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Effect of Variable-Drainage Freeze-Thaw Tests on Post-Thaw Shear Strength

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Research is reported that shows that the effect of freeze-thaw on post-thaw shear strength can be determined by observing the effect of freeze-thaw on the preshear effective consolidation and overconsolidation ratio. It is also shown that availability of water is one of the primary factors that controls the preshear conditions in a saturated soil subjected to freeze-thaw. In order to quantify the effect of freeze-thaw on post-thaw strength, a series of consolidated undrained triaxial tests was conducted on a Manchester silt subjected to drained and undrained conditions during freeze or thaw. Each combination of drained or undrained freeze followed by drained or undrained thaw produced a set of unique and predictable preshear conditions. Based on the results from the variable-drainage freeze-thaw tests, it is concluded that laboratory triaxial tests could be used to study the effect of freeze or thaw on post-thaw shear strength. Specifically, it is shown that (a) freeze-thaw conditions that cause an increase in preshear water content produce a reduction in post-thaw shear strength, (b) freeze-thaw conditions that cause a reduction in preshear water content produce an increase in post-thaw shear strength, and (c) freeze-thaw at constant water content causes a slight reduction in post-thaw shear strength.

Frost action in soils can cause several detrimental effects. The effect most people are aware of is frost heave. A lesser known but equally serious problem is the reduction in soil strength that occurs after freeze-thaw. This problem has been reviewed (1) and researched (2), and still there is no clear link to conventional soil mechanics. The purpose of the research described here is to help establish this link.

For an unfrozen soil unconditioned by freeze-thaw cycles, the shear strength is primarily a function of the preshear history and consolidation stress of the soil. Any factor that affects these conditions, such as an induced pore pressure, will also affect the resulting shear strength. Therefore, because temperature changes can induce pore pressures, it is postulated that the effect of freeze-thaw on shear strength can be defined by observing its effect on the preshear conditions in the soil. Then, once the preshear conditions are known, conventional effective stress analysis can be used to determine the post-thaw strength of the soil.

To explore the effect of freeze-thaw on preshear conditions, a series of tests was conducted in which the soil specimens were subjected to a single freeze-thaw and then to undrained shear tests. The drainage condition during the freeze or thaw phase was either drained or undrained. These conditions were used as an expedient to simulate the effect of various rates of temperature change on the preshear conditions. The drained condition is associated with slow temperature change and the undrained condition with a fast temperature change.

The basic laboratory test used throughout the test program was a consolidated undrained triaxial test with measurement of pore pressure. This test was conducted on all samples after the appropriate temperature and drainage conditioning. In order to observe the possible effect of overburden on soils subjected to freeze-thaw, consolidation pressures from 6.9 to 69 kPa were applied before temperature and drainage conditioning.

BACKGROUND

It has been recognized for some time that certain combinations of soil type and moisture conditions, when subjected to freezing and thawing, result in significant heave and/or reduction in the strength of the soil. The magnitude of the heave and the seriousness of the loss of strength associated with freezing and thawing are a function of many physical and environmental conditions. Climate, ground cover, location of the groundwater table, soil moisture, and rate of freezing and thawing are only a few of the factors that influence what is called frost action. Of the many factors that contribute to frost action, the main villains are pore water and water transported to the freezing front by temperature-induced suction.

The movement of water within soil is limited by conditions that are comparable to the triaxial tests termed "drained" or "undrained". A drained system is associated with movement of water from some external point toward the freezing front, whereas an undrained system is not associated with movement of water other than local redistribution. In the field, the drained condition would be achieved if

the soil was pervious or if the rate of freezing was slow enough to allow movement of water to the freezing front. Undrained conditions would occur when the soil was impervious or freezing was so fast that water could not move to the freezing front fast enough to satisfy the suction induced by the freezing process. Obviously, it would be unlikely that a soil in situ would be either perfectly drained or undrained; rather, these are idealized limits that are easily established in the laboratory.

In general, it would be possible to study the effect of freeze-thaw on either a saturated or unsaturated soil. However, many soils, when subjected to the movement of water associated with a temperature gradient, will become saturated, and the in situ conditions of a soil subjected to freeze-thaw frequently will be saturated. Therefore, the deformation and loss of strength related to freeze-thaw might be divorced from the degree of saturation and be considered only in terms of the effect of freeze-thaw on the preshear conditions of a saturated soil. In relation to undrained shear strength for this condition, the primary preshear parameters of interest will be the stress history (overconsolidation conditions) and the effective in situ consolidation stress.

