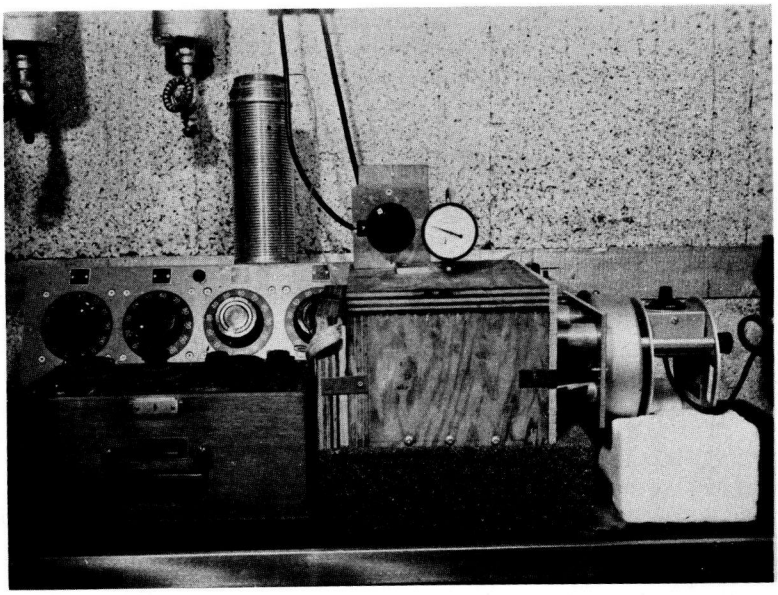

Figure 2. Closed-system side-freezing cabinet.

tests were conducted at rates ranging from 30 to 42 mm per hr. For the problem of vertical sorting, Part I of this report showed that the amount of segregation or particle movement increases with a decrease in rate of freezing. Therefore, it is expected that low rates would produce a greater particle movement. Tests conducted by the Arctic Construction and Frost Effects Laboratory on so-called "frost-susceptible" soils with freezing rates of 0.2 to 0.7 mm per hr show that low freezing rates are more likely to produce ice segregation than the higher rates (6, p. 114).

Experimental Results

Sample a-5-2.—Side freezing tests were performed with the following rates of freezing: 30, 33, and 42 mm per hr. The rate of thawing was approximately the same, 25 mm per hr. The initial dry density of 1.8 g per cu cm (112.4 pcf) was determined before cyclic action and was approximately constant for all the tests. The horizontal surface of the soil near the cooling surface became deeply inclined toward the cooling plate while the average height of the sample continuously increased. Volume changes computed for 1- and 30-mm per hr rates of freezing (Fig. 3) show that the difference in the volume changes for different rates are not as great as in the bottom-up freezing and thawing tests (1, p. 13). This is because of water supply. In the side-freezing test there is not an outside water supply; it is a closed system. It is expected that with an open-system side-freezing cabinet the differences in volume change should be greater under such rates of freezing.

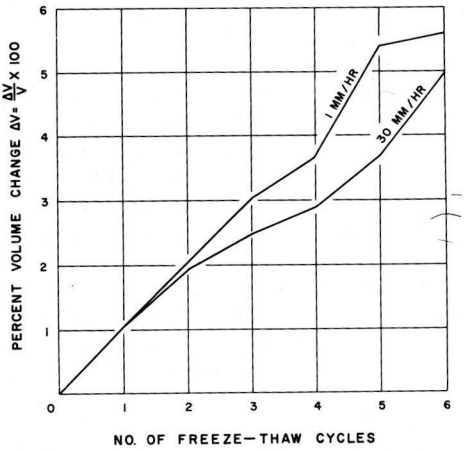

Figure 3. Volume change through six freeze-thaw cycles at two different freezing rates; initial density 1.8 g per cu cm or 112.4 pcf.

After 22 freeze-thaw cycles at 30 mm per hr the sample was divided into nine rectangles 15 by 5 by 2.7 cm. Three layers were taken and each layer included three samples. A grain-size analysis was made on these nine samples and the percentage by weight of particles finer than 0.074 mm was plotted in diagrams (Fig. 4a, b, and c). It was observed that after 22 cycles the percentage of particles finer than 0.074 mm moved steadily away from the cooling plate (Fig. 4a). Also, there is a tendency for the fines to increase from the surface downward. Points having equal percentage of fines were connected. These isograms have a tendency to be parabolic with the axis pointing away from the cooling front. If the samples were smaller, the differences in the amount of fines between extreme planes would become greater. The initial percentage of particles finer than 0.074 mm was 14 percent by weight. This was mixed with other particle sizes in the sample container before conducting the cyclic test. The difference in the percentage of the fraction finer than 0.074 mm before and after the test is a consequence of dry sieving, which gives a smaller amount of fines than the initial percentage mixed (14 percent 0.074 mm). In dry sieving, finer particles cling to larger ones. For the size of samples used, and dry sieving, the difference in fines concentration between the warm and the cold face after cycling is 3.5 percent (Fig. 4a). Fines migrated at a rate of 0.15 percent per cycle.

A second test was performed with sample a-5-2 at the rate of 33.0 mm per hr. The same cabinet was used and the moisture was maintained at saturation. The initial dry density was 1.8 g per cu cm (112.4 pcf). During the freeze-thaw test, it was observed again that soil level close to the plate dropped while at the far side increased slightly in height. After 20 cycles, the sample was divided into 9 rectangular slabs to determine the distribution of particles finer than the 0.074-mm fraction. Again, fines migrating from the cooling plate and from the top down increased. The isograms are inclined toward the cooling plate, but are less inclined than in the preceding experiment with a lower freezing rate of 30 mm per hr (Fig. 4b). Inasmuch as the rate of freezing in this second test was increased to 33.0 mm per hr, it is possible that the inclination of the isograms is a consequence of the freezing rate. More experiments are needed on this matter. The difference in the percentage of the fraction finer than 0.074 mm before and after the test is quite the same. Because this data was obtained with wet sieving this indicates that such sieving is more reliable than the dry sieving performed in previous experiment. The difference in fines concentration between cold and warm faces after cycling (Fig. 4b) is 0.9 percent indicating that fines moved at a rate of 0.04 percent per cycle. The difference in migration between this experiment at 33.0 mm per hr and the previous at 30.0 mm per hr is only a consequence of the sieving method. Wet sieving for this kind of sample is a more reliable test.

A third experiment was made at 42 mm to determine segregation at greater rates of freezing. The initial density 1.8 g per cu cm (112.4 pcf) was approximately the same as in the preceding case. After cycle 20 was completed, although the soil adjacent to the plate dropped 1.7 cm, the over-all height of the sample increased. The sample was cut into nine 15- by 15- by 2.7-cm parallelograms and the percentage by weight of the 0.074-mm fraction was determined. The isograms were more horizontal than in the preceding case, indicating the presence of vertical sorting. With the exception of 17.4 percent close to the freezing plate, there was clear vertical sorting across the sample with a maximum concentration of 18.2 percent opposite the cooling plate (Fig. 4c).

With freezing rates of 30.0, 33.0, and 42.0 mm per hr, the isograms of the finer than 0.074-mm fraction tend to become horizontal as the rate of freezing is increased. It seems that, with higher speed, the particles are knocked down rather than being pushed ahead of the freezing line. More experiments are needed on effect of the rate of freezing.

