Program for frost action studies

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A PROGRAM FOR FROST ACTION STUDIES

by Edward Penner

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PREFACE

The study of frost action in soils has long been of interest to the Division of Building Research. After considerable study and following consultation with the Project Committee on Frost Action in Soils of the Highway Research Board (U.S.) it has been decided to embark upon a long-term research study of some of the fundamentals of frost action.

This report by Mr. E. Penner, a member of the Soil Mechanics Section of D.B.R., who has his Master's degree in soil science from the University of Saskatchewan, has been prepared to outline the approach that is being planned.

It is circulated for the information of others interested in this field and in the hope that the Division may be favoured with critical comments upon it. Comments and suggestions will be most welcome and they may be sent to the undersigned or directly to Mr. Penner.

Ottawa
November 1954

Robert F. Legget,
Director

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Introduction

Some soils when subjected to naturally occurring subzero temperatures, display certain characteristics undesirable from an engineering standpoint. Uniform and differential heaving due to ice segregation and loss of strength upon thawing are perhaps the most notable. This behaviour often results in the deterioration of roads and airport surfaces, destructive action on railroad grades, and bad effects upon building foundations. A better understanding of the fundamental phenomena involved should assist in the formulation of more adequate frost action criteria.

One logical process of research requires a study of available research reports and the formulation of a systematic approach for an experimental phase. There are at least two excellent literature reviews (1, 2) devoted entirely to frost action in soils and associated phenomena. Because of this, it was thought that no contribution could be made by adding yet another. Where possible the original papers have been studied. The bibliography compiled by Johnson and Lovell (3), together with the literature reviews, have served as excellent guides.

The recorded literature on frost action and allied phenomena under field conditions is voluminous. There are by comparison relatively few scientific papers on the theoretical aspects which are supported with laboratory evidence. It is believed that the interpretation and application of frost action data to best advantage, depend a good deal on the understanding of the soil-water system in terms of its physiochemical properties. This report is concerned with an outline of a proposed frost action study. The determination of those soil properties, which will serve as a basis for defining the soil system is considered an essential part of this study.

2. The Experimental Approach

The complete simulation of field conditions in the laboratory is not easily achieved. Despite this, the environmental conditions must be carefully considered since the eventual application will be in the field. The freezing of soil specimens in the laboratory was the basis of the approach of many earlier investigations, in particular in the work of S. Taber, G. Beskow, A. Casagrande and more recently the Frost Effects Laboratories, New England Division, Corps of Engineers, U.S. Army.

The exact method by which the soil specimen is frozen depends on the information required. Both for empirical or semi-empirical studies a comparison of frost action susceptibility is of great importance. This requires rigidly controlled experimental conditions. In nature, the frost action phenomenon has been recognized by all investigators as a very complicated process. Complications arise from such factors as the heterogeneity of the soil mass, the release of latent heat of fusion at the frost line, the difference in heat conductivity of frozen and unfrozen soil, to mention but a few.

Usually, for laboratory studies, an arbitrary set of conditions is imposed on soil specimens with regard to the rate of penetration of the frost line, the depth of water table, the size of sample, the temperature gradient etc. In many instances the assumptions made and the oversimplified conditions imposed are necessary if any useful research is to be carried out. Unfortunately, this may result in some important aspects of the frost action phenomena being overlooked or ignored.

3. A Brief Discussion on the Theory of Frost Action

Water expands approximately 9 per cent when it freezes, which is an unusual property for a liquid. Although early investigations attributed the heaving of soils to this property of water, the work of Beskow (4) and Taber (5) has shown that excessive heave is due to ice crystal growth and consequent lens formation.

In a salt-free soil-water system the freezing-point depression is due to the adsorptive forces of held water. As more water is added the films become thicker thus decreasing the adsorptive force by which the outermost layer of water is held. For any soil, there is a continuous relationship between the force with which water is held and moisture content. It can then be seen that for any one soil the freezing point depression is also a function of water content.

