INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Fundamentals of Vibratory Roller Behavior

Fondements du Comportement du Rouleau Compresseur Vibratoire

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SYNOPSIS The mechanisms by which vibratory smooth-drum rollers achieve compaction are examined and the factors which influence the results are presented. The conclusions are based on a mathematical model representing the dynamic response of the soil-machine system, laboratory model roller tests investigating the relationship between the amount of compaction and the parameters of the roller and the soil, and full-scale field tests for confirmation of the theories. The research showed that the amount of compaction with a vibratory roller could be subdivided into two components, one related to the static ground contact force per unit width of roller, and the other to the amplitude of drum vibratory displacement and the ratio of vibration frequency to travel speed. The dynamic mechanism causing compaction is best described as the accumulation of residual strain produced by cyclic soil straining as a result of drum oscillation. The research results have explained many of the past contradictory observations concerning the effectiveness of vibratory rollers.

INTRODUCTION

Vibration has been increasingly employed as a means of compacting layers of soil over the past 25 years. At one time vibration was thought to be effective only for compacting granular materials like sands and gravels having little binder. However, more recent experience has clearly demonstrated that vibratory rollers are also productive on many fine-grained soils containing clay and on materials like asphaltic concrete.

Compaction with vibratory rollers is probably the least understood of all methods. Uncertainty and contradictory opinions exist concerning what frequency should be used for a given material, whether light or heavy drums are better, the importance of roller travel speed, the significance of resonance, the relative contributions of the static machine weight and dynamic force, and in fact, even why vibration works. One of the reasons for the inadequate state of understanding is that field and laboratory research in the past have tended to focus on either the machine or the soil, but not both, in spite of the fact that it is the combined characteristics of the machine and the soil which determine the amount of compaction.

The research described in this paper was conducted (Ref. 1) to help clarify the situation and to provide a unified theory for multiple-lift compaction of both cohesive and cohesionless materials with smooth-drum vibratory rollers. The research included field experiments with actual rollers as well as laboratory model roller tests and mathematical analysis.

The concepts presented apply to sands, gravels, clays and silty soils, to base course materials and to asphalt concrete. However, the theories are not intended to apply to dry, saturated or submerged, clean sands and gravels, or to saturated silts because these soil conditions involve significantly different mechanisms of vibratory compaction. Plate vibrators are not considered either, although similarities do exist between the action of vibratory rollers and plate vibrators.

VIBRATORY COMPACTION MECHANISMS

Four possible mechanisms for explaining the effect of vibration for compacting soils were deduced from a review of previous publications. These can be designated: particle vibration (Ref. 2), impact (Ref. 3), strength reduction (Ref. 4), and cyclic straining (Ref. 5).

The application of vibration to the ground will cause individual soil particles to vibrate. As they vibrate, the particles can rearrange into either a more compact state or a looser state, depending on conditions. However, a very small amount of cohesion between particles, even as little as provided by capillary moisture films in clean sands, can restrict or prevent this rearrangement. Thus, particle vibration is not believed to be important except for dry or submerged granular materials.

Impact requires that the compactor break contact with the ground surface during each cycle of vibration. Field tests showed that this usually only happens with vibratory smooth-drum rollers on already compacted material, or in the case of asphalt, when it has cooled. Impact appears to be much more common for plate vibrators than for vibratory rollers.

The possibility exists that the application of vibration can reduce the strength of the soil under some circumstances and hence make the soil easier to compact. However, research on the dynamic properties of soils has shown that those with cohesion will generally become stronger during the application of dynamic forces. Thus, strength reduction is not an adequate explanation for the effect of vibration.

The fourth mechanism, particle rearrangement from cyclic deformation of the soil produced by oscillation of the roll, provides the best explanation of why roller vibration causes compaction. This mechanism has been demonstrated to be effective in compaction of soil samples (Ref. 5); furthermore, it is always present, and it even works in materials with significant cohesion.

LABORATORY MODEL TESTS

To demonstrate this cyclic phenomenon, model tests were conducted in the laboratory on clayey sand to simulate a vibratory roller in the field. In these tests vibration frequency was reduced to less than 2 cycles per second to eliminate the dynamic effects related to particle vibration and strength reduction mechanisms. The vertical roll displacement was also controlled so that the roll was always in contact with the soil to eliminate impact. The soil was a moist clayey sand. The roller model was approximately 1/5 scale, and the compaction forces were scaled down appropriately.

