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A Device for Evaluation of Thaw Weakening of Frost-Susceptible Soil

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As a soil freezes unidirectionally, water is drawn up to the freezing front and, under appropriate conditions, ice lenses form. As thawing progresses down-ward, water, which formerly constituted an ice lens, remains perched above the still frozen subsoil. These localized zones exhibit shear resistances below their prefreeze values. A direct simple shear (DSS) device used to investigate this phenomenon on a thawed sample is described. The sample is the upper layer of a large cylindrical specimen that has been thermally conditioned under a carefully controlled laboratory environment. The controlled environment is produced by a frost cabinet with two independent refrigeration units to cool both the air above the specimen and a water supply to the base of the specimen. Either an open or a closed water supply system can be used. After the desired thermal history has been created and the specimen is completely frozen, sequential thawing and simple shear testing begins from the top downward. A carefully controlled heating element thaws the specimen from the top, leaving a thin shear sample. The top surface of the sample is approximately parallel to the bottom surface (the freeze-thaw interface). Undrained, shear testing is then performed. The frozen sublayers inhibit downward drainage, and a reinforced rubber membrane inhibits lateral drainage, thereby effectively duplicating field conditions. The sample is then removed, and the moisture content is deter-mined. Shear testing continues at various elevations down through the speci-men. The shear strength and moisture content versus depth profile is obtained for the initially created thermal history. Results from such tests using the DSS device performed on a frost-susceptible silty sand are presented.

Many areas of the world are subjected annually to freezing temperatures. The consequent freeze and thaw of soils often create severe problems for structures constructed on or near the ground sur-face. Because of these problems, engineers and re-searchers tend to agree that a more stringent treat-ment of all parameters associated with the freeze and thaw phenomenon is needed. This is particularly true if safe, efficient, and economical use of in situ soils is desired. Also, a greater knowledge of the freeze and thaw phenomenon is necessary for the development of a scientific approach to solving en-gineering problems associated with the behavior of thawed ground.

Present techniques for solving engineering prob-lems associated with thawed ground are expensive and quite often wasteful. Thus there is a need for a more thorough understanding of the strength loss of soil subjected to different thermal histories and moisture conditions.

Described in this paper is a direct simple shear testing device, designed and fabricated at Worcester Polytechnic Institute, that is used to measure the post-thaw shear strength of a soil subjected to frost heaving in the laboratory. This direct simple shear device permits evaluation of post-thaw shear strength at different elevations in a previously frozen specimen. The shear sample dimensions permit investigation of minimal shear strength through the localized zones of high water content at the sites of thawed ice lenses. Results from two test series performed on a frost-susceptible silty sand (Ikalan-ian sand) are presented.

EFFECTS OF THAW ON SHEAR STRENGTH

The phenomenon of frost heaving occurs when a soil-water system, consisting of frost-susceptible soil with access to an unfrozen water supply, is sub-jected to a freezing thermal gradient. Then, as the least stressed water at or near the ground surface crystallizes, the heave process begins. If the proper quantity of heat is being removed, so that the frost front remains almost stationary and a con-tinuous supply of unfrozen water is available, the ice crystals enlarge to form an ice lens. In frost-susceptible soils, significant heave is attributed to crystal growth while water is transferred to the frost front. In soils that are not frost suscepti-ble, water does not move to the frost front.

As soil thaws from the top downward, ice within the soil melts creating zones that have a higher water content than at the prefreeze condition. This water remains perched above the still frozen sub-layers. Bishop ([1]) indicates that soil shearing re-sistance for saturated soils is inversely propor-tional to water content when all other factors, such as stress history, are equal. This is true for un-disturbed and remolded cohesionless and cohesive soils. Therefore, a thawing soil with excess water caused by the melted ice will contain thaw-weakened zones exhibiting minimal, possibly zero, strength. After freezing, the continuity of the soil structure will have changed and the ability of the soil grains to resist shearing stresses will be reduced.

Alkire ([2]) conducted triaxial tests on thaw-weak-ened soil that had been frozen with access to water and demonstrated an increase in water content and a decrease in post-thaw shear strength. Skempton ([3]) demonstrated that when a saturated, slowly draining soil is sheared in an undrained mode, the behavior is representative of a material whose strength con-sists of only a cohesive component.

