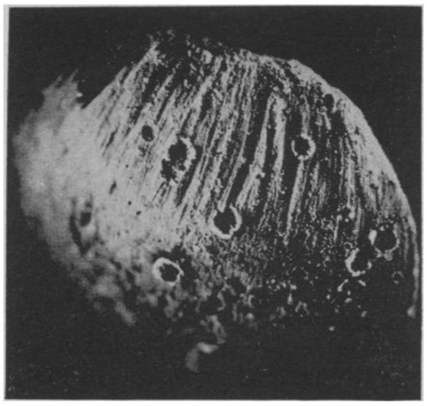

Fig. 1. Lunar particle 4 mm in diameter composed of nickel-iron and iron sulfide.

(*3*, figure 17)]; and (iii) the presence of numerous craters less than 1 $\mu$m in diameter (*3*, figure 14) (these craters imply the presence of very small particles).

Another theory that may account for the furrows is that they are scrape marks caused by the particle impacting the lunar soil. Such an event may form imprints of the soil and leave embedded soil particles on the lower surface of the particle. These features are not apparent in the photograph and description by Mason *et al.* (*1*, figure 2; the *Science* cover is shown here as Fig. 1) but may be present in the photograph on the *Science* cover. Similar features are seen on the surfaces of impact-produced silicate-glass spherules (*3*, figures 29 and 36). Carter and MacGregor have interpreted these features to be the result of a collision of the still-plastic silicate-glass spherule with the lunar soil. If the scrape marks on the metallic particle resulted from impact with the lunar soil, the impact-produced pits must have formed after the collision with the lunar soil. The data of Carter and MacGregor (*3*) and of McKay *et al.* (*4*) suggest that there is a sequential relationship in the impact-produced features on the silicate-glass spherules and further suggest that relatively high-velocity impacts occur in the impact-produced cloud, or, alternatively, that the temperature of the target spherules may be near the melting point. After the furrowing event, the metallic particle was thrown back into the local lunar atmosphere (as a result of meteoroid impact) and pitted. Recycling of near-surface fragments into the local lunar atmosphere is a normal consequence of repeated impacts on the lunar surface.

From the findings of Carter and MacGregor (*3*) and McKay *et al.* (*4*), a general sequence of events in the formation of the metallic particle may be summarized as follows: The silicate-glass spherule, with the solidified mound attached, passed through the impact-produced cloud of hot gas and particulate matter at a high relative velocity, which caused ablating, furrowing, and eroding of the upper and forward-facing portions of the mound. The pattern of the gas flow was determined primarily by the large silicate-glass spherule, but was influenced locally by the mound. As the gas passed to the lee side of the mound, it formed faint, branching, V-shaped patterns on the upper surface of the mound and at the end of the deep furrows, then ceased eroding the mound. Similar furrows and V-shaped patterns are found on experimentally ablated surfaces (*8*). After this ablation, the silicate-glass spherule encountered lunar particles with high relative velocities. The mound was pitted on the upper surface, knocked loose by these impacts, less densely pitted on the lower surface, and splashed with liquid silicate before finally impacting upon the lunar soil. Alternatively, the furrows resulted when the metallic particle struck the lunar surface, and the pitting occurred during a subsequent flight of the particle through an impact-produced cloud of vapor, liquid, and particulate matter.

These explanations may account for the lensoid shape, the peculiar location of the furrows, the ablation or erosion on one surface but not on the other, and the greater porportion of pitting on the upper surface than on the lower. Although this proposed process is complicated and involves several steps, we believe that such an explanation is necessary to explain the complex features of this remarkable particle.

