Growth and Development of Perturbations on the Soil Surface due to the Repetition of Freezing and Thawing*

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Abstract

Model experiments for making clear the processes in earlier stages of mound formation on the ground in arctic climate were carried out with a homogeneous soil bed in a container of 67 x 42 x 15 cm. The soil was put with very smooth surface up to the thickness of 7～10 cm. Repetitions of freezing and thawing, of which one cycle took about 10 days, gave rise to increasing perturbations on the ground. Degree of perturbations were measured by the number of contour lines and also by the standard deviation of the heights of soil surface. These two indices increases linearly with the number of cycles. No habituation of the mound at certain spots on the soil was observed as far as the number of cycles did not exceed five. Importance of differential effects with soils of different kind was made clear by observations on deformations and interactions of soil masses imbedded in the matrix soil in a shape of transversal bank. Some recommendations for further experimental researches are given.

Introduction

Although there are many variations in the types of patterned grounds, one of their remarkable features is that they exhibit convex surface shape in the center of individual unit of the pattern. When the convexity increases, the features are often called by their own name like frost hammocks or frost mounds. It is believed that the features are developed by annual repetition of freezing and thawing of soil in the active layer of permafrost

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or in subarctic earth surface, and that processes of the development naturally take very long time. Therefore, there have been some trials of simulating the processes in laboratory for making clear the mechanisms of mound formation. Purposes of laboratory model experiments are both to shorten the time required to reach the remarkable effect and to make the scale of experiments small. These two requirements are related each other by similarity laws derived from some fundamental equations which govern the processes. In addition, the laboratory experiments can be designed to separate various factors affecting the phenomena. This merit is often one of the purposes of model experiments in laboratory. A similarity law was derived only by considering thermal processes in solifluction phenomena (Corte and Higashi : 1971) and this can be applied to the present experiments.

The present experiments aimed to extend small scale experiments by one of the authors (Corte: 1967 and 1969) to a larger scale. The former were carried out in a scale of 31.5 x 24.5 cm widths and 3 cm depth of soil under rapid alterations of freezing and thawing. Since it was feared that there might be an end effect on the experiment in such a small container and also an effect of unevenness of soil layering of such thin layers (1 cm each) of three different soils, the present experiments were carried out in a larger container with thicker soil of very homogeneous initial packing. In this way, it was tried to make clear the initial stage of mound formation, or the growth and developments of perturbations on the initially flat soil surface under repeated freezing and thawing.

Mechanisms of formation of convoluted structures observed in developed mounds in the former experiments were examined from different approach; observations of deformation of the imbedded soil masses of different types in the homogeneous matrix soil and interactions occuring at the boundaries.

Experimental Procedures

The soil used for the experiments was a very frost-susceptible brown loam (sieved with 1 mm mesh) originated from volcanic ash near Tomakomai area, Hokkaido. It's size distribution curve is given in Fig. 1 together with other kind of soils used for observations of differential effect. The soil was put in a container of which dimensions was 67 x 42 x 15 cm, at first filled homogeneously with dry soil and then the water was soaked from the bottom plate to the water reservoir underneath. Very thin (1 mm) layer of black soil was inserted at a depth of 30 mm from the top, whereas the total thickness of the soil was about 100 mm in the first series and 70 mm in the second. Section view of the container and the soil is illustrated in Fig.2.

Freezing and thawing of the soil were repeated with cooling and warming of air temperature in a freezing cabinet which covered the soil container as is shown in a photograph of plate I. Air temperature was lowered in gradual steps by means of a regulator switch that controlled the value of refrigerating coil and it was risen in the same way with a help of electric heating tape stretched in the cabinet. The average rate of temperature lowing was 2° to 5° per day. The lowest air temperature, approximately $-13^{\circ}C$ was attained in 3 days after it is lowered below $0^{\circ}C$ and it is kept during a period of 2 or 3 days. Following this, the air temperature was risen at the almost same rate as the lowering and kept at about $+20^{\circ}C$ until the complete thawing took place. Therefore, one cycle of the freezing and thawing took approximately 10 days or a little longer.

Soil temperature records through thermocouples imbedded in certain depths in the soil enabled us to draw temperature depth profiles from which we could estimate the freezing interface in the soil at any time. Frost heaving was observed by naked eye from a window of the freezing cabinet. One example of a diagram which shows temperature change in air, freezing line penetration and frost heaving is shown in Fig. 3. Inverse correlation between the time rate of frost heaving and the time rate of freezing line penetration, described by one of the authors (Higashi: 1958) is clear. Modes of ice segregation at the top or in the layer near surface were pure ice filaments and/or ice filaments containing soil particles. Features on the soil surface at the beginning, after one cycle, during freezing and at the final of series II experiments are shown in 4 photographs in plate II.