Samples X1 and X2.—To show the actual migration of particles, a new experiment was set up with two size ranges. At the bottom of the freezing cabinet, a layer was placed with particles ranging between 7.93 and 10 mm in diameter. The coarse particles were placed at the bottom of the container and one-half of this layer was surrounded by uniform sand of size range between 0.71 and 1.00 (X-1, Fig. 5), the other half were surrounded by particles of size range between 0.03 and 0.07 (X-2, Fig. 5). The thickness of the layer was smaller than the size of the coarser particles (7.93 mm).

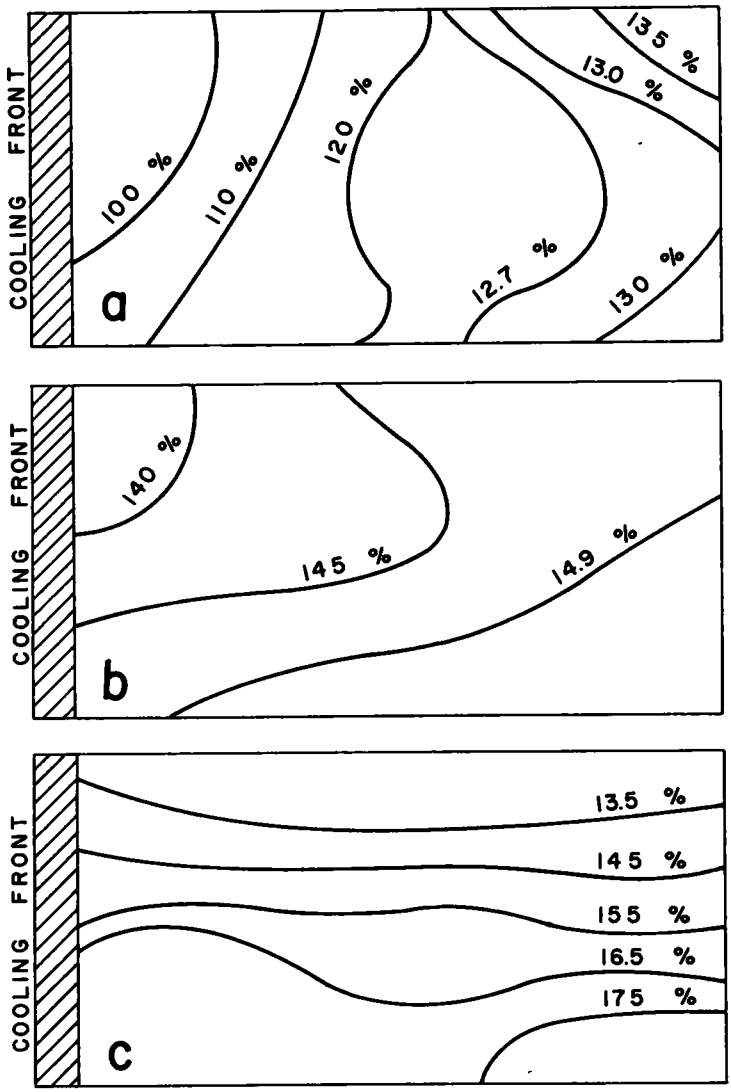

Figure 4. Effect of vertical freeze-thaw plane on distribution of fraction finer than 0.074 mm; closed-system side-freezing cabinet. Rates of freezing at 30.0 (a), 33.0 (b), and 42.0 mm per hr (c) for 22, 20 and 20 cycles, respectively, Sample a-5-2.

Accidentally some of the fines fraction were moved into the coarser material before subjecting the sample to the cyclic freeze-thaw test, as shown in Figure 5. However, the accident proved to be an asset to the experiment. The soil was subjected to 30 freeze-thaw cycles at a freezing rate of 30 mm per hr and pictures were taken at cycles 0, 7, 17, and 30 (Figs. 5 through 8). The cooling side is located at the right side of the picture and the freezing plane moves to the left. By comparing Figures 5 through 8 it can be seen that after 7 cycles the coarse sand which was accidentally moved into the fines has been pushed away from the cooling plate by the freezing front. Also, the white silicrete has moved away from the cooling plate. At cycle 0, only 7 stones were visible; after 30 cycles, 20 more stones can be counted closed to the plate. Fine particles moving from the cooling side cover the exposed stones at the lower half of the box. Of four stones, a, b, c, and d, visible before cycling, only the first (a) remains partly visible after 17 cycles (Fig. 7). The upper part of the coarse-grain sample shows

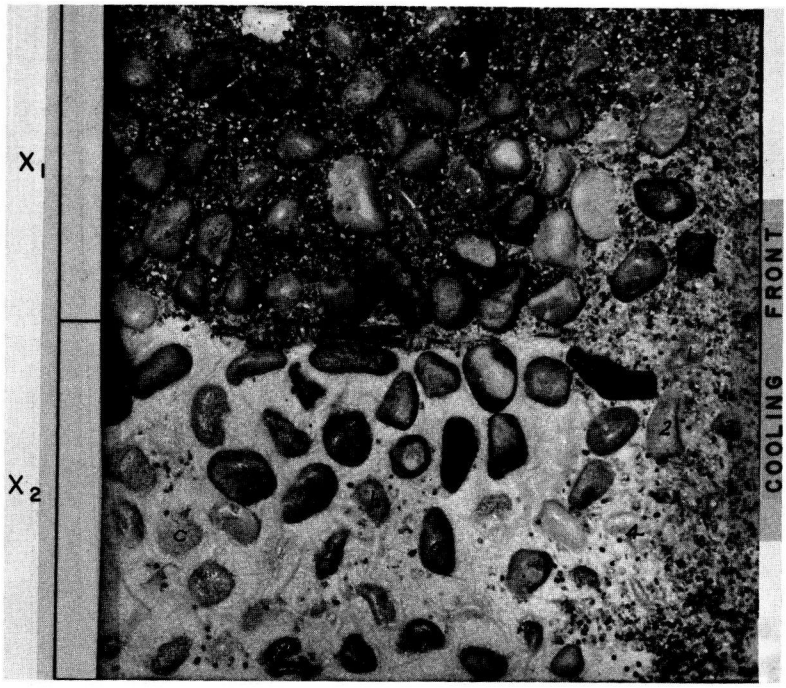

Figure 5. Top view of samples X_1 and X_2 before freeze-thaw cycles.

Figure 6. Samples X_1 and X_2 after cycle No. 7.

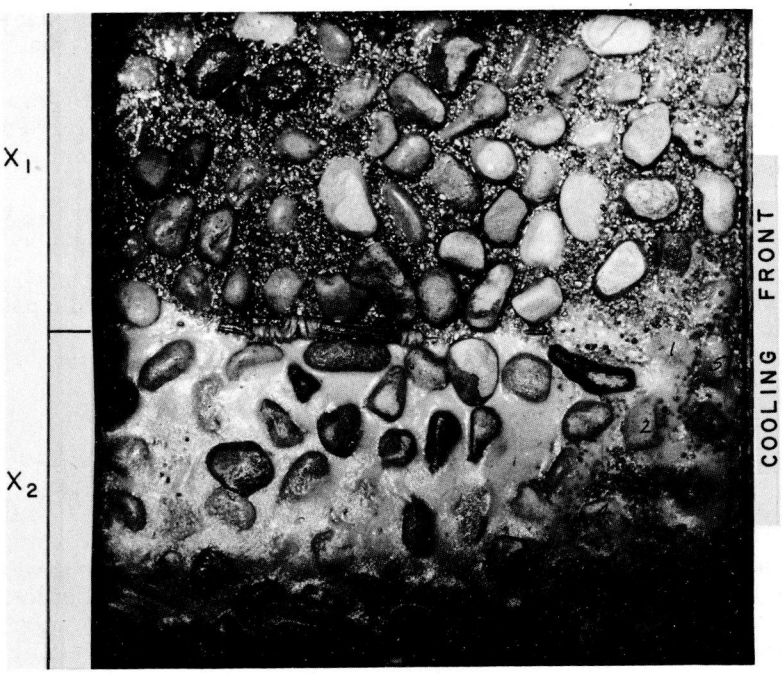

Figure 7. Samples X_1 and X_2 after cycle No. 17.

