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

ERNEST T. SELIG AND TAI-SUNG YOO

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.

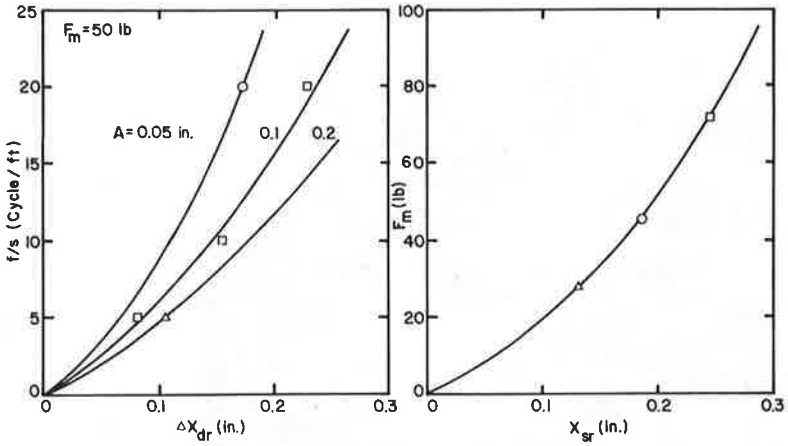
The test apparatus consisted of a moving soil box, with a vertically oscillated roller in which the forces, motions, forward speed, and oscillation frequency could be controlled and measured. The roller model was approximately 1/5 scale, and the compaction forces were scaled down appropriately.

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

Figure 1. Separation of soil deformation into components during preliminary laboratory tests on kaolin clay.



(a) Deformation increase due to oscillation

(b) Deformation during static rolling

between the soil and the drum was measured by using a proving ring. The vertical soil deformation was determined by calculating the average of the readings of two deflection dial gauges located on the ends of the drum axle.

Two different types of soils were used. One was a coarse- to medium-graded silica sand and the other was a kaolin clay. These soils were mixed with a nonvolatile plasticizer liquid instead of water to maintain constant moisture during repeated tests. The liquid contents of the silica sand and kaolin clay were 6.8 and 38.0 percent by weight, respectively. The clay-plasticizer combination had a liquid limit of 61 percent and a plasticity index of 14 percent. More information on the properties of these materials is given elsewhere (3).

At the start of each test, one of these soils was placed loosely in the test box. The resulting densities were 86 lb/ft^3 for the silica sand and 75 lb/ft^3 for the kaolin clay. A typical test began with the lowering of the roller into the prepared soil bed at a constant rate of deformation while the soil box was moved at a constant speed. The speeds of roller and soil box motions were kept low (on the order of 0.1 to 0.6 in/min) so that the response of the roller during the above sequence was considered to be in static equilibrium at all times. After the desired peak deformation was reached, oscillatory deformation of a desired amplitude was superimposed while the constant rolling motion was maintained. The oscillation frequency was on the order of 0.05 cycles/min so that vibration effects were not present. In comparison tests, oscillatory loads were applied with zero travel speed, so that the roller remained at a fixed soil location.

The results showed that a much smaller drum load was needed to produce a given deformation during rolling than when stationary. Also, oscillations during rolling produced closed load-deformation loops with no progressive permanent settlement into the soil. In contrast, oscillations without rolling showed increased permanent settlement with each repeated cycle of loading.

These tests also showed that the superimposing of oscillation causes greater settlement of the drum during rolling than when rolling occurs under a constant load, as in static compaction. This response is similar to the behavior of soil under cyclic shear strain.

Silver and Seed (4) studied the densification characteristics of dry sands in terms of repeated shear strain as part of research on ground surface subsistence induced by seismic loadings. The simple shear tests they conducted indicated that cyclic shear strains deformed the sample and allowed the soil particles to move into a denser packing. They further demonstrated that the vertical strain due to compaction was only dependent on the shear strain amplitude, not the vertical stresses, especially when the shear strains exceed 0.05 percent. Vertical settlement due to compaction was a logarithmic function of number of cycles, but most of the change occurred during the first 10 cycles.

Based on the test results mentioned previously, Youd (5) developed an analytical expression that related the shear strain to the amount of compaction of granular materials, assuming that the shear strain is the primary factor in controlling compaction. He hypothesized that a sequence of small to moderately sized strain pulses would produce a finite density increase through the contraction-expansion sequence with continuous cycles, since contraction predominates at those strain amplitudes. Examples of the compaction prediction were presented by using the void ratio-shear strain relation obtained in the laboratory and simple analytical method of estimating shear strain under a given load.

