Experimental Study on Soil Moisture Transfer In the Film Phase Upon Freezing

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This paper reports on experimental studies on the measured magnitudes of the streaming potentials developed in open freezing soil systems in connection with film flow of soil moisture, as well as illustrates the amount of soil moisture transferred, the magnitude of the developed streaming potentials, and depth of frost penetration as a function of the porosity of the freezing soil systems. The maximum magnitude of developed streaming potential was determined to be 350 mv at about n = 41 percent porosity. The streaming potential developed is approximately proportional to the amount of soil moisture transferred. The maximum frost penetration depth occurs at the same porosity at which the maximum amount of soil moisture is transferred and at which the maximum magnitude of developed streaming potential occurs. The over-all conclusion from observations in this experimental study is that the dry side of the standard compaction test (viz., porosity) seems to be the best condition for minimum amount of soil moisture transferred and minimum frost penetration depth attained.

•THE MOTION of water forced by thermal energy through a fixed porous medium such as a column of silt or clay soil induces an electric potential difference between the two ends of the soil column. A process of soil moisture translocation from points at higher temperature to points at lower temperature in a porous medium brought about by means of a thermal potential (heat, for example) is termed "thermo-osmosis." The induced electric potential in clay-water systems where the water is moving from a higher temperature level to the lower one is also known by the term "streaming potential." The phenomenon of induced electric potential, being a component part of the electric diffuse double layer theory, offer an important basis for the theory of the mechanism for the translocation of soil moisture in the film phase, particularly upon freezing.

As described by the author (1), the phenomenon of the streaming potential, in its turn, is based on the electric diffuse double layer theory. According to this theory, the solid particle of a soil is surrounded by an electric double layer. One layer of this double layer is formed by the negative charge on the surface of the colloidal (clay) particle. The negatively charged soil particles tend to surround themselves mostly with ions of the opposite charge (cations), thus forming the second or outer layer of the electric double layer. This outer layer is formed in the soil water by orientation of the polar molecules of water at the interface between the solid colloidal particle and the dispersion medium, water. Thus in the water (film) near the solid particles an ionic aura, or atmosphere, exists. The electrokinetic effect in a porous system is induced upon the motion of one phase of the disperse colloidal system (water) relative to the other (solid particles).

On the application of a freezing thermal gradient (heat energy) across a vertical column of a soil-water system (freezing temperature at the top of the column) the soil moisture would translocate in the thermal field upward from the ground-water table toward the cold front, thus displacing upward the positive electric charges within the diffuse double layer. Hence the expression "electric diffuse double layer." This phenomenon—streaming potential—results in a potential difference between the two ends of the vertical column of the freezing soil system.

Previous studies by the author (2) on electrokinetic phenomena in open clay-water systems indicate that for each type of soil packed at different porosities different amounts of soil moisture are transferred from the ground-water table to the cold front. Depending on the intensity of the freezing temperature gradient and the position of a reference point above the ground-water table, induced electric potentials (streaming potentials) were measured in the order of magnitude from about 40 to 240 mv (1). Hence the problem in this study is to learn the relationships of the various factors involved in damage to roads by frost when the slow process of upward migration of soil moisture from the ground-water to the cold front takes place at porosities at which the film flow can be expected to be more effective than other soil moisture transfer mechanisms. Particularly, it is interesting to know what the relationship is between the developed streaming potential and the porosity, as well as the amount of soil moisture transferred.

METHODOLOGY

To learn the various relationships involved in the freezing-moisture migration-streaming potential process, Dunellen soil (-10 material), a silty glacial outwash material, classed as A-2-4 by the Highway Research Board classification system, was prepared at different porosities and subjected to a freezing thermal gradient. The particle-size accumulation curve of the soil studied is shown in Figure 1.

The porosity range studied was from n = 27.8 percent to n = 47.8 percent. The prepared soil systems were cylinders, 30 cm high and 15 cm in diameter, placed with their lower ends in "ground-water" so that during the freezing/moisture migration process the ice lenses could be connected via the soil moisture films to the ground-water supply. Thus, open soil systems were studied. The volume of these soil systems was 5,605 cu cm. To prevent lateral heat flux, the soil cylinders were insulated laterally with cork and vermiculite.