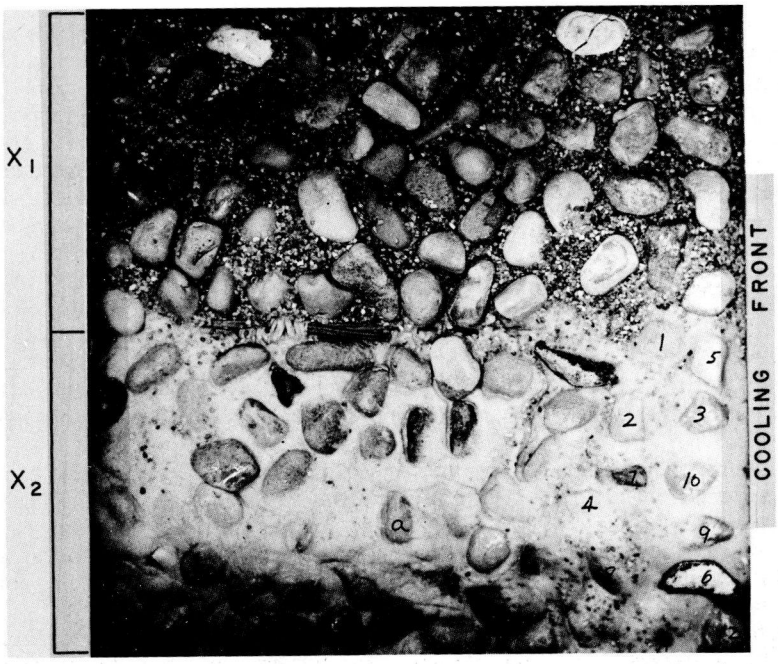

Figure 8. Samples X_1 and X_2 after cycle No. 30.

that the coarser particles are more visible near the cooling plate and that the large particles have moved away from the cold front (Figs. 5 through 8). It may be possible that the coarser particles are heaved at the same time.

The results of this experiment support previous findings that particles move away from the cooling front when the freezing rate is about 30.0-mm per hr. For this experiment the fraction finer than 7.93 mm did move a little at the 30.0-mm per hr rate compared to the finer material. It is likely that lower freezing rates and wider channel openings between particles will aid the movement of the medium size particles.

Mechanics of Sorting.—From the experiments the following conclusions can be derived:

1. Fine particles migrate away from the cooling front in a parabolic path. The downward motion is produced by gravitational forces.
2. Coarse particles between 7.9 and 10 mm also migrated away from the cooling front.
3. The rate of volume change by freeze-thaw cycles for the closed system condition is greater at lower freezing rates than at higher rates.

The mechanics of the sorting phenomenon are not yet fully understood. A few preliminary remarks are given here before a report on the subject. By freezing from the bottom in a laboratory experiment, it is observed that particles tend to migrate or "ride" in front of the ice interface. Particles 3 to 4 mm in diameter have been carried from the top of a saturated soil specimen when the rate of movement of the interface plane was approximately 0.6 mm per hr. For higher rates, the migration of such sizes was not observed. It is expected that each particle size requires a certain rate of movement of the interface in order to be moved. While this report was being revised, the movement of different sizes and shapes of particles at different rates of freezing has been investigated in the laboratory (7).

The following is a summary of the experimental information on the mechanics of sorting obtained from this report and from the previous one (1).

In top-down freezing, coarse particles heave because of either ice lens or expansion by the change of state of water; fines migrating in front of the freezing plane will gravitate (Fig. 9) into the void left by the coarse particles. For the top-down freezing and thawing, coarse particles move up and fines move down (1).

For side freezing, laboratory experiments show that coarse and fines migrate away from the cooling front (Fig. 10). Fines migrate more than coarse particles.

For a better understanding of the movement of particles in the bottom-up freezing, it is necessary to observe the unfrozen soil away from the freezing plane as well as the frozen part. Experiments with freezing from the bottom show that, although the lower part of the soil sample is being frozen, coarse particles are extruded from the unfrozen part of the sample at the surface. There is a concentration of fines at the interface where fines coming down from the unfrozen part are coalescing with fines going up in front of the freezing plane. This sorting is produced mechanically and is observed in the unfrozen soil when the freezing line is in the lower part of soil specimen. For the present experimental setup and by freezing from the bottom up, it is possible to say that mechanical sorting prevails over sorting by migration in front of the freezing plane. Therefore, two kinds of sorting by freezing are differentiated: (a) sorting by migration of particles in front of a moving freezing plane (this kind of sorting is observed when freezing proceeds from the top and the sides), and (b) mechanical sorting produced when freezing from the bottom up.

It can be concluded that soil particles tend to become sorted because of a tendency for the ice to exlude the particles that are in front of the growing ice. The size most likely to be excluded is the one that can migrate in the openings of the pores. It is envisaged that the migration rate of a certain particle size depends on the movement rate of the interface plane where the particle is riding. Experiments in progress are proving the validity of this concept (7).

Volume Change.—In Part I (1) it was demonstrated that sorting by sieving heterogeneous mixtures produces volume changes; for the case of straight-graded samples, there is a clear relationship between the volume changes and the uniformity coefficient of the sample (Fig. 11). If the gradation of the sample is linear, then (1, p. 15)