Before attempting to relate the effect of freeze-thaw to a particular soil, consider the curves of (a) water content at failure versus log effective consolidation stress and (b) shear strength versus effective stress, shown in Figures 1 and 2, respectively.

Figure 1 shows a typical consolidation curve for a normally consolidated soil and three ideal rebound-recompression curves. Three lines of constant water content are also shown. It can be seen that, along any one of the lines of constant water content, the overconsolidation ratio (OCR) increases as the consolidation stress decreases. Thus, the OCR for point A is less than that for point O, which is less than that for point E.

Figure 1. Idealized soil behavior: consolidation characteristics.

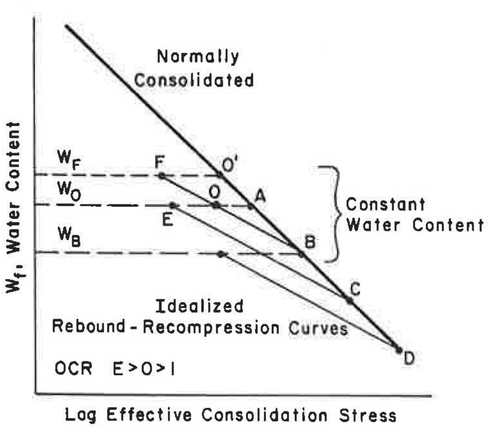
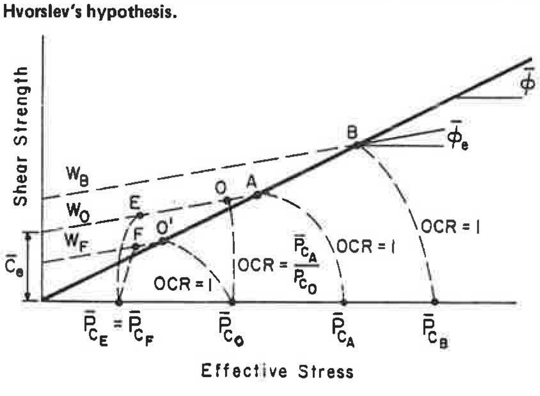


Figure 2. Idealized soil behavior: shear-strength determination based on Hvorslev's hypothesis.



In Figure 2, the shear strength is determined by a combination of water content at failure and effective consolidation stress. When the values are obtained from a series of undrained tests on samples of identical water content but different OCRs, a straight line is defined that is used to establish the "true" friction angle ($\bar{\phi}_e$) and the "true" cohesion ($\bar{c}_e$) [Hvorslev parameters (3)]. When the OCR = 1--i.e., normal consolidation--the shear strength determined from undrained tests falls on a line that defines the friction angle of the soil ($\bar{\phi}$).

Figure 2 shows typical effective stress paths for various OCRs as well as for a normally consolidated soil. It is apparent that the effect of stress history can be substantial. This can be observed by comparing the difference in shear strength between point B (OCR = 1) and point O (OCR = $\bar{P}_{C_B}/\bar{P}_{C_O}$). On the other hand, when conditions are such that constant water content is maintained, the effect of stress history may not be too large: for example, when the shear strength at point A (OCR = 1) is compared with that at point O (OCR = $\bar{P}_{C_B}/\bar{P}_{C_O}$).

Currently, the effect of freeze-thaw on stress history and consolidation stress can only be predicted in a qualitative fashion. However, these predictions can be used to define "critical" conditions and, by approopriate use of the concepts discussed above, it might be possible to quantify the effect of freeze-thaw for some well-defined temperature and loading conditions.

The use of the basic soil relations given above is a promising avenue of approach for studying the effect of freeze-thaw on the shear strength of soil. This approach tends to minimize the effect of physicochemical factors on strength and emphasizes the mechanical factors. However, the mechanical factors are extremely important and are major factors in controlling the shear strength of silts and inactive clays.