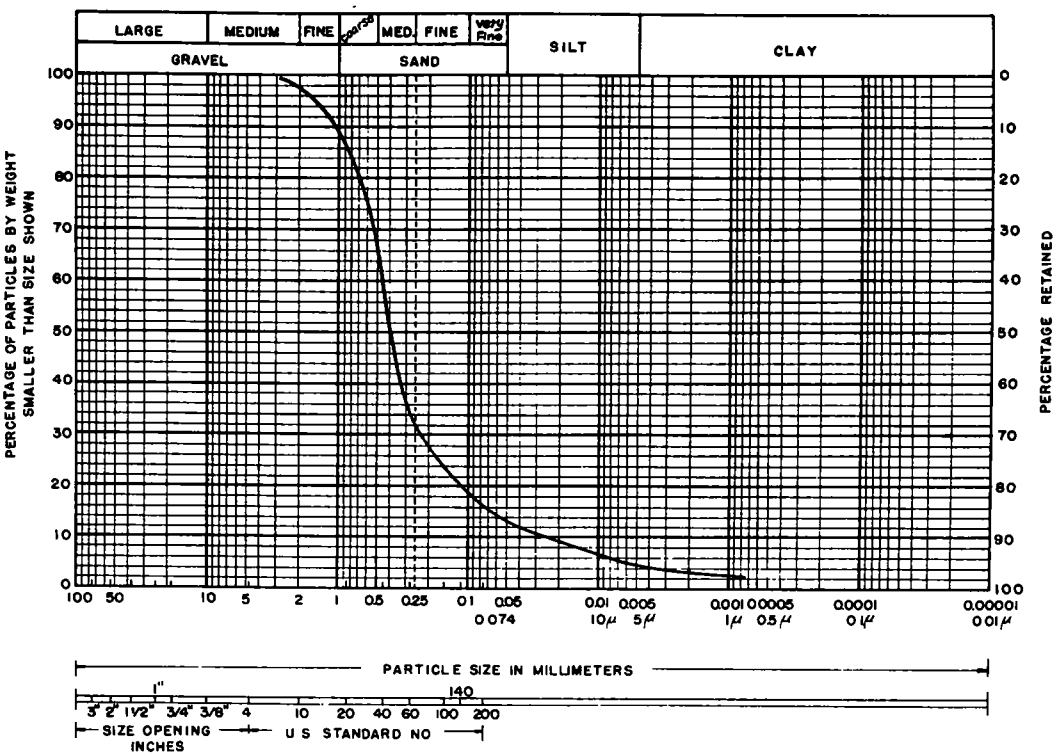


Figure 1. Dunellen soil particle-size accumulation curve.

The freezing period to which the soil systems were subjected was seven days (168 hr) duration, which being consistent with some cold spells observed during the winter months in the New Brunswick, N.J., area. The microclimate was lowered at 24-hr intervals. The lowering schedule was as follows:

Elapsed Time After Start of Test (hr)	Temperature of Microclimate in °C	°F
0	-1.11	+30
14	-6.67	+20
38	-12.22	+10
62	-17.78	0
86	-23.33	-10
110-168	-28.89	-20

Except for the application of a freezing thermal gradient (from this table) across the thickness (=height) of the soil system, all processes in the systems induced by this gradient are natural ones; i.e., all consequent natural processes were triggered off by thermal energy.

INSTRUMENTATION

The freezing apparatus used in these studies was the same as used by the author in previous research on moisture migration in freezing soil systems and shown in Figure 11 (1) and Figure 4 (3).

The principal instrument used for measuring the induced electric (streaming) potentials in the freezing soil systems was a quadrant electrometer consisting of a gold-plated glass needle suspended at its center on a torsion fiber so that it could rotate between four cross-connected plates taking the place of the ordinary quadrants. The electrometer, with standardizing potentiometer and other accessories, is shown in Figure 2. The basic requirement of an electrometer for use in studies of electrokinetic phenomena in freezing soil systems is that it should not draw current from the porous system during the time of measurement of electric properties developed in such systems. The circuit diagram for measuring of streaming potentials in freezing soil systems is shown in Figure 3. The standardization circuit, which includes the potentiometer, is independent of the electrodes.

The electrodes shown in Figure 3 at five different levels in the freezing soil system for measuring the streaming potential are of platinum wire 2.54 mm in diameter. At the "ground surface" and at the bottom of the soil system (Fig. 4) the platinum electrodes are in the shape of a coil, whereas those spaced at depths of 7.5, 15.0, and 22.5 cm from the ground surface have the shape of a needle; viz., wire.

The platinum electrodes, although expensive, are inert in respect to their contamination.

At this point it is pertinent to suggest that all electrodes used in electrokinetic studies of freezing soil systems must be standardized by agreement as to material, size, and shape so that results obtained by other researchers at other institutions and in other countries may be compared with one and the same yardstick, similar to other standardized methods of tests of soils.