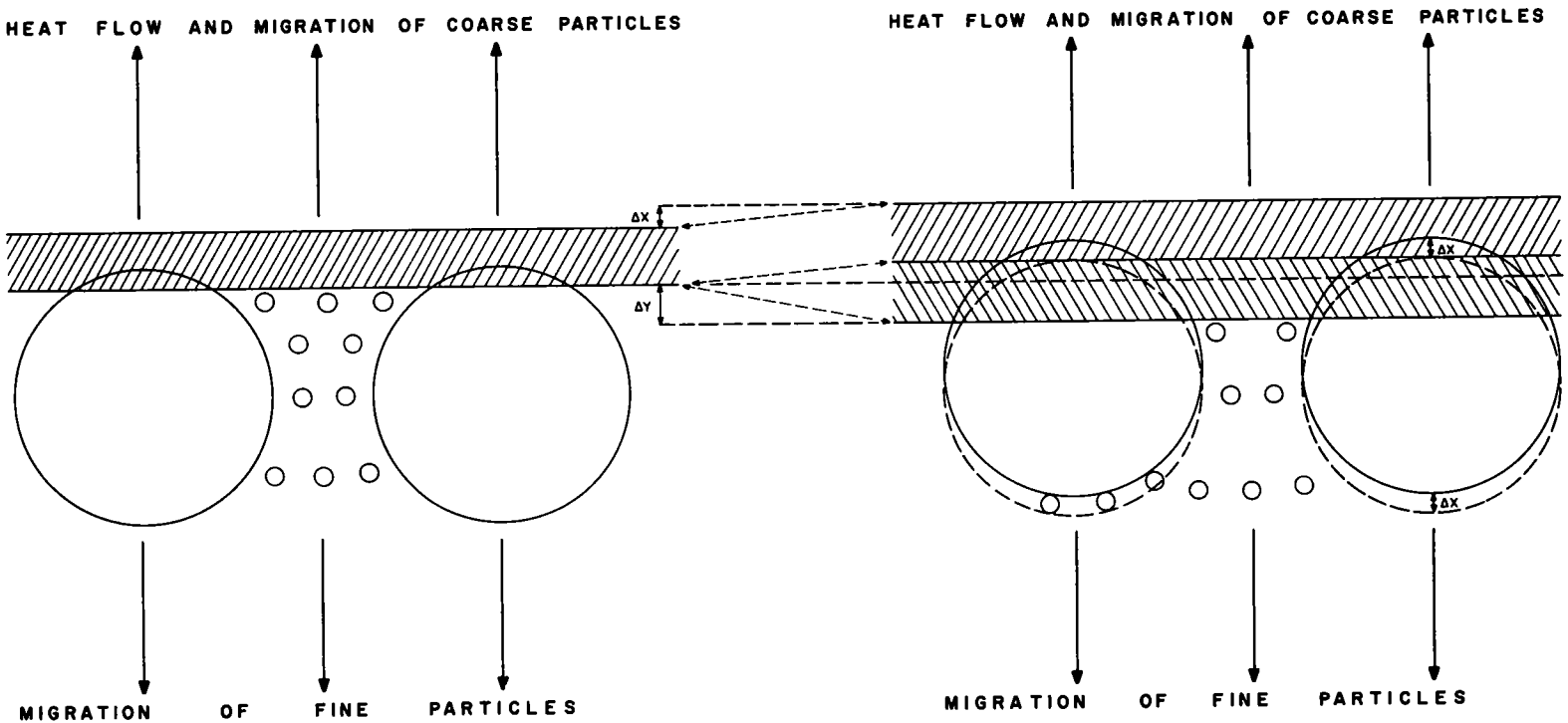

Figure 9. Sorting produced by horizontal freezing plane moving from the top down. As coarse particles are pulled up by freezing, fines migrate downward to voids left by coarse particles.

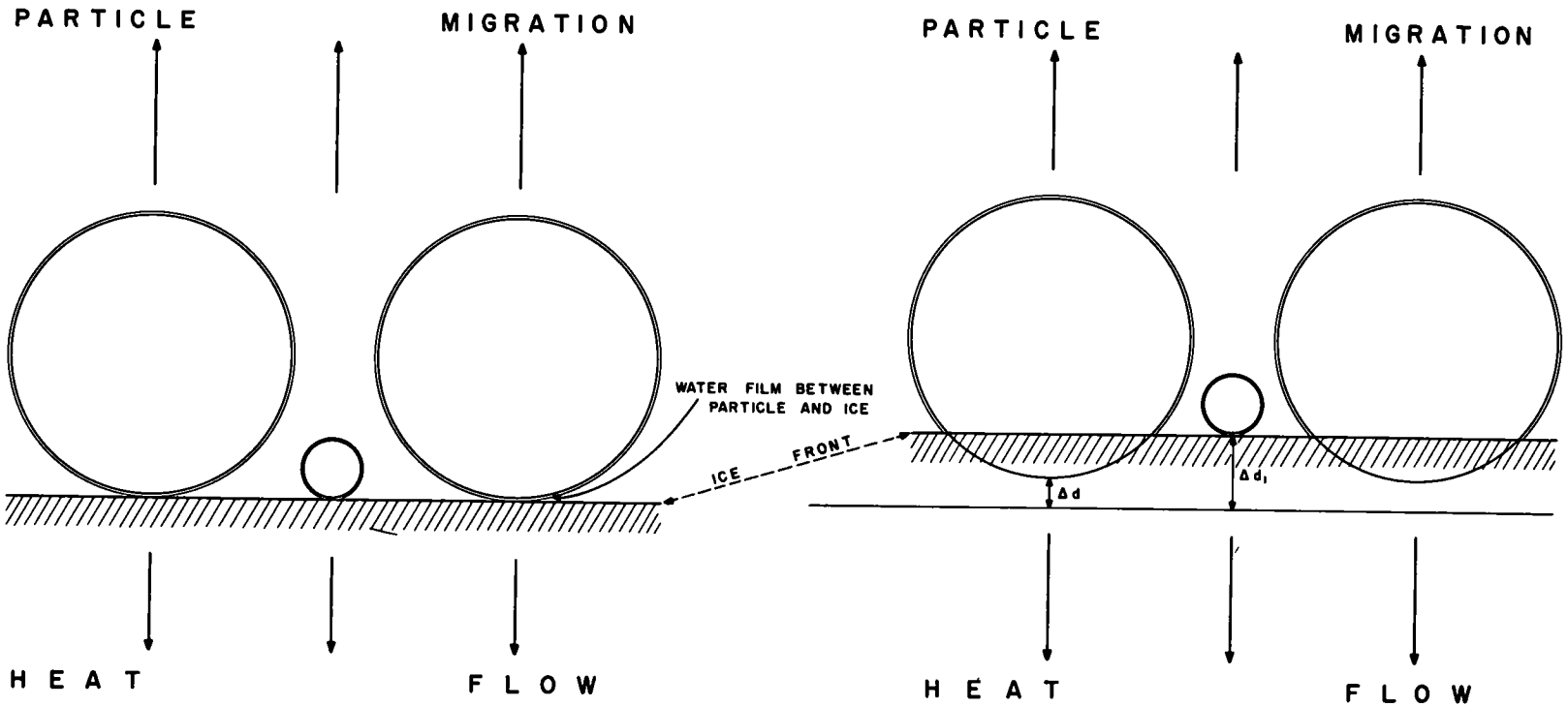

Figure 10. Sorting produced by vertical freezing plane.

$$\Delta v = a + b\,(\log C_u)$$

in which

$$\Delta v = \text{volume increase}$$

$$C_u = \frac{D_{60}}{D_{10}}$$

$$\Delta v = 1.000 + 0.19075\,(\log C_u)$$

An increase in the maximum size of the particles in the mixture by a factor of 10 produces an increase in volume of at least 10 percent.

FIELD DATA

Horizontal sorting in the arctic and high mountains is shown by a segregation of like-size particles in soils formed from bedrock, glacial and alluvial deposits. This segregation is manifested at the soil surface by small circles or "islands" of fine material surrounded by coarser particles. The diameter of the islands of fines ranges from 10 cm (Fig. 12) to several meters (Fig. 13), and the surface may be flat, dome-shaped, or depressed. Islands of fines can be isolated or more closely spaced (Fig. 13). When the islands are closely spaced, the coarse part has a polygonal pattern (Fig. 14). Segregation in flat, saturated areas often produces circular patterns; sorted features on a slope tend to become elongated (Fig. 13).

From surface inspection, it appears that these segregated features can be produced in materials with or without fines. Inasmuch as grain-size composition is one of the most important variables in soil frost action, the first step in field work is to determine the range in grain size needed for segregation.