In the case of thaw-weakened, frost-susceptible soils, a failure is most likely caused by the development of excess pore water pressure. This pore pressure is slow to dissipate because of the fine material present in frost-susceptible soils and the blockage of the drainage paths by the still frozen sublayers. If this is the case, the excess pore pressure caused by load application reduces the effective stress and the ability of the soil to resist the load. Therefore, a $\phi = 0$ analysis is applicable, and the parameter used to evaluate the reduced shear strength would be the undrained shear strength.

The freeze-thaw-shear phenomenon in cohesionless soils may be viewed as consisting of the stages schematically shown in Figure 1. Before a densely packed, saturated soil freezes, it exhibits a void ratio, e_p, and a shear strength, S_p. After freezing, under appropriate conditions for ice lens development, the soil possesses a dispersed particle arrangement whereby the previously adjacent grains are separated by ice. Upon thawing, the soil retains this dispersed packing and exhibits a void ratio, e_t, and a minimal, possibly zero, shear strength, S_t. Eventually, the pore pressure dissipates, and the soil consolidates under load.

During consolidation, the void ratio decreases to some residual value, e_r, with an associated shear strength, S_r. Whether e_r decreases to the prefreeze void ratio, e_p, before the next freezing

period, depends on many factors and is beyond the scope of this paper. The measure of reduced shear strength due to the freeze-thaw phenomenon described here is the thaw weakening ratio (TWR). It is defined as the post-thaw shear strength, S_t, divided by the prefreeze shear strength, S_p.

DIRECT SIMPLE SHEAR DEVICE AND ANCILLARY EQUIPMENT

This section describes the Worcester Polytechnic Institute (WPI) direct simple shear (DSS) device and the WPI frost cabinet. The DSS device consists of a tapered, interlocking, split-disc acrylic mold 11.5 in. in overall height and capable of accepting 6-in.-diameter tapered soil specimens. A loading frame incorporated in the frost cabinet permits the application of shearing stresses to a thawed sample by the use of the top cap assembly.

A tapered rubber membrane laterally reinforced with nylon thread provides lateral support to the soil during shear testing. The reinforced, tapered rubber membrane is fabricated from a 6-in.-diameter by 18-in.-long commercially available membrane stretched over a collapsible tapered former. The former and membrane are placed on a lathe, and nylon thread is fed through a container that applies adhesive to the thread. The container is mounted on the compound arm of the lathe, and the lathe speed is set to provide 58 revolutions of reinforcement per longitudinal inch of membrane.

The WPI frost cabinet used to freeze the specimen is shown in Figure 2. It consists of an insulated, moisture-proofed cabinet with an interior chamber 29 in. wide, 24 in. deep, and 37 in. high. A door with a triple-glazed window provides easy access to the test chamber. The chamber is equipped with the shear load application mechanism for the DSS device.

To simulate frost action in the field, the WPI frost cabinet is equipped with two independently controlled refrigeration units. The temperature of the upper portion of the chamber can be set between $-20°F$ and $+70°F$ and maintained to within $\pm 0.1°F$. The temperature of the lower portion of the chamber can be set between $-20°F$ and $+70°F$ and maintained to within $\pm 0.5°F$. The temperature of the groundwater supply at the base of the specimen is dictated by the temperature in the lower portion of the chamber. Vermiculite insulation placed between the upper surface of the test specimen and the groundwater level facilitates the development of the desired thermal gradient. The window in the cabinet door