Perturbations on the soil surface was determined by measuring the heights of the surface at 126 lattice points on a grid with 5 cm spacings layed on the surface as shown in Fig. 4. The measurement was made manually from the standard horizontal line on the top edge of the container and the measured values were directly used to express the height of soil surface. Therefore, the smaller the value, the higher the height. These values of the height at the lattice points made it possible to draw contour lines on the map as is shown in Fig. 4. Deformations of imbedded different soil masses and their interactions with the matrix soil were examined in cross sections as well as the change of level of thin sheet of black soil inserted at the depth. These cross sections were revealed by digging soil at the end of each series of experiments.

Results of Experiments

Two series of experiments were carried out ; the series I with imbedded banks of sand and black soil, the series II with those of sand and blue clay. The contour lines shown in Fig. 4(0) are of the surface just before the first freezing in the series I experiments. There was a gentle slope which made 2 mm difference between the front and rear parts of the soil surface smoothed in level in the container. Fig. 4(1), (2), (3), (4) and (5) are the contour maps of 2 mm intervals after 1st to 5th cycle respectively. They clearly show that the perturbations on the soil surface began to grow with the first freezing and thawing and developed with repetitions of the process. It is clear that the differential frost heaving and thawing at the sand bank and black soil bank affected the height of perturbations. Especially the sand made more effect since it was upset partly as will be described in detail later. A similar tendency of growing and development of perturbations was obtained in the series II experiments as is shown in Fig. 5.

Since the number of experiments in each series were not enough (5 for series I, 3 for series II), there did not appear the habituation of hillocks or depressions at certain points on the surface. There are, however, good indices to indicate the degree of perturbations ; number of contour lines and standard deviations of the average value of soil thickness. The former can be evaluated by counting number of contour lines in a grid of 5 x 5 cm^2 on the map like Fig. 4(0) and calculating mean values on whole area. This index should express the average steepness of the perturbations on the surface. The latter is obtained from the measured values of thickness at lattice points of the grid. Values only in the central part of the container were used for this purpose to avoid the effect of soil masses of different type imbedded near the both ends of the container. Histograms of the measured values divided in every 2 mm for the series I are shown in Fig. 6. It can be seen that the histogram which originally had sharp peak at its average became dull and flat as repetitions of the cycle proceeded. The standard deviation of the heights of the soil surface was calculated with each measurement after every cycle. In Fig. 7(a), the average number of contour lines and the standard deviation of the heights were plotted against to the number of cycles for the case of series I. The same for the series II is Fig. 7(b). The two indices both increased linearly with the number of cycles but they seem to be saturated at or near the 5th cycle.

Deformations of the different soil masses and their interactions with the matrix soil are shown in Fig. 8(a) and (b) as changes of the cross-sectional shape of the imbedded bank at various distances from the end. Remarkable features common for any of different soils are the cross-section spreaded in width and entrained into the matrix soil at or near the bottom of the bank. In the case of series I experiments, the sand bank gradually tilted and finally upset nearly 90^{0} in the middle part of the bank as is illustrated in Fig. 8(a). Thin sheet of black soil showed only gentle change in level, although the freezing line penetrated deeper beyond this lavel. One cross section of this black soil mark is illustrated in Fig. 9.

Conclusions and Recommendations

Since each cycle in one series of experiments took relatively longer time than in the case of smaller scale experiments carried out by one of the author (Corte : 1967 and 1969), number of cycles in the present experiments were not enough to obtain any definite conclusion on the long term processes of mound formation, especially on the habituation of growing mounds at the same spots on the soil surface. We obtained, however, some important knowledges on the initial stages on the growth and development of perturbations on the soil subjected to repetitions on the freezing and thawing.

The standard deviations of the ground surface and the number of contour lines per unit area are both good indices to indicate the degree of perturbations. They both increase linearly with the number of cycles, up to 5th cycle when we start with a very smooth surface. Probably the number of cycles at which such indices reach the certain level should be related to the amount of frost heaving, rate of thawing and consistency of wet soil. In this case, strong occurence of frost heaving by ice filaments on and in the soil might have accelerated the effect. If there is no action of ice filaments or strong segregation of ice, processes of growth and development of perturbations should be much slower as was the case of smaller scale experiments.

