PRESSURE-TIME RELATIONSHIP IN LATERALLY STRESSED FROZEN GRANULAR SOILS

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A frozen sand-ice layer, when subjected to lateral pressure at a constant temperature, shows reduction in stress with time. Investigations were carried out to study the general tendency of this reduction in lateral stress and also to investigate the effects of certain parameters influencing this behavior. Two different types of sand were used to prepare the sand-ice specimens with a variety of initial porosity and degree of ice saturation. They were tested at various constant temperatures under selected initial pressures. The magnitude of pressure retained by a frozen sand sample at any time, after commencement of the experiment, was measured by means of a pressure gauge attached to the "pressure unit." The reduction in lateral stress, expressed as a percentage of initial pressure applied to a frozen sand layer, was studied as a function of five variables; initial pressure, the initial porosity of the sand, the degree of ice saturation, temperature of sample, and time elapsed after the application of initial pressure. Experimental results were plotted in the form of pressure-time curves to study the time-dependent behavior of the sand-ice system under applied load. Also reduction in stress was plotted against each of the previously mentioned variables to show their influence on the reduction in lateral stress. A general equation to predict the value of lateral pressure retained by the sand-ice layer at any time after the application of a known initial pressure was derived empirically in terms of the five variables.

•A CONFINED frozen soil layer is known to exert lateral thrust on retaining structures during freezing and also during an increase of its temperature in the freezing range. Experimental evidence shows that the pressure developed in the latter case by a sand-ice layer, having high ice saturation and low initial soil temperature, can reach a magnitude that no longer may be disregarded by the design engineer (1). This behavior is further complicated by the fact that the magnitude of the lateral thrust developed by the frozen soil, caused by the temperature increase, will not remain constant but will change with time even if the soil layer itself is no longer subjected to temperature rise. Naturally, to a design engineer seeking a more economical design, the maximum instantaneous pressure developed between frozen soil and a retaining structure will be of interest as well as the soil behavior under applied pressure (2, 3). This in turn requires a knowledge of the magnitude of the reduced pressure that will be retained by the frozen sand layer after any given period of time.

Accordingly, the object of the investigation presented in this paper was to study the general tendency in which the lateral stress in frozen sand samples that have been subjected to radial pressure at constant temperatures diminishes with time. The investigation was further extended to correlate the reduction in lateral stress with some relevant parameters, i.e., temperature, degree of ice saturation, porosity, initial pressure, and time. Granular material was selected for this experimental work because it is frost nonsusceptible and is used in areas subjected to frost action.

SOILS STUDIED

Two different types of sand were used to prepare test specimens of various combinations of initial porosity and degree of ice saturation. Sand No. 1 was a crushed

uniform sand from Ottawa, Illinois (uniformity coefficient of 1.5 and specific gravity of 2.65); sand No. 2 was a natural variety of well-graded sand from Paris, Ontario (uniformity coefficient of 3.8 and specific gravity of 2.67). The grain-size distributions are shown in Figure 1.

APPARATUS

The main apparatus, a pressure unit (Fig. 2), consisted of a steel cylinder with a cylindrical rubber diaphragm positioned inside and sealed to both ends of the steel cylinder. The small void between the $\frac{1}{8}$-in. thick diaphragm and cylinder was filled with oil and connected to a hydraulic pressure pump so that any desired amount of initial pressure could be applied to the frozen specimen. The oil pressure was measured by means of an external pressure test gauge connected to the pressure line in which a high pressure valve was installed between the gauge and the pump. The steel cylinder was insulated all around except for the top surface of the sample so that the freezing and thawing of the sand-ice system followed the pattern existing in nature.

To measure the horizontal radial deformation taking place in the sample under applied pressure, we used BLH Type A-9 bonded resistance strain gauges. They were embedded in the sand-ice specimen and connected to a portable digital 8-channel strain indicator (Strainsert Model TN8C). Six copper-constantan thermocouples connected to the temperature potentiometer through a multipolar rotary switch were used to measure the temperature of a frozen soil and the air temperature inside the freezer.