The effect of the roll oscillation on compaction is illustrated by a typical strip chart recording shown in Fig. 1. The roll was initially suspended so that it just touched the uncompacted soil surface. In this position, the vertical force applied to the soil by the roll was zero and the compaction was zero (position A). The roll was then loaded to apply the desired static contact force to the soil and pulled at a constant speed without oscillation. The compaction achieved by the moving roll under the static vertical force is shown in position B. Finally, an oscillatory force was added to the static force to simulate the effect of a full scale roller when vibration is turned on. Additional compaction was achieved by this oscillatory force (position C) even though the average vertical contact force applied to the soil was still equal to the static force.

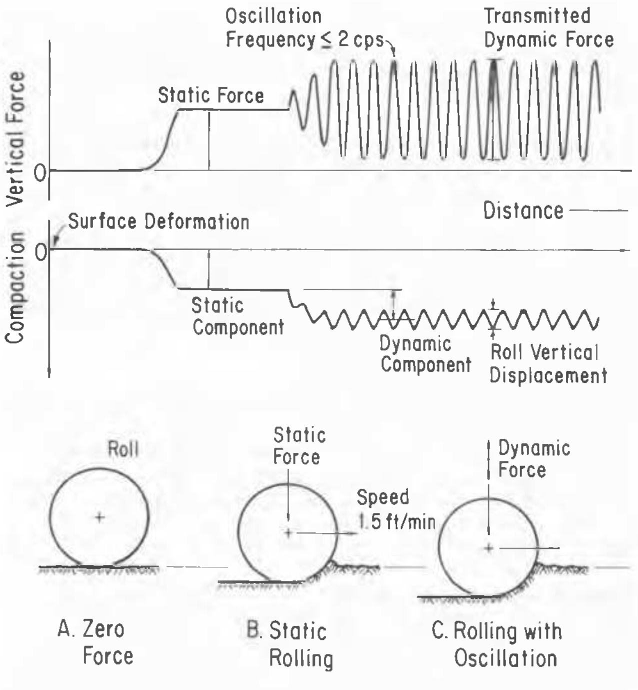


Fig. 1 Typical Model Test Results

The test results clearly showed that the superposition of oscillation significantly increased the amount of compaction, compared with that obtained without oscillation under identical conditions. It was also seen that the total compaction achieved under a vibratory roller could be represented by two components: one is the static component which would be produced by the roller when operated with no vibration, and the other is the dynamic component which corresponds to the additional compaction achieved when the vibration is turned on. Field density measurements showing these two components are given in Fig. 2.

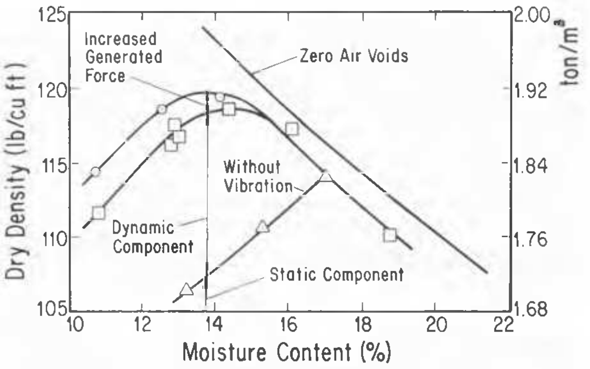


Fig. 2 Compaction Results on 12 in. Layers of Silty Sand with and without Vibration Using a 17000 lb Towed Vibratory Roller (From Ref. 6)

Such model tests were conducted for a range of oscillation frequency, travel speed, static vertical force and oscillating vertical displacement. The trends of the observed relationships for the static and dynamic components of compaction are summarized in Fig. 3.