The model tests suggested that the total settlement (x_{dr}) might be divided into a static component (x_{sr}), which represents the compaction solely due to the dead weight of rolling compactor without oscillatory motion, and a dynamic component (Δx_{dr}), which represents the compaction increase due to the superimposed oscillatory dynamic force.

The compaction results for the tests in kaolin clay are shown in Figure 1 divided into the analogous static and dynamic components. As the mean roller load (F_m) increases, the deformation from compaction increases, but at a decreasing rate (Figure 1b). For a constant mean load of 50 lb, the component of compaction from oscillation increases with an increase in the number of cycles per unit of distance of roller travel [equal to ratio of oscillation frequency (f) to travel speed (s)] and an increase in peak-to-peak oscillation amplitude (A).

MAIN SERIES OF LABORATORY MODEL TESTS

Based on the findings of the preliminary model tests, improved apparatus was developed to permit a more extensive evaluation of the effects of the test parameters. The main emphasis was directed toward the variation of the loading conditions, as represented by (a) the mean or static component of vertical force (F_m) applied to the roller, (b) the amplitude of the superimposed oscillatory force (F_d), and (c) the number of loadings per unit of distance represented by the frequency speed ratio

Figure 2. Model roller in moving soil box for main test series.

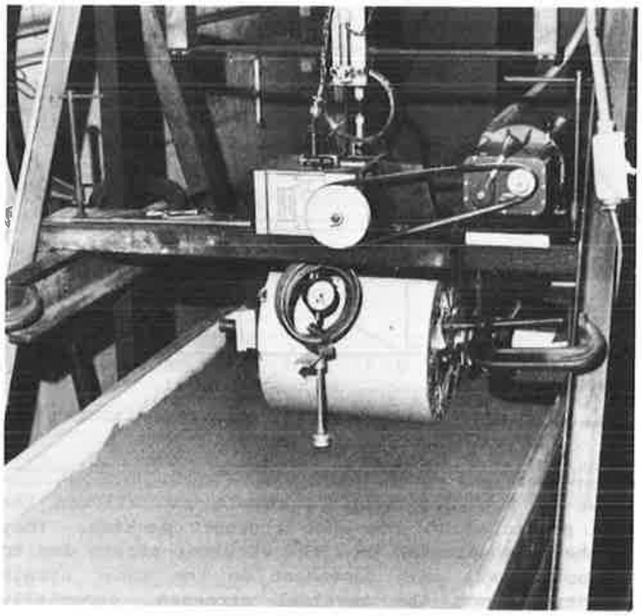
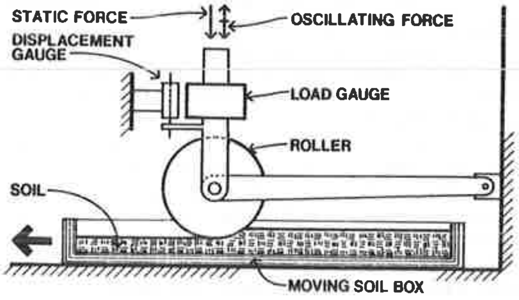


Figure 3. Diagram of model test apparatus.



(f/s). Two different soils were used in the tests, but primarily with one initial lift thickness and one initial density. Some tests were conducted at other initial densities and layer thicknesses and, in many tests, measurements were made with more than one roller pass to observe the effect of changing soil conditions caused by compaction.

Apparatus

The facility (Figure 2) constructed for these tests had controlled vertical force instead of controlled deformation, as in the preliminary tests. The fundamental components are shown in Figure 3 and are as follows:

1. Moving soil box,
2. Small-scale roller,
3. Reaction frame,
4. Servo-controlled hydraulic load cylinder,
5. Force and displacement sensors,
6. Hydraulic power supply, and
7. Instrumentation for controls and measurements.

The roller was approximately a 1/5-scale model of typical full-scale vibratory rollers. The other parameters, such as the applied forces and soil layer thickness, were scaled down appropriately. The mean vertical force, the amplitude and frequency of the oscillating force, and the forward speed of soil box movement could be controlled independently. The instrumentation was capable of measuring the static and dynamic components of the vertical force as well as sinkage of the roller as a function of time.

The roller was made of 12-in diameter plywood discs bonded together to provide a 12-in width. It had a relatively light weight (about 30 lb) to minimize the inertial resistance of the roller that may develop at the higher operating frequencies. This was important because the force applied to the roller was used as a measure of the force applied to the soil.