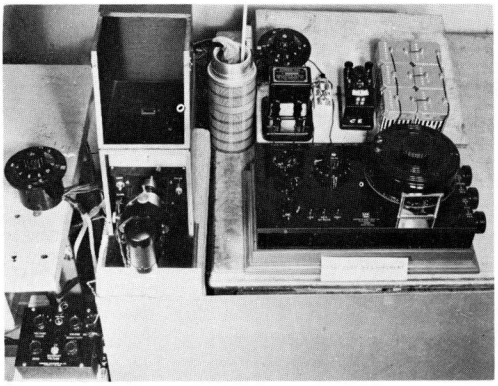


Figure 2. Electrometer with standardizing potentiometer.

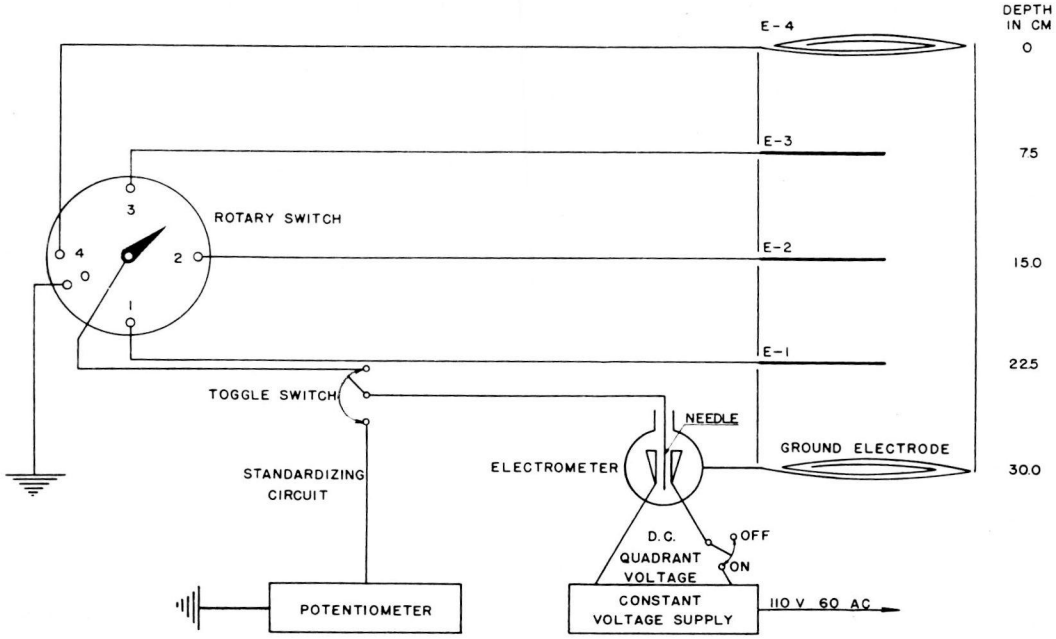


Figure 3. Circuit diagram for measuring streaming potentials.

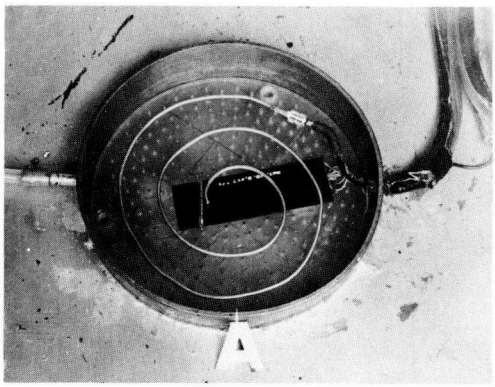


Figure 4. Ground electrode placed at bottom of soil system and located in ground-water reservoir.

Among the principal apparatus other auxiliary devices (such as ground-water supplying devices, thermistors, heat transducers and recorders) were used. The general layout of the instrumentation in these studies is given in Figure 5.

RESULTS

The results of the soil freezing experiments are shown in Figure 6. This figure summarizes the 168-hr test data and shows graphically the amount of soil moisture transferred, the developed streaming potential, and the frost penetration depth as a function of porosity of the soil systems. The nature of the moisture transfer curve has already been established by previous experiments. (2) In the streaming potential experiments described here, therefore, four points on each of the three curves describe adequately the course of these curves within the experimental range of porosities from n = 27.8 percent to n = 47.8 percent.

For the streaming potential at a given porosity, the absolute value in millivolts between the greatest deflections of the electrometer needle for the top-coiled electrode was selected as the best representative value for the 168-hr period of experiment. All other readings relative to electrodes located in the soil systems below their top surfaces are less than reported here.

