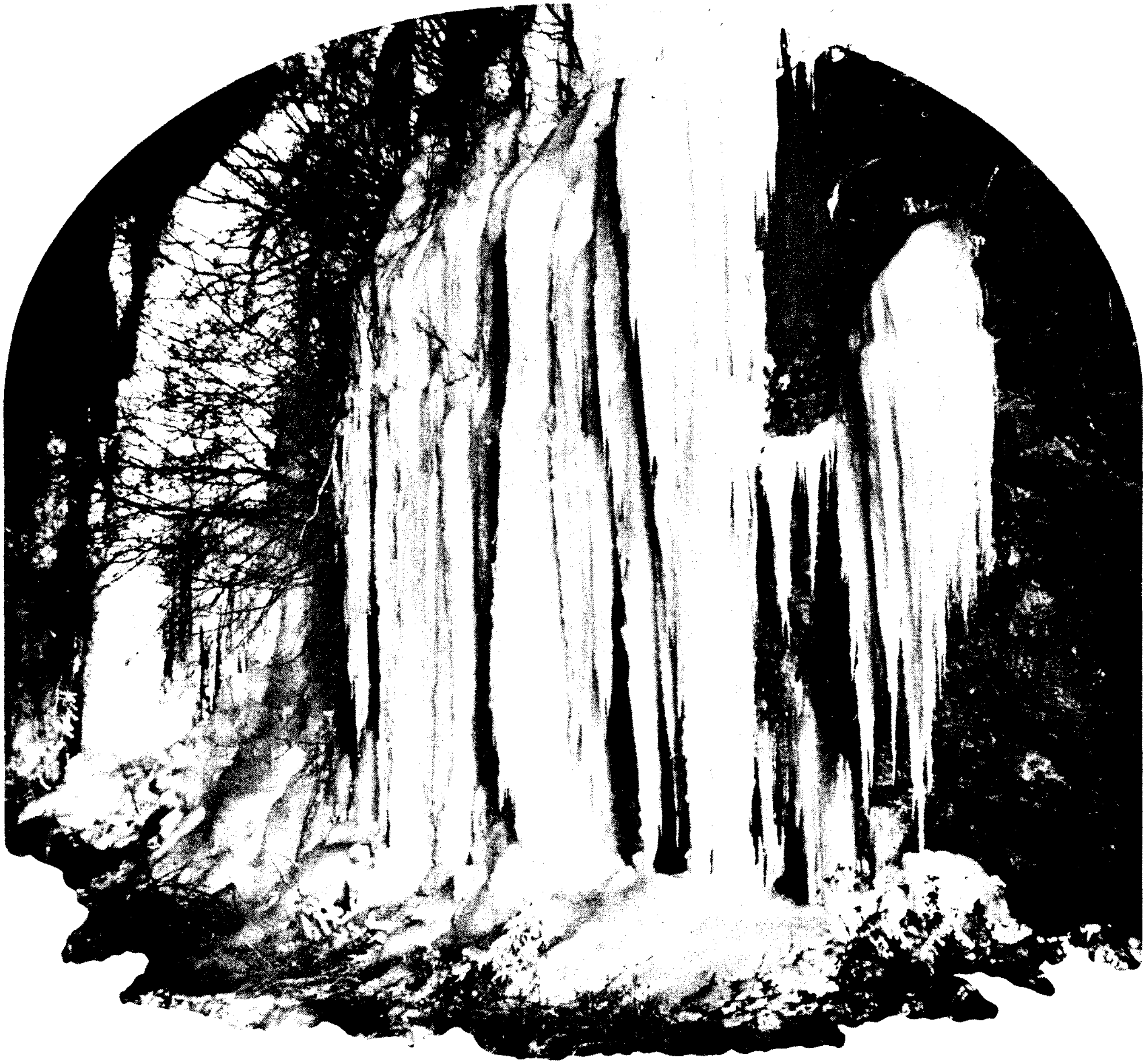

PROCEEDINGS

CONFERENCE ON SOIL-WATER PROBLEMS IN COLD REGIONS

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JAMES N. LUTHIN, Chairman
Department of Water Science
and Engineering
University of California
Davis, California 95616

DUWAYNE M. ANDERSON, Vice-Chairman
Cold Regions Research and
Engineering Laboratory
Hanover, New Hampshire 03755

RICHARD L. HARLAN
Northern Engineering Services
Company Ltd.
Calgary, Alberta, Canada

ROBERT CARLSON
Institute of Water Resources
University of Alaska
College, Alaska 99701

PETER WILLIAMS
Department of Geography
Carlton University
Ottawa, Canada K1S 5B6

We want to express our appreciation for the capable assistance of Mrs. Diana McLaughlin in connection with the conference, and the Proceedings.

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VARIABLES CONTROLLING BEHAVIOR
OF A PARTLY FROZEN SATURATED SOIL

D.D. Kent,
EBA Engineering Consultants Ltd.,
Edmonton, Alberta.

D.G. Fredlund,
University of Saskatchewan,
Saskatoon, Saskatchewan.

W.G. Watt,
University of Saskatchewan,
Saskatoon, Saskatchewan.

INTRODUCTION

Engineering activities in areas of the world's surface underlain by permafrost has initiated increased interest in the behavior of partly frozen soils. Analytical techniques to date, generally treat the soil in permafrost areas as having a frozen zone and a thawed zone with an infinitesimal interface separating the two states. However, in reality, the interface is a transitional zone where only a portion of the pore water is frozen. In the strictest sense, unfrozen water exists at very low temperatures (Williams 1967). However, for this paper the term "partly frozen soil" will be restricted to the case where sufficient pore water exists so that a measurable flow may occur.

In many ways the nature of the ice and water in a porous media is similar to an unsaturated soil where air and water exist at equilibrium under different pressures (Miller 1963). The ice water system is further complicated because the relative amounts of the ice and water are functions of temperature.

The object of this paper is to theoretically propose and experimentally verify a unique set of variables which define the "state" of a partly frozen soil. The term "state" is used in the thermodynamic sense to represent the variables required to characterize a system (Fung, 1965). These "state variables" would provide a sound theoretical basis for further applied research. Continuum mechanics principles were used to derive "state variables" and a laboratory program was used to test their validity. The results are used to advance a mechanism to describe deformations in a partly frozen soil (Kent, 1974).

THEORY

A continuum mechanics approach based upon the principles of conservation of momentum and conservation of energy is used in the analysis of an element of partly frozen soil. Using this approach, the soil can be analyzed from a phenomenological point of view rather than from an interparticle or statistical standpoint. The approach is similar to that used by Fredlund (1973) to study unsaturated soil behavior.

By definition of a continuum, the element must be large enough to contain a "continuous distribution" of each phase (Fung, 1969). The partly frozen soil element contains four continuous phases; soil particles, ice, water and the ice-water interphase (these will be denoted by the subscripts p, i, w, d, respectively). The ice-water interphase is designated as a separate phase because of the pressure difference existing across the interphase, the interfacial free energy and the differing physical properties of the interphase (Jellinek, 1972). The relative amounts of each phase are described in terms of a porosity with respect to that phase. For example,

$$\text{soil particle porosity} = n_p = \frac{\text{Volume of soil particles}}{\text{Volume of element}}$$

$$\text{or } n_p = \frac{\text{Area of soil cut by any plane through element}}{\text{Area of plane}}$$

Each phase is assumed to be evenly distributed throughout the element.

The principle of the conservation of momentum, which reduces to the Newtonian force equilibrium equations, are applied in three directions to each constituent phase and also to the total or overall element. Consider an element of soil with dimensions dx, dy, and dz. The general force equilibrium equation in the y-direction for each phase is:

$$n \cdot \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right] + F_y + n \cdot \gamma = 0 \qquad (1)$$

where

τ_{xy}, τ_{zy} = shear stresses acting on the xy planes respectively

σ_y = the normal stress on the xz plane

n = porosity with respect to the phase

F_y = interaction forces with other phases, for the y-direction

γ = unit weight of the phase

Similar equilibrium equations can be written for each phase and for the total element. For the soil particles, the equilibrium equation for the y-direction is:

$$n_p \cdot \left[\frac{\partial \tau^p_{xy}}{\partial x} + \frac{\partial \sigma^p_y}{\partial y} + \frac{\partial \tau^p_{zy}}{\partial z}\right] + F_{wp} + F_{dp} + F_{ip} + n_p \cdot \gamma_p = 0 \qquad (2)$$

where

F_{wp} = the iteraction force between the water and the soil particles

F_{dp} = the interaction force between the ice-water interphase and the soil particles.