PREPARATION OF SAMPLES

To prepare each sand-ice specimen, we thoroughly mixed a known weight of dry sand and a measured amount of water to provide the desired degree of ice saturation when frozen. The moist sand thus prepared was placed in the pressure unit in four equal, gently compacted layers to form finally a $9\frac{5}{8}$-in. diameter and 4-in. high sample of a certain void ratio. Two 6-in. long strain gauges (previously described) were placed crossways, horizontally halfway down the sample's depth, and symmetrically about the specimen's centroidal axis. Further details on the application and preparation of the strain gauges used can be found elsewhere (1).

The pressure unit with the sand sample was then placed inside the freezing chamber where, after completion of the necessary wire connections to the strain indicator and temperature potentiometer, the specimen was frozen to the required temperature. Before each test, the frozen sample was left at a selected constant temperature for not less than 6 hours to ensure uniform temperature distribution throughout the frozen sample.

TEST PROCEDURE

At the beginning of each test, a selected initial pressure was applied to the frozen specimen, and immediately after that the pressure controlling valve was closed to guard against pressure reduction due to oil outflow. The selected initial pressure indicated by the pressure dial was recorded against zero hour. Afterward, the decrease in pressure shown by the pressure gauge and the change in strain displayed by the strain indicator were recorded after definite intervals of time. The temperature of the specimen, which was kept constant, was frequently checked to ensure no variation during the test. After 24 hours, one set of readings was completed; some tests were continued up to 36 hours or more, but no appreciable change in readings was observed. On completion of a test, the pressure retained by the specimen was released, and, in the case of specimens that were to be reused, the sand-ice system was allowed to recover at 32 F for not less than 36 hours.

TEST RESULTS

The lateral radial pressure σ_t retained by the sand-ice specimen at any time after application of initial pressure was investigated as a function of five variables: initial lateral pressure σ_i, temperature of frozen soil T_F, initial soil porosity n, degree of ice saturation S_I, and elapsed time t.

More than 75 specimens were included in the program. For each investigated specimen, the initial pressure was selected from 25, 50, 75, or 100 psi; temperature was limited to 30, 25, 15 or 0 F; and degree of ice saturation used was 33.3, 50, 66.6, or 100 percent. Initial porosities chosen were 46 percent or 40 percent for specimens of sand No. 1 and 36 percent or 30 percent for specimens of sand No. 2 because they could be obtained with ease without excessive compaction effort. Combinations of these variables were planned in such a manner that maximum information could be obtained from the 75 experiments conducted. Test data were compiled and graphs were drawn to investigate the time-dependent behavior of the sand-ice system under applied pressure as well as the influence of the previously mentioned parameters on this behavior.

Figure 3 shows the relationship obtained between the lateral pressure σ_t retained by frozen sand specimens and the corresponding elapsed time t for indicated values of n, S_I, and T_F. The values of initial pressure σ_I applied to the investigated specimens on commencement of experiments can be read on the ordinates when t = 0 hour. All the pressure-time curves show the same tendency of rapid decrease in pressure during the first few hours and then a slow rate of this decrease with time.

For convenience, a term "reduction in stress" (R_t), expressed as percentage of initial pressure, is introduced and defined as

$$R_t = (\sigma_I - \sigma_t)/(\sigma_I) \times 100 \tag{1}$$

where

R_t = reduction in lateral stress after time t, expressed as a percentage of initial pressure;
σ_I = initial pressure at t = 0, psi; and
σ_t = actual pressure retained after time t, psi.

In the conducted investigation, the decrease in the pressure retained by a frozen soil layer was associated with a nonlinear increase in lateral deformation (strain). Hence, the common rheological term "relaxation" is not applicable in such cases, and the term "reduction in stress" was adapted. Typical experimental strain-time curves showing the change of strain with time are shown in Figures 4 and 5. It can be seen that the strain increases rapidly during the first few hours (causing a decrease in the diameter of the investigated specimen) and then very slowly after approximately 24 hours. The effect of the temperature of the frozen soil on the magnitude of the developed strain can be observed by comparing Figure 4 with Figure 5.

