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

BERNARD D. ALKIRE AND JAMES M. MORRISON

Although the boundary conditions are different, soils subjected to freeze-thaw or repeated loading may exhibit changes in structure that can be indirectly identified by the soils stress-strain characteristics. The objective is to use this concept to help explain the differences in strength and deformation 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 loading 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 structure 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 explanation 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 Manchester silt obtained from New Hampshire. The soil is light brown in color with subrounded to subangular particles. The liquid limit is 25 percent and the plastic limit is 23 percent. The specific gravity 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 Michigan. 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

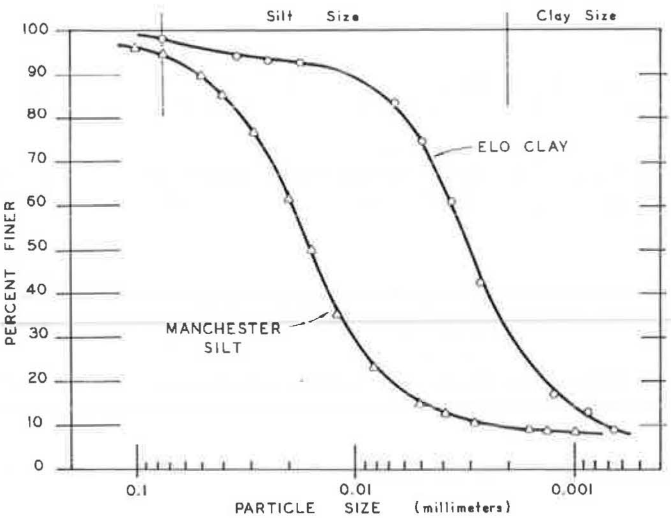
Manchester Silt

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 compacted at a water content of 20 percent. After compaction, 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 sedimentation in upright plexiglass cylinders 35 mm in diameter. 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 preparation technique can be found in Morrison (7).

Figure 1. Grain-size distribution of Manchester silt and Elo clay.



Testing Procedure

Triaxial Tests

All tests were standard, consolidated, undrained triaxial tests. Variations of the different tests were conducted after the consolidation phase and before the undrained monotonic loading phase. Variations consisted of either one cycle of freeze-thaw or a repeated-load sequence or a combination of one cycle of freeze-thaw followed by the repeated-load sequence. All of the variations were conducted with the sample drainage closed. Each type of test is described by a temperature conditioning and loading sequence as listed below:

1. Unfrozen monotonic loading (UF-M),
2. Unfrozen repeated loading (UF-RL),
3. Frozen monotonic loading (F-M), and
4. Frozen repeated loading (F-RL).

Freezing Procedure

Samples to be conditioned with freeze-thaw were mounted, saturated, and consolidated in the same way for all tests. The sample drainage lines were closed, and the triaxial cell was wrapped in an insulating jacket (fiberglass batting). A circulating bath was switched on, and the temperature was lowered to -10°C in 120 min and held at that temperature. After the first signs of freezing (signified by a rapid jump in pore pressure), the sample was allowed to continue freezing for approximately 2 hr. After that time, the freezing system was shut down, the cell insulation removed, and the system allowed to thaw at room temperature.

TEST RESULTS

Effects of Monotonic Loading on Stress-Strain Behavior

Dense Manchester Silt

A comparison of the deviator stress versus strain between samples subject to freeze-thaw conditioning (F-M) and the unfrozen (UF-M) control series can be seen in Figure 2. For dense Manchester silt, samples conditioned with freeze-thaw generally resulted in steeper initial tangent moduli and greater overall strength than the UF-M series. For all silt samples tested, the stress-strain curve flattened out beyond 2 to 5 percent strain. Beyond that point, all samples continued to gain strength until reaching strain levels of 15 percent or larger. Samples subjected to freeze-thaw usually resulted in larger strains at failure than the unfrozen samples.