The soil box, which was 2-ft wide, 6-ft long, and 6-in deep, was built to contain and to move the test soil sample. The box was chain-driven on supporting guide rails by an electric motor, and its speed was varied by using different combinations of sprocket teeth. The speed range provided with such combinations was 1.1 to 0.3 in/s.

Two different soils were used in the tests. One was the silica sand plasticizer mixture used in the preliminary laboratory tests. The other was a clayey sand, composed of 94 percent medium to fine sand and 6 percent kaolin clay. The nonvolatile plasticizer liquid was used to provide the moisture. Compaction tests were performed by using ASTM D698 procedures (AASHTO T99). Optimum moisture content was about 10 percent by weight, and maximum dry density was about 122 lb/ft^3. The dry side of optimum was thought to be the most desirable for the tests because the soil yields a higher strength and sustains a greater compaction effort on the dry side of optimum moisture than on the wet side. Thus, the test soil was prepared at a moisture content of 7 percent.

Experimental Procedures

The placement of the soils in the test box was achieved by allowing the material to fall from a wide shovel being shaken gently while maintaining about a 6-in falling distance. Pouring was continued until a uniform layer approximately 1/4-1/2 in thicker than the desired bed thickness had been placed. Then the uneven soil surface was gradually and carefully shaved to make it flat and smooth. The resulting initial layer thickness was normally 2 in.

After preparation of each test bed, several in situ density measurements were made to check uniformity. The results indicated that the initial soil conditions were reasonably uniform within a test bed and from one test bed to another. The average values of initial loose wet density for the silica sand and clayey sand layers prepared by this method were 86 and 84 lb/ft^3, respectively.

When a denser test bed was desired, the loose layer prepared as above was precompacted with the model roller under a prescribed constant vertical force. Then the compacted surface was again leveled off with a multitoothed scarifier to provide the desired thickness. An average wet density of 95 lb/ft^3 was obtained with the clayey sand mixture when a loose layer was rolled five times under a vertical force of 25 lb.

Both single-coverage and multiple-coverage tests were conducted. The single-coverage test consisted of applying only one roller pass to the test bed under the selected conditions of mean force, amplitude and frequency of oscillating force, and roller speed. These tests were conducted so that general relations among roller sinkage, final density, and soil characteristic changes could be developed for the same initial soil conditions. The multiple-coverage test involved repetition of the rolling tests on the same bed to extend the relations developed during the single-coverage tests and to simulate successive roller passes in the field.

The normal sequence of steps for the single-coverage test was as follows:

1. Apply a prescribed vertical force to the roller while the soil box is stationary and allow the roller to settle into the soil,
2. Move the box at a constant speed to simulate drum rolling until an equilibrium sinkage is reached at the given constant vertical force, and
3. Add the desired vertical oscillating force while maintaining the same mean force and rolling speed, and continue rolling to reach another equilibrium condition.

This procedure provided information on three different characteristic phenomena:

1. Stationary load-penetration relations of the roller,
2. Compaction under constant vertical forces as in static roller compaction, and
3. Compaction caused by drum oscillation.

Test procedures for the multiple-coverage case were the same as those for the single-coverage test, except that the oscillating force was applied when rolling was initiated.

The principal measurements taken throughout each test were the vertical load and roller sinkage. These were monitored as a function of time on a strip-chart recorder, and load was plotted as a function of sinkage on an x-y recorder. In addition, data on in situ density and soil strength for various conditions were accumulated during the single-coverage tests.

LOAD-DISPLACEMENT RELATIONS

Figure 4 illustrates a sample chart recording during a single-coverage test. It illustrates the sequence of load-displacement relations for three different situations that take place during the entire period of a test. It clearly shows the three distinctive equilibrium states. As the vertical force was gradually increased to the selected mean value while the roller remained stationary, the deformation gradually grew to a value indicated by x_{ss}. Then, the initiation of rolling increased the deformation to another equilibrium value (x_{sr}) under the same mean vertical force. For all the tests on both soils, the ratio of x_{sr} to x_{ss} was about 1.4 to 1.6. Additional deformation was observed when oscillation of the vertical force was imposed. The final deformation value during oscillation (x_{dr}) was taken as the mean of the motion whose peak-to-peak amplitude was defined as A. All of the three equilibrium displacements were constant over a sufficient period of time to indicate that they were not transient values. The deformation increase due to oscillation (Δx_{dr}) equals $x_{dr} - x_{sr}$.