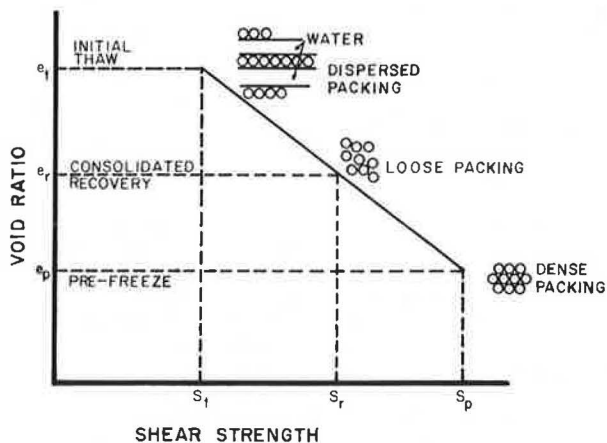**Figure 1. Strength variation during freeze-thaw-recovery cycle.**
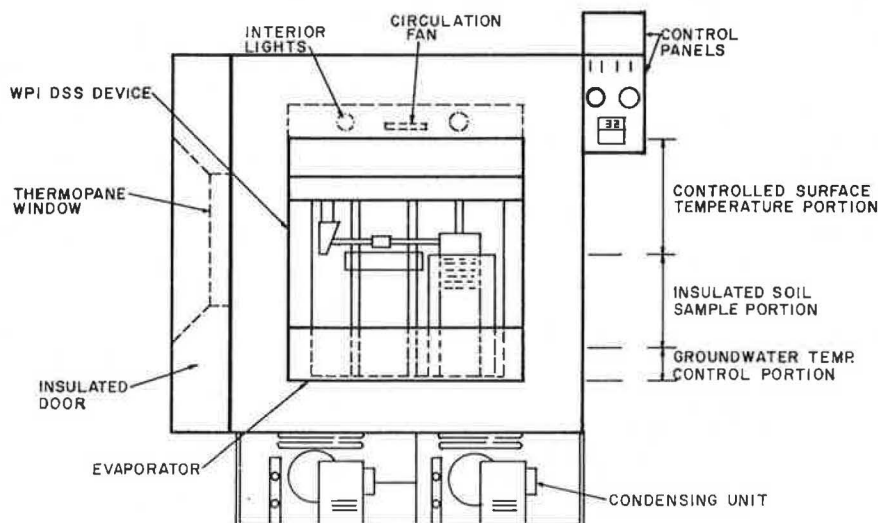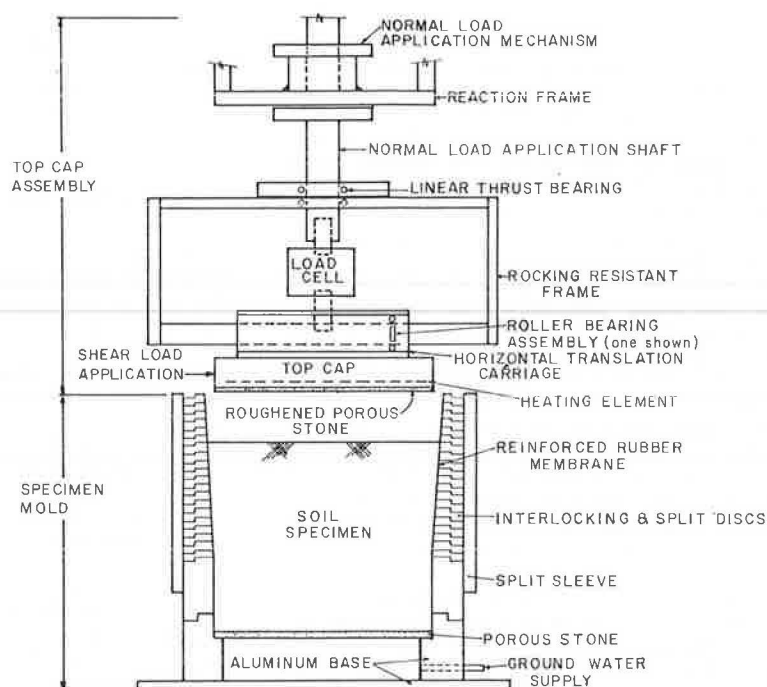

Figure 2. WPI frost cabinet.

Figure 3. Essential features of WPI-DSS device.

permits visual inspection of the upper portion of the test chamber.

The essential features of the WPI DSS device are shown in Figure 3. The DSS device, without the top cap assembly, is placed in the frost cabinet during thermal conditioning. As shown in Figure 2, the top cap assembly is added before thaw and shear testing. To provide clarity, the device is described below within the context of a typical test.

A soil specimen is initially compacted into the membrane-encased tapered acrylic mold. The mold is fabricated from acrylic because most of the thermal characteristics of acrylic are similar to those of soil. This assists the generation of horizontal isotherms during thermal conditioning, inducing horizontal ice lensing within the soil specimen. The resulting compacted soil specimen is 9 in. high and 6 in. in diameter (the diameter increases approximately 4 percent due to taper). The mold and membrane are tapered to minimize friction between the soil and membrane during heave. The upper 6.6 in. of the mold consists of 20 interlocking, split acrylic discs, each approximately 0.325 in. in height. The discs are rigidly held together by a vertically movable acrylic split sleeve. The lower 4.4 in. of the mold is a hollow cylinder. The upper 4.6 in. of the 9-in.-high specimen is subjected to thermal conditioning during freezing. The uppermost 2 in. of the mold accommodates the heaved soil during the freezing phase of the test. The upper 4.6 in. of the specimen and the amount of heaved soil (within the interlocking split discs) are subjected to post-thaw DSS testing.