DAVID S. McKAY
*National Aeronautics and Space Administration Manned Spacecraft Center, Houston, Texas 77058*

JAMES L. CARTER
*Earth and Planetary Sciences Laboratory, University of Texas, Dallas 75230*

WILLIAM R. GREENWOOD*
*National Aeronautics and Space Administration Manned Spacecraft Center*

**References and Notes**

1. B. Mason, K. Fredriksson, E. P. Henderson, E. Jarosewich, W. G. Melson, K. M. Towe, J. S. White, Jr., *Science* **167**, 656 (1970).
2. ———, in *Proceedings of the Apollo Lunar Science Conference*, A. A. Levinson, Ed. (Pergamon, New York, 1970), vol. 1, p. 655.
3. J. L. Carter and I. D. MacGregor, *ibid.*, p. 247.
4. D. S. McKay, W. R. Greenwood, D. A. Morrison, *ibid.*, p. 673.
5. C. Frondel, C. Klein, Jr., J. Ito, J. C. Drake, *ibid.*, p. 445.
6. J. I. Goldstein. E. P Henderson, H. Yakowitz, *ibid.*, p. 499.
7. K. Fredriksson, J. Nelen, W. G. Melson, *ibid.*, p. 419.
8. M. E. Wilkens, *Amer. Inst. Aeronaut. Astronaut. J.* **3**, No. 10, 1963 (1965).
9. Supported in part by NASA grants NGL-44-004-001 and NAS9-10221.
* Present address: U.S. Geological Survey, Menlo Park, California.

5 October 1970

# Solifluction: A Model Experiment

Abstract. *Laboratory experiments that subjected soil to repeated freeze-thaw cycles in an inclined container revealed every process of solifluction, especially of frost creep. Multiple slope-angle effects on the amount of particle movement on the soil surface in every cycle are interpreted by several characteristic processes of frost creep. Gelifluction was found to occur in thicker layers of soil, owing to the excess water retained in soil after thawing. For further development of the problem, a similarity law for the model experiment was derived from thermal considerations.*

Despite many pertinent field observations, knowledge of solifluction (downslope mass-wasting processes) in cold climates is still largely qualitative. Some aspects of the work by Washburn in northeast Greenland (*1*) include perhaps the most precise and quantitative fieldwork to date. He proposed to divide the phenomena into two processes: frost creep and gelifluction. However, so many factors are involved in frost creep and gelifluction, and they are so intertwined in nature, that it is very difficult to separate their effects except in laboratory experiments. The purpose of this experiment was to find good methods for measuring the movement of soil particles, either at the surface or at depth, and to obtain quantitative results for the effects of some of the factors.

Natural slopes were simulated in a cabinet, the lower part of which was a tilted box (67 by 42 by 15 cm) filled with soil to a depth of approximately 10 cm. The box was insulated at the sides and had a perforated bottom, from which many wicks extended

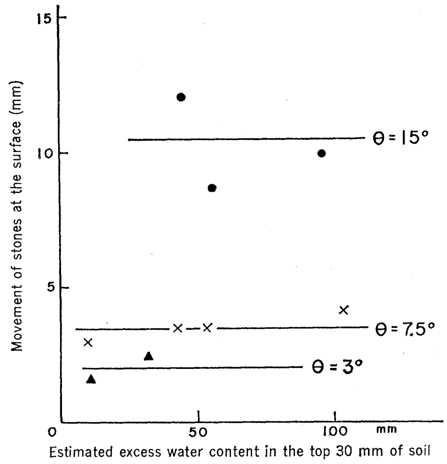


Fig. 1. Relationship between the average movement of stones and the excess water content in the top layer of soil for each freeze-thaw cycle.

downward to a container filled with water. Water was supplied to the soil through the wicks to replenish the deficit caused by buildup of ice lenses during frost heaving. For a 15-deg slope, an auxiliary water container was placed at a higher level to secure an even groundwater level for the upper part of the slope. To complete the cabinet, the lower box was covered with another in which a refrigerating coil and electric wire heaters were installed to control the air temperature of the soil surface. The soil temperature at various depths was measured with thermocouples embedded in the soil.