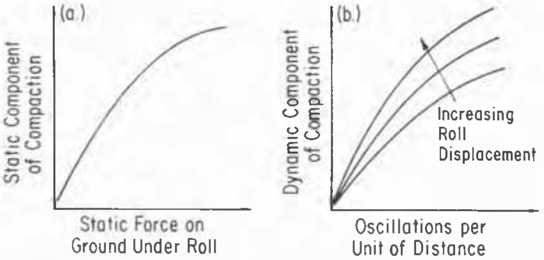


Fig. 3 Factors Affecting Static and Dynamic Components of Compaction

The amount of compaction accomplished by an actual vibratory roller in the field depends on many factors including roll weight, frame weight, roll suspension system, and generated dynamic force. However, the above test results suggest that the combined influence of these factors can be represented by the static ground contact force, oscillation per unit distance, and roll vertical displacement. Based on data from Ref. 7, Fig. 4 shows the expected correlation between compacted density and the factors controlling the dynamic component of compaction.

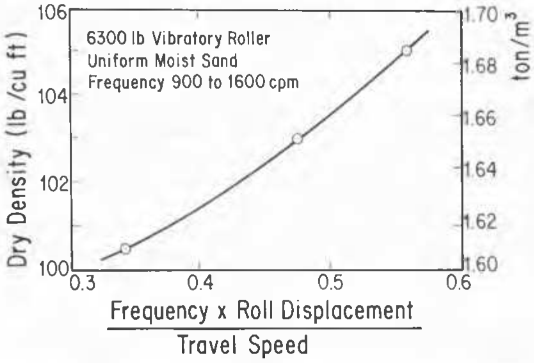
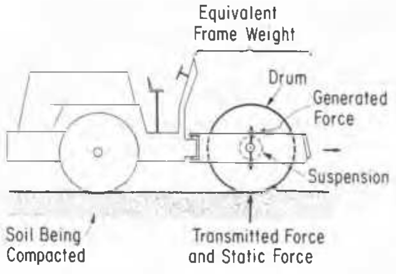


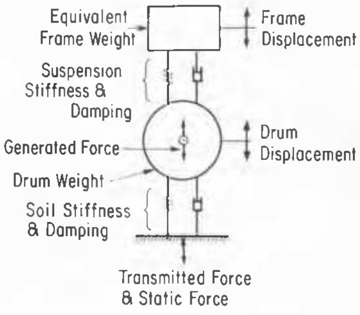
Fig. 4 Relationship of Compaction Results to Dynamic Compaction Parameter Computed from Data in Ref. 7

MATHEMATICAL MODEL

The static contact force and oscillations per unit of travel distance are easily determined and controlled. On the other hand, the roll vertical displacement is based on the dynamic response of the mechanical system consisting of the compactor and soil together. The simplest suitable representation is the linear, two-degree-of-freedom system shown in Fig. 5. The behavior of the mechanical system in Fig. 5b, derived mathematically from well-established vibration theory, is shown in Fig. 6. The effects of the model parameters on the roll vertical displacement determined from the solutions, are illustrated in Fig. 7.



a.) Vibratory Roller



b.) Equivalent Mechanical System

Fig. 5 Illustration of Compactor and Equivalent Mechanical System Model

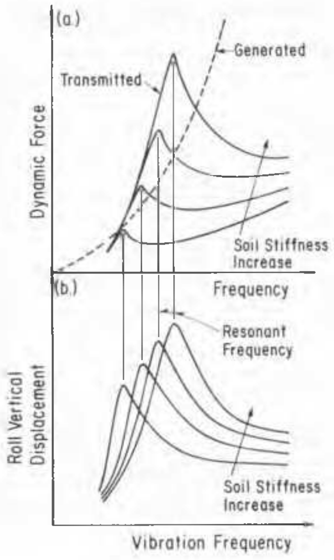


Fig. 6 Relationships Between Dynamic Forces, Displacement and Frequency for a Vibratory Roller

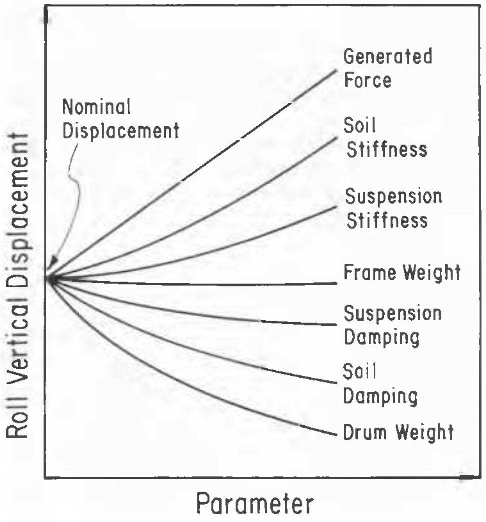


Fig. 7 Representative Effect of Compactor and Soil Parameters on Roll Vertical Displacement at Constant Operating Frequency above Resonance