F_{ip} = the interaction force between the ice and the soil particles.

For the ice-water interphase, the y-direction equilibrium equation is:

$$n_d \cdot \left[\frac{\partial \tau^d_{xy}}{\partial x} + \frac{\partial \sigma^d_y}{\partial y} + \frac{\partial \tau^d_{zy}}{\partial z}\right] + F_{wd} + F_{id} + F_{pd} + n_d \cdot \gamma_d = 0 \qquad (3)$$

where

F_{wd} = the interaction force between the water and ice-water interphase

F_{id} = the interaction force between the ice and the ice-water interphase

F_{pd} = interaction force equal and opposite to F_{dp}

For the water phase, the y-direction equilibrium equation is:

$$n_w \cdot \frac{\partial u_w}{\partial y} + F_{dw} + F_{pw} + n_w \cdot \gamma_w = 0 \tag{4}$$

where

F_{dw} = interaction force equal and opposite to F_{wd}

F_{pw} = interaction force equal and opposite to F_{wp}

For the ice phase, the y-direction equilibrium equation is:

$$n_i \cdot \left[\frac{\partial \tau^i_{xy}}{\partial x} + \frac{\partial \sigma^i_y}{\partial y} + \frac{\partial \tau^i_{zy}}{\partial z}\right] + F_{di} + F_{pi} + n_i \cdot \gamma_i = 0 \tag{5}$$

where

F_{di} = interaction force equal and opposite to F_{id}

F_{pi} = interaction force equal and opposite to F_{ip}

For the total or overall element, a further equilibrium equation can be written.

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\sigma \tau_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + n_p \cdot \gamma_p + n_d \cdot \gamma_d + n_w \cdot \gamma_w + n_i \cdot \gamma_i = 0 \tag{6}$$

Further equilibrium equations can be written for various phase combinations; however, only four equations are independent since it is a four phase system.

In most soil mechanics problems, it is the surface tractions of stresses associated with the soil particles that are of prime importance. However, as in the case of a saturated soil, it is impossible to directly measure stresses associated with the soil particles. This problem is overcome by ignoring the soil particle equilibrium equation and writing its equilibrium in terms of other equilibrium equations that contain stresses that can be measured or related to other measurable variables. To do this for a partly frozen soil it is convenient to divide the system into two multiphases as shown in Figure 1. These are the soil and water multiphase and the ice and ice-water interphase multiphase. By substitution of the remaining force equilibrium equations and by the use of the force equivalencies illustrated in Figure 1, the force equilibrium equation for the soil particles can be rewritten in terms of the remaining stresses as follows:

$$\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(\sigma_y - u_w)}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right] - n_i \cdot \left[\frac{\partial \tau^i_{xy}}{\partial z} + \frac{\partial(\sigma^i_y - u_w)}{\partial y} + \frac{\partial \tau^i_{zy}}{\partial z}\right]$$

$$+ (n_d + n_p)\cdot\frac{\partial u_w}{\partial y} + F_{wp} + F_{wd} + F_{id} + F_{ip} + n_p \cdot \gamma_p + n_d \cdot \gamma_d = 0 \qquad (7)$$

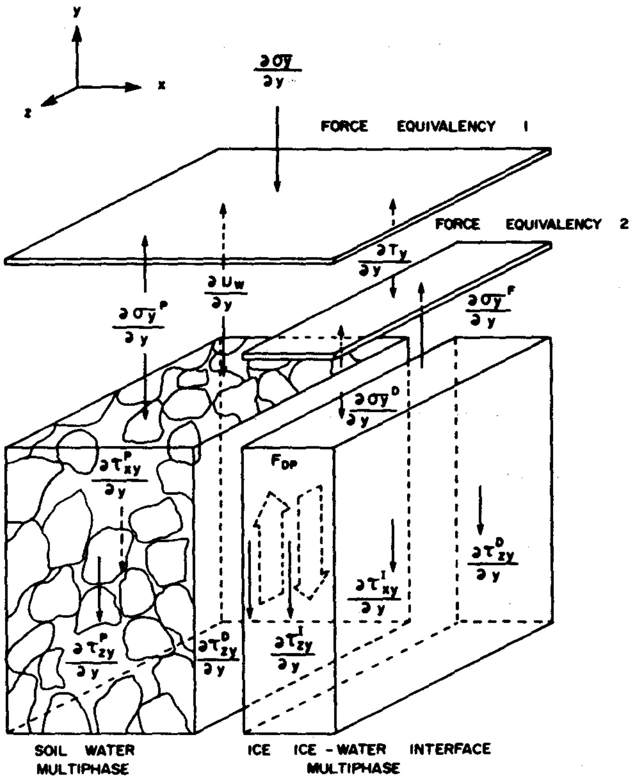

FIGURE 1 REARRANGED PARTY FROZEN SOIL ELEMENT

A similar equation can be derived for the x and z directions. Examination of the equilibrium equations reveals the surface tractions that can be extracted in the form of independent stress matrices that control the equilibrium of the soil particles. Ignoring the independent water pressure that surrounds the soil particles, the stress state variables are:

$$\begin{bmatrix} (\sigma_x - u_w) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_w) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_w) \end{bmatrix} \qquad \begin{bmatrix} (\sigma^i_x - u_w) & \tau^i_{yx} & \tau^i_{zx} \\ \tau^i_{xy} & (\sigma^i_y - u_w) & \tau^i_{zy} \\ \tau^i_{xz} & \tau^i_{yz} & (\sigma^i_z - u_w) \end{bmatrix}$$

The first stress matrix is identical to the stress state variable commonly known as the effective stress which controls the deformation of a thawed saturated soil. The total stress components can be predicted or measured while the water pressure can be measured.

The second stress matrix cannot be determined in the form shown because the stress in the ice cannot, at present, be physically measured. However, in select cases the pressure difference across the ice water interphase can be inferred from thermodynamics principles. The Clausius Clapeyron equation, which can be derived directly from the conservation of energy equation describes the conditions of local equilibrium between ice and water.

$$\frac{L\theta}{v_w \cdot T_o} = P_i - u_w \tag{8}$$

where

L = Latent heat of fusion

θ = Temperature below the normal melting point

T_o = Normal melting point (absolute)

P_i = Normal ice pressure

v_w = Specific volume of the water phase

When the local shear stresses in the ice phase are zero, then

$$P_i = \sigma_i \tag{9}$$

Shear stresses may, however, occur in the ice phase from causes other than external shear loading on a macroscopic scale. Figure 2 shows the ice phase in a hypothetical section of a partly frozen soil element. It is apparent that under conditions of isotropic loading there can be intrinsic shear stresses developed in the ice phase in places such as cross sections A-A' and B-B'. Because of the viscous properties of the ice phase, creep deformation will result from the intrinsic shear stresses. Assuming the ice to be a viscous material, the intrinsic shear stresses will tend to zero when deformation has ceased. In this special case of isotropic loading, the state variable matrices can be written as

$$\begin{bmatrix} \sigma_x - u_w & 0 & 0 \\ 0 & \sigma_y - u_w & 0 \\ 0 & 0 & \sigma_z - u_w \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \theta & 0 & 0 \\ 0 & \theta & 0 \\ 0 & 0 & \theta \end{bmatrix}$$

since $(L/v_w \cdot T_o)$ is a constant.