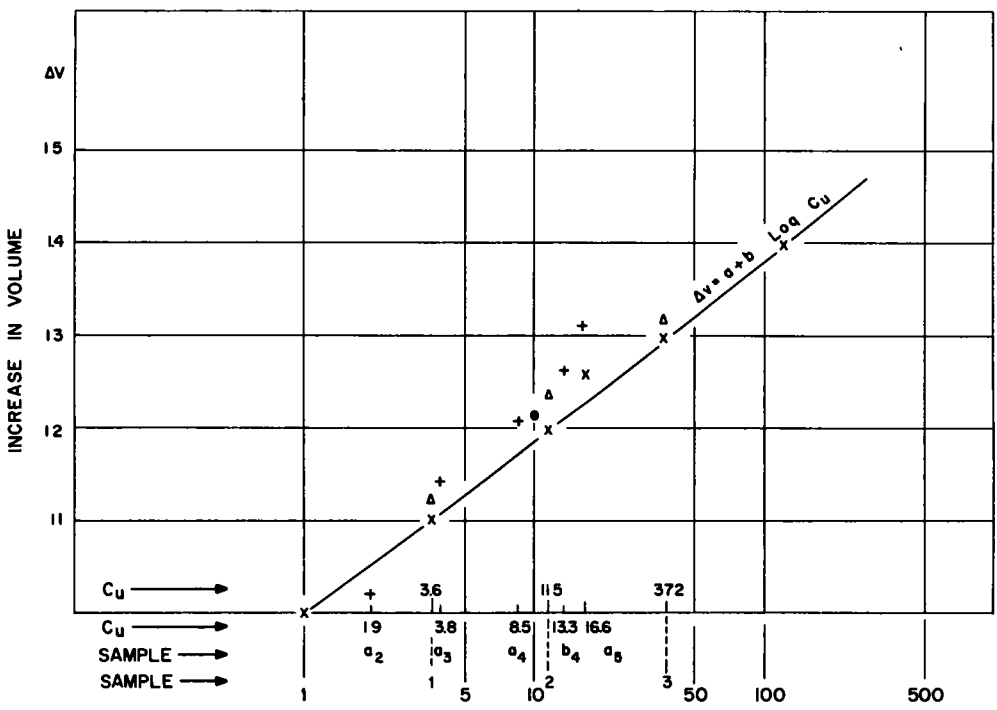

Figure 11. Relationship between volume changes and uniformity coefficient in straight graded samples. Triangles are volume change obtained with sand samples from Lake Michigan shore. Crosses are values obtained with commercial sands. Black dot is sample of glass beads. X on straight line is the 10 percent increase in volume for each 10-mm increase in maximum particle size.

Field data were obtained at the border of the ice cap near Thule, Greenland, where this segregation process has taken place in river-transported materials, moraine deposits, and residual soils. Field data presented here deals especially with transported materials. For clearness and simplicity, it was decided to analyze isolated cells that exhibited variations in their grain-size composition. Eight sorted circles with diameters ranging from 20 to 100 cm were analyzed.

For the analysis of each center of fines, samples were taken from concentric rings with the origin in the center of the circle for the horizontal plane and from equal layers at 20-cm depth intervals for the vertical plane. Alternate layers were taken for vertical sampling and are represented as follows: A, 0-20 cm; C, 40-60 cm; E, 80-100 cm; and F, 100-120 cm. However, for coarser materials, layers were taken at 33.3-cm intervals from 0 to 100 cm.

A grain-size analysis was made on eight sorted circles and all showed horizontal and vertical sorting. Of the eight circles analyzed, three with varying amounts of fines are discussed: Sorted circle No. 3, Figure 15; No. 1, Figure 16a and b; No. 8, Figure 17.

The horizontal and vertical sorting is expressed as the average grain-size value (median value taken from grain-size curves) at different distances from the center of the sorted area (Figs. 18, 19, 20). Because samples were taken at different depths and distances from the center of fines, horizontal and vertical sorting can be determined at any point in the sorted feature. Vertical sorting is expressed as the average grain-size value (median value) for different layers (Figs. 21, 22, 23).

In all three sorted circles analyzed, horizontal sorting shows a maximum at the surface and decreases downward (Figs. 18, 19, 20). Vertical sorting increases with distance from the center of fines (Figs. 21, 22, 23). Computation of the average grain-size value shows that these sorted features are developed in materials which contain 0.1, 1.0, and 2.5 percent by weight particles finer than 0.02 mm (Fig. 24) for sorted circles 8, 1, and 3, respectively, with uniformity coefficients of 10, 428 and 182, respectively. Comparing the grain-size curves with the Beskow frost-susceptibility curves shows that vertical and horizontal sorting occur in the zone of negligible ice segregation or non-frost heaving.

The distribution of the fraction finer than 0.074 mm (No. 200 sieve) in sorted circles 1, 3, and 4 was measured, and the points having equal percentages were connected (Figs. 25, 26, 27). The percentage increases toward the center and downward. The isograms indicate that when horizontal sorting is present, vertical sorting takes place, (Figs. 25, 26, 27). In the case of sorted circle No. 4 (Fig. 27), the finer fraction has risen to the surface and is flowing over it. From this field data, it is possible to make the following conclusions:

1. The horizontal plane of sorted features shows an increase in particle size from the center out, and the vertical plane shows a decrease in particle size downward producing the phenomena called vertical and horizontal sorting. Horizontal sorting is a two-dimensional phenomenon in which sorting is produced along the two directions—horizontal and vertical.

2. The grain-size range where this process has been observed is in the range of "nonfrost-susceptible soils."

CORRELATION BETWEEN LABORATORY AND FIELD DATA

Laboratory experiments show that a soil subjected to a horizontal and vertical freeze-thaw plane will produce vertical and horizontal sorting. Therefore, vertical and horizontal sorting of the active layer has to be produced by a horizontal and vertical freeze-thaw plane. This condition will be present when there are variations in the grain-size distribution in the layer that freezes and thaws. The variations may be produced by original deposition and vertical sorting. Because of the greater heat conductivity, large particles extruded at the surface of soil will freeze before finer ones surrounding them. This will cause a vertical freezing plane around the larger particles. The result will be a migration of fine particles away from the coarser ones. As this migration takes place, the soil under the coarser particles will sink and the soil into which particles migrate will heave.

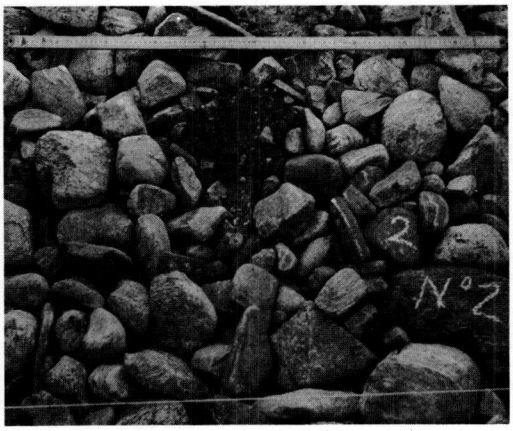

Figure 12. Sorted circle 2.

Figure 13. Air view of sorted circles in Thule area.

Figure 14. Closely spaced sorted circles.

Figure 15. Sorted circle 3.

Figure 16. Sorted circle 1 (a) before excavation for sampling, (b) after removal of outer coarse particles showing layer of finer particles beneath.

Vertical sorting is obtained in the laboratory by freezing from the top, the bottom, or both top and bottom whereas horizontal sorting is produced by side freezing. It is expected that horizontal and vertical sorting may be found in areas of seasonally frozen ground where the ground freezes from the top and from the sides only. Whenever different points in a layer begin to freeze with a horizontal thermal gradient, the finer fraction will tend to accumulate. These centers of fines may be dome-shaped (Fig. 15), flat (Fig. 14), or depressed with respect to the coarser areas.

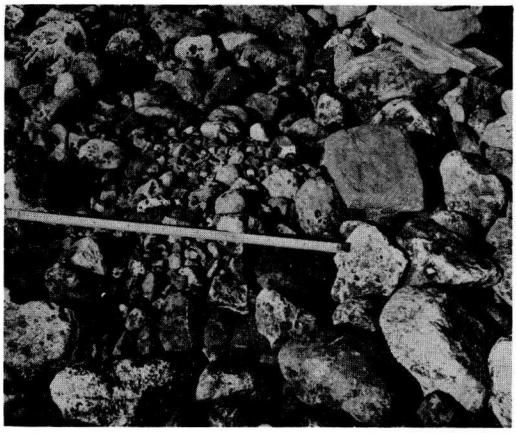

Figure 17. Sorted circle 8 developed in sand and gravel without fines.