The soil used was a very frost-susceptible silty clay (sieved from volcanic ash and pumice from the Tomakomai area, Hokkaido), and special care was taken to distribute the soil homogeneously in the lower box. Soil movement was measured with the aid of reference particles on the surface of the soil or within it. The particles were glass marbles (15 mm in diameter), thin rectangular plastic plates (20 by 10 by 1 mm), and pumice stones of nearly cubic shape (with sides approximately 10 by 10 mm). Particles of the same kind were aligned at 5-cm intervals on the soil surface and at depth increments of 2 cm. The lines were perpendicular to the slope and spaced at intervals of 13.5 cm. Positions of surface particles, their vertical distances from a reference level, and their distances along the slope from their original position were measured manually after each freeze-thaw cycle; the same data for particles at depth were obtained after two or three freeze-thaw cycles. Calculations were based on an average of downslope movements of particles on the line.

Air temperature in the freezing cabinet was lowered in gradual steps by means of a regulator switch that controlled the valves of the refrigerating coil. The average rate of temperature lowering was 2° to 5° per day. Soil temperature records on charts of a potentiometer recorder enabled us to draw temperature-depth profiles from which we could estimate the depth of the freezing interface at any time. Frost heaving was observed by naked eye from a window in the upper side of the cabinet. Both the amount of frost heaving and the depth of the freezing interface were plotted against time, and these two curves were used to evaluate the moisture content of the frozen soil, especially the excess moisture near the soil surface where needle ice developed.

This evaluation of moisture content is based on an equation relating the moisture content of frozen soil of a certain thickness to the heaving ratio (*2*), defined as

$$\frac{\text{Height of segregated ice}}{\text{Depth of freezing line penetration}}$$

Then,

$$\text{Heaving ratio} = \frac{\Delta\xi}{\Delta X} = \frac{\Delta\xi/\Delta t}{\Delta X/\Delta t}$$

$$= \frac{\text{(Mass of excess water)} \times \text{(specific volume of ice)}}{\text{Volume of water-saturated soil}}$$

$$= \gamma(W - W_s)V_i$$

where $\Delta\xi$, $\Delta X$, and $\Delta t$ represent differentials of frost heaving, freezing line penetration, and time, respectively, whereas $\gamma$ is the dry density of soil, $W$ the moisture content of frozen soil, $W_s$ the saturation moisture content of the soil, and $V_i$ the specific volume of ice. By using this equation, we can evaluate $W$, the moisture content of frozen soil, from the time rate of frost heaving $\Delta\xi/\Delta t$ and the time rate of freezing line penetration $\Delta X/\Delta t$. The excess water content $(W - W_s)$ thus calculated for the frozen soil, for an original (unfrozen) soil depth of 30 mm, was correlated with the movement of the reference particles at the surface.

Experiments were performed for three different angles of slope (3, 7.5, and 15 deg), with the general trend of freeze-thaw cycles kept as similar as possible. The movement of the reference particles was measured immediately after the frozen soil had thawed and settled—except in the case of the final measurement for the 3° slope, when the thawed soil remained inclined in the cabinet for 1 week before the measurements were made.

The depth profile of particle movement after three cycles of freeze-thaw for the 15-deg slope showed a very large amount (~ 30 mm) of downward movement at the surface, whereas downward movement was only several millimeters in the soil deeper than 20 mm. This indicates that the soil movement at and near the surface was much affected by the freezing and thawing phenomena occurring there. This process of soil movement at and near the surface is called frost creep. The particle movement for the 3-deg slope after three freeze-thaw cycles showed no such sharp increase near the surface, and the total movement was considerably less (5 ~ 10 mm). The comparative lack of depth dependence was understood to result from the downward movement of a thicker layer of soil, which was caused by retention of excess water in the inclined soil for a week's period after the thawing took place. Therefore, the process of gelifluction accounted for the major part of particle movement in this case, and the amount of movement would be determined by the length of time that excess water remains in the soil.

