Undrained Failure of Compacted Plastic Embankments

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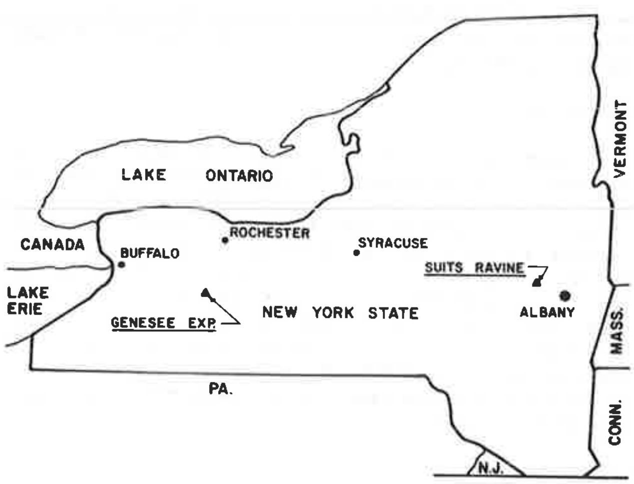
This paper deals with the effectiveness of the New York State Department of Transportation earthwork compaction specifications, which are based on a percentage of standard Proctor maximum density as they relate to overall embankment stability. A number of failures have occurred in recent times within moderate to low plastic soil fills in New York State. These failures have been traced to the placement of plastic materials in a condition where the moisture content exceeds the optimum moisture content for standard compaction. Although the percentage of standard Proctor maximum density that is required by New York State construction specifications was equaled or exceeded, the resulting shearing strength of the fill was inadequate to support the additional proposed fill loads. Two detailed case studies are shown to identify the nature of the problem. A discussion of potential alternative methods of compaction control is given.

New York State Department of Transportation's specifications require embankment lifts to be compacted to 90 percent of standard Proctor maximum density. Several plastic glacial till embankments up to 40-ft high have failed in recent times where the density of the fill was found to be as high as 94 percent of standard Proctor. Laboratory tests on samples of fill obtained from two such areas have confirmed that undrained failures of plastic fills can take place when they are placed at standard compaction and at greater than optimum moisture contents.

The two embankment areas reported in this paper are located on the Interstate highway system, one on the Genesee Expressway near Mount Morris, and the other on I-88 at Suits Ravine (see Figure 1).

Figure 1. Site locations.



GENERAL BACKGROUND OF FAILURES

Genesee Expressway, SB 549+ to SB 555+

In May 1978, shortly after embankment construction reached subgrade (65- to 70-ft high fill), a crack developed in the surface of the Genesee Expressway and a bulge appeared on the embankment slope 40 or more ft below subgrade. The first 45 ft of fill was a brown plastic glacial till, which possessed an average plasticity index (PI) of 13. It was placed in the fall 1977. The remainder of the fill was constructed of broken shale to subgrade in the spring 1978. After several days this crack opened up to ±1-ft wide (see Figure 2). Approximately 10 ft of fill was then removed to relieve the embankment stresses. The fill was eventually stabilized by flattening the side slopes to 1 on 3 with shale.

I-88 - Westbound East Abutment, Suits Ravine

The abutments on I-88 at Suits Ravine were constructed and backfilled in the fall 1979. Bridge movement records over the winter indicated 0.35 ft of vertical downward movement and 0.14 ft of horizontal outward movement. The fill was constructed

Figure 2. Typical side slope section of Genesee Expressway.

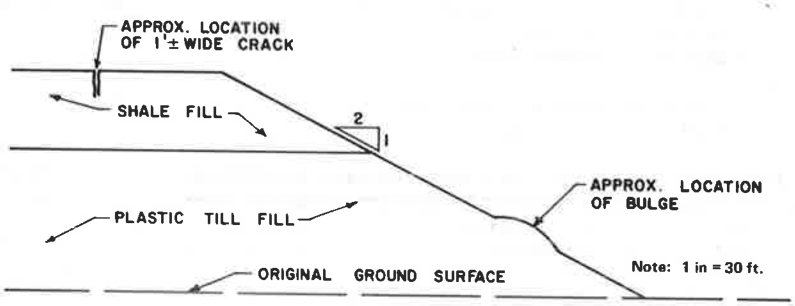
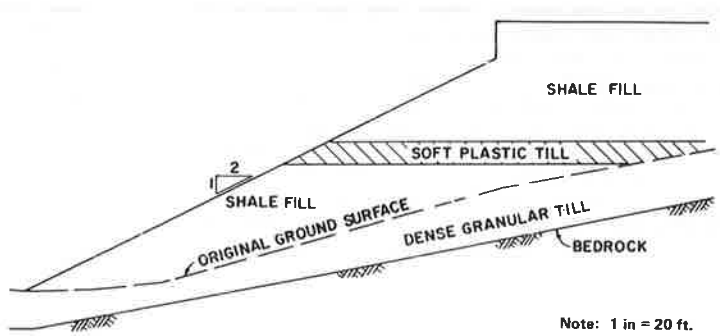