Figure 11 shows that sorting of straight samples with a uniformity coefficient between 100 and 400 can produce volume changes between 35 and 45 percent. From this, in circles No. 1, 3, and 8 (Fig. 24) with C_u 428, 182, and 10, respectively, sorting can produce volume changes of 43, 42, and 18 percent, respectively. The volume changes in nature can be more readily compared to the volume changes shown in Figure 11 if sample gradations are straight as in sorted circles No. 1 and 3 (Fig. 24). According to the volume change uniformity coefficient criteria, sorted features 1 and 3 have increased in volume up to 45 percent since the feature started to develop. Volume change can be a phenomenon of vertical and horizontal sorting. Because this sorting occurs in a heterogeneous material about 1 m thick with a C_u between 100 and 400, volume changes of 35 to 45 percent have to be expected.

In the present experimental set-up, a "closed system" cabinet with a limited water supply was employed. The freezing rates used between 30 and 42 mm per hr are too

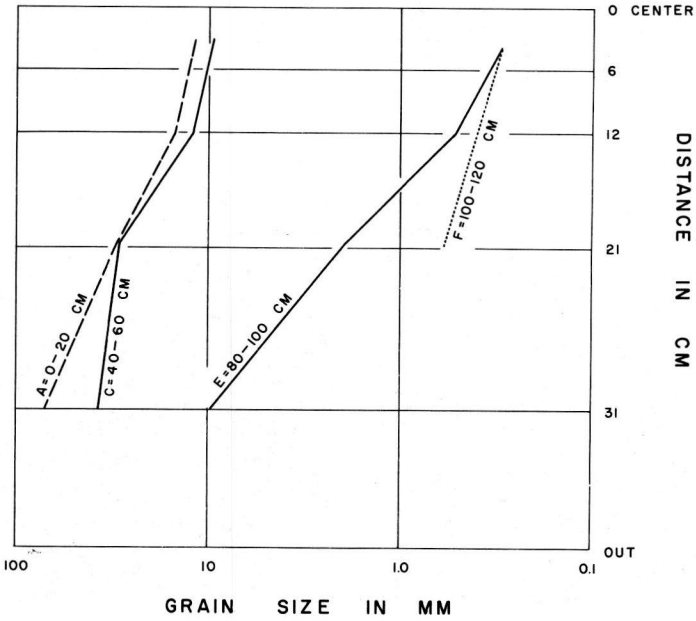

Figure 18. Horizontal sorting in circle 1 expressed as average grain size (median value) for different depths and distances from center of sorting.

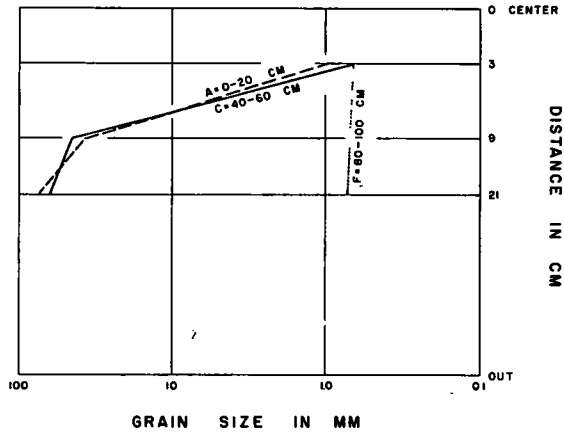

Figure 19. Horizontal sorting in circle 3 expressed as average grain size (median value) for different distances and different depths starting at center of sorting.

high compared to the freezing rates of the active layer. Taylor (8, p. 189) reported freezing rates in the order of 2.4 mm per hr within the active layer in the Thule area. K. A. Linnel (USA CRREL, personal communication) stated maximum rates of freezing in the order of 12 mm per hr for the upper part of the active layer. Part I of this report showed that particles segregation is greater at slow rates of freezing for top down

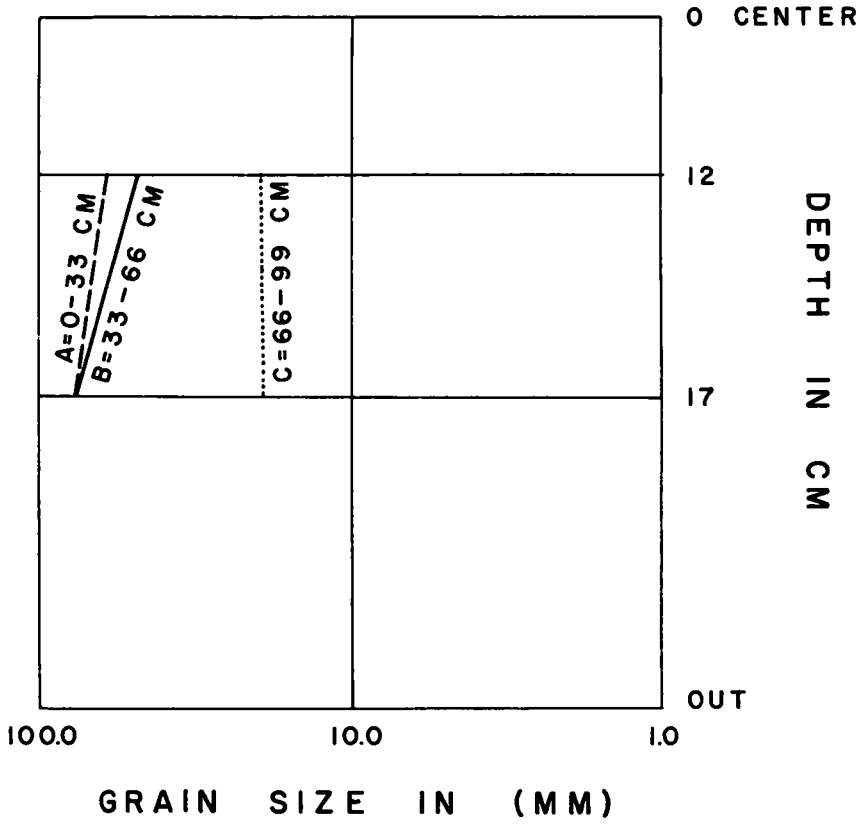

Figure 20. Horizontal sorting in circle 8 expressed as average grain size (median value) for two different distances and different depths starting at center of sorting.

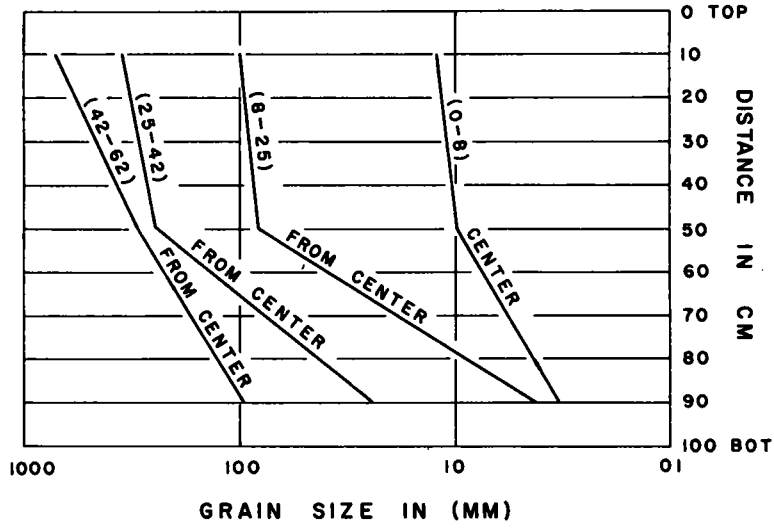

Figure 21. Vertical sorting in circle 1 expressed as average grain size (median value) for different depths and distances from center of sorted circle.