MATERIAL AND TEST PROCEDURE

Soil Tested

The soil for the test program was a Manchester silt. It is described as having subrounded to subangular particles with a specific gravity of 2.73. The liquid limit is 26 percent, the plastic limit is 21 percent, and the maximum dry unit weight is 1.73 g/cm^3 at a water content of 11.6 percent. The coefficient of uniformity of the soil is 3.0, and 92 percent of the soil particles are less than 0.074 mm and greater then 0.002 mm in effective diameter. The gradation curve is shown in Figure 3. The soil is highly frost susceptible.

Sample Preparation

Soil for the triaxial samples was prepared by weighing out 500 g of air-dry soil and adding a predetermined amount of deaired, distilled water to produce a water content of 20 percent. The soil was then thoroughly blended and cured for at least one day to allow equal moisture distribution. Once the samples were to be prepared, the soil was remixed and water was added, if necessary, to bring the moisture content to the desired level.

Samples were prepared by using a split mold 50.8 mm in diameter and 127 mm high. The soil was compacted in five equal layers by using a tamping rod

and hammer. The weight of soil in each layer was predetermined to achieve a final dry unit weight of 1.60 g/cm³ at a water content of 20 percent.

Once the soil was compacted, the sample was removed from the mold, weighed, and measured. The final weight was typically within 0.5 percent of the calculated weight.

Saturation and Consolidation Procedure

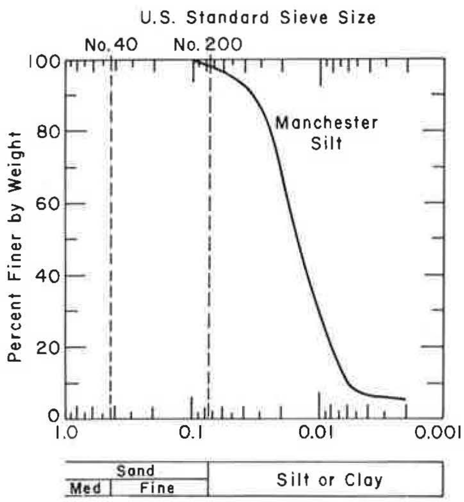
After the sample was removed from the split mold and weighed, it was mounted in a triaxial test cell that had a modified base 50.8 mm in diameter. Two 0.127-mm-thick latex rubber membranes were used to encase the sample and minimize air leakage.

The sample was saturated by connecting the top and bottom drain lines to a vacuum source. Upward drainage was achieved by keeping the vacuum on the top of the sample at a slightly greater value than the vacuum on the bottom. Typically, this differential was 35 kPa. Once water was seen to pass through the top platen, the top and bottom drain lines were closed.

After vacuum saturation, the sample weight was again determined, the top of the triaxial cell was placed over the sample, the sample was connected to a water-filled burette, and a selected consolidation pressure of 6.90, 34.5, or 69.0 kPa was applied.

Consolidation continued until water uptake ceased (usually 18 h or less). The drain line of the sample was then closed, and the sample was ready for the next stage in the test sequence.

Figure 3. Gradation curve for Manchester silt.