Figure 3. Section at bridge end slope of Suits Ravine, I-88.



mostly of broken shale with some layers of brown plastic glacial till (PI≈8) benched into shallow till (original ground) over bedrock. Subsequently a slope inclinometer installation indicated horizontal movements to be occurring in two thin soft till layers located 14 and 18 ft below footing level, which was ±16 ft below the theoretical grade line. Cracks were not evident at the surface of this fill (see Figure 3). This fill was eventually stabilized with 20-ft wide side berms and 40-ft wide end berms.

Testing Program and Results

Both failures were apparently due to undrained displacements (overstress) of relatively thin layers of moderate-to-low plastic glacial till. A review of the compaction records indicated that the soils that were moving passed the state's minimum 90 percent standard density requirement. This prompted our testing program, which was progressed to compare unconsolidated undrained shear strength results with percentage of standard density wet of optimum and to relate this percentage of density to maximum allowable fill height via slope stability analysis. Samples of the fill were obtained from large diameter borings. The samples from each site were mixed into batches and dried to below optimum. During this process the large stones (i.e., +1/4-in stones) were removed from each batch. The materials were then compacted at standard effort and at successively higher moisture contents to produce the compaction curves shown in Figure 4. The full diameter (3.375 in ϕ) soils were then extruded from the compaction molds and were subjected to failure at an unconsolidated undrained (UU) confining pressure (σ_3) of 25 psi (see Figure 5). Information from a report by Weitzel and Lovell (1) on a highly plastic St. Croix clay (PI≈31) is also shown in Figures 4 and 5 for comparison. Note that the shear strength curves are plotted directly below the compaction curves between optimum moisture content and the moisture contents at 90 percent density for comparison purposes. Very low shear strengths were obtained for all three soils at 90 percent density.

The Genesee Expressway till was also compacted to modified effort and failed at UU strengths above optimum moisture contents. The results are compared with standard effort and are shown in Figures 6 and 7. These plots show that the moisture content has more of an influence on shear strength of samples compacted over optimum than the actual compaction effort. This is also verified in Figures 8 and 9, which show results for the St. Croix clay. Others (1-3) have found the same to be true in relating California bearing ratio or undrained shear strength to moisture content at various compactive efforts.

Figures 10 and 11 were obtained from and quantify the information shown in Figures 4 and 5. These figures show that only a ±200 psf shear strength is obtained at 90 percent standard density and at 7 percent moisture content over optimum. The shear strength increases to ±1000 psf at 95 percent standard density and at 3.5 percent moisture content over optimum. These curves show that the increase in shear strength and the percentage of moisture content over optimum decreases are sensitive to small changes in the percentage of standard density over optimum moisture content.

Slope Stability Analysis

Slope stability analyses were run to equate safe and equilibrium fill heights to shear strength with the use of the simplified Bishop circle analysis. In addition, overstress analyses were run to more accurately simulate a squeeze-type failure that appears to be the governing criteria. The results of these analyses are shown in Figure 12.

Figure 13 shows the relation of percentage of standard density versus equilibrium fill heights for both fill areas by using information from Figures 11 and 12. This figure also shows that only 10-15 ft of fill can be safely constructed if the soil is compacted to 90 percent of standard density at over optimum moisture content. Of major significance is that these curves indicate that 93-95 percent of standard density at over optimum moisture content is required for most grade crossing embankment fills constructed of plastic fill materials (i.e., embankment fills between 23 and 40 ft high).

Compaction Control

Figure 13 shows that a fill height of 23 ft is marginally safe if it is constructed to 93 percent of standard density at greater than optimum moisture content and a fill height of 40 ft is marginally safe if it is constructed to 95 percent of standard density at greater than optimum moisture content. Figure 10 indicates that the percentage of moisture content over optimum is relatively insensitive to the degree of plasticity of the soil in the 93-95 percent of standard density range. In other words, in order to safely construct a 40-ft high fill for a soil of any plasticity the moisture content should not be greater than 4 percent greater than optimum.