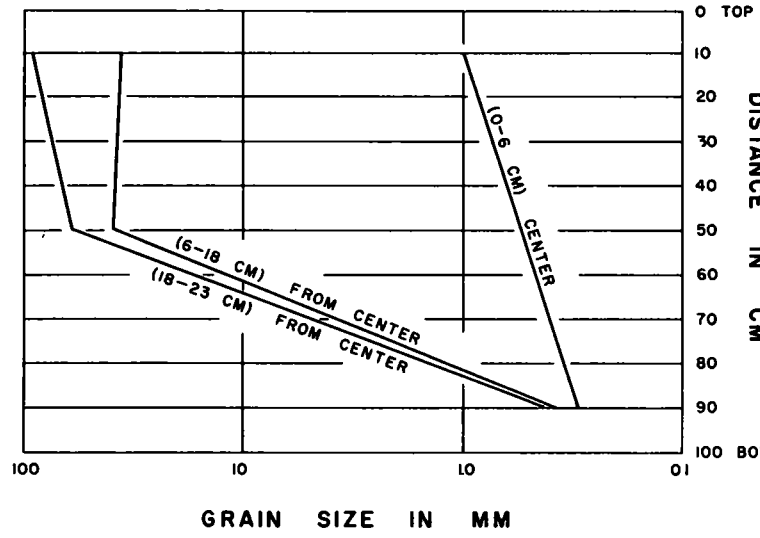

Figure 22. Vertical sorting in circle 3 expressed as average grain size (median value) for different depths and different distances from center of sorted area.

and bottom-up freezing (1, pp. 4, and 13). It is therefore clear that also in the side-freezing cabinet segregation will increase with a decrease of the freezing rate. Inasmuch as segregation of particles must be a direct function of the amount of water available at the freezing plane, it should increase as the moisture supply is increased. Therefore in an "open system" cabinet with an unlimited water supply, segregation of particles should be greater than in a "closed system" cabinet. The present experimental set-up shows segregation of particles regardless of a limited water supply and high rates of freezing. It is predicted that segregation of particles should increase with an increase of the moisture supply and decrease with an increase in the rate of freezing. While this paper was being revised, data became available on the segregation

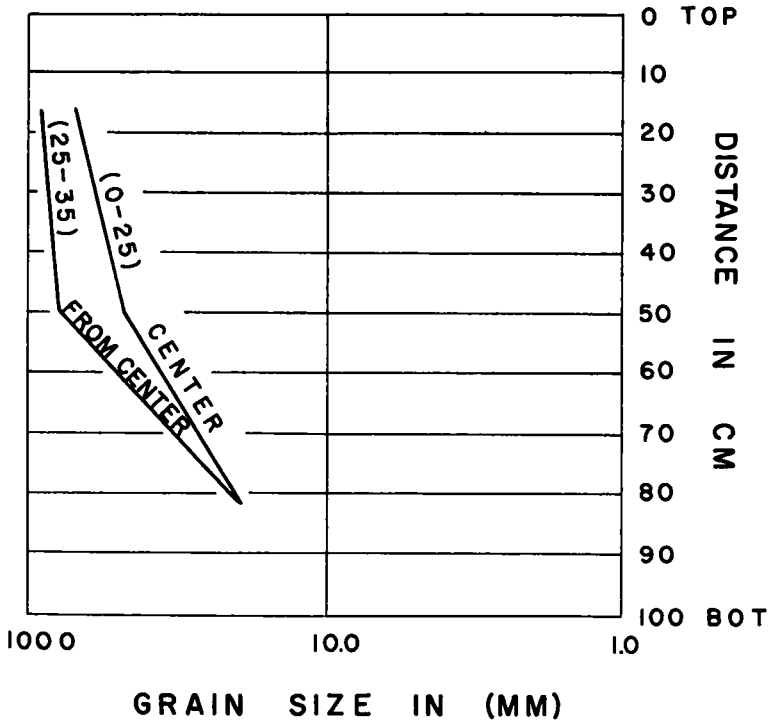

Figure 23. Vertical sorting in circle 8 expressed as average grain size (median value) for different depths and distances from center of sorted area.

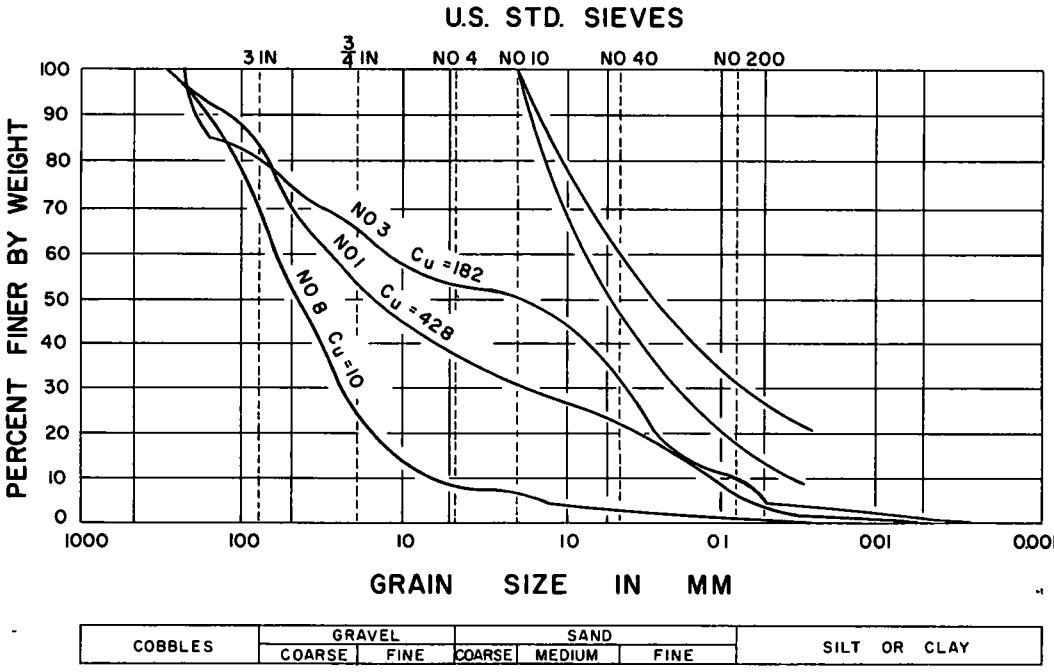

Figure 24. Average gradation curves for sorted circles 1, 3, and 8 for the active layer 0 to 100 cm in depth. Solid line curves are Beskow's frost susceptibility.