At the lowest consolidation stress of 2.5 psi, the difference in strength observed between the F-M and the UF-M series was minimal. The 2.5-psi samples that were subjected to freeze-thaw, however, showed a slightly steeper tangent modulus after initial loading. Also, at any given strain beyond 1 percent, the strength of the F-M samples was slightly less (less than 2 percent) than that of the UF-M samples. These results are consistent with those reported by Alkire for samples at low consolidation stress in an unpublished report to the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

Loose Manchester Silt

Samples of loose Manchester silt that were conditioned with freeze-thaw also resulted in greater overall strength and larger strains at failure than those of the UF-M control series, as shown in Figure 3. However, the samples subjected to freeze-thaw showed an initial soft spot when loaded followed by a steeper stress-strain curve up to the inflection point than that observed in the UF-M series. Also, unlike the dense silt, the loose silt showed a pronounced strength gain at the lower consolidation stresses: up to a 66 percent gain at the 2.5-psi level compared with virtually no strength difference for the dense silt.

Elo Clay

The stress-strain behavior of Elo clay subjected to freeze-thaw appears to be dependent on the overconsolidation state of the samples at the time of testing. As shown in Figure 4, F-M samples that were consolidated at pressures less than the preconsolidation stress (up to approximately 10 psi) showed an increase in initial tangent modulus and much higher strength at low strain levels than the UF-M series. Once the overconsolidation ratio approaches unity at 10 psi, the initial loading curve for the freeze-thaw conditioned sample becomes somewhat softer than that seen with the UF-M samples. At 20-psi consolidation pressure, the F-M sample is initially significantly softer than the UF-M samples. At larger strains the ultimate strength is greater for the F-M series at all confining pressure.

Effects of Repeated Loading on Stress-Strain Behavior

Dense Manchester Silt

After repeated-load conditioning, samples of dense Manchester silt showed a significant increase in strength and stiffness when loaded to failure (see Figure 5). Samples were first loaded to an estimated 50 percent of the failure load and then subjected to 600 cycles of repeated loading between 75 and 25 percent of the estimated failure load. Strains of between 5 and 10 percent were typical during the repeated-load sequence; the most strain occurred in the first 200 cycles. After repeated loading, samples were loaded to failure and experienced a significant increase in the stress-strain modulus.

Loose Manchester Silt

Samples of loose Manchester silt experienced significantly more strain during repeated loading than dense silt, as shown in Figure 6. This presented some problems during this phase of the testing program because the repeated load could not always be increased to 75 percent of the expected failure stress without causing excessive strain. Again, most of the deformation that did take place occurred during the first 200 load cycles. When loaded to failure, all samples showed an increase in strength and stiffness, and most failures occurred in a brittle manner.

Elo Clay

Elo clay samples also showed a tendency toward large

Figure 2. Average stress-strain curves for dense Manchester silt.