Fig.7 trends represent a constant frequency, higher than resonance. In each example the values of all other parameters are held constant except the one being shown. An increase in the mass of the roll, the suspension system damping and the soil damping decreases the roll displacement. In contrast, an increase in suspension system stiffness, soil stiffness and generated dynamic force increases the roll displacement. Change in the frame mass has no effect as long as the suspension system stiffness is constant.

The full-scale experiments with actual vibratory rollers compacting soil under various conditions in the field verified the predicted trends. An example of field measurements is given in Fig. 8 for comparison with the mathematical results in Fig. 6.

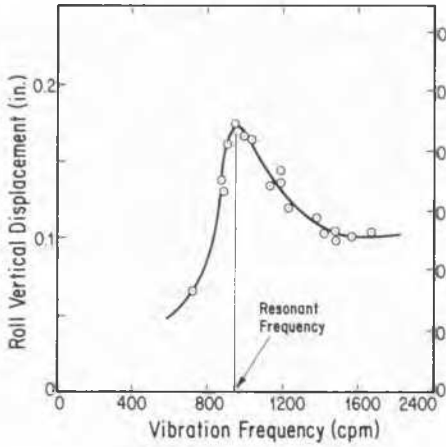


Fig. 8 Variation of Displacement with Frequency for a 20,000 lb Roller on 12 in. of Gravel and Sand Material

The discovery that a linear soil model works well for compaction, which obviously involves significant non-linear, inelastic soil behavior, was an important finding that led to an understanding of the mechanisms of vibratory compaction. The reason is explained by the roll vertical force-displacement relationships from the model tests in Fig. 9. When the roll is lowered onto the soil surface with a contact force F_s it compresses the soil by an amount X_s. During rolling without oscillation the soil compression under F_s is X_r (Position B in Fig. 1); with oscillation the net compression is X_d (Position C in Fig. 1). The closed loop represents the soil stiffness and damping felt by the roller, corresponding to the soil elements shown in Fig. 5b. The actual force-deformation behavior of the stationary soil undergoing compaction is obviously nonlinear and highly inelastic. However, because the roller is moving over the soil during oscillation the soil "appears" to the roller to have no inelastic characterics.

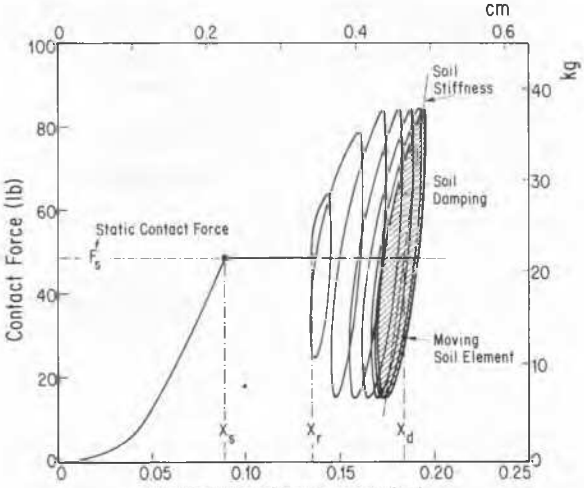


Fig. 9 Typical Vertical Dynamic Force-Displacement Relationship for Model Roller on Soil

The peaks on the curves in Fig. 6 are known as resonance peaks. The resonant frequency is the frequency at which the amplitude of motion is maximum. The present research shows that the values of resonant frequency are affected by the properties of both the soil and the machine. This conclusion is supported by the past experience shown in Fig. 10.