On the basis of the phase diagram of water by Tammon and Bridgeman, the work of Winterkorn (6) appears to support the theory of the mechanism of moisture movement near the frost lens postulated by Taber and Beskow. While the layers of water immediately adjacent to the soil particle are immobilized completely, there can exist subsequent layers (with a reduced freezing point) which may act as conducting channels. These layers remain as liquid water, however, under the influence of the soil particle. Since the amount of water held at any given energy level varies inversely with the particle size, heavier textured soil should have a greater ability to transfer water by this mechanism than light textured soils. This appears to be the basis of the criteria set forth by Casagrande (7).

Benkelman and Olmstead (8) placed emphasis on the naturally occurring fluctuations of the frost line. The validity of the supporting evidence produced by these workers under laboratory conditions is still questioned and their conclusions are not generally accepted.

Provided an ice lens is initiated, its rate of growth is believed to depend largely on the ability of the soil to transmit water to the freezing zone. In nature the driving force can be attributed to (a) a temperature gradient and (b) a soil moisture suction gradient induced by the liquid to solid phase change. How much each contributes to the total moisture flow depends on the environment conditions. In the laboratory it is dependent on the arbitrary conditions chosen by the investigator. This appears to justify the independent study of flow rates due to each of these conditions and how it is modified when both are acting simultaneously.

4. Soil Properties and Identification

(a) The clay fraction, some characteristic properties and influence on soil behaviour.

The sand and silt fractions in soil serve largely as a skeleton material since they possess a rather low specific surface. In contrast, the clay fraction possesses a high specific surface which accounts for the high moisture content of clay soil compared to lighter soils at similar suction levels. This greatly influences the physicochemical properties of the soil system. The clay fraction - if 0.002 mm. is taken as the upper limit - lies almost completely within the colloidal range (0.001 mm). Many attempts to develop concepts of the behaviour of soils in the past were based on the assumption of spherical particles. It is now well known that within the clay range the particles are mostly non-spherical. This limits the usefulness of mechanical analyses; it is, however, an important and easily obtained function for characterizing soils. Assuming spherical particles, the calculated surface area of clays compared to sand and silts are large. Real surface areas are still greater if actual shapes are taken into account (9). The shape, in addition to affecting specific surfaces, also influences the mechanical properties of the soil.

The importance of identifying the clay mineral composition of the soil systems studied is unquestioned. Complex mixtures of clay minerals are often encountered in soils; in addition, considerable variation in the properties of a particular clay mineral originating from different localities, can occur. Because of this, further methods of characterizing clays, such as measurement of interlayer swelling, surface areas, base exchange capacity and base exchange ions are necessary.

Recognizing the importance of the clay fraction in the soil system and that the large associated surface is a characteristic property, research workers have developed methods to determine an index of surface area. The expanding lattice clays possess an internal as well as an external surface. In montmorillonite clays, the internal surface is approximately 20 times as great as the external surface depending somewhat on the nature of the adsorbed ion. Dyal and Hendricks (10) have developed a method using ethylene glycol to determine interlayer swelling. They have shown that in specimens of clay heated for 23 hours at 600°C., interlayer swelling is inhibited. The difference in glycol retention between heated and unheated samples serve as a basis for approximating the extent to which the clay has montmorillonoid interlayer swelling. Grim (11) and Dücker (12) predicted that of the clay minerals montmorillonite should be the least susceptible to frost heaving. Preliminary tests by the Frost Effects Laboratory, Corps of Engineers, U.S. Army (13) have, in part, verified this prediction.

Orchiston (14) has recently investigated the usefulness of water vapour adsorption data for specific surface determinations. The adsorption data obtained from the vacuum desiccator method was used as a basis for comparing the basically different theories of Brunauer (15) Harkens and Jura (16) and Bradley (17). The adsorption isotherms for all the soils tested were shown to be sigmoidal or S shaped, to which the theories examined apply.