Twelve thermocouples are placed in holes drilled through the acrylic split discs so that the sensing element of the thermocouple touches the outer surface of the membrane. These thermocouples monitor temperature during freeze and thaw.

The 6-in. diameter or larger specimen is used so that the height to diameter ratio (1:16) of the shear zone is half that recommended by Shen, Sadigh, and Herrmann (4). This ratio is needed to ensure relatively uniform shear strain distribution during DSS testing. Also, if conditions warrant, two discs can be removed before shear testing; the height-to-

diameter ratio will still be sufficiently small to produce minimal strain concentration.

After the compacted soil specimen and mold are placed in the frost cabinet, a wet connection is made to the monitored, temperature-controlled water supply at the base of the mold. A 6-in.-diameter aluminum plate weighing 1.62 lb is placed on top of the specimen. This plate retards evaporation and sublimation and provides a solid platform for the heave measurement system. The mold is surrounded with insulating vermiculite.

During the ensuing thermal conditioning, soil temperature is monitored by the thermocouples, heave is monitored by a DC-DT differential gauging transducer, and moisture migration (if permitted) is monitored by a constant-head moisture transfer system. All data from periodic readings of temperature, heave, and moisture migration are permanently stored by using a data-acquisition system. Manual readings are occasionally taken to ensure accuracy of the system. The moisture migration system is constructed so that an open or closed water supply system can be used. After the desired thermal history has been created, the entire specimen is frozen, including the base of the mold. After thermal equilibrium (20°F throughout the specimen) has been established, thaw and shear testing may begin.

Before thaw, the aluminum plate is removed from the top of the specimen and the upper surface of the specimen shaved to a horizontal plane. If the specimen has heaved less than 2 in., the split sleeve is lowered and one or more split discs removed. A specially designed top cap assembly, used to perform DSS testing is positioned on the frame in the frost cabinet.

The top cap assembly shown in Figure 3 performs two functions: (a) normal load application and (b) shear load application. Shearing stresses are applied to the top of the thawed sample by applying pressure to the roughened porous stone attached to the base of the top cap. The top cap base also contains a precisely controllable heating element that thaws the specimen top unidirectionally to produce the thaw-weakened DSS test sample. The top cap is connected to the normal load application shaft with

a specially designed horizontal translation carriage consisting of a roller bearing assembly. This assembly ensures horizontal translation along one axis only, thereby imparting appropriate strain conditions across the top surface of the shear sample. A fixed linear thrust bearing mounted in the rocking-resistant frame ensures that there will be no rotation of the top cap during application of the shear load.

Between the carriage and the load application shaft is a load cell that is used to monitor the initially applied normal load and any changes in normal load during a shear test. The load application shaft extends upward from the load cell through the linear thrust bearing to the normal load application mechanism that is mounted on the reaction frame. This mechanism is designed so that constant sample height during shear is attained by manual adjustment of the mechanism.

The shear-load application mechanism, shown in Figure 3, consists of a drive shaft that forces a loading wedge downward along a grooved track. The wedge forces a horizontal ram toward the top cap that applies a shear load to the sample. The horizontal ram incorporates a load cell that monitors shear load. The rate of shear load application is controlled by a variable-speed motor and gear box.

The elevations of the shear load application mechanism and the top cap assembly are adjustable; this permits the performance of a series of shear tests on each frozen-thawed specimen.

After the top cap assembly is positioned in the frost cabinet, the acrylic sleeve is manually lowered to the elevation of the next lowest disc and securely clamped. The soil within this top disc is thawed unidirectionally from the top by the heating element. As thawing begins, any air trapped between the top of the sample and the top cap is bled from the sample by applying a normal load. The membrane is then sealed around the top cap. The desired normal load is then applied; when a drop of water is visible through the drain in the top cap, the drain is closed.