As was described in our previous paper on a model experiment of solifluction (Higashi and Corte : 1971), selection of the dimensions and time scale should be based on a similarity law derived from fundamental equations governing the phenomena to be investigated. If we only take the differential equation for heat conduction as the fundamental equation and consider that the same soil was used, a simple nondimensional equation should hold for the ratio of both time t and depth of soil x in model and nature as follows,

$$\frac{t_m}{t_n} = \left(\frac{x_m}{x_n}\right)^2$$

where the suffix m and n correspond to the model and nature respectively. If we assume that the actual freeze-thaw cycle is 6 months (180 days) as was done in our previous paper, 7 days cycle in the present experiments reduces 30∼40 cm for the freezing depth of soil in nature corresponding to 5∼7 cm freezing depth in model. It so happened that the 3 cm depth of soil in a small scale experiment by Corte (1967) with 1 day cycle also gives approximately 40 cm depth in nature. Therefore, there is no difference in similitude between these two model experiments as far as the problem is only concerned in heat conduction. However, since the rate of freezing in the smaller experiment was much faster than in the present larger scale experiments, the modes of freezing should be different; probably concrete type freezing in the former whereas ice filaments layers in the latter. It should be noticed that the difference in modes of freezing is also due to the nature of the soils. Anyhow, this difference should reflect to the degree of perturbations on the soil surface in each cycle and give rise to the difference on the number of cycles required to observe remarkable development of perturbations.

Deformations and interactions of different soil masses in the matrix soil are due to the differential frost heaving and thawing between the soils. Since the matrix soil is the most frost susceptible among the soils used, banks of the sand or other soils were heaved up attached to the matrix on both sides and as a result there appeared cavities underneath. Uneven heaving and also the uneven falling of the sand or other soil masses into the cavities during the thawing stage gave rise to tilting and/or rupture in the masses themselves and also at the boundaries as shown in Fig. 9. These differential movement exaggerated the perturbations on the ground, although otherwise they were developing with cycles. Therefore, it can be concluded that the insertion of different soil masses cause the exaggerated perturbations of ground surface when the soils are subjected repeated freezing and thawing.

Degree of perturbations seems to damp very rapidly with the depth in a homogeneous soil, because the horizontal line in 30 mm depth marked by a thin layer of black soil was not much disturbed as shown in Fig. 9. There still remains, however, a danger that this is a hasty conclusion in view of relatively small number of cycles performed.

Quantitative treatments on the grown and developed perturbations on the soil surface were made possible by the use of such quantities as the contour line density or standard deviations of the heights. It should be, however, mentioned that such quantities depend on the areal density of measurements, in other words, the size of grid covered on the surface in this case. Perturbations smaller in area than 5 cm square could not be detected by the measurements used and we should admit that the actual perturbations observed had more minute structures than those shown in contour maps of Figs. 4 and 5.

It should be recommended for further experiments to measure the topographic profile all over the surface either by a stereoscopic cartographic instrument or by some kind of scanning device with which measurements can be recorded in data recorders. By the use of these instruments, it will be possible to obtain more accurate data on the surface topography and also some index quantities for describing the degree of perturbations in any level of accuracy.

Acknowledgements

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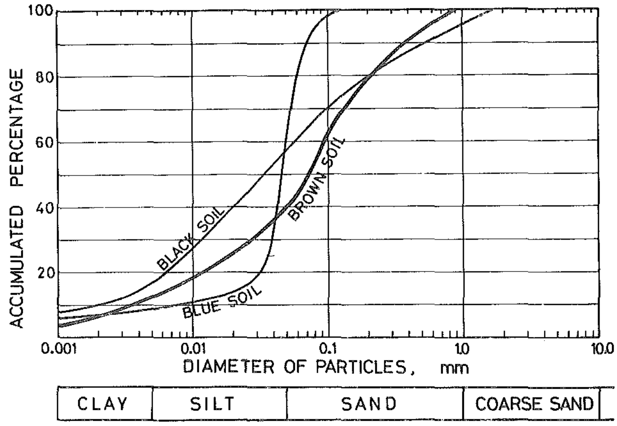


Fig. 1 Grain-size distribution of soils used for experiments.

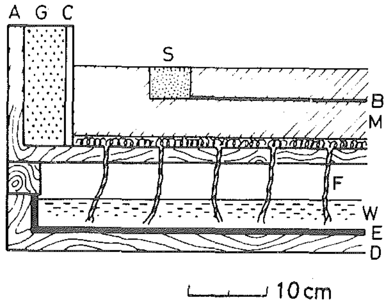


Fig. 2 Longitudinal cross-section view of soils in the container. A: Outer wooden box, G: Styrofoam thermal insulator, C: Inner plastic container, S: Bank of different soil, B: Thin sheet of black soil, M: Matrix brown soil, F: wicks, W: Water, E: Plastic water container, D: Wooden box.