A thorough study (18) of water adsorption isotherms has proven useful in elucidating the adsorption mechanism. Adsorption data for a series of homionic montmorillonites and kaolinites were determined with a somewhat different apparatus. The magnitude of the effect of various exchangeable cations on adsorption isotherms was demonstrated. The application of the B-E-T theory to the data, in the case of kaolinite, the authors concluded, appeared justified on the grounds that the adsorption data showed the usual characteristics of physical adsorption. The authors further concluded that only in the case of Li kaolinite were true surface areas measured. A comparison of the Li molecule size and spaces occupied in the clay lattice structure justifies this to some extent. Assuming this to be true, the number of water molecules associated with each cation of the other homionic kaolinites could then be calculated. Whereas adsorption and desorption were perfectly reversible for kaolinite, there was considerable hysteresis in the case of montmorillonite. Adding further to the difficulty, adsorption values were not reproducible. This was attributed to slight variations of moisture content at the beginning of the determination. Accordingly desorption data were used for calculating B-E-T functions, since these were both reproducible and also were believed to represent true equilibrium values more closely. Again, as in the case of kaolinite, large differences in adsorption isotherms occurred with different cations. The effect of exchangeable cations on the adsorption isotherm has been previously shown. This additional evidence was however obtained by a somewhat different approach.

Normally, in the field, exchange ions are of a complex nature. Thus the B-E-T surface area, determined by water vapour adsorption, although not an absolute measure of surface area, still remains a well defined characteristic value for a given soil under natural conditions.

(b) Soil identification.

The Atterberg limits and grain size distribution are engineering aids for soil identification. The dry density is known to affect frost action so that normally different soil systems will be compared at constant densities. These determinations will be based on the approved methods (19) used by the Soil Mechanics Laboratory of the Division of Building Research. While the above identification tests for the classification of soil appear limited in scope these should be sufficient for normal soils; others will be added as they appear necessary.

The ultimate aim of the frost action studies will be to make possible the prediction of the frost susceptibility of a soil from its characteristic properties. It appears desirable therefore to evaluate these properties of the soil systems to be used in the investigation of the more fundamental aspect of frost action. That a single soil property is not sufficient has already been shown by the use of the Casagrande criteria based on particle size and particle distribution. Many "tools" are now available, although their usefulness depends on the employment of rigidly controlled laboratory techniques if different soils are to be compared with reasonable success.

5. Soil Water Potentials

The introduction and application of the energy concept in soil moisture retention and movement has placed the study of soil water on a fundamental basis. Many research workers have contributed to the better understanding of soil moisture energy relationships but the most comprehensive theoretical treatise has been contributed by Edlefson and Anderson (20). Several attempts in the past to classify soil water arbitrarily have failed. The continuity of the adsorption isotherm clearly shows that the forces involved overlap in water retention. Nevertheless, some distinction may be warranted between adsorbed water and water held by surface tension forces since the mechanism of retention is vastly different.

The force with which water is held on the soil particle is usually described in terms of suction pressure and is negative in character compared to a free water surface. Normally the suction pressure is expressed in centimeters of water. At very high suction pressures, the values are usually expressed in terms of Schofield's pF. For example, suppose a moist soil sample is in suction equilibrium with a column of water 10 cm. above a free water surface. The suction pressure or potential would then be -10 cm. of water, and the corresponding pF would be $\log_{10} - (-10) = 1$.

The suction - moisture-content relationship is by no means unique but depends on whether it is determined by drying or by wetting. All porous materials, like soil, exhibit the hysteresis phenomenon. The moisture content at any given suction pressure is greater if determined by drying than by wetting. The exact mechanism is not fully understood but it appears that the quasi-equilibrium theory is no longer completely tenable. The hysteresis effects has been an important factor in hampering a solution of the water movement mechanism.