Figures 6 to 9 show some typical "reduction in lateral stress versus time" curves obtained for different combinations of n, S_I, T_F, and σ_I. Figure 6, magnitudes of n, S_I, and σ_I are kept constant to show how the "R_t versus t" curves tend to change at different temperature levels. Similarly, Figure 7 shows the effect of the different initial pressures on the behavior of the R_t versus t curves. Figure 8 shows the effect of porosity, and Figure 9 shows the effect of the degree of ice saturation on the previously mentioned curves.

For each "R_t versus t" curve, the relationship between reduction in lateral stress (expressed as a percentage of initial pressure) and the corresponding time could be approximated by the following general equation.

$$R_t = A \exp(-B/t) \tag{2}$$

where

A = f (n, S_I, T_F, σ_I) = reduction factor,
B = f (S_I, σ_I, T_F) = time factor, and
t = time in hours.

Every "R_t versus t" curve was obtained as a function of n, S_I, T_F, and σ_I; therefore, for each combination of these variables, there are unique values for reduction factor A and time factor B. If we place t = 0 into Eq. 2, it follows that R_t = 0, which satisfies the initial boundary condition. When t is taken to be very large, R_t approaches A, which defines the maximum expected reduction in lateral stress for a given frozen soil.

Figure 1. Grain-size distributions.

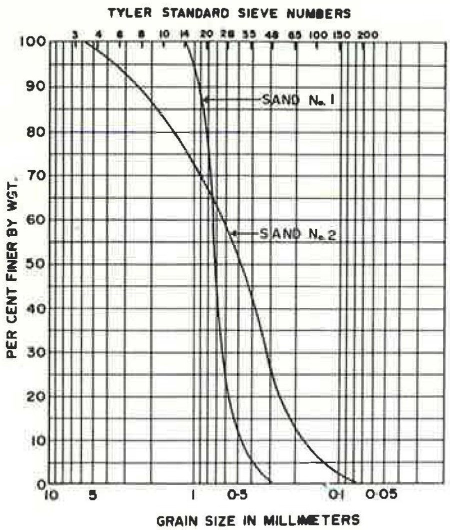


Figure 2. Pressure unit showing steel cylinder with rubber diaphragm.

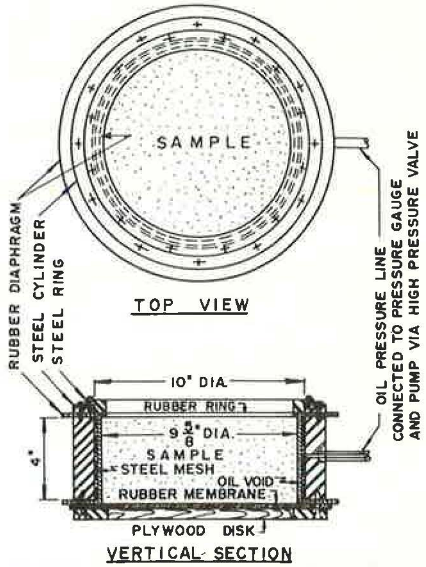


Figure 3. Pressure-time curves for specimens at 0 F having 100 percent ice saturation under three different initial pressures, 25, 50, and 100 psi.