Within the experimental range of porosities from n = 27.8 percent to n = 47.8 percent, the streaming potential curve may be represented satisfactorily by the general Fourier series equation,

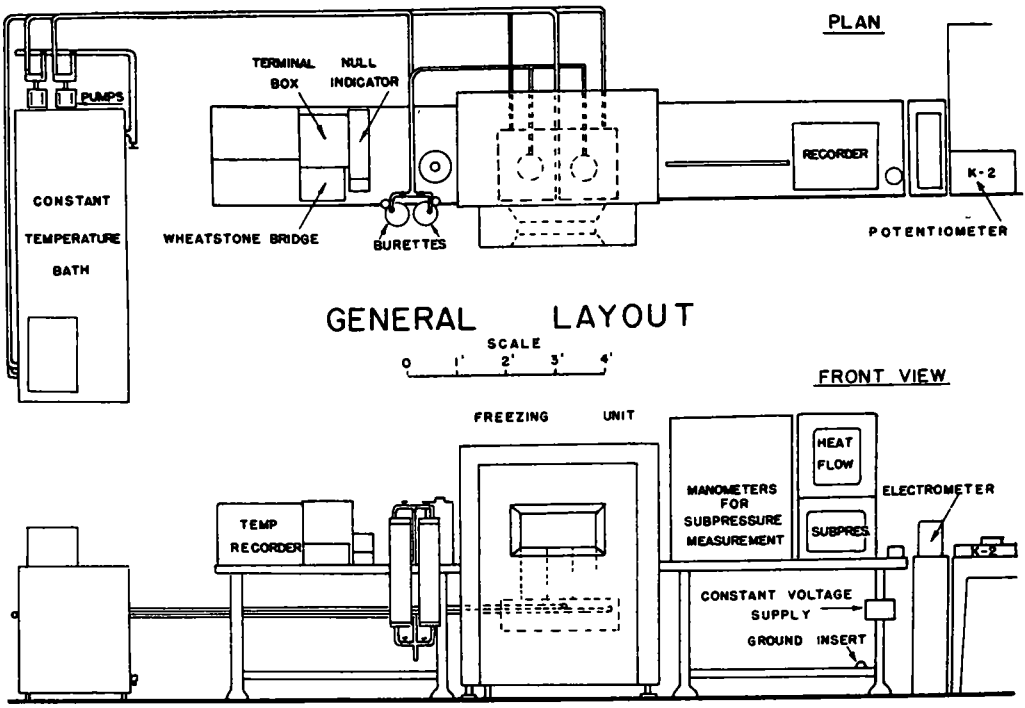


Figure 5. General layout.

$$y = f(x) = a_0 + a_1\cos x + a_2\cos 2x + \ldots a_m\cos mx + \ldots + b_1\sin x + b_2\sin 2x + \ldots b_m\sin mx + \ldots$$

in which

y = ordinate of streaming potential, EMF, in mv;
x = porosity, n, abscissa: $x = c \cdot \pi \cdot n$,
c = an experimental coefficient
$a_0, a_1, a_2, \ldots a_m, \ldots b_1, b_2, \ldots b_m \ldots$ are Fourier coefficients.