To show that the deformations x_{sr} and x_{dr} represent compaction, penetration tests were performed before and after rolling by using a 1-in^2 flat circular bearing plate, shown in Figure 2. Typical results indicate an increase in bearing resistance by a factor of 3.5 from rolling without oscillation compared with the initial uncompacted state, and an increase by a factor of 7 from rolling with oscillation compared with the uncompacted state. This confirms the effectiveness of oscillation in compacting soil.

Figure 5 illustrates the roller force plotted as a function of vertical deformation as measured by the x-y recorder. A well-defined, repeated, closed hysteretic loop was formed during oscillation after a few initial cycles. The soil stiffness during stationary penetration is the slope of the curve following initial sinkage. The corresponding stiffness during oscillation is the average slope of the steady state hysteresis loop. This stiffness represents the soil behavior as felt by the moving roller. The stationary soil elements, in contrast, experience large plastic deformation represented by x_{dr}, which is essentially unrecovered after the roller passes. Hence, x_{dr} is a measure of the soil compaction.

A typical x-y recording during the multiple-coverage tests is shown in Figure 6. By controlling the recorder pen, only one cycle of the equilibrized loop was recorded for each roller pass, so that comparison of the change in deformation during each pass was possible. As expected, Figure 6 shows that the deformation (compaction) increment for each pass decreased with each additional roller pass. Simultaneously, the stiffness during oscillation increased and the hysteretic damping decreased.

Because changing soil stiffness that results from compaction can cause a change in the dynamic force applied by a vibratory roller, two tests were performed in which the oscillatory force was changed for each pass. Figure 7 represents a test with increasing oscillatory force for each roller pass, and Figure 8 is the counterpart for decreasing force. In both cases, the mean force was maintained constant at about the same value as in the constant force amplitude test. Clearly, the changes in stiffness and damping are different for these cases.

COMPACTION DEFORMATION

The component of compaction caused by rolling without oscillation (static component) is shown in Figure 9 for dense clayey sand and for loose silica sand in terms of soil deformation (x_{sr}). As expected, the amount of compaction increases at a decreasing rate with increasing compaction force.

The additional component of compaction caused by the oscillation is shown in Figures 10-12 in terms of the deformation increment (Δx_{dr}) for three soil conditions. The oscillation is represented by the peak-to-peak vertical displacement amplitude (A) rather than by the oscillatory force (F_d) for two reasons: (a) previous research has indicated that cyclic strain is a better measure of expected compaction than cyclic stress and (b) oscillation amplitude can be easily measured on vibratory compactors, whereas the dynamic force applied to the soil cannot be determined easily.

For the initially loose soils (Figures 10 and 11), the dynamic component of compaction (Δx_{dr}) increases at a decreasing rate with increasing oscillation amplitude (A) and with the number of oscillations per unit travel (f/s). For the initially compacted clayey sand (Figure 12), Δx_{dr} increased linearly with A, but increased at a decreasing rate with f/s. Although the value of mean force (F_m) is expected to affect the magnitude of Δx_{dr} obtained for any f/s and A, within the range of conditions tested this effect was not a major one.

MULTIPLE PASS COMPACTION

The effect of number of roller passes on the amount of compaction produced by rolling without oscillation is shown in Figure 13. Compaction is represented by the percentage of soil layer compression, which is equal to the soil deformation divided by the initial layer thickness. The percentage of

Figure 4. Force and deformation relation from strip chart recording during test.

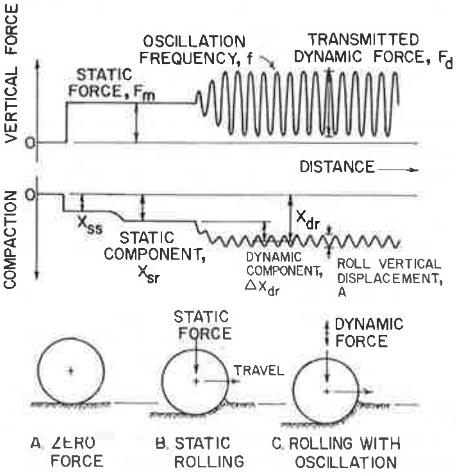


Figure 5. Roller force compared with soil compression as observed by X-Y recorder.