This information indicates a need for more than the normal degree of control for plastic fills placed over optimum moisture content. It indicates that the control can be placed either on the degree of compaction or on the percentage of moisture content over optimum, depending on the fill height. The question is what would be the easier way to control the operation for adequate safety of these fill materials? Since statewide compaction control curves are available for most soils in New York State, percentage compactions could be performed routinely on these types of soils and a minimum 95 percent standard dry density be required of these soils for all embankments up to ±40 ft high. The determination of moisture content is still a requirement. Greater percentage of standard densities would be required for embankments that exceed this fill height.

The above information on stable embankments is based on the fills being field compacted with standard effort. The heavy compaction equipment that is available today produces compactive efforts that exceed the normal. Based on the information in Figures 6 and 7 (i.e., an increase in the compaction effort at a constant moisture content over optimum decreases the undrained shear strength), greater field compactive efforts will require even greater percentage standard densities than are recommended for stability. For instance, from these curves the maximum allowable percentage of moisture content over standard optimum is 2 percent for the modified effort as compared with the 4 percent for the standard effort to provide a stable embankment. This is equivalent to requiring a 98 percent standard density at greater than optimum moisture content. At greater field compactive efforts than the modified effort the stable standard density approaches 100 percent at greater than optimum moisture contents. This condition further complicates the method of field compaction control.

Based on the above discussion concerning the current use of heavier-than-standard compaction equipment, soils of low-to-moderate plasticity should be compacted to at least 98 percent standard density at greater than optimum moisture contents or be compacted to at least 90 percent standard density at

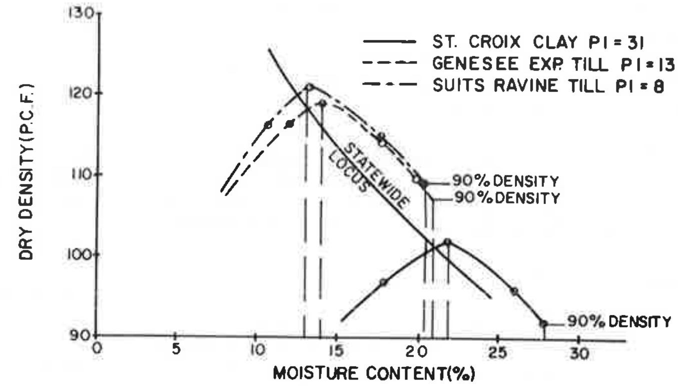


Figure 4. Moisture content versus dry density: standard compactive effort.

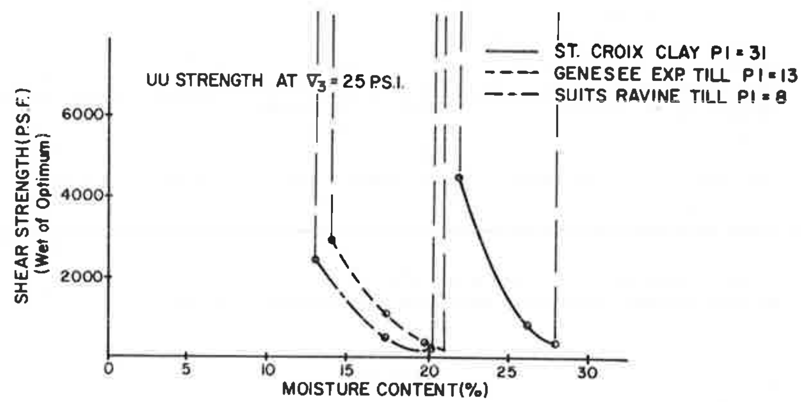


Figure 5. Moisture content versus shear strength: standard compactive effort.

Figure 6. Moisture content versus dry density: Genesee Expressway till.

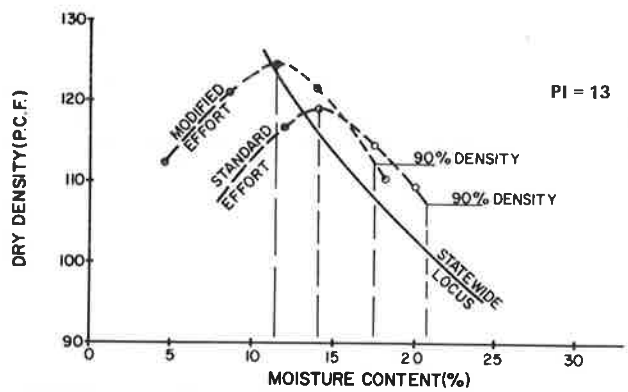


Figure 7. Moisture content versus shear strength: Genesee Expressway till.