The relationship between the aver-

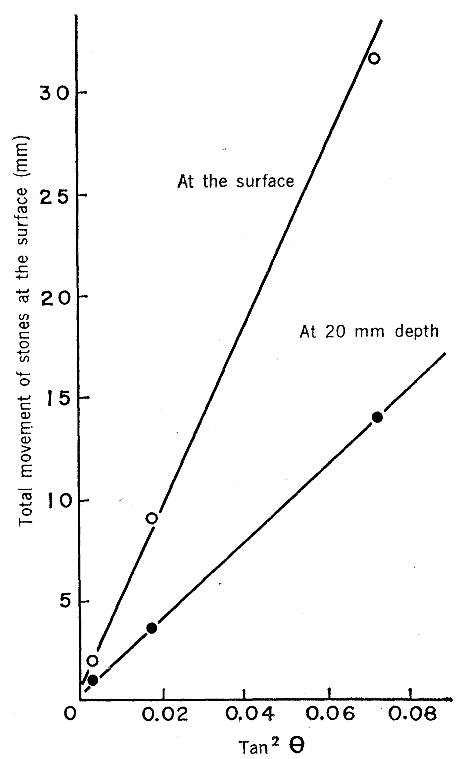


Fig. 2. Total movement of stones at the surface and at 20-mm depth after three cycles of freeze and thaw as related to angle of slope.

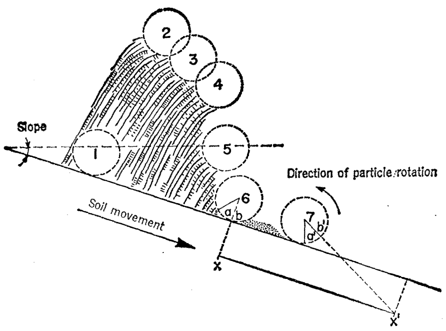


Fig. 3. Schematic diagram showing the path of movement of a particle at the surface of a slope undergoing growth and thawing of needle ice. Nos. 1 and 2, lifting by growth of ice needles; Nos. 2–4, gliding of particles associated with bending of ice needles; Nos. 4–6, drop of particles by melting or evaporation of ice needles; Nos. 6 and 7, slip of particles on wet soil surface; $X$–$X'$, gelifluction. Points $a'$ and $b'$ correspond to the original points $a$ and $b$ on the particle after it rotated.

age surface movement of reference particles and the estimated excess water (calculated for the top 30-mm layer of soil) in each cycle of these experiments at different slope angles is shown in Fig. 1. When the anomalous value for the third cycle on the 3-deg slope is ignored, Fig. 1 shows that the movement in the frost-creep stage, prior to significant gelifluction, is influenced not so much by the amount of excess water as by the angle of slope. If we take the values on the horizontal lines as the average for each angle of slope and plot them against the square to the tangent of the angles $\theta$, the straight lines shown in Fig. 2 are obtained. The same relation also holds for the average movement of stones (originally at 20-mm depth) subjected to the influence of needle ice in the top layer.

Proportionality of the movement to the $\tan^2 \theta$ is interpreted as a multiple effect of the angle of slope, because, if the movement of surface particles in frost creep is due only to lifting by ice needles in the direction of needle ice growth followed by vertical collapse, as is commonly asserted in textbooks, the amount of movement along the slope should be proportional to $\tan \theta$. We often observed during the freezing cycle that the ice needles, which sometimes exceeded a few centimeters in height, bent downslope under their own weight and, as a result, the particles on top were carried downslope. Another kind of movement occurred by slip or rotation of particles (or by both), especially in the case of glass marbles. This additional movement is dependent on the loss of adhesion between particles and ice, a property that is very sensitive to temperature. Slip and rotation also occur during the thawing of needle ice and in the wet soil after the needle ice has completely thawed, but the movement in thawed material should be included in gelifluction. Figure 3 is a schematic representation of the sequence of processes that reflect the multiple effect of the slope angle on the particle movements that we studied. It might be argued that this multiple effect is limited to particles larger than soil particles; soil particles often occur on and within needle ice, however, so that the same process should also hold for soil particles on and near the surface. Figure 3 also demonstrates that the breakdown of solifluction into two components (frost creep and gelifluction) is justifiable.