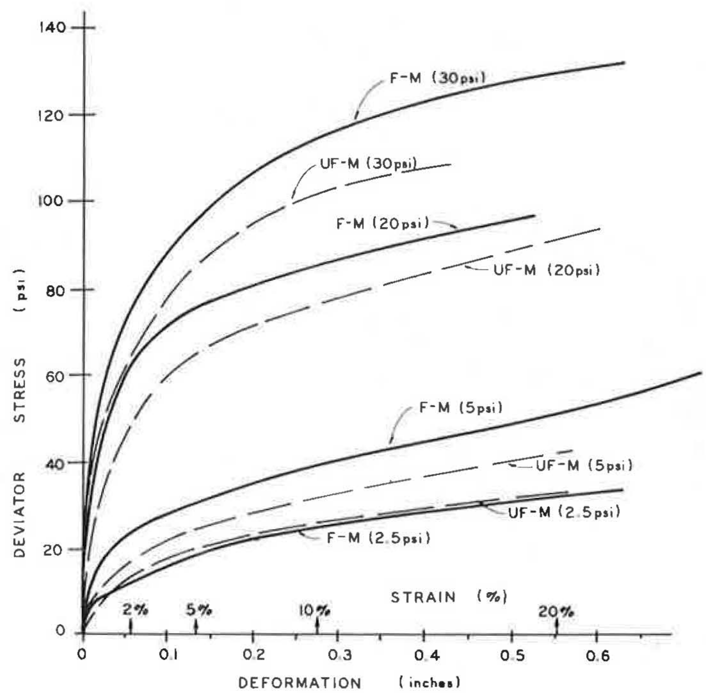
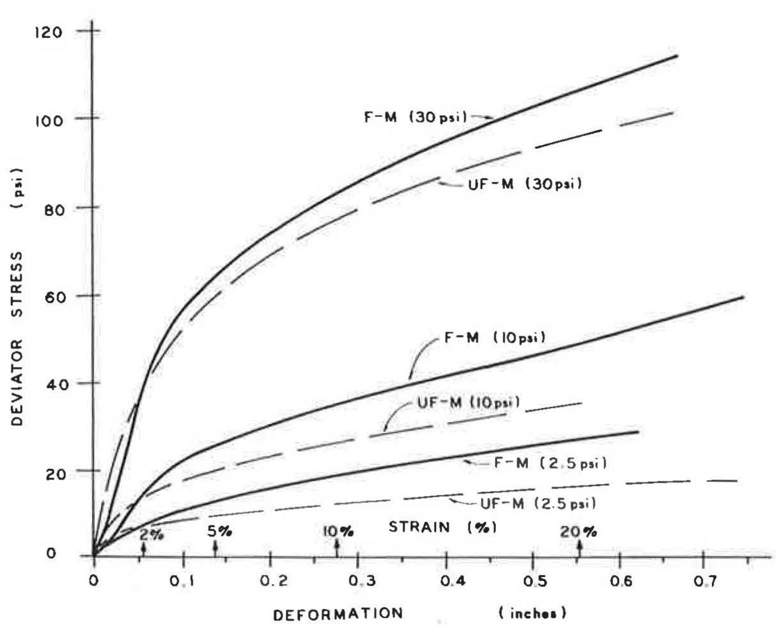
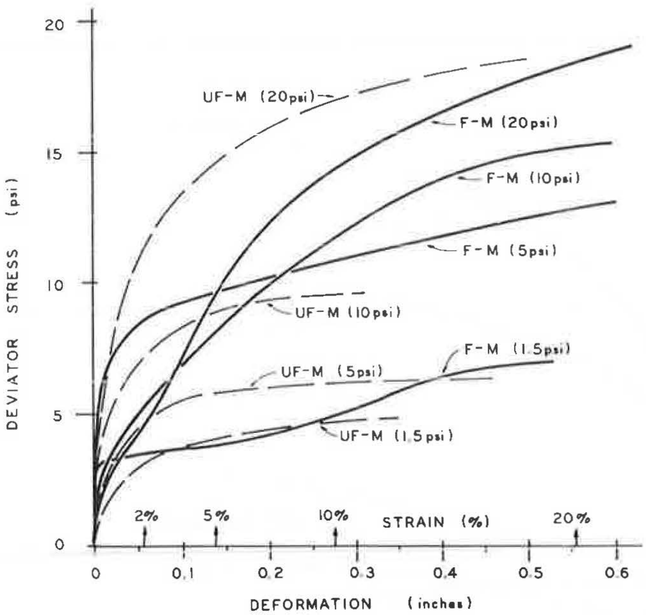


Figure 3. Average stress-strain curves for loose Manchester silt.



strains during repeated loading. To ensure against premature failure, the repeated loading was often started at a low stress level and increased until a satisfactory load level was reached, as shown in Figure 7 for 5- and 10-psi samples. Again, a judgment had to be made for each sample as to how large a repeated load could be applied without causing failure. Most samples showed an increase in both strength and stiffness when loaded to failure. The 10-psi sample shown in Figure 7 failed on the first load increment applied beyond the repeated-load level.

Figure 4. Average stress-strain curves for Elo clay.



Stress-Strain Behavior of Samples Conditioned with Freeze-Thaw Before Repeated Loading

Samples that were conditioned with freeze-thaw before repeated loading usually showed less displacement during the repeated-loading sequence than those not conditioned by freeze-thaw, as indicated by the displacement measurements given in Table 1. For dense Manchester silt, the difference was not particularly significant; but, for loose silt and Elo clay, the difference was quite apparent. Care must be taken in making comparisons from this table, however, because the maximum load levels of each test had to be adjusted. Load levels for the UF-RL and F-RL series were generally within 10 percent for any given consolidation stress; the F-RL samples often received the higher repeated load. Therefore, the observations are assumed to be at least qualitatively valid.