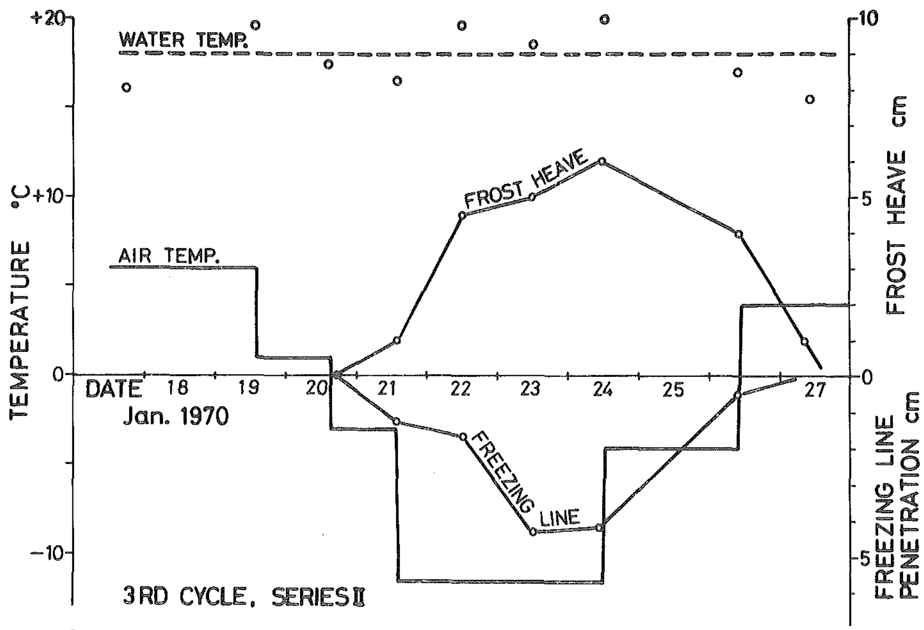


Fig. 3 An example of the process of freezing and thawing of the soil

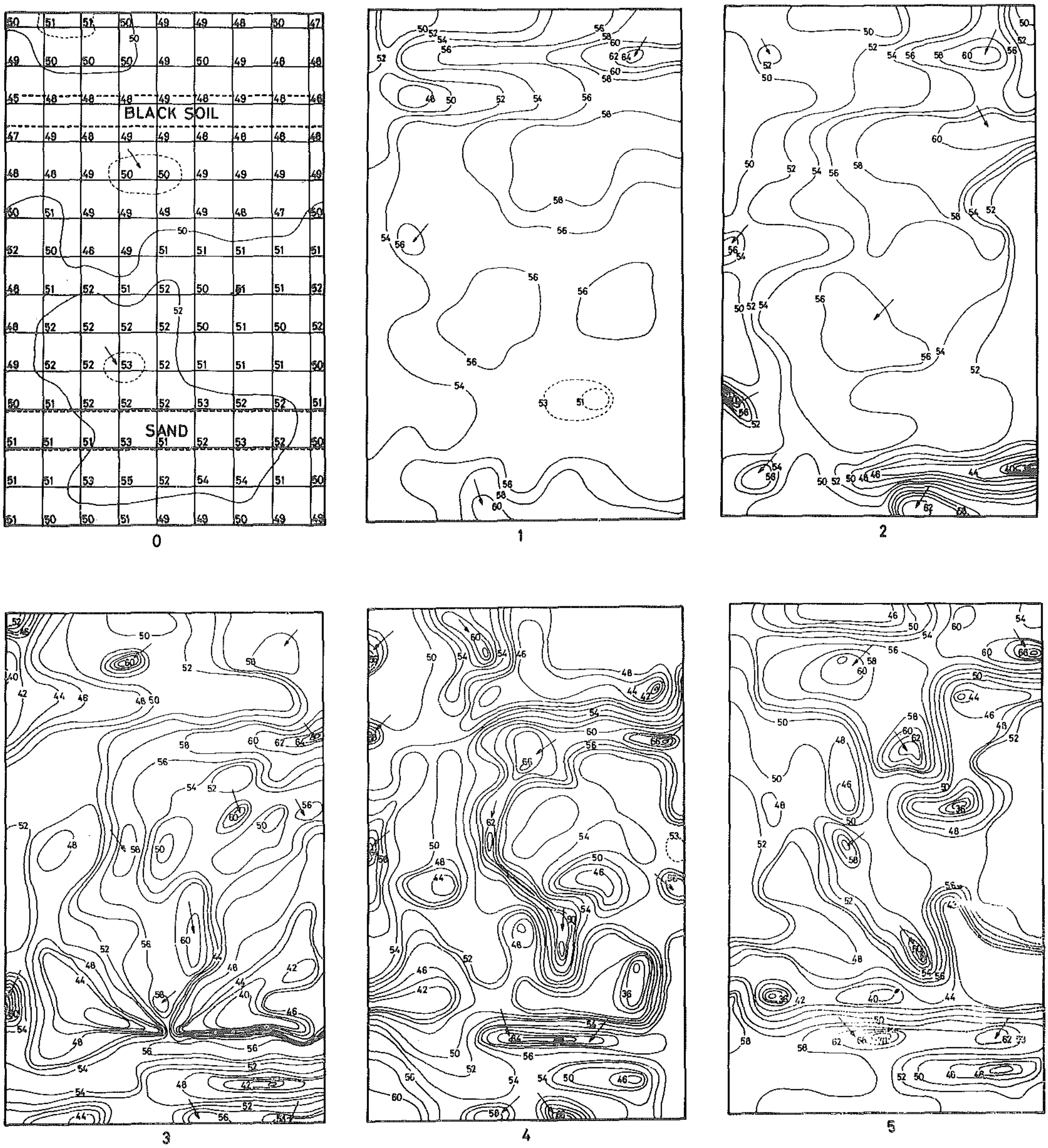


Fig. 4 Grids formed by measuring points of the height of the soil surface together with dispositions