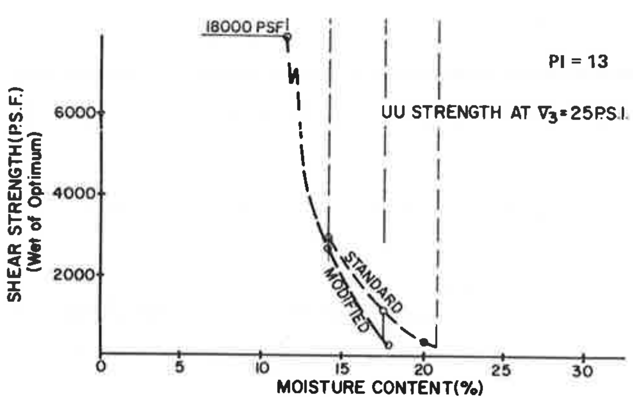


Figure 8. Moisture content versus dry density: St. Croix clay.

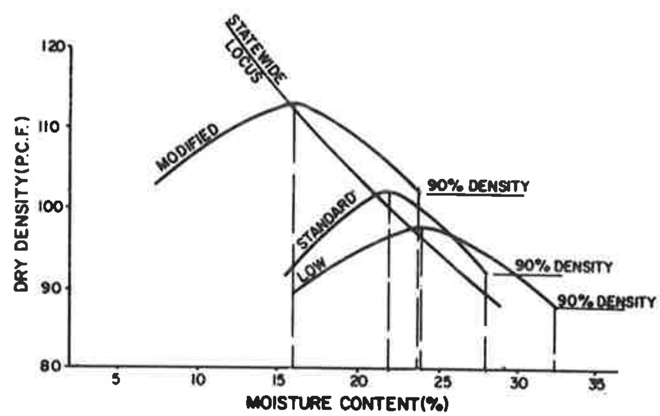
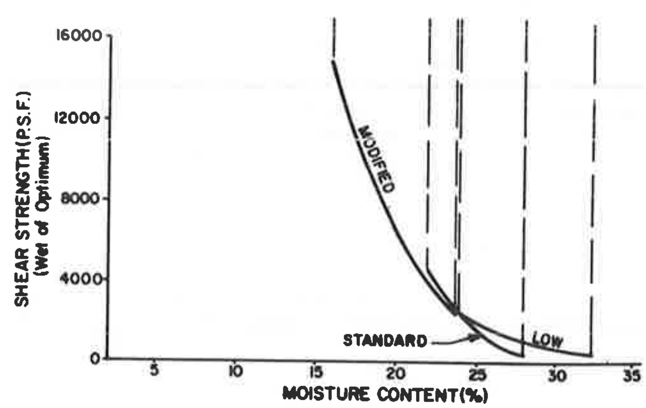


Figure 9. Moisture content versus shear strength: St. Croix clay.



below optimum moisture contents. To be on the safe side for all conditions, these soils should not be compacted at greater than standard optimum moisture content.

The above comments are based on properties of plastic soil in their final states in an embankment. Compaction of an embankment to between 2 and 4 percent over standard optimum moisture content would require the use of light equipment. An embankment could be compacted with heavy equipment and subsequently become over optimum relative to the standard effort with precipitation. However, if the embankment surface becomes too wet it is either removed or allowed to dry back and be recompacted prior to placement of subsequent lifts. Initially placing an embankment below standard optimum moisture content could become a problem by using heavy vibratory equipment. This equipment could draw moisture from lower lifts into the lift being compacted and cause it to become over optimum. However, this and other similar conditions are usually rectified during construction.

Figure 10. Moisture content over optimum versus PI: standard compactive effort.

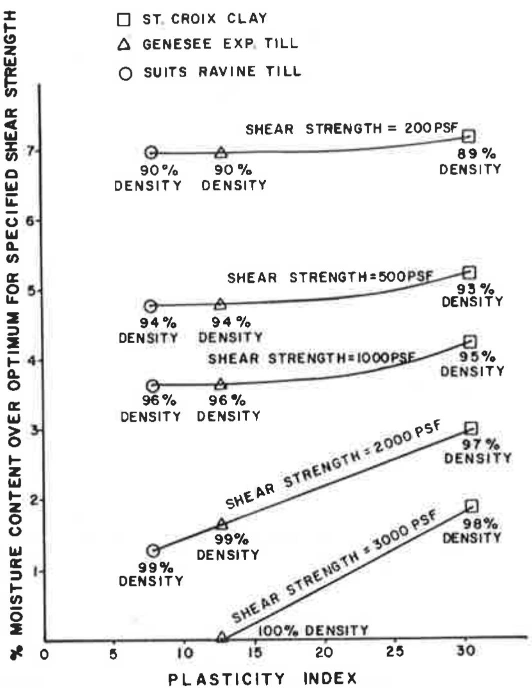


Figure 12. Shear strength versus fill height.