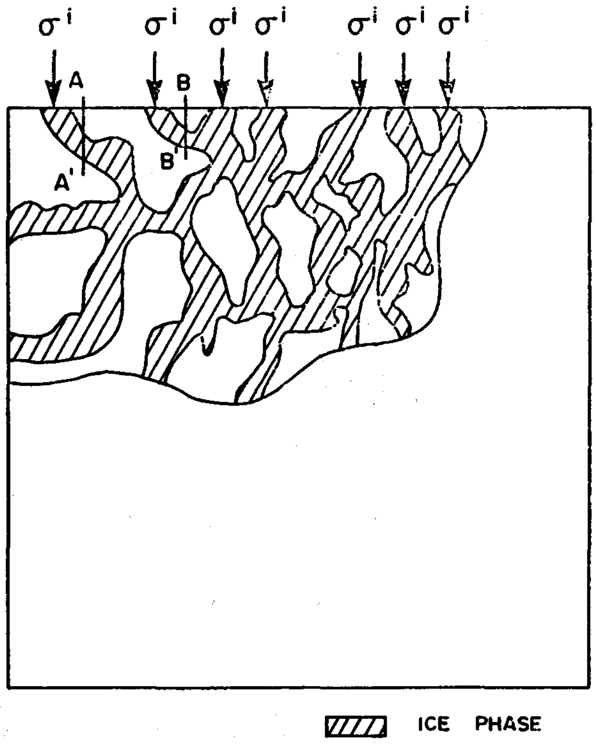

FIGURE 2 PARTLY FROZEN ELEMENT SHOWING INTRINSIC SHEAR STRESSES IN THE ICE PHASE

EXPERIMENTAL VERIFICATION OF PROPOSED STATE VARIABLES

Laboratory experiments were conducted to verify whether $(\sigma - u_w)$ and θ were the state variables that controlled the volume change of a partly frozen soil. To verify the stress state variable $(\sigma - u_w)$, null type tests were conducted whereby the components σ and u_w were independently varied while the overall stress state variable was kept constant (i.e.$\Delta(\sigma - u_w) = 0$). If any process was found to occur, this would signify that other state variables were involved. On the other hand, θ, was tested by subjecting a partly frozen soil to minute temperature changes.

A saturated sample was enclosed in a pressure cell which was then immersed in a glycol bath. Isotropic compression was achieved using a modified 4-inch diameter triaxial cell as shown in Figure 3. The porewater pressure, total confining pressure and temperature could be varied independently and the total volume and water volume changes were measured. All measurements were made with electronic outputs connected to a data acquisition system. A schematic drawing of the system is shown in Figure 4.

PORE WATER MEASURING SYSTEM

The pore water in the sample was connected to the pore water measuring system through a 2 micron porous disc. An ethylene glycol mixture was used to prevent freezing in the pressure measuring system. The plumbing was arranged such that a fresh ethylene glycol mixture could be flushed through the measuring system and the base of the cell to remove any diluted mixture which might possibly freeze and any dissolved air which may have come out of solution.

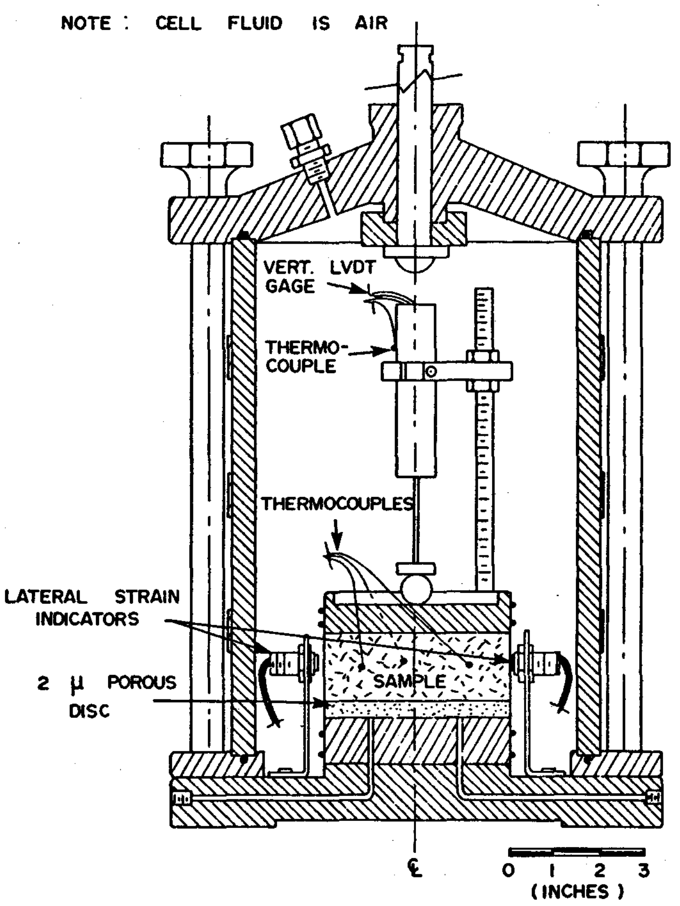

FIGURE 3 MODIFIED TRIAXIAL CELL

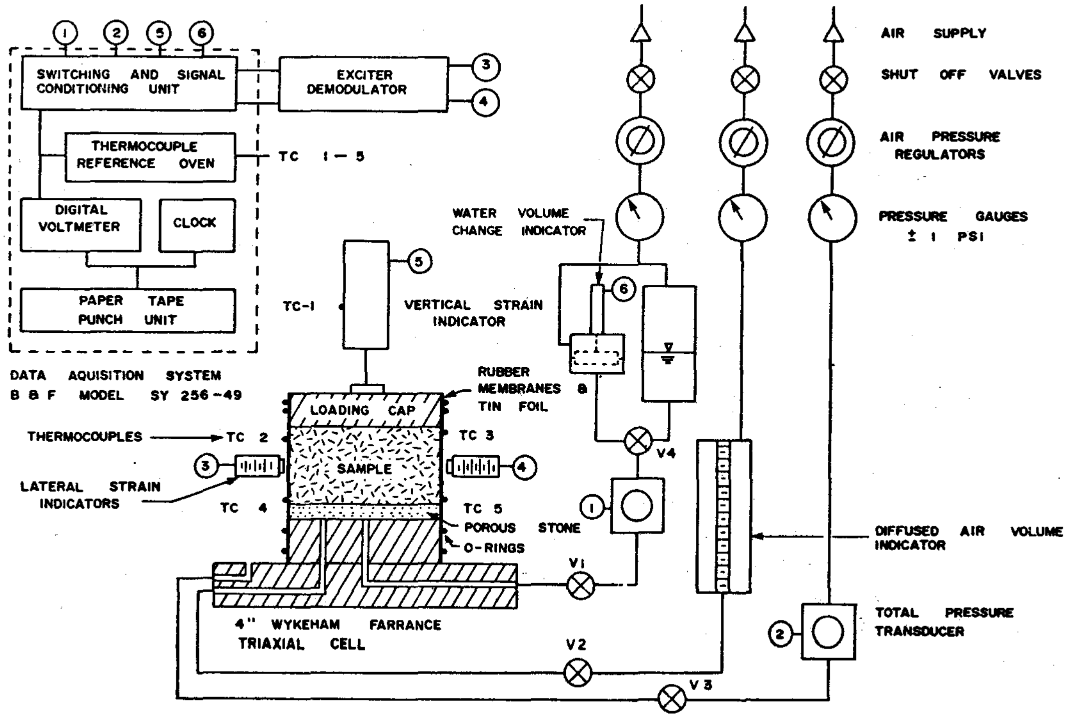

FIGURE 4 SCHEMATIC REPRESENTATION OF EQUIPMENT

The porewater volume change was measured using a DCDT (Direct current displacement transducer) and float arrangement with a displacement up to 20ml. and an accuracy of ± 0.05 ml. The porewater system could be back-pressured by applying an air pressure to the porewater measuring device. Pressure control was obtained using null type air pressure regulators.

SAMPLE CONFINEMENT

Air was used as a confining fluid. The sample was isolated from the air by two latex rubber membranes separated by slotted aluminum foil and silicon grease. These measures were necessary to minimize diffusion of air from the cell into the sample (Fredlund, 1973).

The volume change of the sample was computed from one vertical displacement measured with a DCDT and two horizontal displacements measured at mid-height on opposite sides of the sample with two Sciences KD-2400 multi-vit displacement transudcers. These transducers, which operate on the eddy current loss principle, are able to measure very precisely the distance to the conducting foil surface without touching the surface. Based upon displacement measurements, the accuracy of the total volume change measurement was ± 0.014% of the total volume.

TEMPERATURE MEASUREMENT AND CONTROL

Three copper constantan thermocouples placed on the outside of the sample were used for temperature measurements. The thermocouples were calibrated at 0°C with an ice point reference and tabulated values used to define the emf-temperature relationship. Temperature control was provided by submerging the cell in a 30 gallon water-glycol bath. Temperature variation of the sample with time was typically less than 0.55°C.