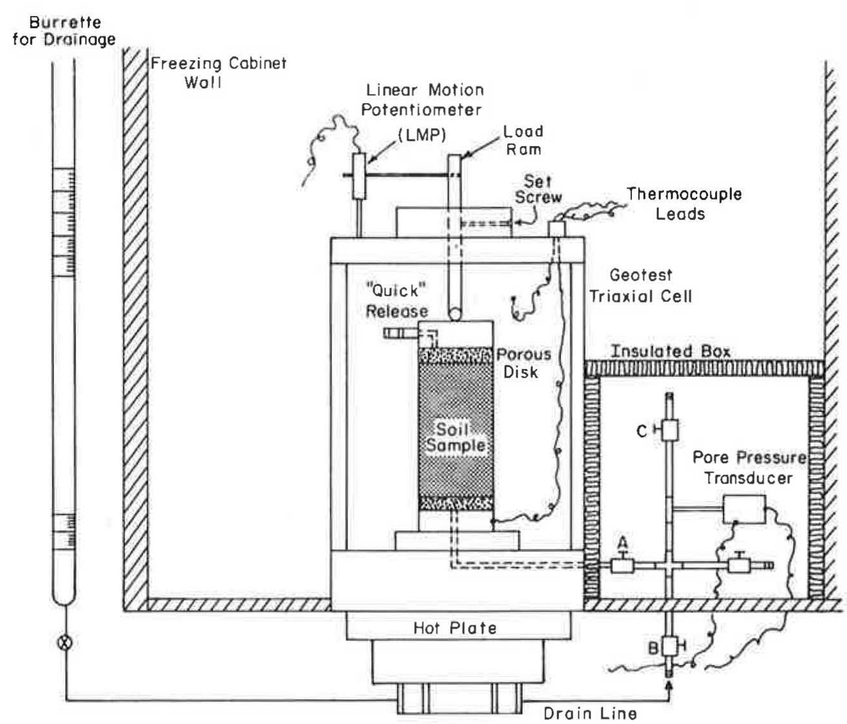
Temperature Conditioning

Triaxial tests were conducted on consolidated samples that were subjected to a set freeze-thaw temperature-conditioning sequence. In addition, several series of tests were conducted on samples that were never frozen. All samples were prepared and saturated at 18°C and consolidated and shear tested at 5°C.

All freeze-thaw temperature conditioning took place in a freezing cabinet similar to the one shown in Figure 4. During freezing the cabinet temperature was lowered from +5°C to -7°C in approximately 30 min and was held at this temperature for 24 h. By adjusting the hot-plate temperature, the temperature of the base of the sample was kept above the temperature of the top and side. Thus, the base was always the last to freeze and the first to thaw. This type of temperature control produced a "pseudo" one-dimensional freezing condition. The thaw cycle was also 24 h and was initiated by turning off the refrigerating unit and allowing the sample to return to the ambient temperature of 5°C.

Various drainage conditions were obtained by controlling the sample's access to water during the freeze or thaw cycle. Four types of variable-drainage tests were conducted: (a) undrained freeze/undrained thaw (UF-UT), (b) undrained freeze/drained thaw (UF-DT), (c) drained freeze/undrained thaw (DF-UT), and (d) drained freeze/drained thaw

Figure 4. Triaxial test equipment and freezing cabinet.



(DF-DT). For any given test, the selected drainage condition was maintained for the entire 24 h of freeze or thaw.

Consolidated Undrained Triaxial Tests

Axial loads for all undrained shear tests were applied by using an electromechanical loading system with an axial rate of displacement of 1.0 mm/min. Axial deformation was measured by using a linear position transducer. Loads were measured by using a load cell with bonded-wire strain gages.

Pore pressure was measured at the bottom of the sample by using a pore-pressure transducer attached to the drainage line of the triaxial cell. The pore-pressure measuring system was subjected to the same temperature regime as the test specimen and had to be protected from the freezing temperatures that occurred in the cabinet. Initially, heat tape was wrapped around the drainage lines and valves. Later, this system was abandoned and an insulated box was constructed that fit over the drainage system (Figure 4). This, along with circulation of room air around the piping, provided a system that was adequate to prevent freezing of the pore-pressure measuring system.

TEST RESULTS

For the test results described here, the soil is defined as undrained if the soil sample is subjected to freeze or thaw without access to water from the drainage burette (Figure 4). Drained conditions, on the other hand, allow access to water from the drainage burette. Obviously, the undrained condition is a constant-volume freeze or thaw, whereas drained freeze or thaw may involve changes in water content.

Each freeze-thaw test was subjected to the same temperature-conditioning sequence. The effect of different rates of freeze or thaw was simulated by the drainage condition. In interpreting the results, the words "fast" and "slow" could be substituted for undrained and drained, respectively; i.e., a drained freeze is equivalent to a slow freeze test, where temperature is lowered slowly enough to allow migration of water to the freezing front. To establish a basis for comparison, a series of consolidated undrained tests was conducted on samples that had undergone no freeze-thaw temperature conditioning. These tests are labeled no freeze-thaw (NFT) in the discussion below.

A single freeze-thaw cycle was used in all tests. Actual soils would be conditioned by some number of freeze-thaw cycles prior to the conditions simulated by the variable-drainage tests.

The results of the variable-drainage freeze-thaw tests are given in Table 1. It will be noted that each drainage and freeze-thaw condition is duplicated at three levels of consolidation stress. All values of shear strength were determined from undrained tests on the thawed sample.