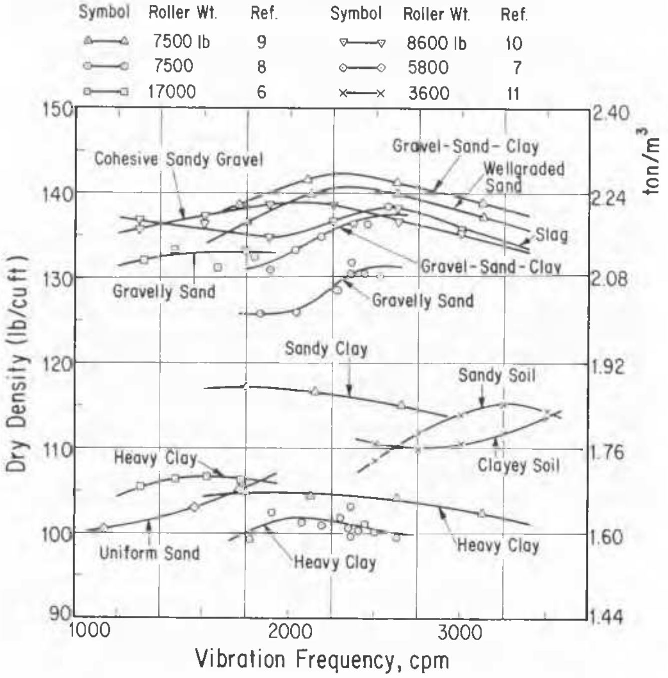


Fig. 10 Variation with Frequency of Compaction by Smooth-Drum Vibratory Rollers

Because roll motion will occur at any frequency, a dynamic contribution to compaction will occur at any frequency. The advantage of operating at the resonant frequency is increased efficiency of energy utilization and possibly increased productivity.

The generated dynamic force increases with the square of the frequency when a rotating eccentric mass is used as the vibration source. Even so, experience shows that increasing the operating frequency may result in either an increase, a decrease, or no change in the amount of compaction (Fig. 10). The mathematical relationship between generated dynamic force and roll vertical displacement shows that this is indeed possible depending on the frequency, soil conditions, and the design details of the compactor.

APPLICATION EXAMPLES

The following examples of actual compaction situations illustrate how the preceding concepts will explain some results observed in the field:

1. An increase in frequency above resonance may produce a decrease in compaction.

An increase in frequency above the resonant frequency will increase the generated dynamic force, but not the transmitted force. As shown in Fig. 11, the roll vertical displacement decreases from A_3 to A_2. This will cause a decrease in compaction produced by roll oscillation which is partially compensated by an increase in oscillations per unit of travel distance. Since static force remains unchanged, compaction produced by the static force will not change. The net effect of frequency increase in this example is to decrease the amount of compaction. Hence, if the operator is not getting enough compaction in this situation, he should decrease frequency to get better results.

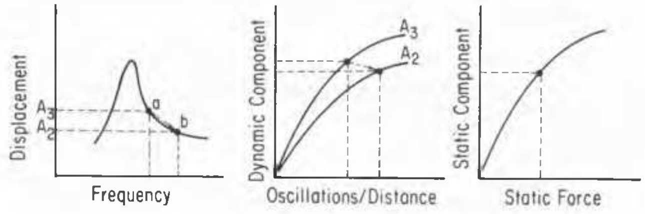


Fig. 11 Illustration of How Increasing Frequency Can Decrease Compaction

If, however, the frequency is far enough above resonance so that the roll vertical displacement does not change much with frequency, then the increase in the number of oscillations per distance from increasing frequency could more than compensate for the reduction in roll vertical displacement. The net effect would then be increased compaction with increasing frequency. When the operating frequency is below resonance, an increase in frequency will also increase compaction because both the roll vertical displacement and the oscillations per unit of travel will have been increased. The curves in Fig. 11 can also be used to show that effect of frequency can increase, decrease, or not change the density achieved.

2. As the number of roller coverages increases the compaction effort per coverage can increase.

Soil stiffness will be higher for each successive roller coverage because of the continuing increase in the amount of compaction that has already taken place. As is shown in Fig. 12, above the resonant frequency this will result in increasing roll vertical displacement for the same frequency, and hence, a greater dynamic component of compaction will be produced while the static component of compaction will be unchanged. In the case of asphaltic concrete compaction, stiffness can increase even more rapidly with each coverage because of the combined effect of compaction and cooling. This could result in system resonant frequency increasing to equal the operating frequency (Point c, Fig. 12). In such a situation, the roll may no longer remain in contact with the surface throughout each vibration cycle. Instead, the roll could impact the surface, a condition which could cause undesirable rippling in some situations.