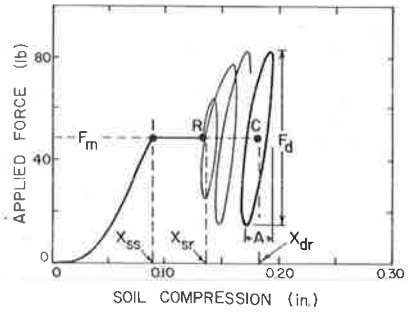
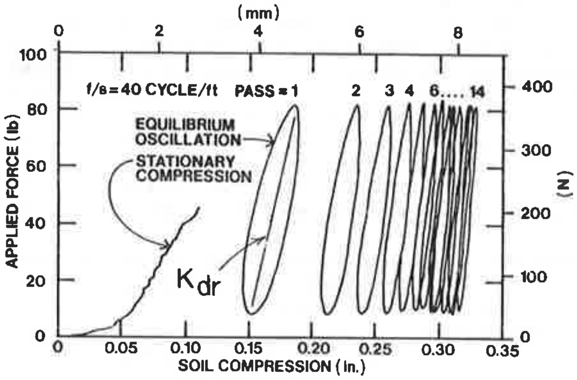


Figure 6. Oscillatory force-compression relation for repeated passes of constant force amplitude.



density change is approximately the same in magnitude as the percentage of compression. The compaction growth curves in Figure 13 are characteristic of those observed in the field (6).

The effect on the compaction growth curves of adding oscillation is illustrated in Figure 14. Two passes without oscillation were made first, followed by repeated passes with a constant oscillatory force (F_d) and a constant f/s ratio. The addition of oscillation not only increased the compaction for any number of passes but also increased the rate of compaction compared with the results with no oscillation.

Figure 7. Oscillatory force-compression relation for repeated passes of increasing force amplitude.

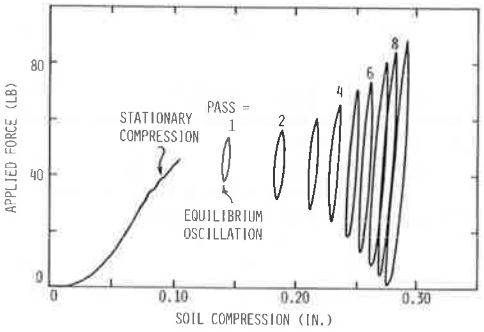
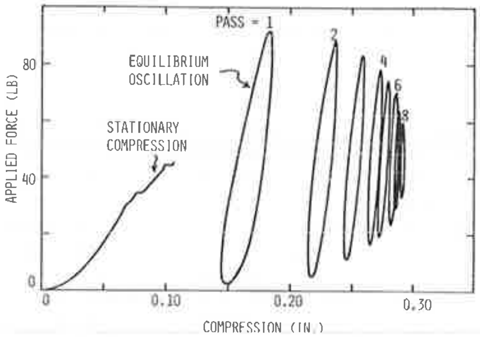


Figure 8. Oscillatory force-compression relation for repeated passes of decreasing force amplitude.



The compaction growth curves for the cases of constant F_d (Figure 6), increasing F_d (Figure 7), and decreasing F_d (Figure 8) after each pass are compared in Figure 15. The decreasing F_d case, which had the highest F_d initially, had the highest rate of compaction growth for the first four passes, but only a small increase after that. The constant F_d case, which had a lower F_d than the decreasing F_d case initially but a higher average over 9 passes, showed a smaller amount of compaction, but compaction continued to increase up to 12 passes, when it then equalled that from the decreasing F_d case. The increasing F_d case had about the same average F_d over 9 passes as did the decreasing F_d case but much lower values for the first 4 passes. The amount of compaction achieved remained well below that of the other two cases for the entire test. The results in Figure 15 indicate that the amount of compactive effort applied during the first few passes is a primary factor in determining the total amount of compaction that will be achieved after a reasonable number of passes, such as 8.

STIFFNESS AND DAMPING CHARACTERISTICS

The average soil stiffness as felt by the moving roller is the slope (k_{dr}) of the line that connects the maximum and minimum points on the force-deformation hysteresis loops, as shown in Figure 6. Soil stiffness was observed to decrease with increasing F_d, decreasing f/s, and decreasing F_m (Figure 16).

The hysteretic damping felt by the moving roller was represented by the area within the hysteresis loops, which is expressed as foot-pounds per cycle of oscillation. This damping factor (c) was observed to increase with increasing F_d and decreasing f/s (Figure 17). The magnitude of F_m did not appear to influence the damping.