In this laboratory, three methods have been selected to measure pF from saturation to oven dryness. At low pF's (0 to 3) the ceramic plate apparatus is used; for pF's from 3 to 4.5 porous membranes replace the ceramic plates. The liquid water tension is conditioned by air pressure in the normal way. The pF's from 0 to 4.5 are usually considered to constitute the so-called "suction range". For pF's from 4.5 to 7, the vacuum desiccator technique is used. Here, the relative humidity is controlled by sulphuric acid solutions of known concentration. It is usually not considered practicable to extend the vacuum desiccator technique below pF 4.5, since the corresponding values of R.H. lie too close to 100 per cent for accurate control. In saline soils the use of R.H. for pF control includes in addition the osmotic potential. Thus a complete pF - moisture-content curve determined from both suction and R.H. controlled potentials may show some discontinuities.

Every porous material like soil has a characteristic water-content - suction potential relationship within the limits of hysteresis. Recently Croney and Coleman (21) have shown pF - moisture-content curves for several soils which illustrate differences in the behaviour of various materials, in particular soil structure and its relation to pF. The concept of soil-moisture - suction potential relationships has caused a shifting of emphasis with regard to soil moisture. Formerly the moisture distribution in a soil profile was considered of prime importance; now it is realized that the forces which retain the soil water governs its movement and distribution.

6. Unsaturated Permeabilities

Beskow (4) and other have attached considerable importance to saturated permeability studies in connection with frost action. In many cases the water table lies below the frostline. It appears reasonable to suspect that the unsaturated permeability may then be of more significance. One important feature of unsaturated permeability needs emphasis. The magnitude of the permeability coefficient depends directly on the average suction potential, even if similar potential gradients are used. As the average pF increases, the thickness of the water films decreases, and moisture transfer along the liquid films decreases. Consequently, lower permeability coefficients are obtained.

Beskow concluded from his studies that liquid water transmission and not vapour diffusion was the important mechanism in frost heaving. Since the suction potential gradients in the soil determine the direction of water movement, this may imply movement in the liquid phase in the absence of temperature gradients. It is well to note that there is a continuous relationship between suction potential and R.H. (22). The relative importance of vapour movement in systems of this kind is still a controversial issue. Darcy's law developed for saturated laminar flow states that the flow rate is proportional to the hydraulic gradient. The most simple mathematical form is:

$$V = k_s i$$

where V = velocity of flow
k_s = saturated permeability constant
i = hydraulic gradient

The counterpart of this expression for unsaturated conditions is generally applied in a modified form.

$$V = \frac{Q}{AT} = k_u \frac{(S_1 - S_2)}{L}$$

where V = velocity of flow/unit time/unit area
Q = volume of water
A = area
T = time
k_u = unsaturated permeability coefficient
S_1 and S_2 = suction potentials at the planes under consideration
L = flow path length

The above expression is in its simplest, and basic, form. Such refinements as temperature effects on liquid density and pF and flow rate may be introduced. Moore (23) and Russell and Spangler (24), and Richards and Moore (25), have described in detail laboratory apparatus for the measurement of unsaturated permeability. It is of interest to note that Russell and Spangler in their treatment of moisture potentials stress the significance of unsaturated permeabilities in relation to frost action.

The apparatus shown in Fig. 1 has been designed to measure moisture flow in soils in the unsaturated state. The spiral grooves and tubes attached to the upper and lower porous plate holders are carefully filled with water and flushed until all the bubbles are removed. The copper tubing coil is attached to a constant pressure water reservoir. This is necessary so that a constant pressure is maintained while water flows from the reservoir through the system. The sample holders are perforated near the outer surface of the porous plates for suction conditioning by the controlled air pressure, P_1. To obtain a suction differential, any desired back pressure P_2 is applied from the constant pressure water reservoir. The upper plate holder is spring loaded to allow good contact between soil sample and porous plates when the soil shrinks or swells depending on the degree of saturation. The amount which flows through the sample is measured with a pipette or capillary tube depending on the flow rate. For any desired suction values the flow rate is measured intermittently until it reaches a constant rate.