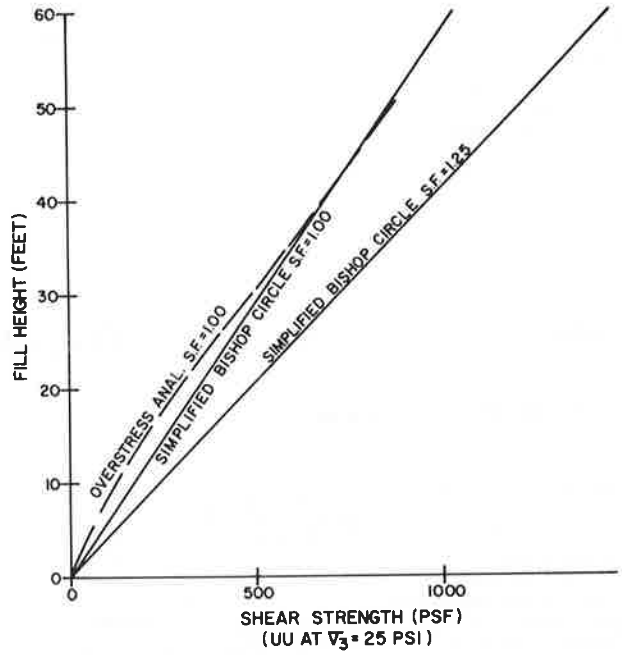


Figure 11. Shear strength versus percentage of standard density.

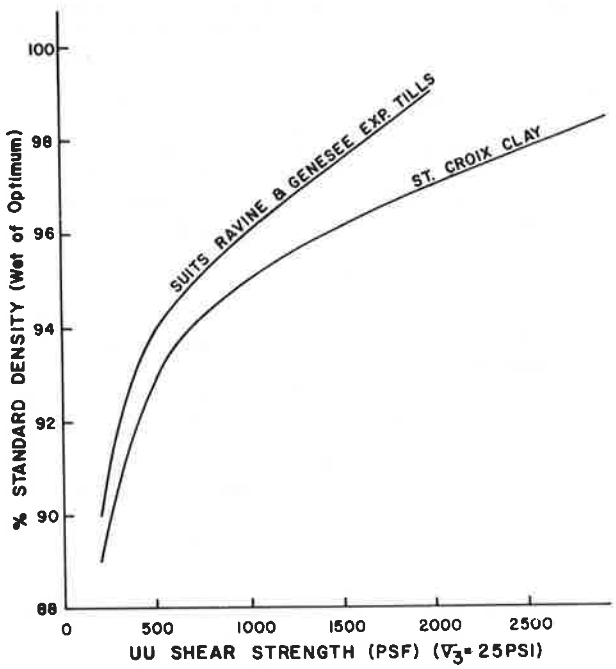
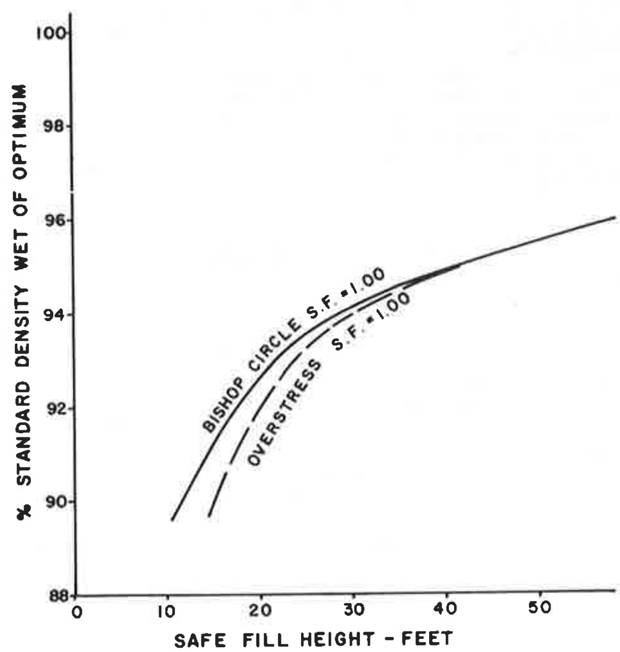


Figure 13. Safe fill height versus percentage of standard density: Suits Ravine and Genesee Expressway tills.