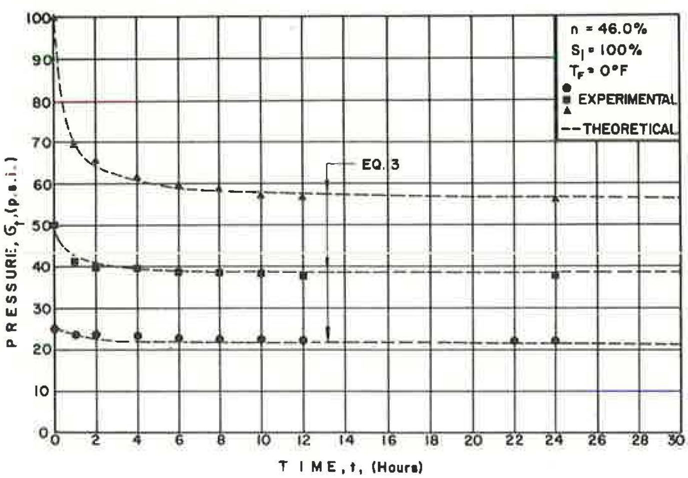


Figure 4. Experimental curves showing strain-time relationship for three different initial pressures under indicated conditions.

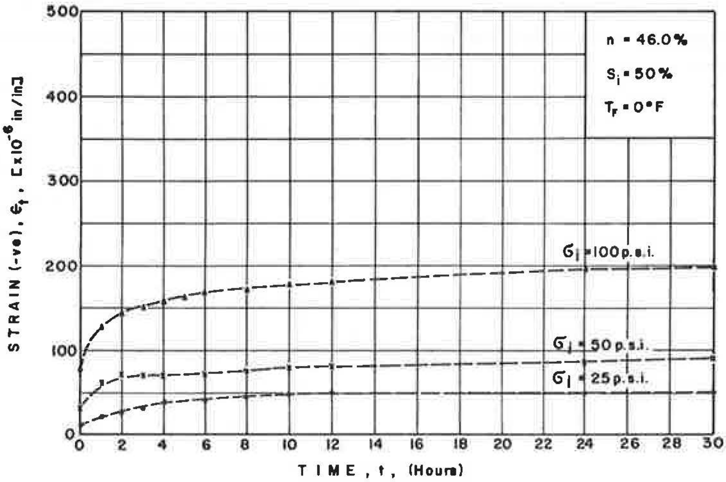


Figure 5. Experimental curves showing strain-time relationship for three different initial pressures under indicated conditions.

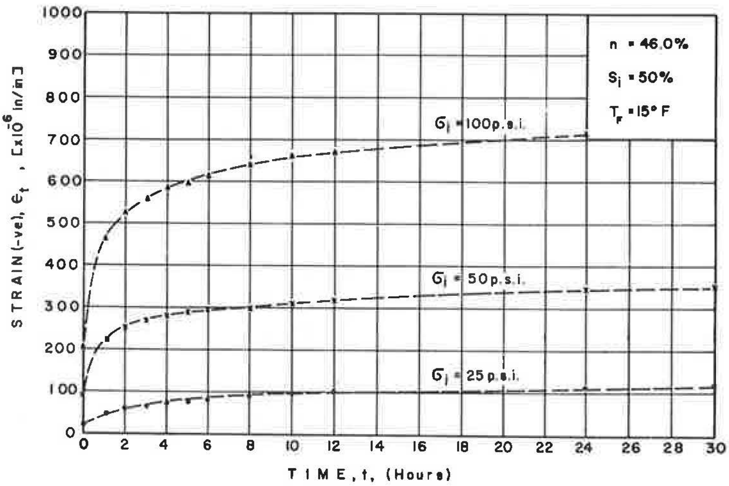
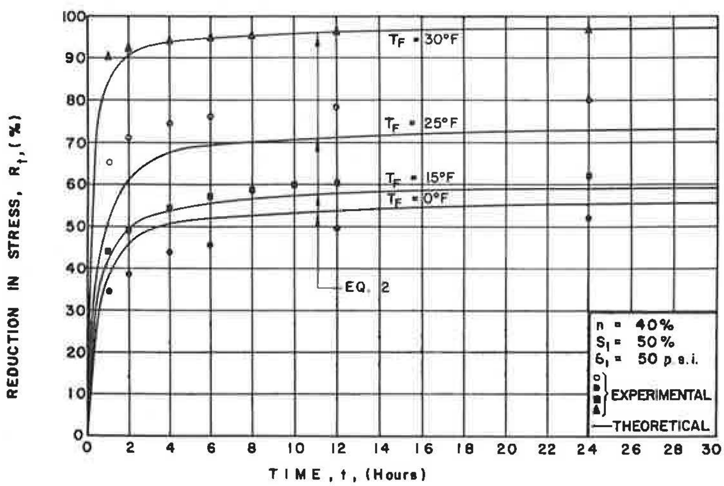


Figure 6. Reduction in lateral stress versus time for different constant temperatures under indicated conditions.