of different soils (0) and contours of the surface height after each cycle (1~5) for series I experiments.

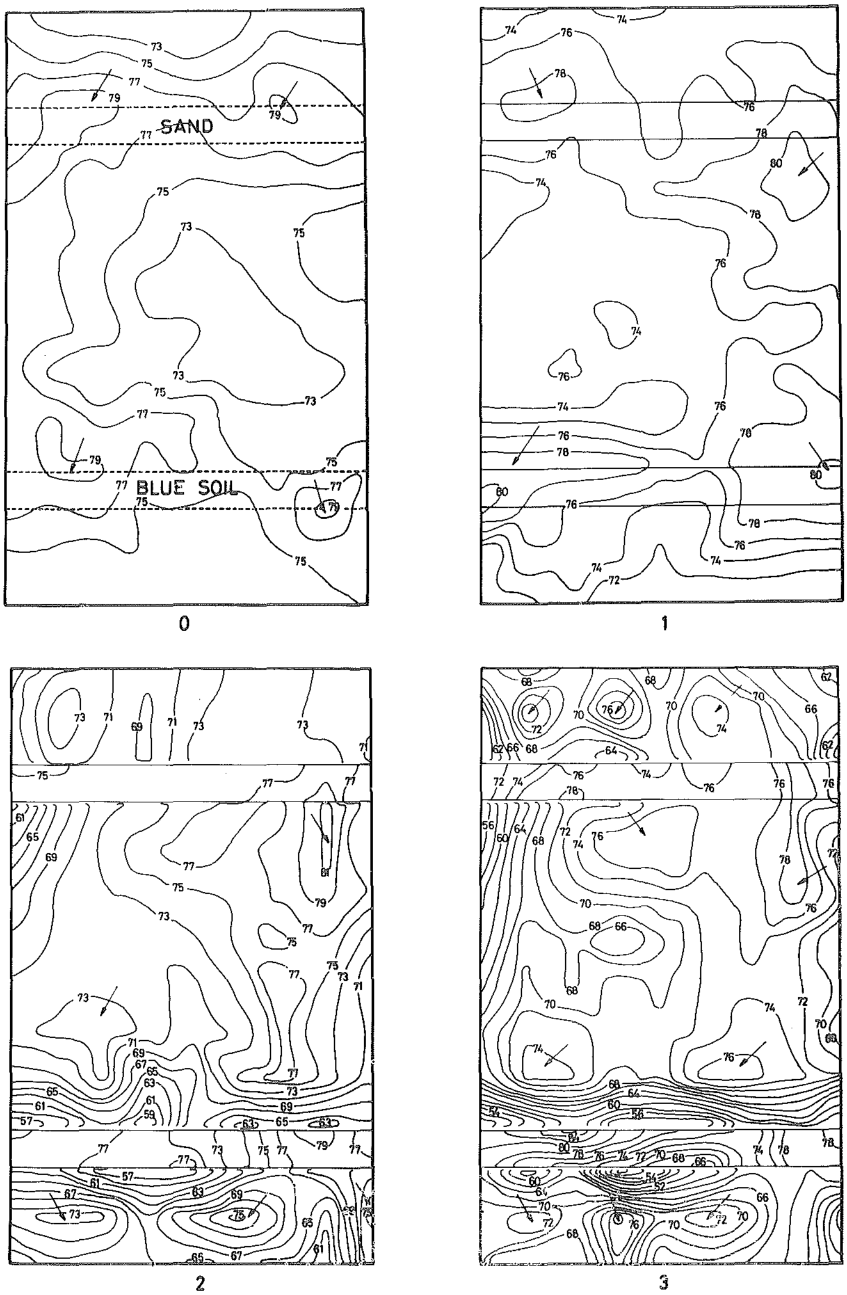


Fig. 5 Contours of the surface height before (0) and after each cycle(1~3) for series II experiment.