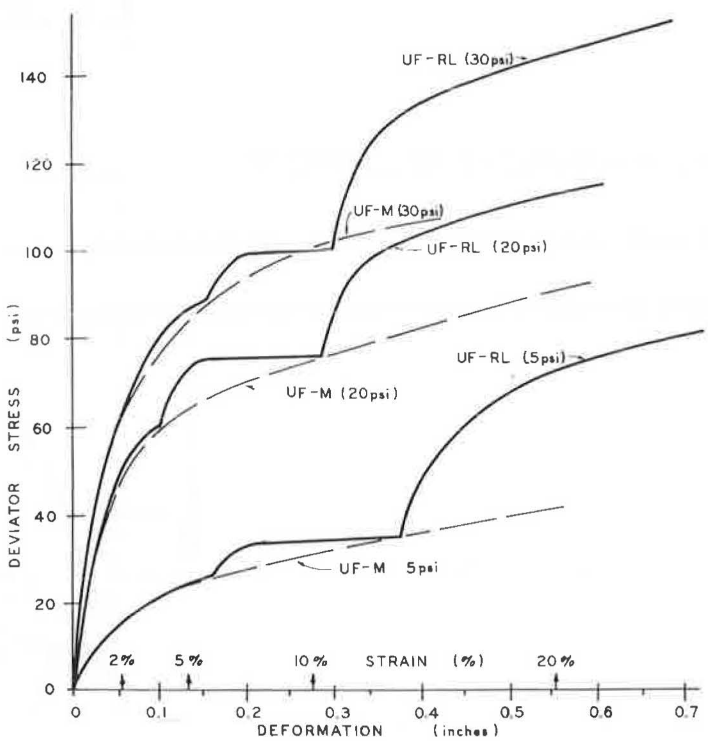
When loaded to failure, samples of the F-RL series were clearly not as strong as those of the UF-RL series. Figures 8 and 9 demonstrate this by showing the deviator stress versus deformation curves for representative samples of both dense and loose silt. In both of these curves, the strain has been normalized to the point of monotonic loading to failure. Also in both cases, the stress-strain modulus when loaded is much less for the samples conditioned with freeze-thaw. Failure was usually more brittle for samples of the F-RL series.

DISCUSSION OF RESULTS

To understand the changes brought about by the various conditioning sequences, the results are presented in terms of structural changes caused by freeze-thaw and repeated loading. It is hoped that these conclusions can be extended to explain the strength reduction observed in samples subjected to both freeze-thaw and repeated loading.

In the following discussion, the term fabric is defined as the physical relationship between location and orientation of soil particles and void

Figure 5. Stress-strain response for samples conditioned with repeated loading: dense Manchester silt.



spaces. The term structure is defined as the relationship among soil fabric, composition, and interparticle forces.

Freeze-Thaw

Figures 2-4 demonstrate typical stress-strain response during the freeze-thaw cycle for Manchester silt and Elo clay. With few exceptions, the soil was stiffer after freeze-thaw, which indicated that a change was brought about by freeze-thaw. Although the evidence of structural change is indirect and the actual mechanism of structural change is speculative, the following are presented as possible explanations.

It is known from investigations into the deformation mechanism of granular soils (8) that in the dilative zone of dense soils the soil particles will reorient themselves to project their largest contact area normal to the direction of greatest principal stress. It is also known that at the freezing front there is a decrease in pore pressure and consequently an increase in effective stress. This increase in stress alone may be large enough to initiate dilation and structural rearrangement of the soil, or it may be aided by the expanding ice crystals.

If the soil particles retain their configuration after thaw, the particle contact orientation will be primarily horizontal or normal to the direction of

Figure 6. Stress-strain response for samples conditioned with repeated loading: loose Manchester silt.