The stiffness changes observed in the multiple-pass tests are shown in Figure 18. For constant F_d, the stiffness increased each pass in a manner similar to the compaction growth. For the decreasing F_d case, the stiffness increased rapidly with each pass. For the increasing F_d case, the stiffness only increased for the first three passes, after which the stiffness remained constant for three passes and then decreased for the remaining passes. For this case, the tendency for increased stiffness from compaction was offset by the tendency for decreased stiffness from the F_d increase.

Accumulation of roller passes under a constant dynamic force produced a decrease in damping and displacement amplitude with each successive cycle. For the case of decreasing F_d, both parameters decreased much more rapidly. In contrast, the case of increasing F_d caused a gradual increase in both damping and displacement.

The trade-off between the effects of stiffness and damping increases suggests the possibility that

Figure 9. Compaction produced from rolling without oscillation.

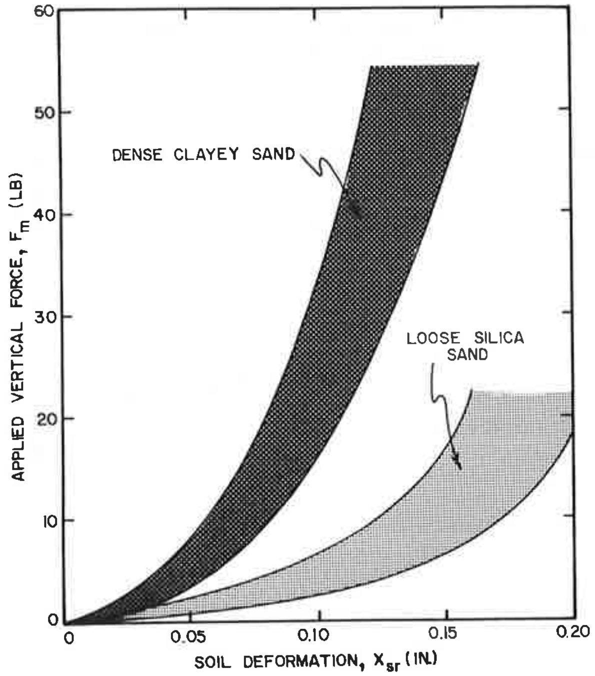


Figure 10. Roller sinkage increase due to oscillation for loose silica sand.

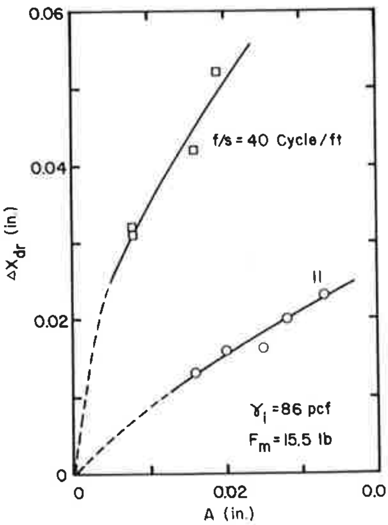


Figure 11. Roller sinkage increase due to oscillation for loose clayey sand.

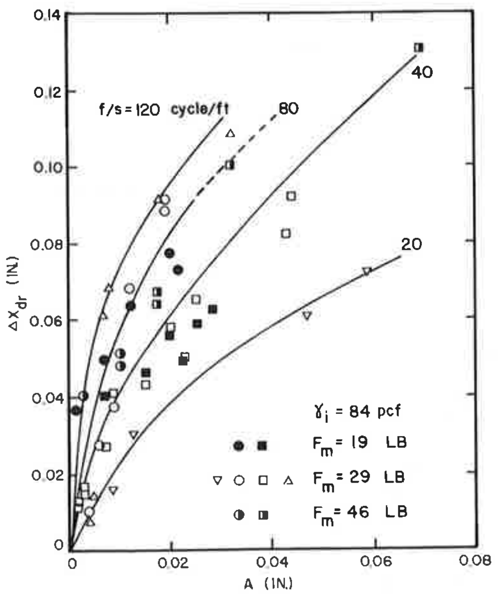


Figure 12. Roller sinkage increase due to oscillation for dense clayey sand.