The frost-creep phenomena described here are associated with the growth of needle ice, which reflects the frost-susceptible character of the soil. Even with such frost-susceptible soils, extrinsic conditions favoring growth of needle ice are confined to certain ranges. For example, the limiting thermal condition is that the amount of sensible heat loss at the freezing interface should not exceed a certain limiting value, which for Bloomington silt is 80 cal/day (*2*). If such a strong effect applies to needle ice in nature, the natural thermal conditions should be consistent with the above limiting value, which is a reasonable one for the beginning of winter in cold climates.

For the inverse approach of designing model experiments to fit conditions in nature, the model experiments should be based on a similarity law derived from fundamental equations governing the phenomena to be investigated. The fundamental equation for thermal conditions is the differential equation for heat conduction in one dimension (heat flows only into or out of the soil):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \qquad \kappa = \frac{K}{c\rho}$$

where $T$, $t$, and $x$ designate temperature, time, and depth, respectively; $\kappa$ is the thermal diffusivity of the soil and is equal to the thermal conductivity $K$ divided by the specific heat $c$ and by the density $\rho$ of the soil. A nondimensional equation for the ratio of every physical quantity in model and nature is given by

$$\frac{T'}{t'} = \kappa' \frac{T'}{x'^2}$$

where the ratios carry the same sign with prime; for example,

$$T' = \frac{\text{Temperature in model}}{\text{Temperature in nature}}$$

Since the temperature scale is the same for the experiment and for nature (that is, $T' = 1$) and since the model is imitating the phenomena with the same soil as in nature (that is, $\kappa' = 1$), the nondimensional equation can be reduced to

$$\frac{1}{t'} = \frac{1}{x'^2}$$

Since our experimental freeze-thaw cycle was about 1 week long, whereas the actual freeze-thaw cycle might be 6 months long (3 months of freezing, 3 months of thawing) in a mid-latitude environment, the time ratio $t'$ is reduced to 1/25 and the depth ratio $x'$ becomes

$$x' = \sqrt{t'} = 1/5$$

This implies that a depth of 10 cm in the model corresponds to a depth of 50 cm in nature. This depth is typical of that in which most movements of soils in alpine-arctic areas take place.

However, the above calculation is limited to thermal conditions governing the growth of needle ice. A more realistic similarity law for such model experiments should be consistent with results derived from fundamental equations that govern both mechanical behavior (bending) of ice needles and the flow of water-soil mixtures (oversaturated soil). To satisfy all these requirements, it is necessary to establish a flow law for water-soil mixtures—a matter requiring further research.

AKIRA HIGASHI*
*Quaternary Research Center, University of Washington, Seattle 98105*

ARTURO E. CORTE
*Departamento de Geología, Universidad Nacional del Sur, Bahía Blanca, Argentina*

### References and Notes

1. A. L. Washburn, *Medd. Groenland* **166**, No. 4 (1967); *ibid.* **176**, No. 4 (1969).
2. A. Higashi, *SIPRE Res. Rep. 45* (U.S. Army Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill., 1958).
3. This work was performed at Hokkaido University, Sapporo, Japan, where one of us (A.E.C.) was a senior visiting scientist, sponsored by the Japan Association for Promotion of Sciences and by the Argentine National Council of Science and Technology. We thank K. Matsuda and K. Kanda for their help in experiments; and we thank the University of Washington for giving one of us (A.H.) the opportunity to complete this work at the Quaternary Research Center.
* Now at Hokkaido University, Sapporo, Japan.

24 August 1970; revised 24 October 1970