The main trends apparent from the tabulated results are as follows:

1. Each of the four different drainage conditions produced a different set of preshear conditions with different shear strength. For the Manchester silt, the DF-DT tests at consolidation stress of 6.90 kPa resulted in approximately zero shear strength when the soil was tested after thaw. For the same consolidation stress, a soil not conditioned with freeze-thaw has an undrained shear strength of approximately 130 kPa.

2. For all drainage conditions, undrained shear strength increases as consolidation stress increases. Typically, the shear strength will double as consolidation stress increases from 6.9 to 69 kPa.

3. Pore-pressure response is more erratic, and trends are not clear-cut. The positive pore pressure recorded for the DF-UT test at consolidation stress of 69 kPa is particularly suspect. As would be expected for unfrozen soils, the higher negative pore pressures are associated with the lower levels of consolidation stress. It appears that freeze-thaw did not alter this general behavior in any way.

4. Water content at failure decreases as undrained shear strength increases. Considering all the possible drainage conditions for the Manchester silt, water contents varied by approximately 8 percent for the tests at consolidation stress of 6.9 kPa to less than 1 percent for tests at consolidation stress of 69 kPa.

5. Strain at failure generally reflects the undrained shear strength. The lower the strength, the larger is the strain at failure. Strain in excess of 20 percent was observed for the softest sample. It is interesting to note that even at the higher strains the samples were dilating, as indicated by the negative pore pressures at failure.

Table 1. Summary of results of variable-drainage freeze-thaw triaxial tests.

Drainage Test	Consolidation Stress (kPa)	Undrained Shear Strength (kPa)	Excess Pore Pressure at Failure (kPa)	Water Content at Failure (%)	Strain at Failure (kPa)
DF-UT	6.9	0	NA	36.87	20+
	34.5	43.3	NA	31.10	+10.00
	69.0	150.4	+62.2	27.54	3.33
DF-DT	6.9	90.4	-41.4	30.33	16.3
	34.5	115.2	-42.8	28.18	4.67
	69.0	187.7	-33.1	27.38	5.33
UF-UT	6.9	89.7	NA	28.68	6.70
	34.5	115.2	-33.8	26.68	3.33
	69.0	179.4	-46.2	28.00	6.33
NFT	6.9	127.6	-59.3[a]	28.06	2.83
	34.5	134.6[a]	-36.6[a]	26.73[a]	2.84
	69.0	191.8	-40.7[a]	26.93[a]	2.54
UF-DT	6.9	108.3	-41.4	28.44	3.92
	34.5	126.3	-16.6	26.63	3.33
	69.0	221.5	-39.3	26.94	6.66

[a]Average of two tests.

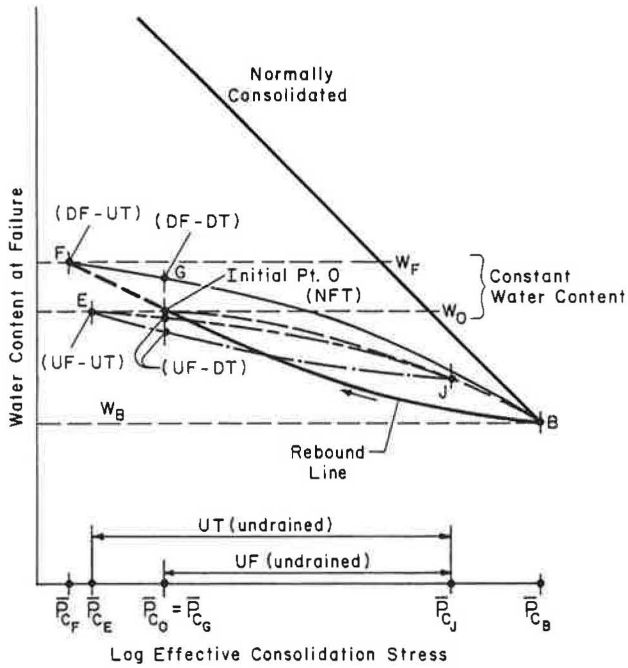
DISCUSSION OF RESULTS

By using the concepts discussed in the background material, it was possible to establish a relation among preshear consolidation stress, stress history, and the resulting undrained shear strength. Now it is also possible to discuss how freeze-thaw will affect the preshear conditions and thus shear strength. Consider, for example, what might occur during various freeze-thaw cycles by using Figure 5. Shown in this figure are a normal consolidation curve and several rebound-recompression curves. On the curves are points with coordinates that represent preshear water content and effective consolidation stress along with a designation of the drainage condition that is associated with the point.