After the sample has thawed, the disc(s) is removed; this results in a thaw-weakened sample approximately 0.375 to 0.75 in. in height and slightly greater than 6 in. in diameter. Water movement is prevented laterally by the membrane, downward by the still frozen subsoil, and upward by the top cap. The shear load application mechanism and deformation gauge are positioned vertically. As the DSS test is performed, the top cap is adjusted vertically to maintain a constant sample height. Constant sample height ensures constant volume during shear.

Bjerrum and Landva (5) have demonstrated that the constant-volume shear resistance of a soil is equivalent to the undrained shear strength of the soil. The shear load and normal load are measured and recorded at different intervals of horizontal deformation until a strain of a least 16 percent is reached. Because the principal stresses are of unknown direction, the only parameter determined is the undrained simple shear strength (the shear load divided by the cross-sectional area of the sample at midheight). If the sample possesses markedly different shear strengths on parallel horizontal planes, it may not undergo uniform shear strain and fail along the weakest plane. However, if this is not the case, a spatial average strength is obtained.

When the test is completed, the top cap assembly is removed and the entire thawed sample taken for moisture content determination. The new specimen top is shaved to a horizontal plane. The top cap assembly is replaced and thermal equilibrium (20°F throughout the specimen) reestablished.

The procedure described above is repeated until the entire specimen within the split discs has been tested using the DSS device. The resulting relationship of both undrained simple shear strength and moisture content versus depth is obtained.

ASSESSMENT OF THAW WEAKENING

As part of the ongoing Frost Research Program at WPI, the previously described DSS device is being used to investigate the loss of shear strength in Ikalanian sand due to the freeze-thaw phenomenon. This soil is one of many that have been extensively monitored during field freeze-thaw conditions at the Massachusetts Department of Public Works Frost Research Station in Winchendon, Massachusetts. Results of tests conducted on two specimens of Ikalanian sand are reported below. The specimens were designated FTS-3 and FTS-4.

The Ikalanian sand was originally obtained from a pit in East Princeton, Massachusetts. Index and compaction characteristics were investigated, and the results obtained are presented below along with the associated AASHTO test specifications (NP = not plastic).

Property	AASHTO Specification	Value
Specific gravity	T100-75	2.68
Liquid limit	T89-76	NP
Plastic limit	T90-70	NP
Particle size	T88-78	
Percent by weight finer than		
No.4		100
No. 10		99
No. 20		96
No. 40		88
No. 60		77
No. 100		61
No. 200		36
0.002mm		9
0.005mm		2
0.001mm		1
Maximum dry density > (pcf)	T99-74	108.0
Optimum water content > (%)	T99-74	13.0

Both specimens FTS-3 and FTS-4 were at approximately the same prefreeze dry density and moisture content. These specimens were placed in the membrane-encased mold by vibrating the mold on a shake table while air-dried soil was poured through standing water.

Both specimens were placed in the frost cabinet and preconditioned to 40°F throughout for 48 hr. The constant-head groundwater supply was set at the elevation of the top surface of the specimen for the first 24 hr and then lowered to 8.5 in. below the surface of the specimen (with excess water allowed to drain) for the remaining 24 hr, which yielded capillary saturated specimens.

The specimens were then incrementally frozen from the top downward, while the thermal gradient was varied to produce varying degrees of ice lensing. The quantity of moisture that migrated to the frost front and the associated heave were carefully monitored. Table 1 gives a summary of the freeze cycles for the two specimens. After the freeze cycle, both specimens were completely frozen to an ambient temperature of 20°F.

To demonstrate the use of the DSS device to investigate the strength of thaw-weakened soils, the

DSS testing procedure was conducted on specimens FTS-3 and FTS-4. The results of the thaw shear tests are reported in Table 2. The shear stress, S, at a strain, γ (shear displacement divided by sample height), equal to 10 percent, is defined as the shear strength. The thaw-weakening ratio (TWR), defined as the measured post-thaw shear strength at 10 percent strain divided by the prefreeze shear strength, is used as a measure of strength loss. The prefreeze shear strength (90 psf) was obtained by performing DSS tests on unfrozen samples of Ikalanian sand at an equivalent void ratio. The variation of thaw-weakening ratio with depth is shown in Figures 4 and 5.

SUMMARY

A device that permits the measurement and evaluation of the loss of shear strength of soil due to thaw weakening under various thermal and water conditions in a carefully controlled laboratory environment is described. The device uses the direct simple-shear method to measure the shear strength through a localized weakened soil zone with a high moisture content caused by melted ice lenses. By using the DSS device, it is possible to produce a shear-strength profile in a highly nonhomogeneous, anisotropic material typical of a frozen-thawed soil column.