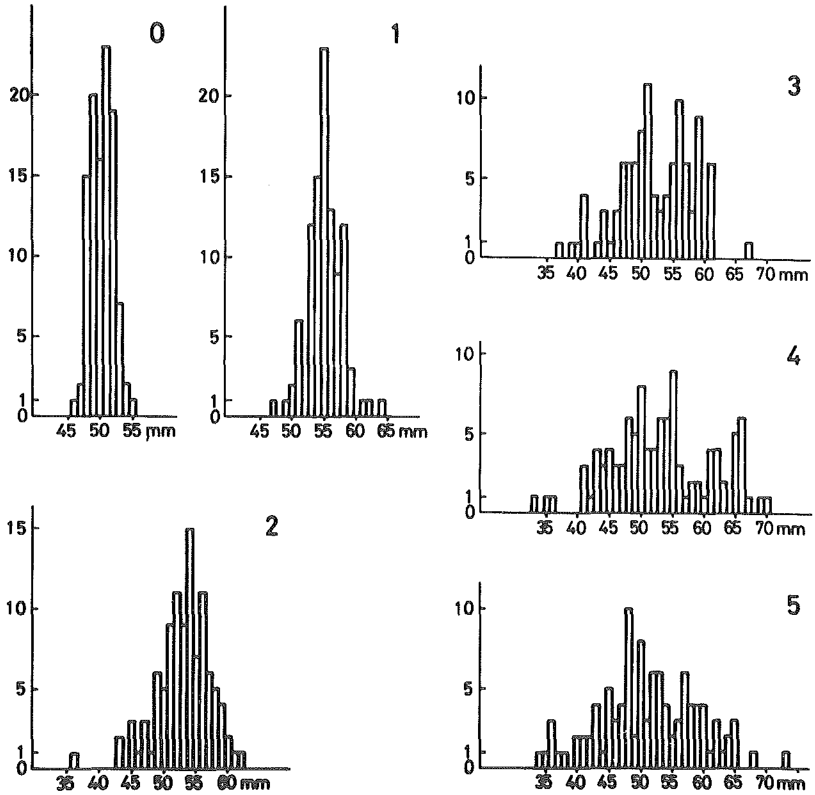


Fig. 6 Histograms of the measured height of soil surface before (0) and after each cycle (1～5) for series I experiment.

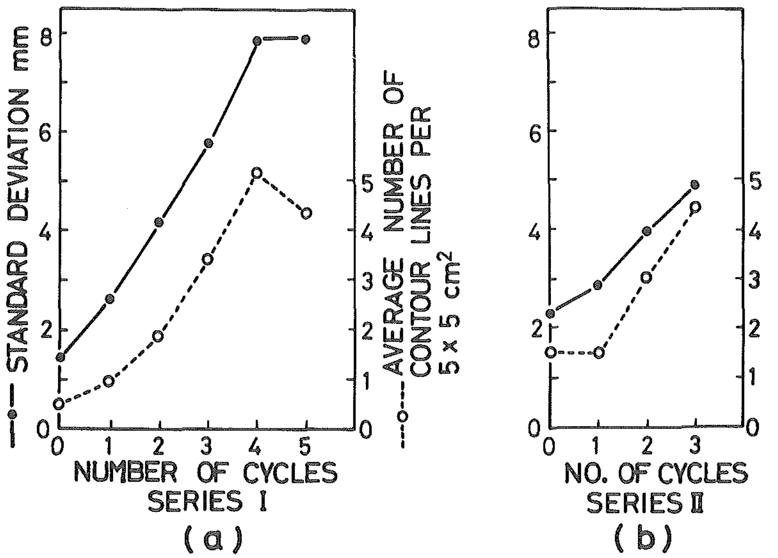


Fig. 7 Changes of the average number of contour lines and the standard deviation of heights due to repetitions of freezing and thawing of the soil in series I experiment (a) and series II (b).