It is assumed that point O is the initial point for all tests and is the as-compacted or in situ condition for a soil that has never been subjected to freeze-thaw. Because point O is on a recompression curve, the OCR is $\bar{P}_{C_B}/\bar{P}_{C_O}$, the preshear water content is w_A, and the effective consolidation stress is $\bar{P}_{C_O}$. The undrained shear strength obtained for these preshear conditions would be comparable to that obtained for point O in Figure 2.

Starting at point O, the same soil subjected to

Figure 5. Relation between drainage condition and resulting void ratio and effective consolidation stress.



UF-UT would produce the following set of events. First, as the temperature is lowered and drainage is prevented, a negative pore pressure (UF) develops and the soil experiences an increased effective stress and reconsolidates, at least on a microscale, to point J (4). Then, as undrained thaw occurs, the pore pressure increases (UT), the effective consolidation stress decreases to $\bar{P}_{C_E}$, and the soil rebounds to point E. If the soil is now subjected to undrained shear, the preshear condition is defined by the initial water content w_A, the consolidation stress $\bar{P}_{C_E}$, and an OCR of $\bar{P}_{C_B}/\bar{P}_{C_E}$. Because points E and O are at the same water content, they produce undrained shear strengths that fall on a line of constant water content defined by the true friction angle and true cohesion. The difference in shear strength would be a function of OCR as was observed in Figure 2 for points O and E. From these observations, it is possible to predict that the undrained shear strength of a soil subjected to undrained freeze followed by undrained thaw is less than that for a soil not subjected to any temperature conditioning.

Similar observations may be made for a sample subjected to other drainage conditions, such as drained freezing followed by undrained thaw. For this case, starting at the initial point O, the following sequence is predicted. During lowering of the temperature, potential negative pore pressure will develop, as it did in the case of undrained freezing. However, drainage conditions are such that the negative potential causes water to move toward the freezing front with an associated increase in water content to some point F. (The actual water content of point F will be a function of the freezing conditions that control the potential for the development of negative pore pressure.) Because drainage is prevented during thaw, the water content remains at the level of point F and, for post-thaw undrained shear, the preshear conditions are w_F, $\bar{P}_{C_F}$, and an OCR equal to $\bar{P}_{C_B}/\bar{P}_{C_F}$. The resulting shear will be similar to that for point F in Figure 2. In comparison with point O in the same figure, it can be seen that this condition is more severe in terms of loss of strength than the UF-UT conditions previously discussed. In fact, this is the most critical condition that can develop during a freeze-thaw cycle.

In summary, it can be stated that the effect of freeze-thaw on post-thaw undrained shear is reflected in its effect on water content after thaw, preshear overconsolidation ratio, and preshear consolidation stress. When a soil not conditioned with freeze-thaw (NFT) is compared with a soil conditioned with freeze-thaw, the following observations are appropriate:

1. Freeze-thaw drainage conditions that increase preshear water content cause reductions in strength.
2. Freeze-thaw drainage conditions that decrease preshear water content cause increases in undrained shear strength.
3. Freeze-thaw drainage conditions that maintain a constant water content cause a reduction in post-thaw shear strength that is proportional to the excess pore pressure that remains after thaw.

According to the observations made above, the shear strength of a soil subject to the various combinations of drainage conditions should increase in the following order: (a) DF-UT, (b) DF-DT, (c) UF-UT, (d) NFT, and (e) UF-DT. Table 2 summarizes the results of the variable-drainage tests and verifies the trends suggested above.

When compared with NFT samples, the shear strength of soil subjected to freeze-thaw varies from 0 to 115 percent. The low value occurs with the lowest confining pressure and increasing water content (DF-UT), and the high value is associated with the highest confining pressure and decreasing water content (UF-DT). These are extreme conditions, the latter of which might occur when a saturated soil near the surface is subjected to slow freezing and the former of which would occur when a saturated soil at greater depth is subjected to a fast freeze followed by a slow thaw.