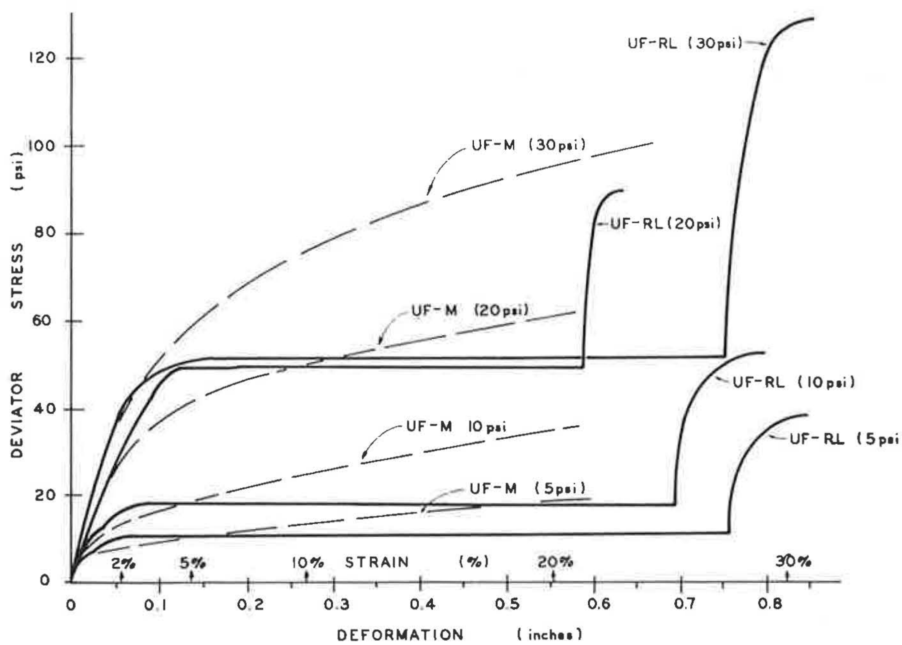


Figure 7. Stress-strain response for samples conditioned with repeated loading: Elo clay.

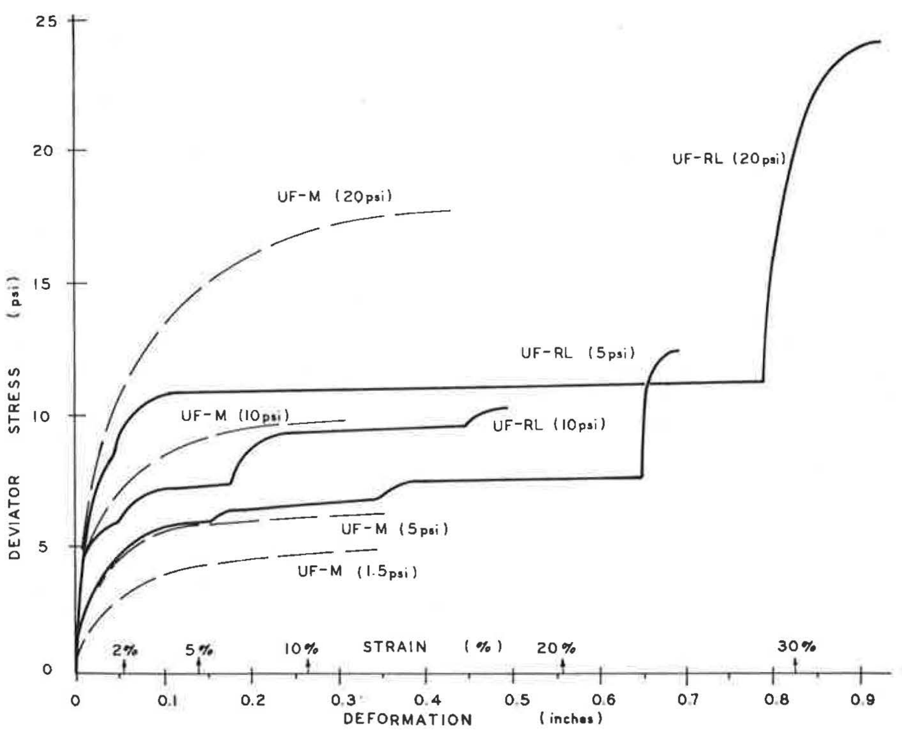


Table 1. Displacement following repeated-load conditioning.

Soil	Consolidation Pressure (psi)	Average After Loading UF-RL (in.)	Deformation Repeated F-RL (in.)
Dense Manchester silt	30	0.300	0.320
	20	0.391	0.259
	5	0.431	0.280
	2.5	-	0.326
Loose Manchester silt	30	0.750	0.170
	20	0.580	0.300
	10	0.700	0.620
	5	0.637	0.221
	2.5	0.560	0.264
Elo clay	20	0.100	0.440
	10	0.448	0.039
	5	0.640	0.057
	1.5	-	0.179

Figure 8. Loading to failure after repeated-load conditioning: dense Manchester silt.