CONCLUSIONS

Moisture content over optimum has more of an influence on shear strength than does the actual compaction effort (Figures 6 and 7). An increase in the compaction effort at a constant moisture content over optimum decreases the undrained shear strength (Figures 6 and 7). Both the shear strength increase and percentage of moisture content over optimum decrease are sensitive to small changes in percentage of standard dry density greater than optimum moisture content (Figure 10).

Plastic embankment fills placed over optimum at standard effort should be compacted to at least 95 percent standard Proctor to ensure stable fill placements up to 40 ft high. Greater percentage densities will be necessary for fills that exceed this height. This was found to be true of plastic soils that have PIs in excess of 8 percent. Additional investigation is required to determine whether this is a problem for the lower PI soils.

In reality, with the use of heavier-than-standard field compaction equipment the stable degree of compaction for plastic embankment fills is at least 98 percent of standard density at greater than optimum moisture contents or 90 percent of standard density below optimum moisture contents. To be on the safe side for all conditions of compactive effort and fill heights, these soils should not be compacted at greater than standard optimum moisture contents.

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Compaction Effects of Oscillating Rollers

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Studies of vibratory compaction with smooth-drum rollers have indicated that the amount of compaction is highly dependent on two parameters: the magnitude of the vertical oscillatory displacement of the drum and the number of oscillations per unit of distance of travel. Model tests with small-scale rollers were carried out in the laboratory to study the effects of these parameters on the amount of compaction. The roller had a 12-in diameter. Applied compaction forces and soil layer thicknesses were scaled down appropriately. The frequency of oscillation was reduced to eliminate the vibration effects but maintain the number of oscillations per unit of distance of travel within the range representative of full-size rollers. The mean and oscillatory components of the force applied to the soil were varied as well as the number of passes and the number of oscillations per unit of distance. The test soils were a coarse- to medium-graded silica sand and a fine clayey sand prepared with several initial density states. The results of the tests showed the relations of the test variables to the amount of compaction and to the soil stiffness and the internal damping. The stiffness and damping observations were valuable in explaining the soil-machine interaction of full-scale vibratory rollers and led to the development of an analytical model for predicting the magnitude of drum oscillation during vibration. The paper describes these model tests and presents the experimental results. The implications of the results in compacting soil with vibratory rollers are also discussed.

Some basic concepts relating to vibratory roller behavior have been presented elsewhere (1). The reference suggested that

1. One of the major mechanisms of compaction with such rollers was volumetric strain caused by the cyclic nature of the loading;
2. Key parameters that control the amount of compaction include the number of drum oscillations per unit of travel distance (equal to vibration frequency divided by travel speed) and the amplitude of drum displacement during vibration;
3. Drum displacement is a function of the dynamic soil-roller interaction, which may be modeled as a mechanical system of masses, springs, and damping elements; and
4. Soil stiffness and damping characteristics relevant to a moving roller are quite different from those that would be measured in any soil property test.

The dynamics of the soil-roller system have also been described in detail (2). The interaction between the soil and machine parameters was shown and the influence of these parameters on the magnitude of drum displacement was illustrated.

This paper uses model roller tests to investigate the relation between the amount of compaction and the controlling parameters, which are oscillations per unit of distance and drum displacement. The effects of the test parameters on soil stiffness and internal damping for a moving roller are also shown.

The test apparatus consisted of a moving soil box, with a vertically oscillated roller in which the forces, motions, forward speed, and oscillation frequency could be controlled and measured. The roller model was approximately 1/5 scale, and the compaction forces were scaled down appropriately.

PRELIMINARY LABORATORY TESTS

A preliminary series of laboratory tests was carried out to illustrate the stress-strain relation of soils associated with vibratory compaction so that it can be properly used in the analytical model. Another reason for the tests was to postulate a possible way to relate the calculated motions from the analytical model to the amount of compaction so that the analytical results become meaningful for prediction of compaction.

The roller was modeled by a 12-in diameter drum positioned over a moving box of soil. The drum was raised and lowered at a prescribed deformation rate during horizontal sliding of the soil box to simulate sinusoidal drum motion with the desired amplitude and wave length. The vertical contact force