Also of interest is the close relation between water content at failure and undrained shear strength. As expected, the DF-UT condition produced the highest water content. This was true at all consolidation stresses, although the difference in water content at the highest consolidation stress is

Table 2. Effect of temperature and drainage conditioning on Manchester silt.

Drainage Test	Consolidation Stress (kPa)	Undrained Shear Strength (kPa)	Undrained Shear Strength[a] (%)	Water Content at Failure[a] (%)
DF-UT	6.9	0	0	131.4
	34.5	48.3	35.9	116.3
	69.0	150.4	78.4	102.3
DF-DT	6.9	90.4	70.8	108.1
	34.5	115.2	85.5	105.4
	69.0	187.7	97.9	101.7
UF-UT	6.9	89.7	70.3	102.2
	34.5	115.2	85.5	99.8
	69.0	197.4	94.5	
NFT	6.9	127.6	100	100
	34.5	114.6[b]	100	100
	69.0	191.8[b]	100	100
UF-DT	6.9	108.8	84.9	101.4
	34.5	126.3	93.8	99.6
	69.0	221.5	115.5	100.0

[a]Comparison with NFT samples. [b]Average of two tests.

only 2 percent greater than the value for the unfrozen test. This emphasizes the stabilizing influence of surcharge on the effect of freeze-thaw, as has been observed by others (5-7).

Overall, the discussion given above shows that the undrained shear strength of a soil is a function of preshear history and consolidation stress. In addition, the results of the variable-drainage triaxial tests showed that freeze-thaw altered the preshear conditions in a rational and quantifiable way and these tests could be used to simulate several well-defined temperature paths--i.e., fast or slow freeze or thaw. If this is the case, then it should be possible to evaluate the effect of freeze-thaw on post-thaw soil properties by using a stress-path approach. The stress path in this case would have to simulate both anticipated temperature and load.

For example, to follow the usual stress-path approach (8), it would be necessary to perform the following:

1. Select one or more critical points within the soil region influenced by the design temperature and loading.
2. Estimate the magnitude and duration of the temperature and stress changes at the critical points.
3. Perform laboratory tests following the estimated temperature and load paths. Because of time constraints, it might not be possible to follow the anticipated temperature path exactly, and it would be necessary to simulate the effect of the temperature path by using the idealized method presented in this paper--i.e., using drained freeze or thaw to simulate a rapid temperature change and undrained freeze or thaw for slow temperature change. The appropriate loads could be applied at any time during the test sequence but usually would be applied after thaw. In addition, the soil could be tested by using drained or undrained conditions during loading as required from the stress path determination.
4. Use the results from the laboratory tests to predict the effect of the design temperature and load conditions on the in situ soil.

The results from an analysis of this type could be used not only to predict the post-thaw shear strength but also to define deformation or other material properties required by the design engineer.

SUMMARY AND CONCLUSIONS

The undrained shear strength of a soil is a function of the preshear history and effective consolidation stress and can be determined by using Hvorslev's hypothesis in conjunction with the Mohr-Coulomb failure criteria.

Test results showed that freeze-thaw affects shear strength by altering the preshear history and consolidation conditions. In general, it was observed that test conditions that simulated fast or constant-water-content freezing (undrained) caused an effect similar to that caused by increasing the overconsolidation ratio and reducing the effective consolidation stress. This caused a slight reduction in the post-thaw shear strength. Slow freezing or freezing with increasing water content (drained) caused an increase in overconsolidation ratio and a reduction in effective consolidation stress but also caused an increase in water content, which produced a substantial reduction in post-thaw shear strength.

Results also showed that tests in which a constant-temperature conditioning procedure was used could simulate critical rates of freeze or thaw by controlling access to water during the freeze or thaw. Thus, undrained test conditions produced the results expected for fast freeze or thaw. Drained conditions during freeze or thaw produced results expected for slow temperature change.

Specifically, the results of the variable-drainage freeze-thaw triaxial tests on the Manchester silt showed the following:

1. The DF-UT condition produced the lowest post-thaw shear strength at all levels of consolidation stress.
2. As the level of consolidation stress increases, the post-thaw shear strength increases for all freeze-thaw drainage conditions.
3. The highest water content and largest strain at failure is associated with the DF-UT condition. The lowest water content occurs for the UF-DT condition.

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