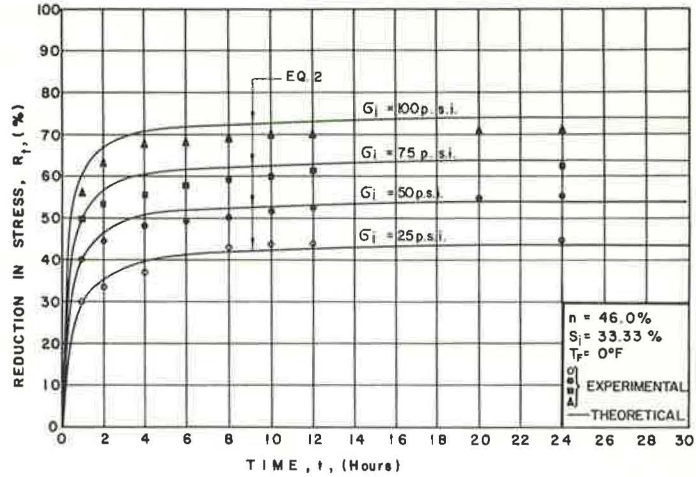


Figure 7. Reduction in lateral stress versus time for different initial pressures under indicated conditions.

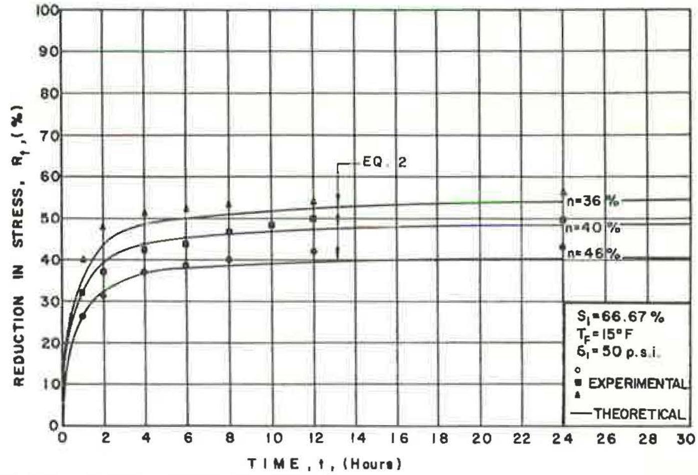


Figure 8. Reduction in lateral stress versus time for different initial porosities under indicated conditions.

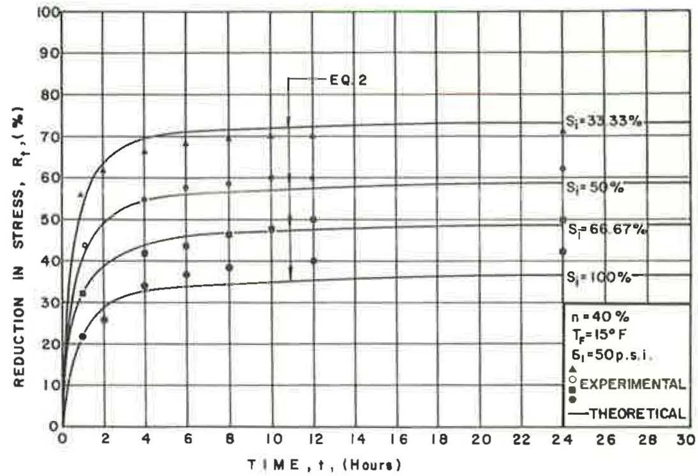


Figure 9. Reduction in lateral stress versus time for different degrees of ice saturation under indicated conditions.