7. Soil Water Potentials Induced by Ice Lensing

In a recent paper, Jumikis (26) deals with a mathematical analysis of moisture flow in a soil system under the influence of a temperature gradient and a freezing plane. His treatment of the forces involved in water transmission to the freezing zones is a significant contribution in this field. The method of approach suggested in this outline recognizes two fundamentally different processes involved in water movement under natural conditions which are the movement of moisture due to (a) the temperature gradient and (b) to the suction gradient.

It is proposed that in the initial studies these two processes must be evaluated separately, recognizing as stated before that these processes, acting simultaneously, are not necessarily a simple summation of the two. In addition both processes are unnecessarily complicated experimentally by an advancing frost line.

The requirements of a practical frost cell for evaluating the suction phenomena independently are (a) a controlled stationary frost line, (b) a sharp temperature gradient at the frost line with a constant temperature spanning the main body of the specimen (as shown in Fig. 2). Thermocouples imbedded in the specimens at fixed positions would be used to indicate the temperature distribution. A frost cell to fill these requirements is now being designed. The moisture tension at the lower end of the soil specimen will be controlled by a tension-conditioned suction plate to any desired suction value. When the rate of moisture flow has reached a constant rate the specimen will be sectioned for moisture content determination. During constant rate of heave (ice lens growth) the rate of water entry into the sample will be also noted. This is more desirable than attempting to estimate the quantity of water moved from the thickness of the ice lens. Since the moisture content - pF relationship can be easily determined for each soil tested, the unsaturated permeability equation can be applied:

$$k_u = \frac{Q}{AT} \frac{(L)}{(S_1 - S_2)}$$

where Q = quantity of flow in cm^3
A = cross-sectional area of the specimen in cm^2
T = time in seconds
L = distance in cm. from ice lens to lower end of sample in cm.
$(S_1 - S_2)$ = expressed in cm. of water
k_u = unsaturated permeability coefficient in cm/sec.

The values of k_u obtained in this way should be numerically equal to the k_u values obtained with the unsaturated permeability cell under similar conditions of suction. The equality of these coefficients would provide evidence on the importance of flow due to suction gradients during ice lens formation. This approach would also make possible the indirect measurement of suction values in the soil water near the ice lens without interference from moisture movement due to thermal gradients.

The suction potential of the soil would be equal throughout for specimen moulding. In the frost cell a predetermined suction would be applied at the lower end of the specimen and sufficient time would be allowed for equilibrium to be established. If the steady-state suction distribution during freezing were such that one end of the specimen was higher than the suction potential at which it was prepared, and the other end lower, both legs of the hysteresis loop would be represented. This would be undesirable. It is believed that with practice the original moisture content could be adjusted so that both ends of the sample were either on the drying or the wetting curve.

The study of suction correlations with the properties of the soil such as suction values limiting ice lens formation and rates of moisture movement will constitute the initial phase of the frost action program. In the second phase the effects of temperature gradients on moisture movement in combination with suction gradients would be studied. The Materials Section of the Division of Building Research are investigating the movement of moisture in various porous materials at temperature gradients above freezing. These studies are mainly concerned with the mechanism involved and considerable progress has been made. The third phase would be concerned with the study of variables such as density, and surcharge. These constitute at the moment the greater portion of the research carried out by the Frost Effects Laboratory, New England Division, Corps of Engineers, U.S. Army.

8. Soils for Test Specimens

Since frost action phenomena contain all the complexities of moisture movement studies, plus the additional freezing process, there is considerable justification for attempting to control the physical properties of the soil within certain limits. The use of blended soils is being considered. From stock samples of sand, silt, and clay of known composition a wide range of grain size distributions could be prepared by varying the proportions of the various fractions. In this way, some undesirable variables could be eliminated. It would further reduce the experimental work involved in determining the physical properties proposed. Such a procedure has been followed by the U.S. Frost Effects Laboratory at Boston in one phase of their work.