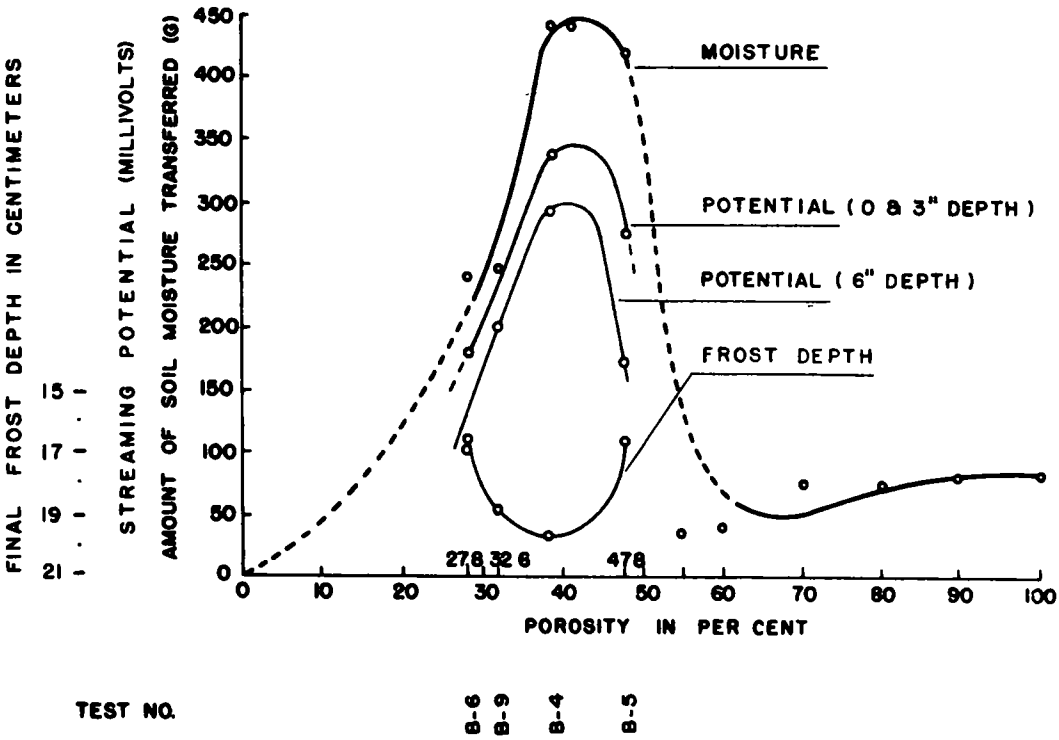
The EMF values reported here in millivolts appear to reflect the shape of the parent soil moisture transfer curve. The soil moisture transfer graph also indicates that the amounts transferred in the film phase (up to approximately n = 47.8 percent porosity) are about five times greater than by way of pure vapor diffusion (porosity range from n = 60 to 100 percent).

Thus, Figure 6 shows that the streaming potential developed in a freezing soil system is approximately proportional to the amount of soil moisture transferred in the film phase. The vapor transfer mechanism is here considered as ineffective in soil moisture translocation.

The maximum magnitude of developed streaming potential in the freezing soil system studied, as seen in Figure 6, can be scaled off as being 350 mv at about 41 percent porosity. The porosity of the Dunellen soil at its maximum dry density of 1,215 pcf = 1.95 g per cu cm by standard Proctor compaction test is n = 26.2 percent.

The frost penetration depth curve (Fig. 6) as a function of porosity n justifies the following statements:

1. The maximum frost penetration depth occurs at the same porosity as the porosity at which the maximum amount of soil moisture is transferred and the maximum magnitude of streaming potential occurs. There appears to be no time lag between these three phenomena.



SUMMARY OF 168 HOUR TEST DATA

	POROSITY %	MOISTURE GM	POTENTIAL MV (0 & 3")	POTENTIAL MV (6")	FINAL FROST DEPTH CM
B-6	27.8	239	180	100	165
B-9	32.6	250	250	200*	188
B-4	38.5	446	340	285	196
B-5	47.8	424	275	170	165
*A-9	32.8				

Figure 6. Streaming potential, frost depth, and moisture transfer in soil upon freezing as a function of porosity.

2. At n = 27.8 percent porosity, 119.8 pcf = 1.925 g per cu cm dry density, the passages between the soil particles may be so small that they restrict to some degree the flow of heat and soil moisture and hence hinder the upward flow of the cations.

3. At n = 32.6 percent, 112 pcf = 1.795 g per cu cm dry density, the heat and soil moisture transfer is greater because the soil particles are packed less densely than in the case of statement 2.

4. At n = 38.7 percent porosity, 102 pcf = 1.635 g per cu cm dry density, to about n = 41 percent porosity the soil particles are in such a packing as to cause the most effective film moisture transfer. This brings about the maximum frost penetration depth in these experiments, and the greatest accumulation of frozen moisture in the frozen soil system.

5. At n = 47.8 percent porosity, 86.7 pcf = 1.39 g per cu cm dry density, the amount of film moisture transferred begins to decrease because of the loose packing of the soil particles. This permits the heat to rise more easily through the voids of the soil from the ground-water, retarding the downward-progressing freezing isotherm.

6. The over-all conclusion from these statements is that the standard compaction of this soil on the dry side of its optimum moisture content (~12 percent) and maximum dry density (viz., porosity) seems to be the best condition for minimum amount of soil moisture transferred and minimum depth of frost penetration attained.

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C. V. Longo of the Department of Electrical Engineering at Rutgers University was consulted and checked the development of the streaming potential measuring circuit.

W. Douglas Smith, Jr., a graduate student at Rutgers University, Department of Civil Engineering, took part in the soil freezing experiments and performed conscientiously the difficult measurements of the developed streaming potentials in the freezing soil systems.

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