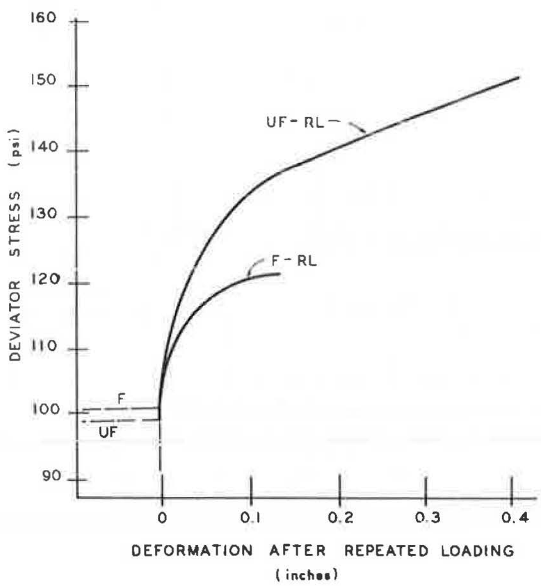
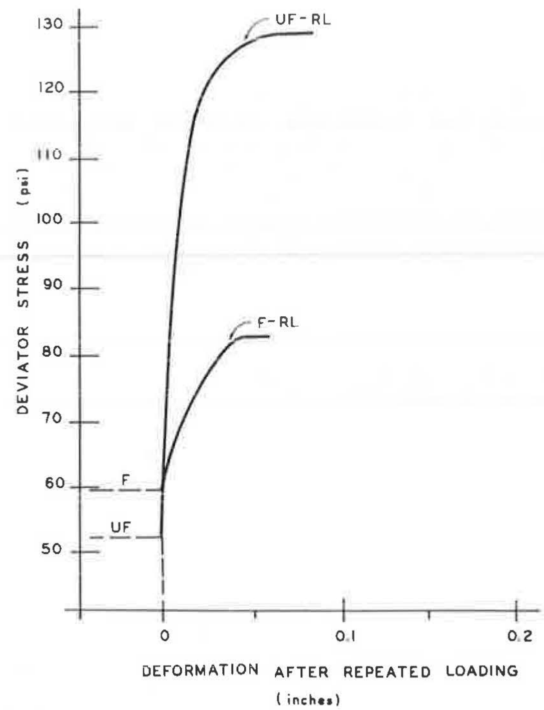


Figure 9. Loading to failure after repeated-load conditioning: loose Manchester silt.



freezing. Oda (8) found that sands with a majority of contact planes normal to the direction of loading resulted in higher shear strength and more potential for dilative volume change than samples with random contact orientation. This is consistent with the increase in initial modulus experienced by samples of dense Manchester silt subjected to freeze-thaw in this investigation.

Because the negative pressure at the freeze-thaw interface is a function of the pore size, one would expect to see more dilative behavior with denser material than with loose, but this was not generally observed for Manchester silt. However, the tendency to dilate may be masked by increased consolidation pressure. It was noted by Alkire and Morrison (9) that dilation at low consolidation pressure was greater for the dense Manchester silt than for the loose Manchester silt.

Another complementary theory presented to explain observed post-thaw soil structure in clays was described by Czeratzki (10), Wood (5), Morganstern and Nixon (4), and Chamberlain (11). Again, at the freeze-thaw interface, there is an increase in effective stress due to a decrease in pore pressure. As ice nucleates at various points along the freezing front, soil particles will tend to form clusters between the ice crystals, and water for the crystals will be drawn from the clusters. As a consequence the soil within these clusters will become more highly consolidated because of the increased effective stress and desiccation.

As thawing begins, the clusters may or may not reabsorb the melt water but will remain in an overconsolidated state when compared to the original soil conditions. It is conceivable that the new aggregated soil clusters could retain some of their net freeze-expanded configuration when thawed and that negative pore pressures would be observed. However, these clusters may also collapse when thawed, resulting in a denser system in which excess water and positive pore pressure would be observed.