EXPERIMENTAL PROCEDURE AND PROGRAM

The soil used in the test program was a well graded sandy clay glacial till of the Battleford formation. The sample was prepared as a slurry and consolidated one dimensionally in a mould under a total stress of 17 psi. The sample was then installed in the cell and allowed to consolidate under an isotropic pressure of 20 psi. After consolidation, the samples were frozen as a closed system. This minimized any intake of the water-glycol mixture from the measuring system into the sample.

Results from two series of tests (F-6 and F-8) are presented in this paper. Table 1 summarizes the Volume-Weight data. In both cases, the test procedures were arranged such that water was always flowing out of the sample, minimizing the effects of glycol diffusion into the sample. Each series of tests lasted approximately three weeks and consisted of several independent tests. The tests can be summarized as studies of:

I). Volume change due to a change in total pressure,
II). Volume change due to a change in water pressure,
III). Volume change resulting from an equal change in water and total pressures,
IV). Volume change due to a small temperature increment.

TABLE I

Volume-Weight Data

	F-6	F-8
Specific gravity	2.70	2.70
Weight of Solids	422.63 gm.	443.51 gm.
Volume of Solids	156.33 cc.	164.26 cc.
Initial Height	1.210 in.	1.198 in.
	1.204 in.	1.220 in.
	1.149 in.	1.165 in.
Diameter	3.082 in.	3.987 in.
	3.986 in.	3.985 in.
	3.992 in.	3.989 in.
Total Volume	246.43 cc.	245.94 cc.
Wet Weight	498.72 gm.	522.45 gm.
Weight of Water	76.09 gm.	78.94 gm.
Water Content	18.0 %	17.80 %
Void Ratio	0.486	0.481
Final Weight	1.109 in.	1.75 in.
	1.113 in.	1.130 in.
	1.141 in.	1.109 in.
Diameter	3.913 in.	3.945 in.
	3.904 in.	3.943 in.
	3.911 in.	3.932 in.
Total Volume	220.81 cc.	227.36 cc.
Wet Weight	482.36 gm.	499.65 gm.
Weight of Water	59.73 gm.	56.13 gm.
Water Content	14.13 %	12.66 %
Void Ratio	0.382	0.342

Detailed logs of test series F-6 is given in Table II and graphically presented in Figures 5 and 6. A similar log for test series F-8 is given in Table III and graphically presented in Figures 7 and 8. Corrections have been made to the water volume change for cavitation during freezing and the effects of any air diffusing through the pore water and accumulating in the measuring system.

The ice porosity at any time during a series of tests was obtained from volumetric considerations of the partly frozen soil.

$$\Delta V_i = \frac{\Delta(V_t - V_{wf})}{(1 - \frac{v_w}{v_i})} \qquad (10)$$

where

ΔV_i = Change in volume of ice

ΔV_t = Change in total volume

ΔV_{wf} = Change in water volume flowing from sample

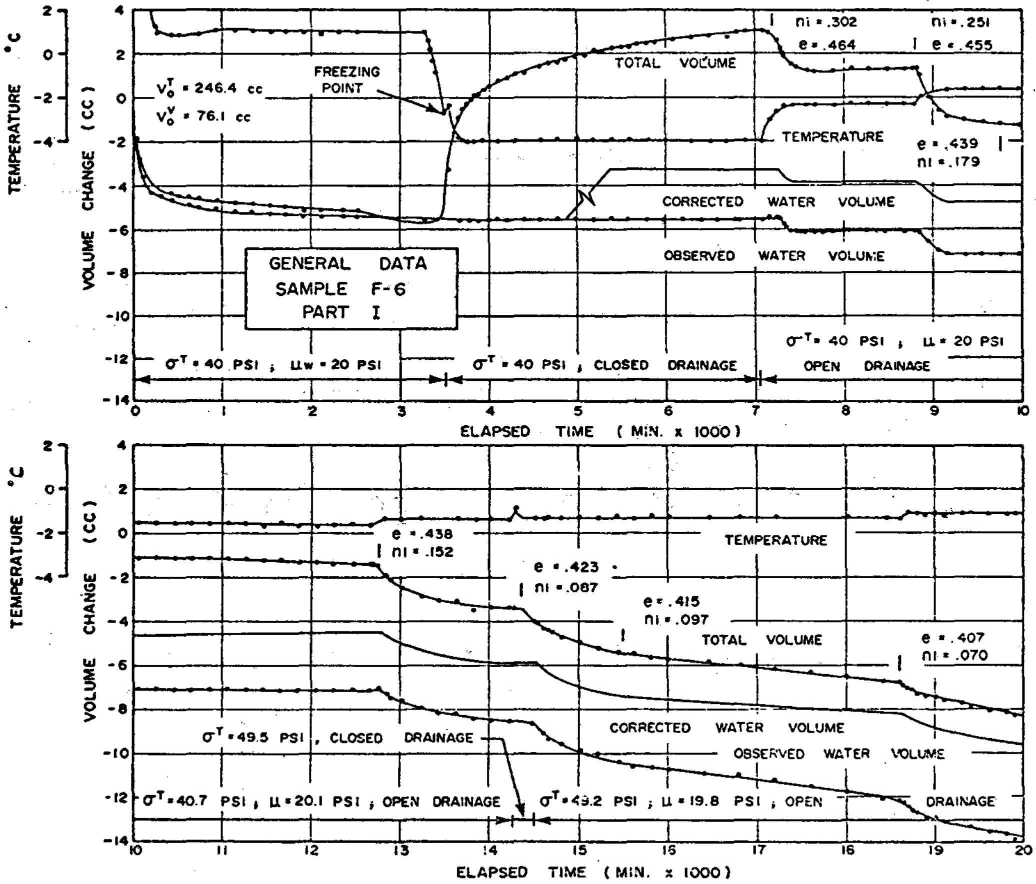

FIGURE 5 TEST RESULTS FOR THE F-6 SERIES

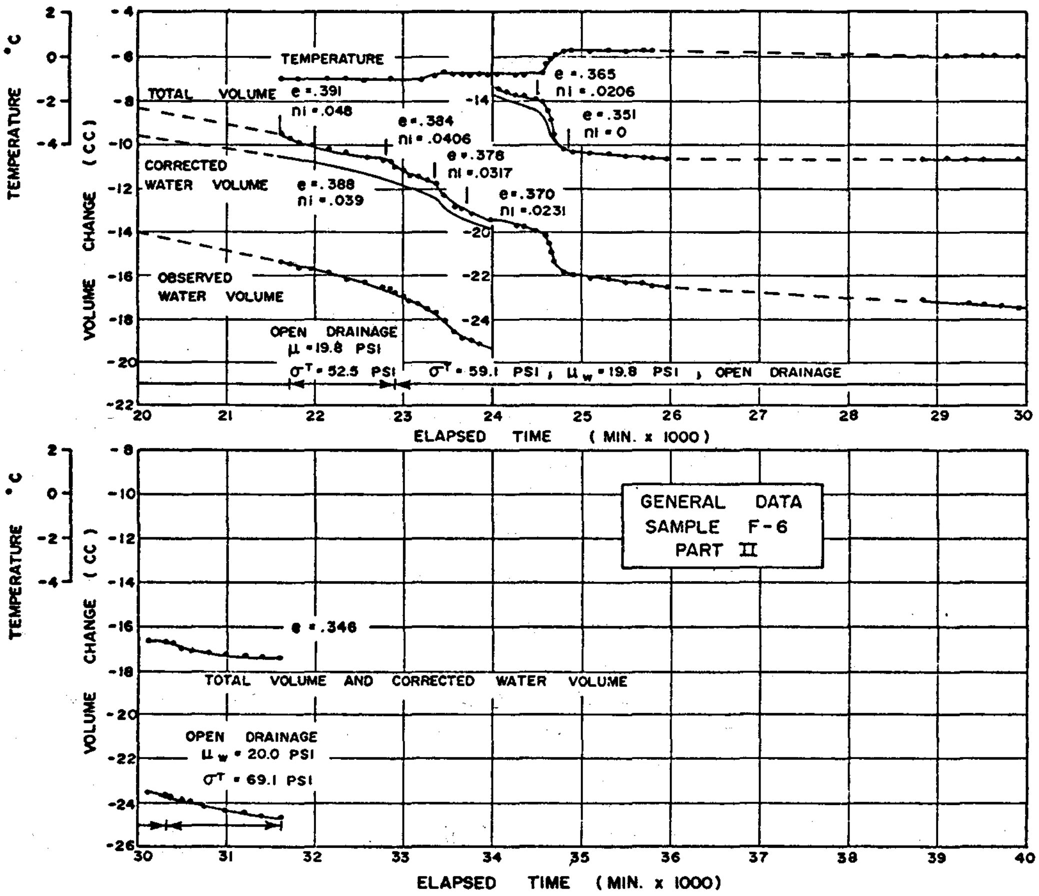

FIGURE 6 TEST RESULTS FOR THE F-6 SERIES (CONTINUED)