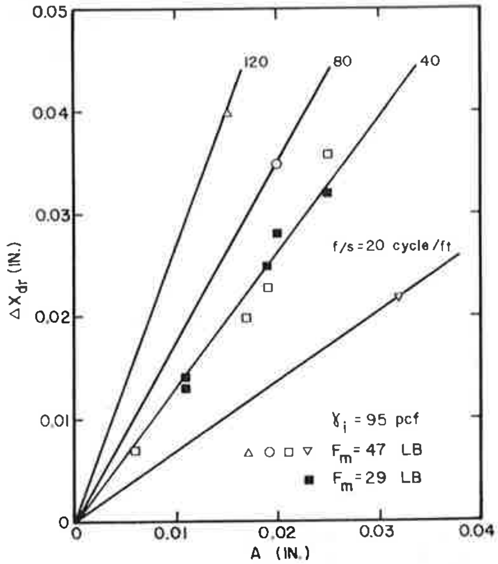
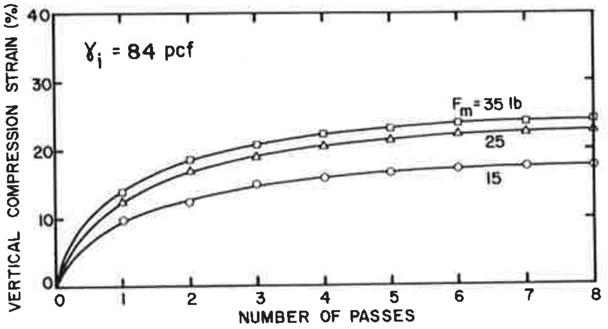
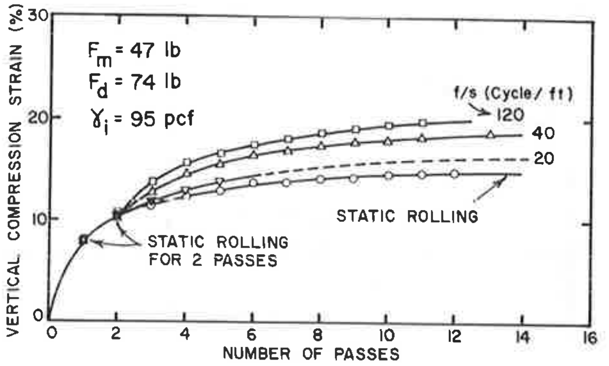


Figure 13. Compaction growth curves during rolling without oscillation under various vertical mean forces in loose clayey sand.



the amplitude could either remain constant, decrease, or increase with additional passes of a vibratory roller, depending on which effect is greater. When the trade-off is about the same, the amplitude would remain constant, which is what many investigators have observed in the field (7-10).

Figure 14. Influence of oscillation on compaction growth curves for dense clayey sand.



However, when effects of the stiffness are predominant compared with the damping effect, the amplitude would increase. The reverse trend would also be true when the damping effects play the major role.

CONCLUSIONS

Small-scale model roller tests were performed in the laboratory with the cyclic force applied to the soil at low enough frequencies to avoid dynamic effects such as soil particle vibration and wave propagation. These tests showed that the amount of compaction can be represented by a static component that is a function of the static roller weight and a dynamic component that is a function of the vibration frequency to travel speed ratio and the magnitude of drum vertical displacement during oscillation. The repeated strain caused by the drum vertical oscillation appears to be one of the principal causes of the compaction with vibratory rollers. Other suggested mechanisms such as impact, particle acceleration, and strength reduction during vibration are not required in order to achieve compaction.

Stiffness and damping behavior for the soil associated with the moving and oscillating roller are quite different from the behavior during stationary

Figure 15. Comparison of soil strain growth curves for various oscillatory force trends in dense clayey sand.

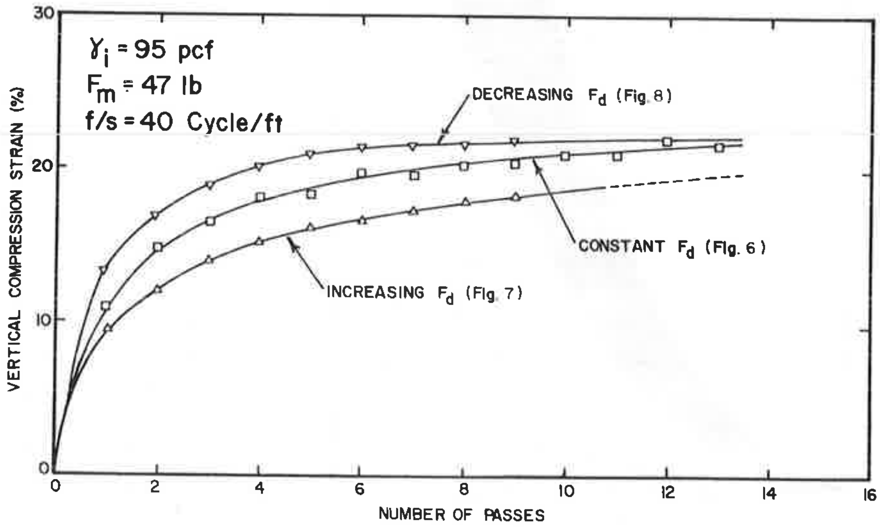


Figure 16. Variation of soil stiffness during oscillation under different mean forces in loose clayey sand.