9. Summary

The rate of ice lens formation in soils is believed to depend on the ability of the soil mass to transmit moisture. This in turn is a function of its physiochemical properties. Whether an ice lens can be initiated depends on the adsorptive force of water in the vicinity of the frost line. The total driving force is believed to be a combination of (a) the temperature gradient and (b) the soil moisture suction gradient.

The first phase of these proposed studies will be concerned with a study of the limiting pF at which ice lensing can be induced and the determination of soil moisture potential gradients under steady-state flow conditions in the absence of temperature gradients, except in the immediate vicinity of the ice lens. The flow rates induced by ice lensing will be compared with flow rates in the unsaturated permeability apparatus. The physiochemical properties are largely determined by the clay mineral fraction and will be described in terms of its type, specific surface area index, interlayer swelling, base exchange capacity and base exchange complex etc. Some identification tests will also be done as a means of describing the soil for classification purposes. The test specimens will consist of artificially blended sand silt and clay fractions. Further studies will include the effect of normal temperature gradients. It is believed that such an approach will assist in the formulation of more adequate frost action criteria.

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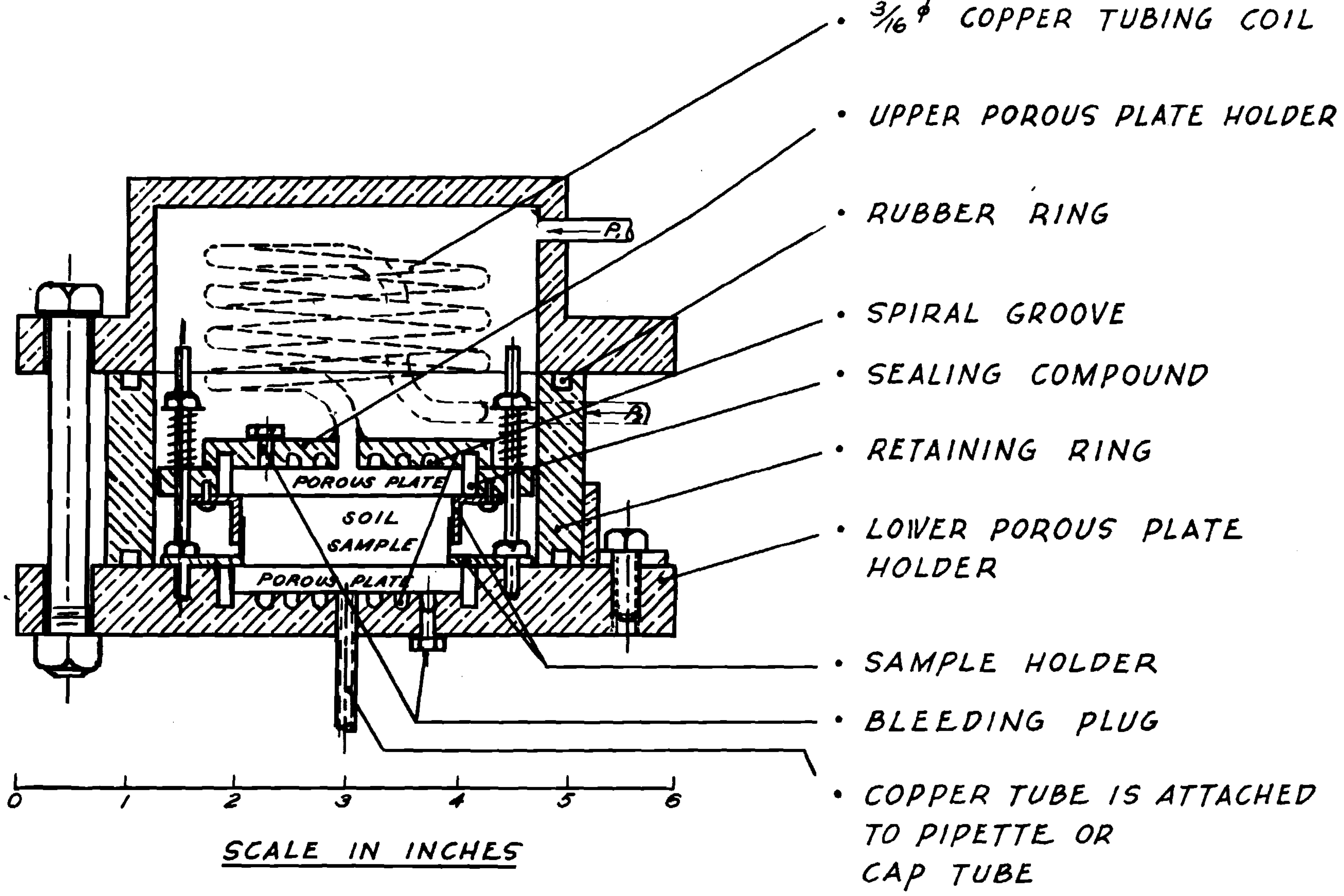