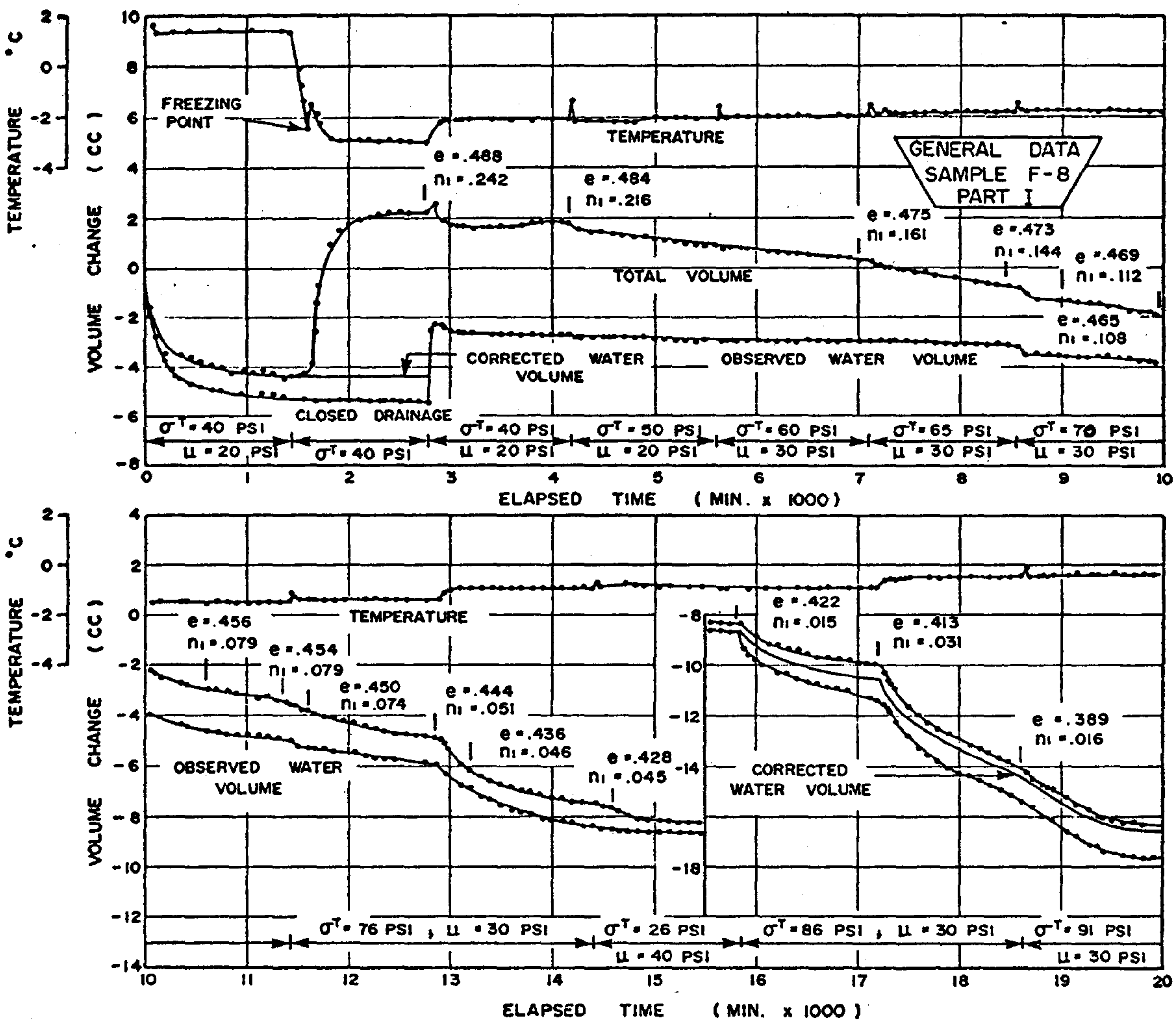

FIGURE 7 TEST RESULTS FOR THE F-8 SERIES

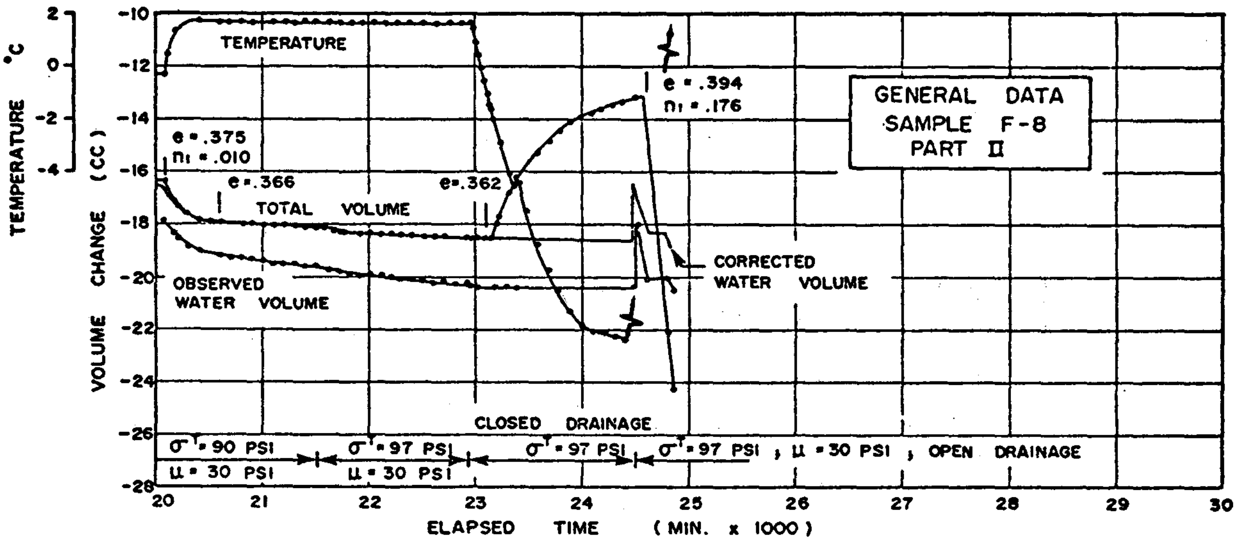

FIGURE 8 TEST RESULTS FOR F—8 SERIES (CONTINUED)