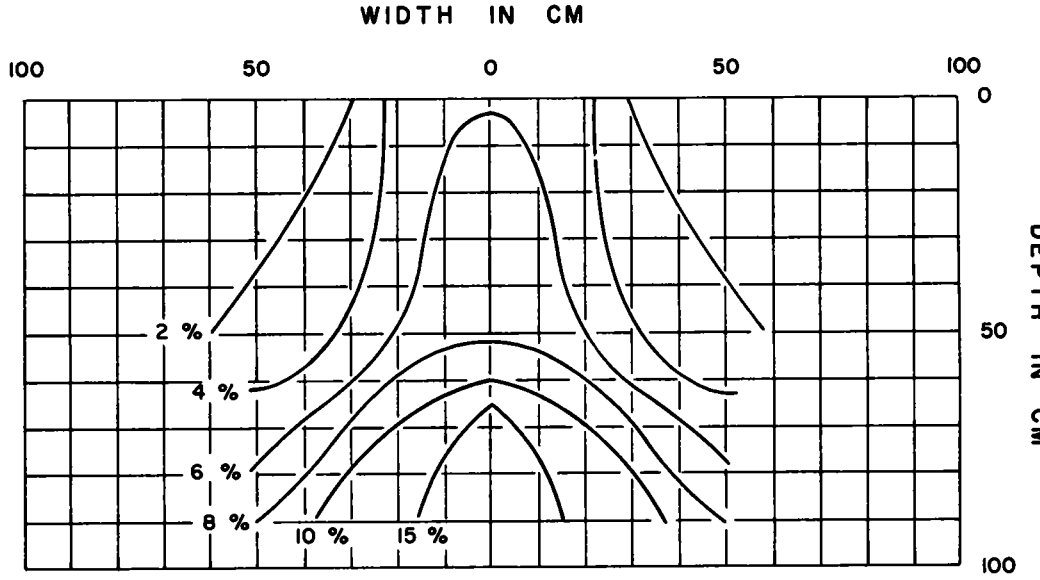

Figure 25. Distribution of equal percent of material finer than No. 200 sieve in sorted circle 1 between 0- and 100-cm depth.

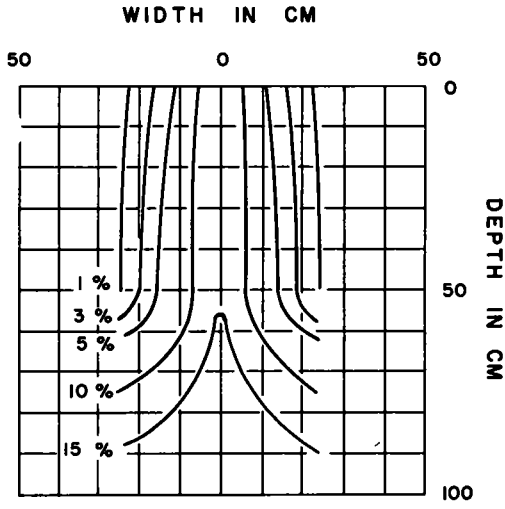

Figure 26. Distribution of equal percent of material finer than No. 200 sieve in sorted circle 3 between 0- and 100-cm depth.

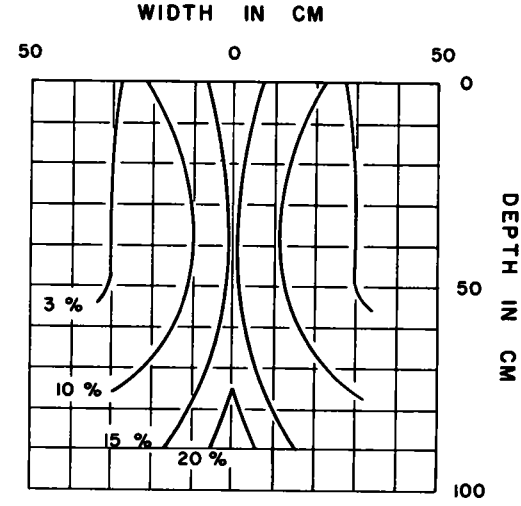

Figure 27. Distribution of equal percent of material finer than No. 200 sieve in sorted circle 4 between 0- and 100-cm depth.

of particles in front of a moving freezing plane (7) confirming the validity of this statement.

CONCLUSIONS AND RECOMMENDATIONS

Laboratory and field studies indicate that a heterogeneous mixture of grains tends to become vertically and/or horizontally sorted when subjected to alternate cycles of freezing and thawing under saturated conditions. Sorting is observed in soils with or

without fractions finer than 0.02 mm. At the present time, engineering standards consider the latter "nonfrost-susceptible." The active layer where such sorting is observed freezes from the top, the sides, and slightly from the bottom up (8, and A. Poulin, oral information). Therefore, the presence of horizontal and vertical sorting in the active layer is attributed to a vertical and horizontal freeze-thaw plane. In natural conditions, horizontal sorting starts around large particles where a vertical freeze-thaw plane is produced. Inasmuch as vertical sorting is obtained by freezing from either the bottom or the top, horizontal sorting is caused by freezing from the sides. It is expected that vertical and horizontal sorting exist outside permafrost regions in areas of seasonal frozen ground where the ground freezes from only the top and sides.

Laboratory experiments performed in a closed system with a vertical freeze-thaw plane demonstrated that particles migrate from the cooling side in a parabolic path. The path is parabolic because of the gravitational forces acting on the particles. As in the case of the inverted open system, the volume changes for the closed system are greater at lower freeze rates. The freezing rates used seem too high for natural conditions. Because it has been demonstrated that segregation is an inverse function of the rate of freezing, it is predicted that lateral segregation should increase if the freezing rate decreases, when a side-freezing "open system" cabinet is used.

On the basis of cyclic experiments in which freezing and thawing proceeds from the top, bottom, and sides, a general principle of sorting which is presented is a function of the rate of freezing and gravitational forces and independent of the direction of freezing. This principle implies that the finer fraction of a mixture tends to move away from the cooling front riding in front of the interface. Therefore, fines move down when freezing is from the top, and move laterally in a parabolic path when freezing is from the side. Upward movement is impeded by gravitational forces when freezing is from the bottom up. When freezing is from the bottom, it has been found that, while the lower layers are being frozen, fine particles move toward the bottom and coarse particles move toward the top of the upper unfrozen layer; therefore, in the light of these experiments, two kinds of sorting are differentiated: (a) sorting by freezing when particles migrate in front of the freezing plane (top and side freezing) and (b) mechanical sorting is produced by disturbance in the upper unfrozen layer while the lower parts are being frozen (bottom-up freezing). Such sorting is inverse of the sorting by migration in front of the freezing plane.

Based on preliminary experiments, the segregation phenomena can be tentatively explained by a tendency for the ice to exclude particles located in the growing front of the ice. It is predicted that the particle size that can migrate depends on the rate of movement of the interface plane where the particles are riding.

Experiments indicate that sorting produces volume changes which are a function of the uniformity coefficient of the soil among other factors. According to this research, vertical and horizontal sorting in soil with a uniformity coefficient C_u between 100 and 400 will produce volume changes between 35 and 45 percent. This research provides the tools for the explanation of areas of fine particles surrounded by coarser ones in the active layer and in seasonal frozen ground. A separate report will treat this problem.

It is recommended that particle migration caused by side freeze-thaw cycles be studied for engineering application in certain types of construction. Research indicated that the soil adjacent to a retaining wall will have a tendency to become less "frost susceptible" as fines migrate away from the cooling surface. A road embankment will tend to become more "frost susceptible" as the fines migrating from the sides towards the middle cause the possibility of a greater differential heaving in the transverse plane.

It is recommended that a new criterion for frost behavior be established that takes account of the effects of freeze-thaw cycles under field conditions with a large range of particle sizes. More research is needed to determine (a) rate of movement for different particle sizes; (b) rate of volume change caused by vertical and horizontal sorting; (c) effect of a fluctuating water table on particle-size migration after thawing; and (d) effect of rate of freezing on sorting different grain-size gradations.

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