The magnitude of the pressure retained by the frozen soil layer after time t, can be obtained by equating Eqs. 1 and 2 and solving for σ_t, which gives

$$\sigma_t = \sigma_i - C\sigma_i \exp(-B/t) \text{ [psi]} \tag{3}$$

where C = A/100.

Based on the experimental results obtained, values of reduction factor A and time factor B can be expressed in the form of the empirical equations that were derived by searching systematically for unknown functions by means of an electronic computer. The reduction factor may be computed from the following equation:

$$A = M\sigma_i + 100 \exp(K) + 0.08\, T(46-n) \tag{4}$$

with a maximum value of A = 100 percent

where

$M = 0.245 \log_{10} T + 0.35$;
$K = -0.00717\, S_i\, (\sqrt{T} - 1.15)$;
$T = 32 - T_F$ = temperature below freezing point, deg F;
T_F = temperature of frozen soil, deg F; and
n = initial soil porosity in percent.

The time factor may be estimated from the relation

$$B = \left[0.46\, (S_i)^{0.185} - 0.33 \log_{10}\sigma_i \right] N \tag{5}$$

where

S_i = degree of ice saturation, percent;
N = 1 for $T_F \leq 27$ F; and
N = T/5 for 27 F $\leq T_F \leq$ 31 F.

If, for a given frozen sand layer, the value of n, S_i, T_F, and σ_i are known, factors A and B can be easily calculated from the equations already given. If we put the values of A and B into Eq. 2, the percent of reduction in lateral stress can be estimated as a function of time. Equation 3 can be used to calculate the magnitude of reduced pressure retained by a sand-ice layer at any given period of time after application of initial pressure. From Eq. 3, taking t to be very large, the long-term stable lateral stress capacity (σ end) of the sand-ice system can be estimated as follows:

$$\sigma \text{ end} = \sigma_i - C\sigma_i = (1 - C)\, \sigma_i \tag{6}$$

The theoretical curves shown by the dotted lines in Figure 3 and by the solid lines in Figures 6 to 9 were obtained by using Eq. 2 and Eq. 3 respectively. They show good agreement with the points that were obtained experimentally.

The experiments indicated that, 24 hours after the application of initial pressure to the frozen sand layer, there was very little or practically no reduction in the lateral stress taking place in the frozen soil. To be more specific, it should be stated that, on the average, 98 percent of the value of A was reached in the first 24 hours, where A, the reduction factor, defines the maximum long-term reduction in lateral stress for a given frozen sand. Therefore, to demonstrate the effects of porosity, ice saturation, temperature, and initial pressure on the decrease of lateral stress in frozen soil, we took as a basis for comparison the percentage of reduction in stress that took place at the time t = 24 hours (R_{24}).

Figure 10 shows the influence of the magnitude of initial pressure σ_i on the stress reduction R_{24} as a function of T_F, S_i, and n. Figure 10a indicates the effect of soil temperature on "R_{24} versus σ_i" curves, whereas Figures 10b and 10c show the effect of the degree of ice saturation and the initial porosity respectively on the aforementioned curves. Within the experimental range, the relationship between R_{24} and σ_i is approximately linear; this is true for all combinations of the variables used.

Figure 10. Stress reduction after 24 hours versus initial pressure showing the influence of (a) temperature, (b) degree of ice saturation, and (c) porosity.