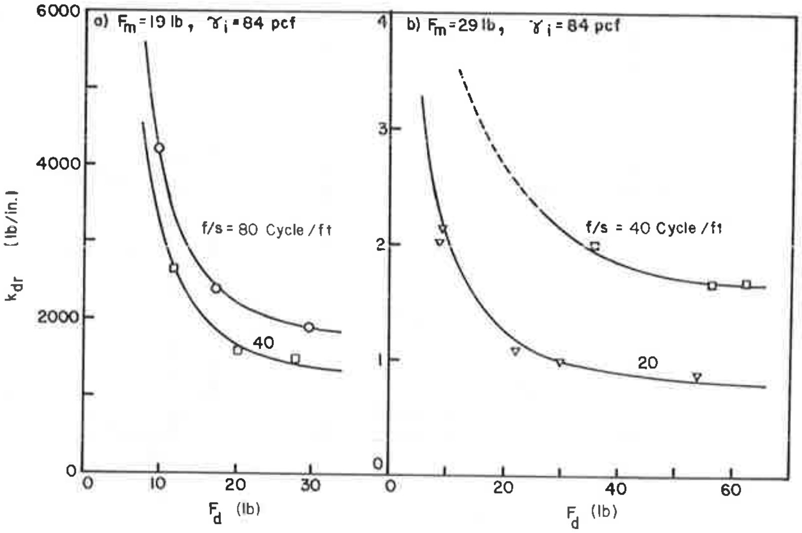


Figure 17. Soil hysteresis damping loss during oscillation in dense clayey sand.

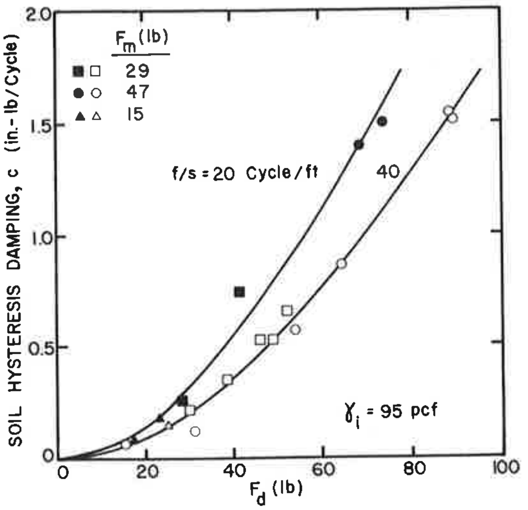
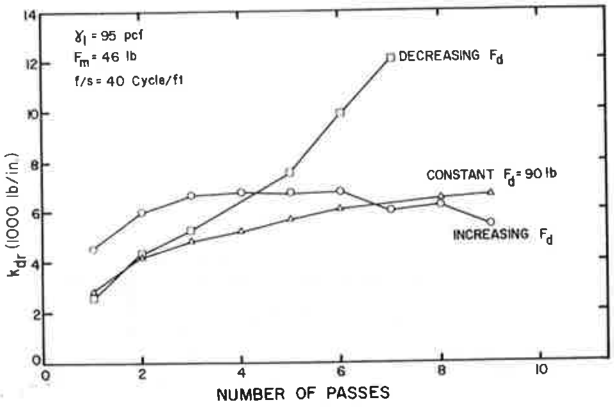


Figure 18. Variation of soil stiffness during oscillation with number of passes under different dynamic loading conditions in dense clayey sand.



soil loading. Although the soil behaves as a plastic material during compaction, it appears to the moving roller to be elastic and exhibits no permanent strain. The stiffness and damping properties cannot be measured directly with any of the common methods such as the field plate load test and the laboratory triaxial test. Thus, the soil properties used in dynamic roller analysis must be derived indirectly from measurements with a moving roller.

ACKNOWLEDGMENT

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