Repeated Loading

In all cases, the soils investigated that were subjected to repeated loading showed an increase in strength and stiffness when compared to the unconditioned soils. In this case, it is assumed that the soil structure is changed by repeated loading in such a manner that the soil skeleton can withstand the applied stress. Because of its high density the dense Manchester silt became dilative by a mechanism similar to that described for the dilative response to freeze-thaw. For loose Manchester silt and Elo clay, the tendency to compact into a more stable arrangement is explained by Seed (12) and described by the effective stress models presented by Sangrey and others (13), Egan and Sangrey (14), and Finn, Lee, and Martin (15). Of importance here is the fact that particles tend to act as single grains, not as clusters or units, and compact under the action of repeated loading. Both observations appear to be valid; samples subjected to repeated loading showed an increase in stiffness as well as an increase in ultimate strength when compared to the unfrozen monotonic (UF-M) series.

Combined Effects of Freeze-Thaw and Repeated Loading

It has already been stated that repeated loading will cause an increase in soil strength and stiffness by compacting soil particles into a more stable fabric. But test results show that when samples of Manchester silt and Elo clay were conditioned by freeze-thaw before repeated loading, they experienced a decrease in strength and loss of stiffness. Because these observations do not reinforce each other, it is concluded that the mechanism of structural change is not the same for freeze-thaw as for repeated loading.

The actual mechanism of structural change that results in the decrease of strength during repeated loading after freeze-thaw can be developed from the previously discussed mechanisms. As part of this development, it must be assumed that some form of metastable or clustered soil structure is developed as a result of freeze-thaw. When loaded monotonically, these clusters will remain intact during deformation and form a more stable system. If, however, a cyclic load is applied to the soil, these clusters break apart or collapse and the soil particles take a more random orientation with a loss of strength.

The collapse required by this theory may be due to a decrease in effective stress within the soil clusters caused by an increase in pore pressure during repeated loading. If the clusters are broken into a random orientation during repeated loading, total deformation after the repeated-load conditioning would not be as great as if the particles were consolidated into an ordered assemblage of particles. This was noted in Table 1 by the fact that strain after freeze-thaw followed by repeated loading was usually less than after unfrozen repeated loading.

Also, when loaded to failure, it was observed that the samples preconditioned with freeze-thaw were much softer than those conditioned by repeated loading alone, indicating either a dispersed or more random particle orientation. This is similar to the response observed by Oda (8), where sands with random particle orientation were softer when loaded than sands with oriented particle structures. For clays, Seed (12) observed that soils with random or dispersed particle orientation were softer than soils with a flocculated fabric when loaded.

Effect of Soil Density

The major difference between the results for dense and loose Manchester silt is that the loose silt was more affected by freeze-thaw conditioning, both in terms of increase in strength as a result of monotonic loading and decrease in strength due to repeated loading. Of prime interest is the fact that the loose silt samples when monotonically loaded to failure showed an initial soft spot on the stress-strain curve; it is assumed that this represents a collapse of the post-thaw soil structure. This lends support to the idea of a particle-cluster arrangement with an open void network where the open void network collapses into a more stable arrangement when loaded, allowing the increased load-carrying capacity. For the dense silt, either the open void network was not formed or was formed on such a small scale that the collapse was not detected.

SUMMARY

Both freeze-thaw and repeated loading were seen to produce a change in the stress-strain behavior of soils. It was concluded therefore that a change in the basic soil structure occurs during both forms of cyclic stress conditioning. It was assumed that some form of clustered or other metastable structure was developed in loose silt during freeze-thaw and was seen to collapse under initial monotonic loading. The dense silt either did not develop the metastable cluster structure or did so to such a small extent that the collapse was not detected. Whatever the post-thaw soil structure was, it was definitely stronger and resulted in increased dilative behavior when loaded.

Samples conditioned with repeated loading also resulted in higher strength when loaded to failure. The structure of dense Manchester silt dilated under the action of repeated loading whereas that of loose silt and Elo clay contracted. The resulting structure in all three cases produced a stiffer response and higher shear strength at failure than the monotonically loaded control series.

In all cases, when samples subjected to freeze-thaw were followed with repeated loading, they exhibited softer stress-strain behavior and lower strength than soils not conditioned with freeze-thaw. As an explanation, it was hypothesized that although the structure resulting from freeze-thaw will remain stable under monotonic loading, it will be broken apart or collapse into a weaker system under repeated loading. This is explained by the collapse of the clusters formed during freezing into a dispersed or randomly oriented fabric because of reduced effective stress caused by the action of the repeated loads.