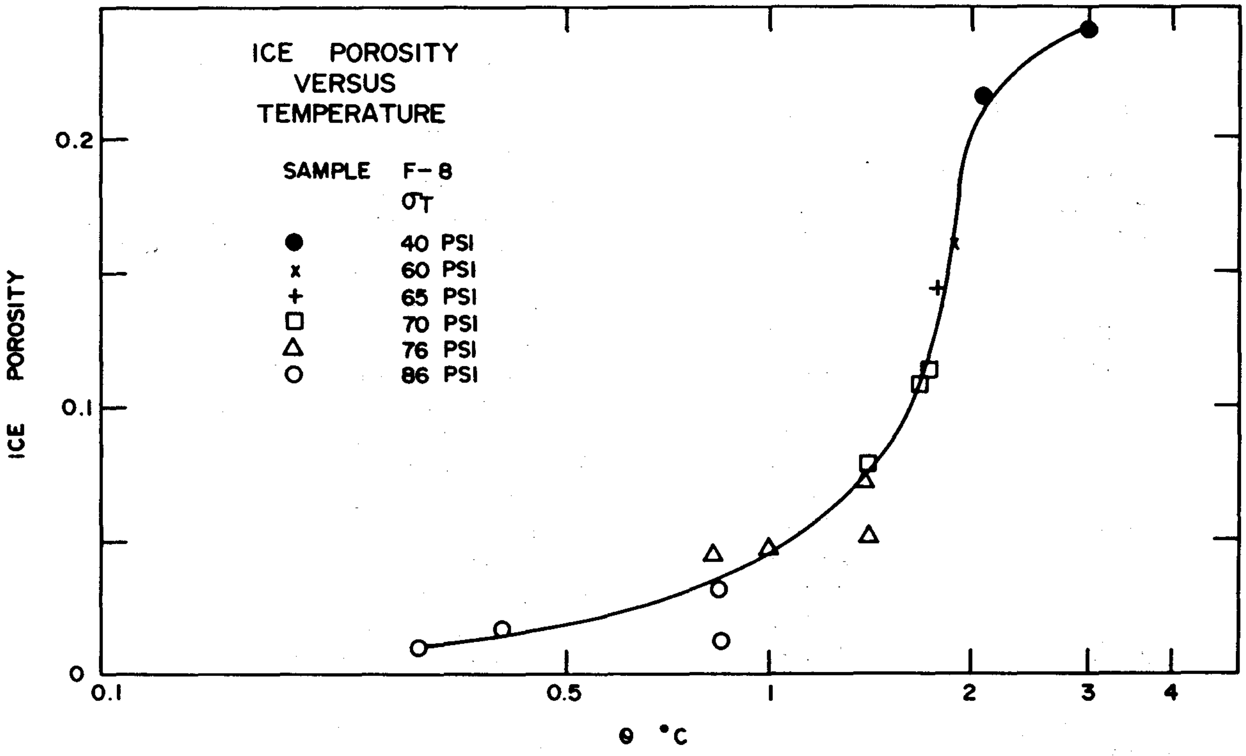

FIGURE 9 ICE POROSITY VERSUS TEMPERATURE

v_w = Specific volume of water

v_i = Specific volume of ice

Figure 9 shows the ice porosity computations versus the temperature below zero degrees for the F-8 series of tests. All results indicate that the ice porosity is independent of the total pressure.

PROCESSES OBSERVED

During all of the series of tests it was observed that processes never came to complete equilibrium. Rather, after the initial process was complete, there was a continuous linear volume change. This behavior is similar to the creep of a frozen soil under uniaxial stress described by Ladanyi (1972). He describes creep strains which occur in a frozen soil as a result of the shear stresses developed in a uniaxially stressed sample. In the case of an isotropically loaded sample, the externally applied shear stresses are zero. A possible source for the volume changes is the intrinsic shear stresses discussed previously. These intrinsic shear stresses are believed to be the cause of the linear "creep" volume change observed. Because of their internal nature the presense of these stresses is difficult to prove or disprove.

TABLE II

Series F-6 Log

Date	Elapsed Time (Min.)	Activity
March 16, 1974	0	- Began test.
March 18,	3300	- Reduced temperature under closed drainage.
March 21	7100	- Noticed a slight flow of water into sample when drainage was opened.
		- Raised temperature.
March 22	8500	- Flushed base - no air observed.
March 25	12700	- Raised temperature.
March 26	14200	- Flushed base 0.48 cc @ 20 psi.
	14300	- Performed a pore pressure reaction test.
	14560	- Opened drainage.
March 29	18600	- Increased temperature.
March 31	21600	- Increased cell pressure to $\sigma = 52.5$ psi.
April 1	22800	- Flushed base 2.34 cc @ 20 psi.
	22900	- Increased cell pressure to $\sigma = 59.1$ psi.
	23300	- Increased temperature.
April 2	24500	- Flushed base 0.22 cc @ 20 psi.
	24500	- Increased temperature.
April 3		- Data acquisition system failed.
April 4	27100	- Flushed base 0.92 cc @ 20 psi.
April 5	28500	- Flushed base 0.66 cc @ 20 psi.
April 6	30330	- Increased cell pressure to $\sigma = 70$ psi
April 7	31200	- Flushed base 1.40 cc @ 20 psi.
April 8		- Flushed base 0.81 cc @ 20 pai.
		- Took down sample.

For analytical purposes the volume change can be visualized as consisting of two processes: a process with a rate which decreases with time and a process with a constant rate. The volume change associated with the variable rate process can be obtained by extrapolating the linear portion of the curve back to the time of initiation of a state variable change and subtracting the linear volume change from the total volume change. This is the 'revised volume change' shown in Figures 5 to 8.

EFFECTS OF CHANGES IN TOTAL AND/OR WATER PRESSURE

Figure 10 shows an enlargement from the F-6 series where the total pressure was increased by 3.6 psi. The processes are similar to those observed for a 10.0 psi decrease in the water pressure from the F-8 series (Figure 11). It is seen that an increase in total pressure or a decrease in water pressure results in a decreasing rate process followed by a constant rate or creep volume change process. The constant rate volume change was subtracted from the total volume change leaving the revised volume change due to the pressure change. When the revised volume change is plotted on semilogarithmic scale the resulting curve resembles a typical consolidation curve in conventional soil mechanics. This suggests that the rate of volume change in a partly frozen soil due to a pressure increment is governed by pore water dissipation.