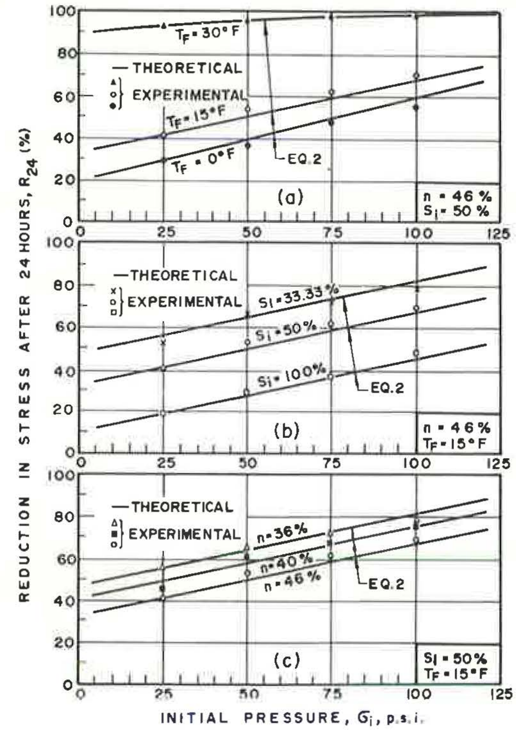


Figure 11. Reduction in stress after 24 hours versus temperature showing the influence of (a) initial pressure, (b) degree of ice saturation, and (c) porosity.

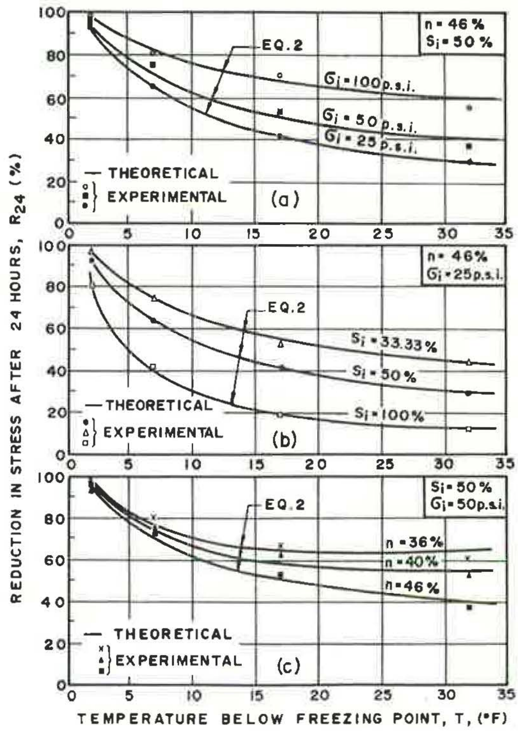


Figure 12. Reduction in stress after 24 hours versus degree of ice saturation showing the influence of (a) initial pressure, (b) temperature, and (c) porosity.

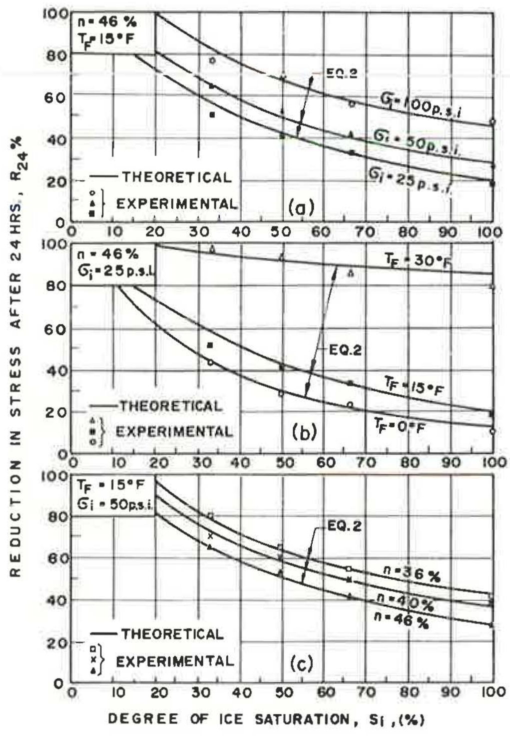


Figure 13. Reduction in stress after 24 hours versus initial porosity showing the influence of (a) initial pressure, (b) temperature, and (c) degree of ice saturation.