Although the results presented here are preliminary, we believe that results from this testing mode are of value in estimating the post-thaw shear strength of soils. It is evident that the loss of shear strength is due, at least in part, to the increased moisture content caused by the frost-heave phenomenon. Whether the loss of shear strength can be predicted is a possible avenue of study.

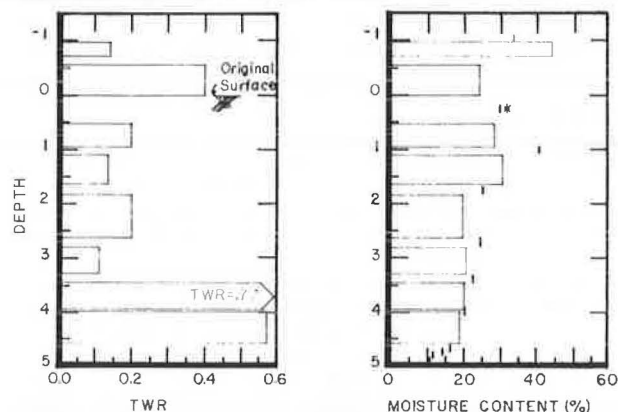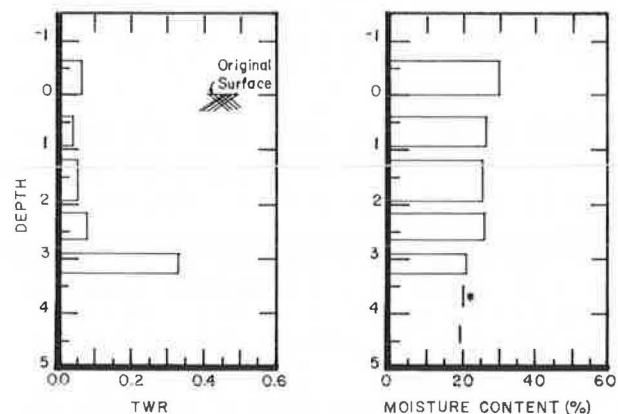Figure 4. TWR and moisture content versus depth for specimen FTS-3.

Figure 5. TWR and moisture content versus depth for specimen FTS-4.

*Note: Moisture Content Determined From Trimmings

Table 1. Summary of freeze tests on specimens FTS-3 and FTS-4.

Parameter	FTS-3	FTS-4
Prefreeze dry density (pcf)	112.0	113.0
Prefreeze moisture content (%)	18.4	19.1
Prefreeze void ratio	0.49	0.51
Prefreeze degree saturation (%)	100.0	100.0
Duration of freeze (hr)	2,186.0	116.0
Incremental temperature drops (no.)	14.0	2.0
Depth of groundwater (in.)	8.5	8.5
Groundwater conditions	Open	Open
Surcharge load (lb)	1.62	1.62
Maximum frost depth (in.)	4.2	3.5
Minimum rate of frost penetration (in./day)	0.00	0.22
Average rate of frost penetration (in./day)	0.05	0.72
Maximum rate of frost penetration (in./day)	0.90	5.04
Average thermal gradient (°F/in.)	1.0	1.2
Total moisture migration (in.³)	27.0	12.6
Average moisture migration rate (in.³/day)	0.30	2.61
Total heave (in.)	1.2	0.6
Corrected heave (subtract 9% volume change) (in.)	1.1	0.5
Average heave rate (in./day)	0.01	0.10

Table 2. Results of post-thaw shear tests on specimens FTS-3 and FTS-4.