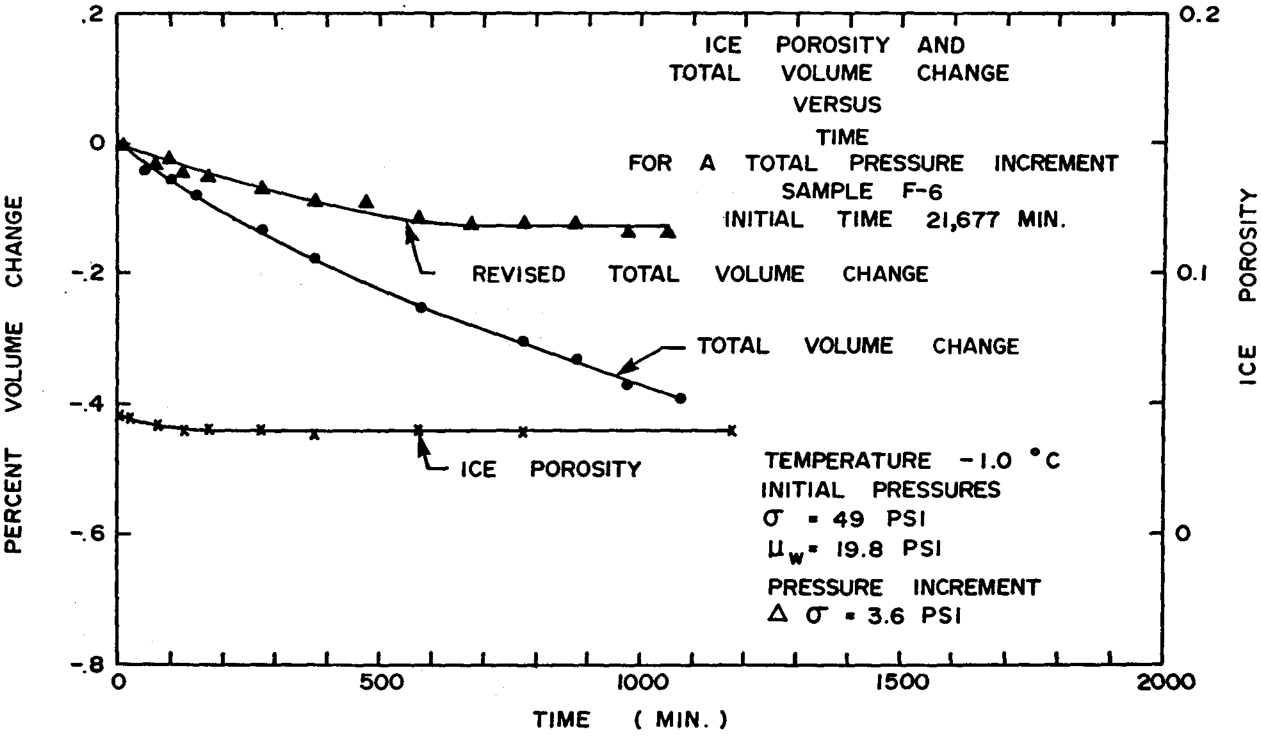

FIGURE 10 TOTAL VOLUME CHANGE FOR A TOTAL PRESSURE INCREMENT

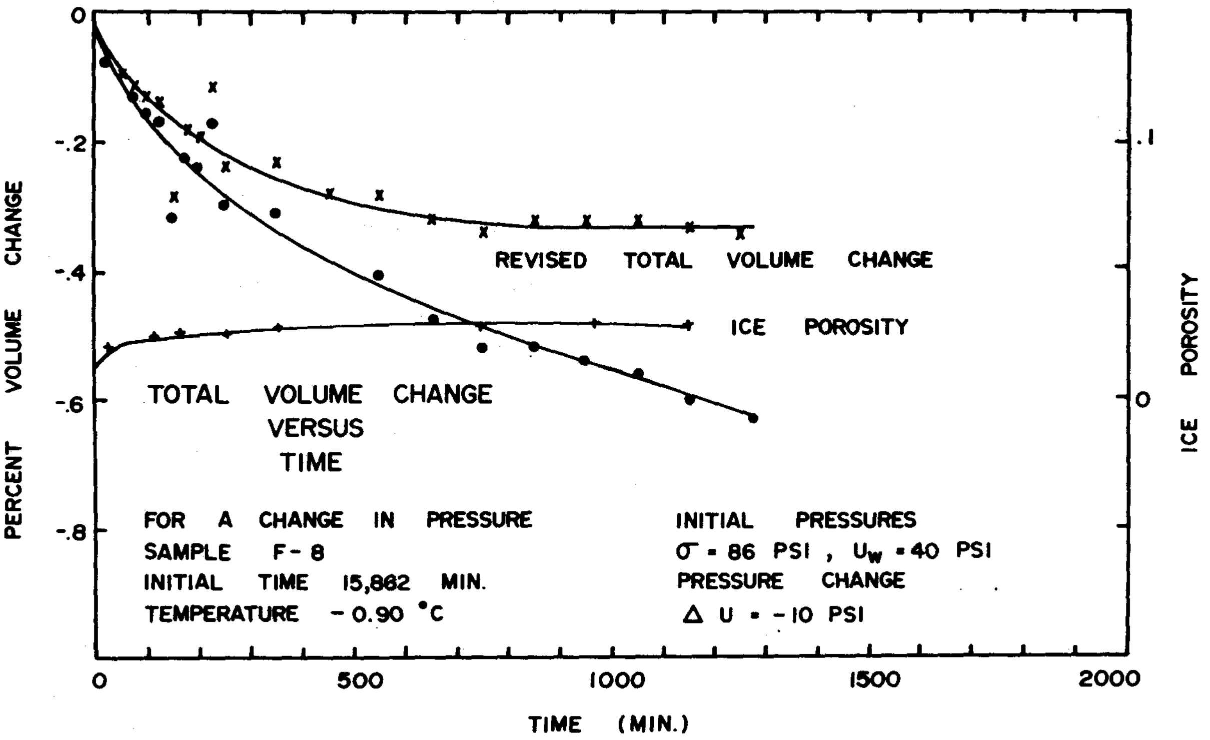

FIGURE 11 TOTAL VOLUME CHANGE FOR A WATER PRESSURE DECREMENT

TABLE III

Series F-8 Log

Date	Elapsed Time	Activity
April 17, 1974	0	- Began test. - Flushed base for approximately 10 min.
April 18	1439	- Flushed base 1.19 cc air @ 20 psi. - Reduced temperature with closed drainage.
April 19	2790	- Volume change of 2.84 cc after 1 minute when valve V1 was opened. - Flushed base 0.19 cc air @ 17 psi. - Raised temperature under open drainage.
April 20	4170	- Flushed base 0.13 cc of air @ 20 psi. - Increased cell pressure to σ = 50 psi.
April 21	5605	- Flushed base - no air. - Raised cell and water pressure to σ = 60 psi; u_w = 30 psi.
Arpil 22	7090	- Flushed base 0.09 cc air @ 30 psi.
April 23	8530	- Flushed base - no air - Raised cell pressure to σ = 70 psi
	8920	- Flushed base - no air
April 24	9970	- Flushed base - no air. - Raised temperature under open drainage.
April 25	11410	- Flushed base - no air.
April 26	12850	- Flushed base - no air. - Raised temperature under open drainage.
April 27	14410	- Flushed base 0.04 cc air @ 30 psi. - Raised cell and water pressure to σ = 86 psi; u = 40 psi.
April 28	15820	- Flushed base - no air.
April 29	17170	- Flushed base 0.37 cc @ 30 psi.
April 30	18610	- Flushed base 0.14 cc of air @ 30 psi. - Increased cell pressure to σ = 91 psi.
May 1	20050	- Flushed base 0.28 cc air @ 30 psi.
May 2	21490	- Flushed base 0.02 cc air @ 30 psi. - Raised cell pressure to σ = 97 psi.
May 3	22930	- Flushed base 0.41 cc air @ 30 psi. - Decreased temperature under closed drainage.
May 4	24475	- Opened valve V1 volume change of 2.11 cc. - Flushed base 0.13 cc @ 30 psi. - Reset volume change indicator by $\approx$ 4 cc. - Raised temperature.
May 4	24715	- Took down sample.

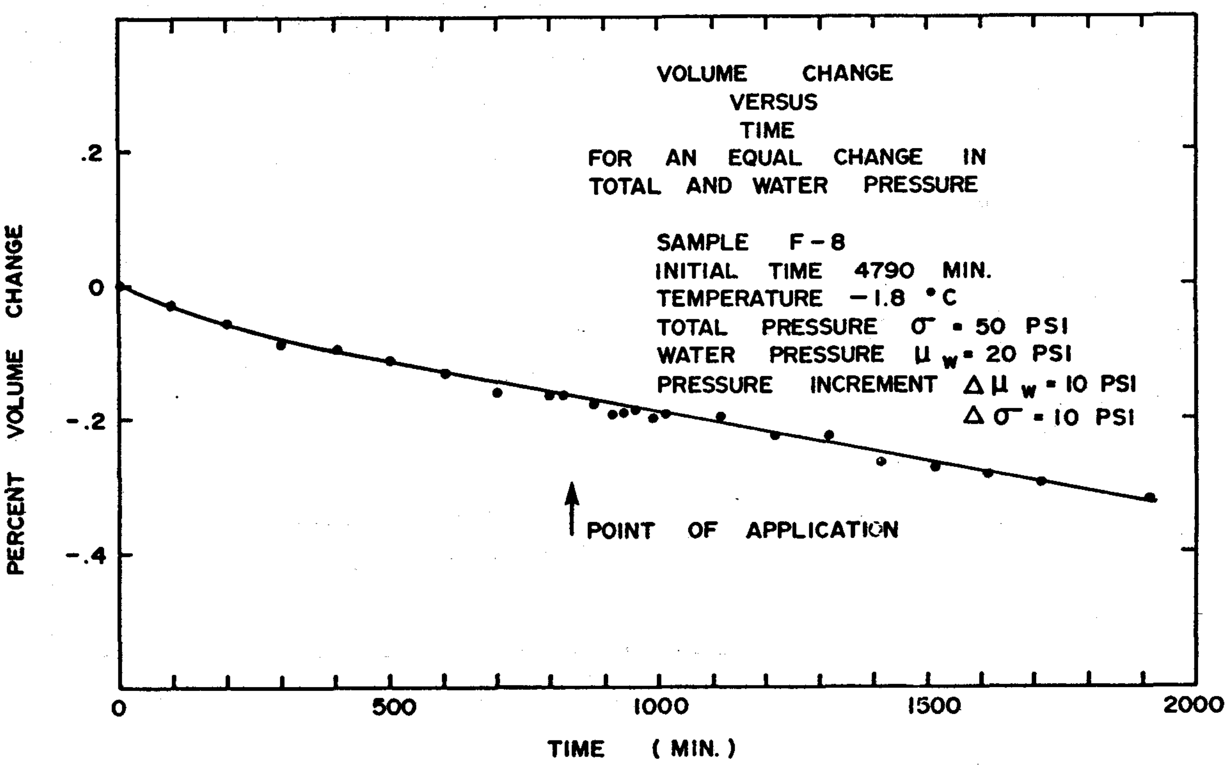

FIGURE 12 TOTAL VOLUME CHANGE FOR EQUAL TOTAL AND WATER PRESSURE INCREMENT

The result of changing the total and water pressures by an equal amount is shown for a test in the F-8 series (Figure 12). This tests the hypothesis for the $(\sigma - u_w)$ stress state variable since the individual components are changed but the overall stress state variable is kept constant. The results indicate that no process was initiated by the stress changes. Therefore, $(\sigma - u_w)$ is validated as a legitimate stress state variable.