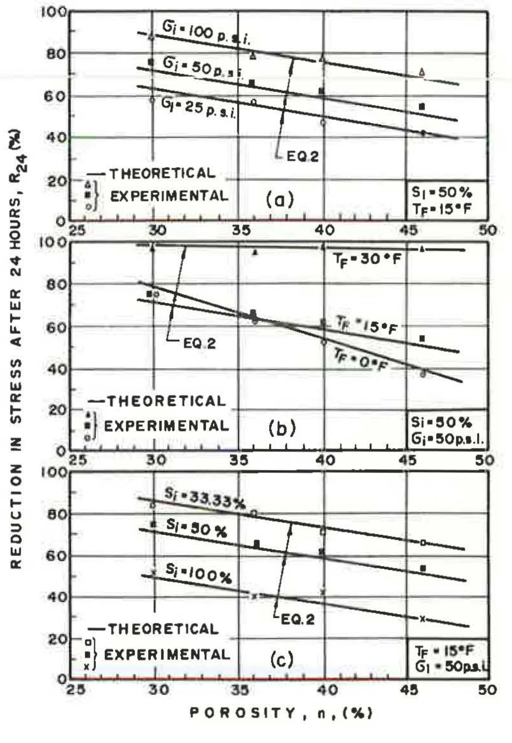


Figure 11 shows the variation of R_{24} with temperature below freezing point T as well as the effects of initial pressure (Fig. 11a), degree of ice saturation (Fig. 11b), and porosity (Fig. 11c) on "R_{24} versus T" curves. All three figures indicate that at low values of T, the rate of reduction in stress is rather rapid, but as value of T increases, the rate becomes smaller.

Figure 12 shows the variation of R_{24} with the degree of ice saturation S_i and also the effects of σ_i, n, and T_F on the "R_{24} versus S_i" curves. These curves reveal that, in general, the magnitude of R_{24} decreases with an increase in ice saturation. It can be seen that, when low ice saturation occurs simultaneously with high initial pressure or high frozen soil temperature (i.e., 30 F), 100 percent of the long-term reduction in stress can occur even before the elapse of a 24-hour period.

Another general relationship is shown in Figure 13, which indicates that reduction in stress R_{24} is inversely proportional to the initial soil porosity. The aforementioned figure also shows that an increase in initial pressure (Fig. 13a) or a decrease in ice saturation (Fig. 13b) shifts the "R_{24} versus n" curves upward in a parallel manner. An increase in the temperature of the frozen soil (Fig. 13c) moves the curves upward and also tends to decrease their slopes.

The solid lines shown in Figures 10 to 13 are not the lines of best fit for experimentally obtained points but represent Eq. 2 when the value of t = 24 hours.

CONCLUSIONS

Lateral stress developed in a confined sand-ice layer due to temporary temperature increase or to application of external pressure decreases with time if, after development of the initial pressure, the temperature of the frozen soil remains relatively constant. A more economical design can be achieved when the reduction behavior of the lateral thrust developed between a frozen soil layer and a retaining structure is known. The empirical equations introduced in this paper may serve as a guide in this case.

In general, the major part of the long-term reduction in lateral stress occurs during the first few hours after application of initial pressure. In fact, more than 85 percent of the total stress reduction occurs during the first 5 hours, and approximately 98 percent occurs during 24 hours.

The magnitude of reduction in lateral stress is highly influenced by the temperature of the sand-ice system. At a temperature of 30 F, the stress reduction R_{24} measured 24 hours after application of the initial pressure to a frozen sand was found to be more than 90 percent of the initial pressure, whereas at 0 F it was approximately half of this value.

Initial soil porosity and degree of ice saturation are also two major factors affecting the stress reduction process. An increase in both will result in a decrease in the value of R_t, seemingly because of the increase in ice content.

Initial pressure applied to a sand-ice system at a constant temperature also shows a significant effect on the magnitude of stress reduction; R_{24} increases almost linearly with the increase in initial pressure.

The influence of the type or grading of sand, in this particular case, seemed to be negligible. However, this conclusion may need further experimental evidence.

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