Test No.	Level (in.)	Height of Shear Zone (in.)	Initial Normal Stress (psf)	Shear Strength (at 10% strain) (psf)	Thaw Weakening Ratio (S ÷ 90)	Moisture Content (%)	Void Ratio
FTS-3							
1	-0.82	0.26	140.8	13.4	0.15	44.0	1.17
2	-0.27	0.54	132.9	35.9	0.40	24.4	0.65
3	0.72	0.43	135.1	18.2	0.20	28.0	0.75
4	1.38	0.54	134.8	12.5	0.14	30.3	0.81
5	2.22	0.80	136.0	18.0	0.20	19.6	0.53
6	3.02	0.50	135.0	10.3	0.11	20.5	0.55
7	3.67	0.47	139.3	69.3	0.77	20.0	0.54
8	4.27	0.59	137.6	51.2	0.57	19.1	0.51
FTS-4							
1	-0.31	0.62	208.4	5.0	0.06	30.0	0.80
2	0.67	0.54	131.9	4.0	0.04	26.3	0.70
3	1.57	0.74	133.9	4.5	0.05	25.4	0.68
4	2.39	0.47	141.6	7.0	0.08	25.7	0.69
5	3.08	0.37	142.9	30.0	0.33	20.4	0.55
6	3.60	0.60				18.4	0.49
7	4.23	0.67				17.6	0.47

Note: Blanks indicate malfunctioning of shear apparatus.

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Change in Soil Structure Due to Freeze-Thaw and Repeated Loading

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Although the boundary conditions are different, soils subjected to freeze-
thaw or repeated loading may exhibit changes in structure that can be in-
directly identified by the soils stress-strain characteristics. The objective
is to use this concept to help explain the differences in strength and de-
formation observed when soils are conditioned with either freeze-thaw or
repeated loading or both. The strength and deformation characteristics
are obtained from isotropic, consolidated, undrained triaxial tests on
Manchester silt and Elo clay. Four series of tests were performed: (a)
unconditioned followed by monotonic loading to failure, (b) conditioned
with a single cycle of freeze-thaw before monotonic loading to failure,
(c) conditioned with 600 cycles of a repeated load before monotonic
loading, and (d) conditioned with a freeze-thaw cycle and repeated load-
ing before monotonic loading to failure. Results show that freeze-thaw
or repeated-load conditioning causes a strength increase, but freeze-thaw
followed by repeated loading causes a strength decrease when compared
with unconditioned soil. The results are explained in terms of changes in
structure caused by the various conditioning phases.

Many natural processes affect the fabric and struc-
ture of soils (1). Freeze-thaw is a good example:
changes in structure have been used to explain the
phenomena of thaw consolidation (2-4) and changes in
strength upon thaw (5,6). The work reported here
continues along these lines and provides an explana-
tion for changes in strength and deformation based
on changes in structure that occur due to the
freeze-thaw and repeated-load processes.

The strength and deformation characteristics are
obtained from isotropically consolidated, undrained
triaxial tests on both Manchester silt and Elo
clay. Four series of triaxial tests were performed
for each soil. Axial load and deformation were
monitored for each test. The results from tests on
soils subjected to freeze-thaw or repeated loading
were compared with the results from the unfrozen,
monotonically loaded control series.

MATERIALS AND EXPERIMENTAL PROCEDURES

Soils Investigated

Manchester Silt

The primary soil in this investigation was Man-

chester silt obtained from New Hampshire. The soil
is light brown in color with subrounded to subangu-
lar particles. The liquid limit is 25 percent and
the plastic limit is 23 percent. The specific grav-
ity is 2.72. The Unified Soil Classification is ML.

Elo Clay

The second soil investigated was an Elo silty clay
obtained from the western upper peninsula of Michi-
gan. The soil is reddish brown in color. The
liquid limit is 48 percent and the plastic limit is
25 percent with a specific gravity of 2.79. The
Unified Soil Classification is CL. The grain-size
distribution curves for Manchester silt and Elo clay
are shown in Figure 1.

Sample Preparation

Manchester Silt

Samples 35 mm in diameter and 70 mm in height were
compacted in a split model in five equal layers to a
density of either 100 or 93 pcf. The soil was com-
pacted at a water content of 20 percent. After com-
paction, the samples were removed from the mold,
weighed, measured, and placed in the triaxial cell
for saturation and testing.

Elo Clay

Elo clay samples were formed by accelerated sedimen-
tation in upright plexiglass cylinders 35 mm in di-
ameter. The clay was first pulverized and then made
into a slurry of approximately 500 percent water
content. The plexiglass cylinders were filled and
allowed to sit overnight; then, the apparatus was
placed in a consolidometer. After consolidation at
26 psi, the samples were extruded from the tubes and
trimmed to a length of 80 mm. All samples came out
to a saturated density of 110 pcf and a void ratio
of 1.3 ± 2 percent. Details of the sample prepa-
ration technique can be found in Morrison (7).