FIGURE 1 UNSATURATED PERMEABILITY APPARATUS

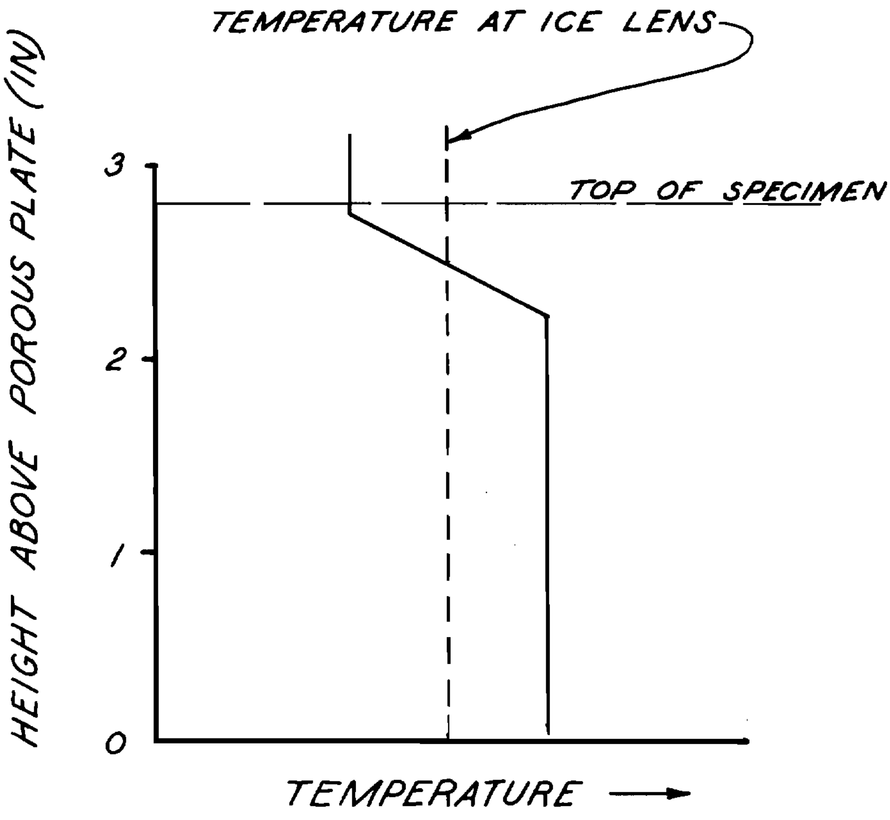

FIG. 2. VERTICAL SOIL TEMPERATURE DISTRIBUTION IN FROST CELL.