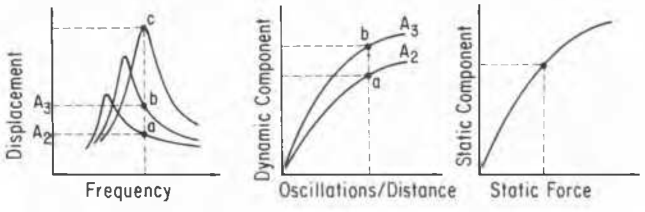


Fig. 12 Illustration of How Compaction Effort Can Increase with Increasing Roller Coverages

3. If roller speed is increased, compaction per pass will be decreased.

An increase in roller speed will not cause much change in soil stiffness. Therefore, roll vertical displacement will not be changed (Fig. 13). However, as the oscillations per unit distance decrease, the dynamic component of compaction from the oscillations will decrease. Because the static component of compaction will remain unchanged the total compaction achieved will decrease. Examples of this trend are shown in Fig. 14. In general, any increase in roller speed, when using vibratory compactors, will cause a decrease in the amount of compaction. To offset this decrease in compaction additional coverages will be required. The best productivity will be obtained at the slowest practical speed which normally ranges between 1 and 4 mph.

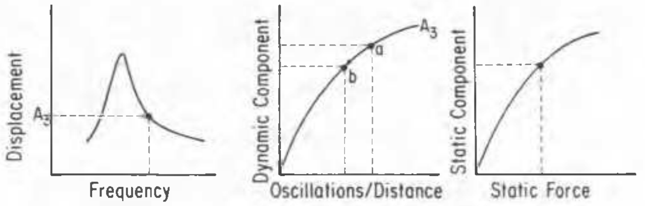


Fig. 13 Illustration of How Roller Speed Increase Can Decrease Amount of Compaction

SUMMARY

The basic principles governing compaction with vibratory rollers have been presented. The purpose is to provide a rational basis for selecting rollers and for determining the best operating conditions. The concepts can help explain many conflicting opinions resulting from an incomplete determination of the controlling factors in the past. Although many factors influence the amount of compaction which can be achieved with a vibratory roller, the research results indicate that their net effect can be simply represented by: 1.) the ratio of vibration frequency to travel speed (oscillations per unit of travel distance), 2.) the roll vertical displacement during oscillation, and 3.) the static contact force on the ground under the roll per unit of roll width. These factors should be recorded in each field operation to establish a proper correlation with compaction results.

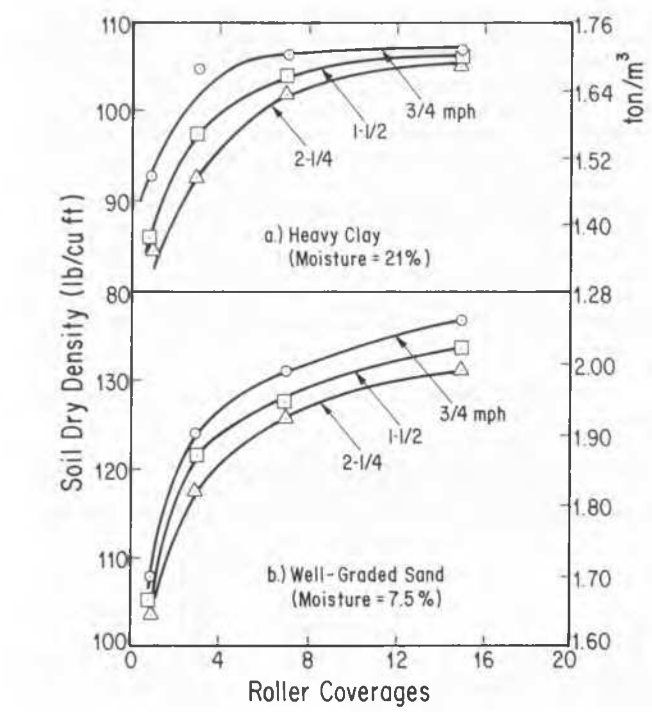


Fig. 14 Effect of Roller Travel Speed on Amount of Compaction with 17000 lb Towed Vibratory Roller (From Ref. 6)

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