In summary, the main conclusions resulting from this research are as follows:

1. Samples of Manchester silt and Elo clay subjected to either freeze-thaw or repeated loading usually result in higher shear strength at failure than samples not so conditioned.
2. Samples of Manchester silt and Elo clay subjected to a combination of freeze-thaw and repeated loading usually result in a decrease in shear strength at failure when compared with samples conditioned by repeated loading or freeze-thaw alone.
3. Loose Manchester silt proved to be more responsive to the effects of freeze-thaw, both in terms of increased strength under monotonic loading and decreased strength under repeated loading and freeze-thaw.
4. The soil structure resulting from freeze-thaw is not the same as that resulting from repeated-load conditioning, as indicated by the observation that the structure resulting from freeze-thaw was broken apart by repeated loading. It is assumed that, if the resulting structures were the same, the combined effects would have served to reinforce each other, which would have resulted in strengths at least equal to those seen for repeated loading alone.

ACKNOWLEDGMENT

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Fatigue-Based Criteria for Seasonal Load Limit Selection

JAMES H. HARDCASTLE, ROBERT P. LOTTMAN, AND TRI BUU

During spring thaw, restrictions on allowable axle weights (load limits) are often applied to flexible pavement sections in seasonal frost areas to prevent premature failure of thaw-weakened pavements. Currently, load limits are selected on the basis of experience. An approach to load limits that is based on controlling seasonal rates of fatigue consumption is described. Fatigue consumption can be determined from fatigue curves that relate critical tensile strains in the pavement section to the number of load repetitions causing fatigue failure. By using a layered-elastic computer program, strain is determined for the traffic loads applied to the pavement while it is in various seasonal states. Seasonal values for elastic-response parameters (resilient modulus and Poisson's ratio) are determined in laboratory tests on appropriately conditioned specimens. By relating the fatigue damage produced to the number and magnitude of loads applied during each of the seasonal pavement conditions, the effects of alternative load limit policies on remaining pavement life can be compared. In an application of the method to an existing pavement it was decided that the maximum axle load permitted during the spring-thaw period should be one that produced the same rate of fatigue consumption as the normal summer-fall legal maximum of 18.9 kips. Using this criterion, the maximum spring-thaw load for the pavement would be 11.5 kips. Comparisons indicated that the remaining service life under the posted 14-kip load limit would be 80 percent of the life remaining if the 11.5-kip load limit were imposed. If no special spring-thaw period load limit is imposed, the remaining service life of the pavement will be reduced to 40 percent of the life remaining under the 11.5-kip limitation.

Highway managers recognize that the load-carrying capability and the rate of decrease of useful service life of flexible pavements vary during the year. Under uniform traffic, these variations reflect seasonal changes in the physical state (e.g., temperature and water content) of the materials within the pavement structure. In areas of seasonal frost, the critical period in the annual cycle of temperature and moisture changes occurs during the spring-thaw (spring breakup) period. The increased water content that results from melting of accumulated ice in the subgrade soil and in the unbound granular layers within the pavement section can cause reductions in both the strength and stiffness of the materials (1). The application of normally acceptable, heavy axle loads while the pavement materials are in the moisture-weakened condition leads to an accelerated deterioration rate and premature permanent failures.

Two general approaches are currently available to the pavement manager to account for seasonal variations in pavement performance. For a new pavement, anticipated variations in pavement condition may be accounted for by using design parameters based on measurements of materials conditioned to reflect an average or a worst in-service condition instead of the immediate post-construction condition. Examples of this approach are the 4-day soaking period to which California bearing ratio (CBR) test specimens are subjected before testing and the compression of compacted stabilometer (R-value) test specimens at higher than immediate post-construction degrees of saturation. In addition to special conditioning of materials, regional factors also may be used to account for adverse climatic and environmental conditions (1).

In recognition of the markedly increased vulnerability of flexible pavements to unusual damage during the spring-thaw period, highway managers in many northern states impose special temporary restrictions on vehicle speeds and maximum axle weights (load limits) for selected highway sections. Seasonal load restrictions are usually limited to older routes designed for relatively low traffic