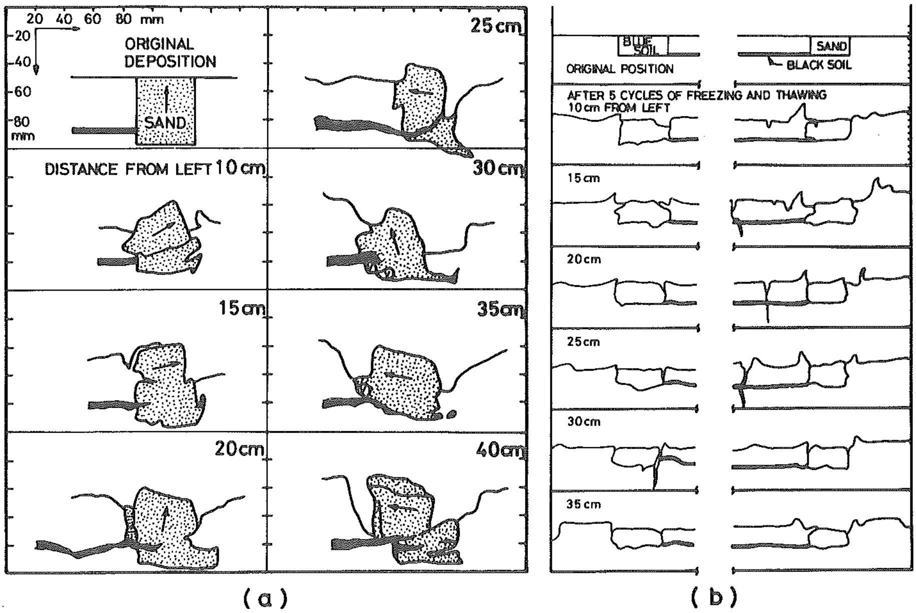


Fig. 8 Deformation of the different soil banks and their interactions with the matrix soil. Note that the sand mass tilted in different directions at different cites along the bank.

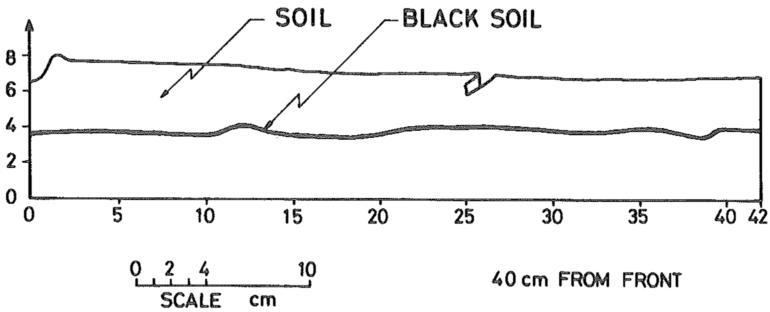


Fig. 9 Change of the depth of black soil sheet : transversal cross-section at 40 cm from front of the container.