EFFECT OF CHANGES IN TEMPERATURE IN A PARTLY FROZEN SOIL

Figures 13 and 14 show that a change in temperature results in two processes: a change in ice porosity and a change in total volume. The change in ice porosity occurs quite rapidly, usually within one hundred minutes, compared with the total volume change process which takes up to fifteen hundred minutes.

The total volume change observed during a process is much larger than that which can be attributed to a phase change alone. In this instance, the change in ice porosity of 0.03 would result in a total volume change of 0.25 percent while the measured volume change was 0.8 percent. This implies that the greater amount of volume change must be the result of

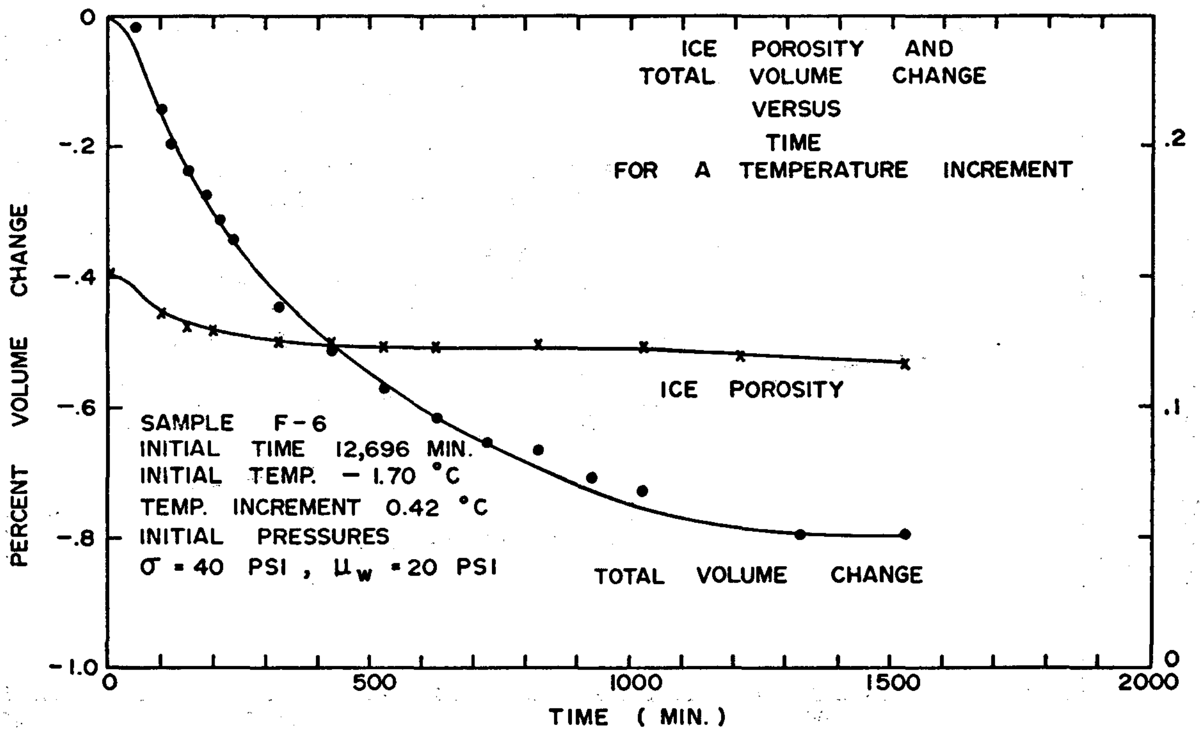

FIGURE 13 TOTAL VOLUME CHANGE FOR A TEMPERATURE INCREMENT

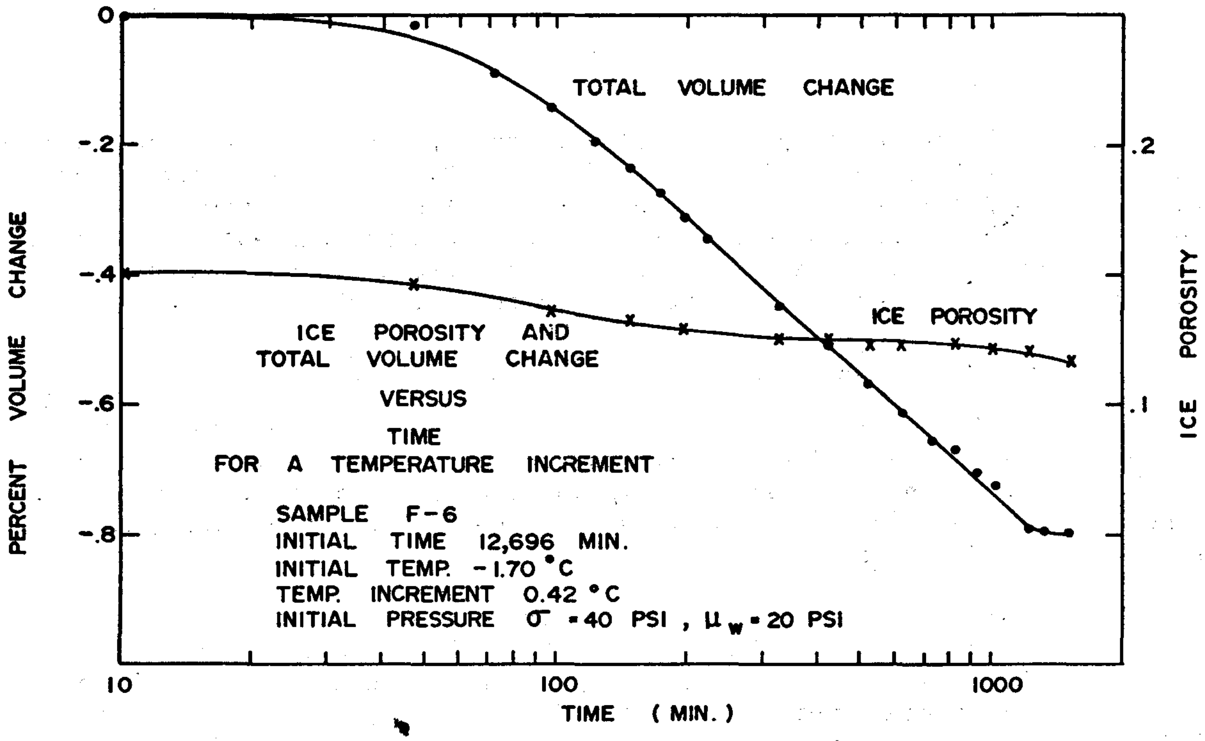

FIGURE 14 TOTAL VOLUME CHANGE FOR A TEMPERATURE INCREMENT

a change in the shape of the ice matrix which in turn allows for a denser arrangement of the soil particles. When the corrected total volume change is plotted on a logarithmic time scale, the relationship again suggests a consolidation type process.

Based upon the preceding observations, the following explanation is suggested for the behavior of a partly frozen soil subjected to a temperature increment. An increase in temperature results in melting of the ice phase until a new equilibrium position of the ice-water interphase is reached. This reduces the ice porosity and subjects the remaining ice to increased normal stresses. Because the intrinsic shear stresses in the ice depend upon both the configuration of the ice matrix and the normal ice stress, they will also increase. Under the increased intrinsic shear stresses the ice phase would be in equilibrium at a much higher creep rate, but the dissipation of pore fluid controls the rate of volume change. During deformation, the stress on the soil structure will increase and the ice phase will assume a new denser configuration. The new state will have a new stress in the soil structure, a new stress in the ice matrix and a new creep rate.

SUMMARY

The main conclusions based on the observations from the testing program are:

(1) A linear creep process occurs under external isotropic loading which suggests the existence of intrinsic shear stresses in the ice phase. Subsequent volume changes from the creep process were significant.

(2) $(\sigma - u_w)$ is validated as a stress state variable for a partly frozen soil.

(3) From theoretical considerations, the temperature change below 0°C appears to be a state variable. Experimental limitations prevented conclusive verification. A temperature increment was found to initiate a volume change process which essentially came to equilibrium at new ice porosity. The rate of this process appeared to be controlled by pore water dissipation.

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