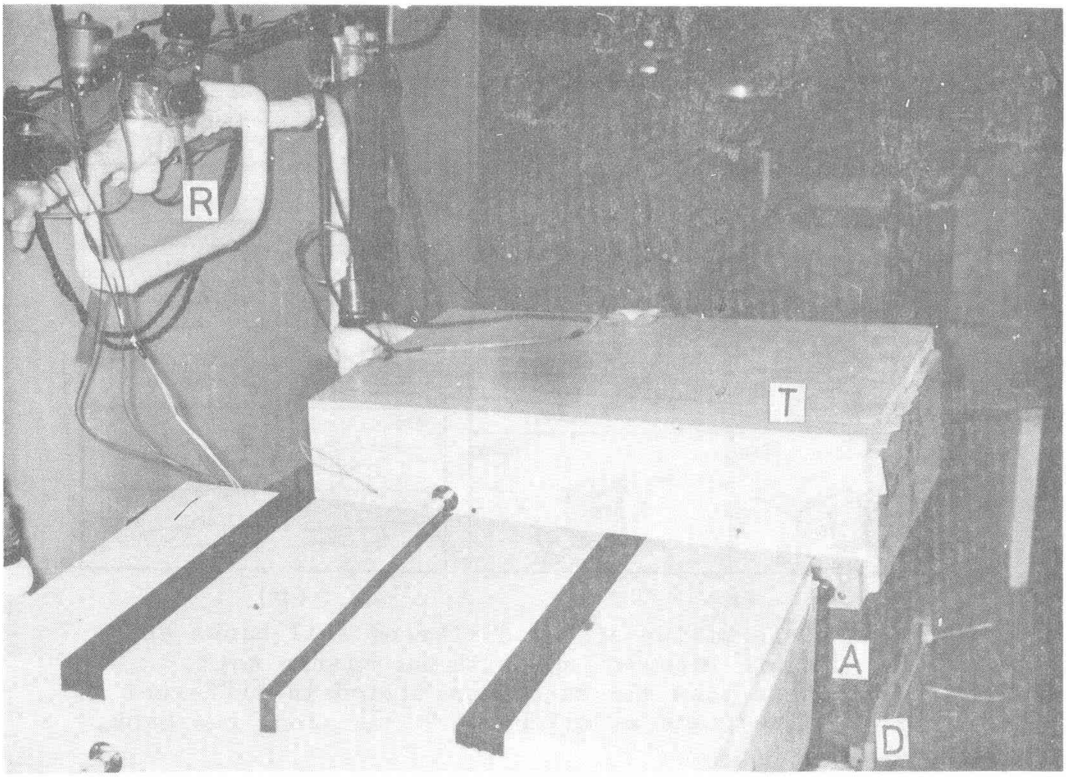
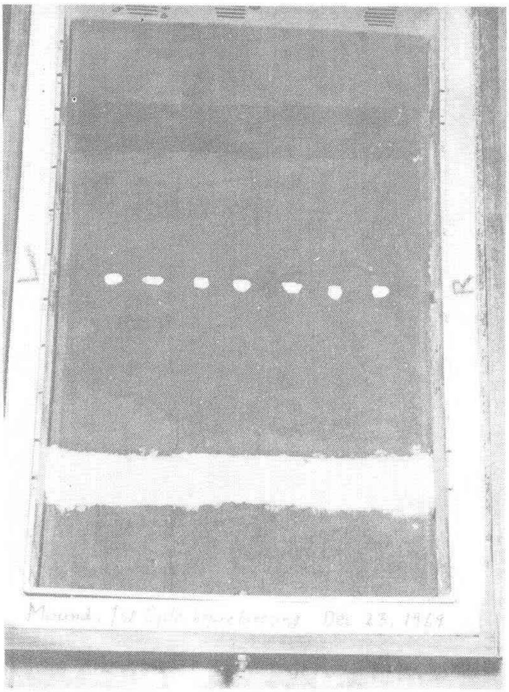
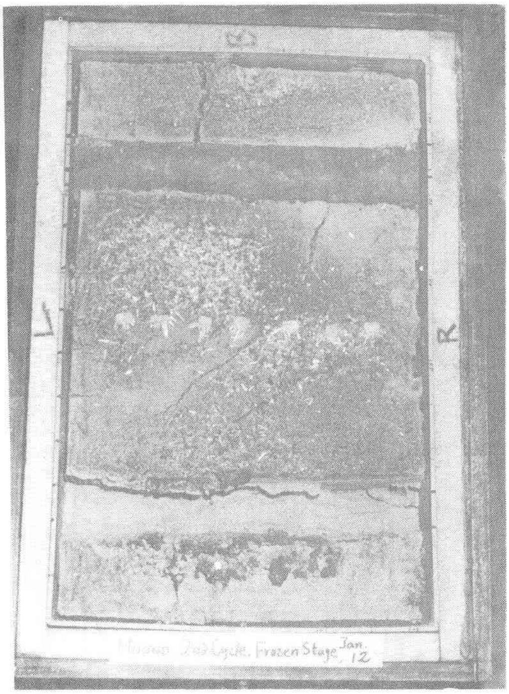


Plate I Two apparatus used for the present experiments, R: Refrigerating system with electromagnetic valves, T: Freezing cabinet covered on the soil container underneath, A: Wooden box indicated in Fig. 2 by the same symbol, D: Wooden box in which the water container is installed.

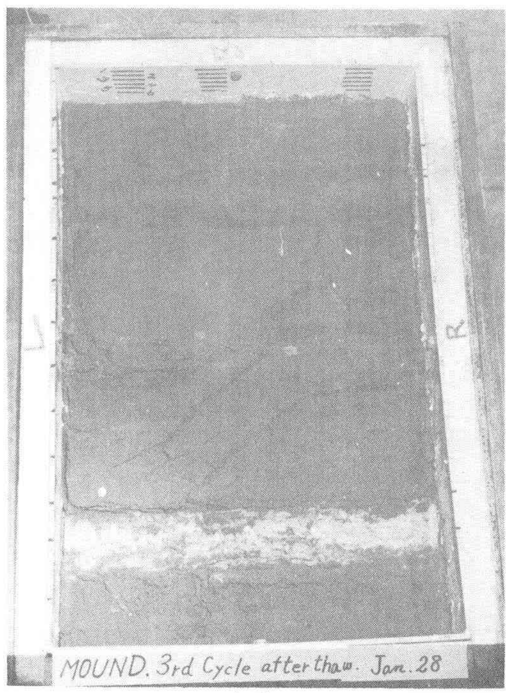


(a)



(b)

(c)



(d)

Plate II Surface features of the Series II experiment, Initial very flat statc at the beginning (a), During freezing in the 2nd cycle (b), After thaw in the 2nd cycle (c) and After thaw in the 3rd cycle (d). Note the penetrated brown soil on the sand bank in (c) and (d).