Effect of Vibration on Soil Properties

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This study presents the response of various gradations of a clean, granular sand to vibratory pressures and motions. The research is based primarily on the assumption that subgrade settlement is attributable to a microseismic vibratory phenomenon caused by vehicular traffic vibration.

The effect of vibration on the settlement, density, and vibration pressure of soil was determined for various frequencies, amplitudes, moisture contents, and soil gradations. The results indicate that a relatively insignificant vibratory motion can cause a large volume change in granular soils.

The effect of vibration of soil on the amount of vibration pressure transmitted through the soil was investigated. The variation in the magnitude of the vibratory pressure of the granular soil indicated a critical frequency or resonance of the soil particles. Further tests indicated the independence of the critical frequency from the loading condition.

• A RECENT comprehensive report on the factors affecting the compaction of soils indicates that vibratory compactors may compact certain types of cohesionless soils to a much greater unit weight and in thicker lifts than heavier static rollers (8). Therefore, it is possible that some soils compacted to specification density by heavy static rollers during construction might, after the roadway is opened to traffic, settle due to the vibration of the lighter, but still quite heavy, dynamic truck loading. Additional settlement might also occur as a result of dynamic precompaction of subsoil by a vibratory compactor at a less effective frequency than the frequency of the in-service vehicular traffic vibrations. The possibility of this additional compaction is magnified by the increased speeds and loads of present-day vehicles. Vibratory settlement and the practice of dynamic precompaction of subsoils have stimulated research in the field of soil dynamics. It is becoming apparent that not only static but also dynamic loads must be considered in the design of highway soil structures.

The basic dynamic soil properties must be isolated, understood, and evaluated. Such dynamic soil values as modulus of elasticity, energy dissipation, and resonance phenomena are felt by some authors to be fundamental in predicting the behavior of soils subjected to dynamic loads (3). It has also been noted by others that vibratory loads reduce the angle of internal friction and transform a soil into a viscoelastic medium (1). However, there is some doubt as to the nature of the most fundamental soil properties and how these properties are affected by vibration. After a review of the literature on soil vibration, it is apparent not much "basic" research has been done and, as a result, more studies should be made to isolate and examine the basic dynamic soil properties.

This paper reports the results of an evaluation of the fundamental properties that govern the response of soils to vibratory loads. The objective was to study the changes in soil properties caused by soil pressure waves, with particular emphasis on the effect of soil waves adjacent to rigid highway structures. The first step necessary to accomplish this objective has been an evaluation of the fundamental soil properties that govern the response of soils subjected to vibratory loads. The second step in this research,

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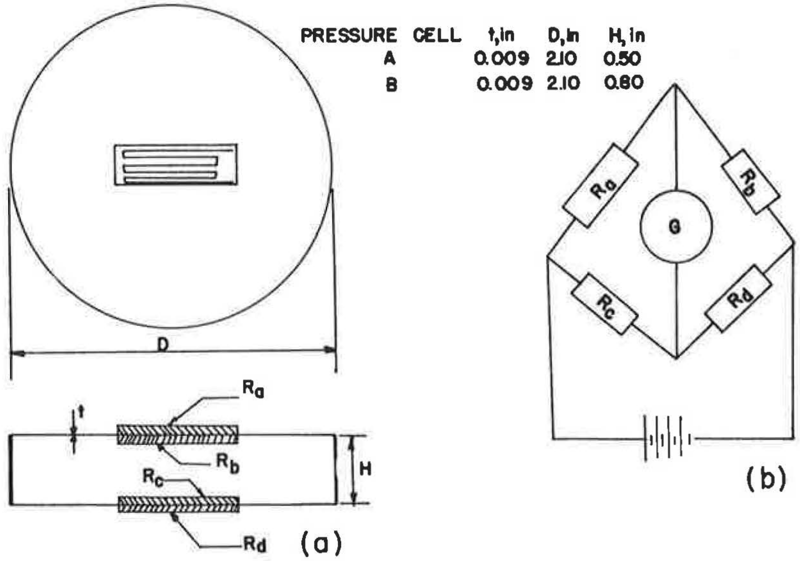


Figure 1. Construction and instrumentation details of diaphragm-type pressure cells: (a) pressure cell; (b) instrumentation diagram.

which is now in progress, is an attempt to correlate these changes in soil properties with the effects of highway traffic. The objectives of this research are based primarily on the assumption that subgrade settlement might be attributed to a microseismic vibratory phenomenon caused by vehicular traffic vibration.

EQUIPMENT AND PROCEDURE

The type of test instrumentation was very important in this study because the settlement, deformation, and pressure-time relationships were necessary. Therefore, not only the magnitude of the settlement, pressure, and deformation were necessary but also their relationship to time and to forces that are a function of time.

Soil Pressure Cells

Two types of diaphragm pressure transducers were built to measure the soil pressure. Each pressure gage was instrumented with four bonded resistance-type strain gages which made up the four legs of one Wheatstone bridge. Two strain gages were located on the interior of the pressure cell diaphragms and two on the exterior of the pressure cell diaphragms. This provided a pressure cell four times as sensitive as a typical diaphragm-type cell with one strain gage. This extreme sensitivity was necessary to measure the small soil pressures studied in this research.

Figure 1 shows the dimensions of each type of cell, the strain gages, and the location of these gages in a Wheatstone bridge. These two cells have approximately the same dimensions; however, the amount of fixity of diaphragms and the difference in materials resulted in a much different calibration factor. The calibration curves are shown in Figures 2 and 3 for pressure cells A and B, respectively.

Strain Equipment

The strain readings were recorded by a Sanborn strain gage preamplifier (Model 150-1100) used in conjunction with a Model 150-400 amplifier and a model 152 direct-writing recorder. This equipment produces a continuous record of strain for which the time base can be varied by the speed of the recording chart paper. The speeds available vary from 0.25 to 100.00 mm per sec. A 1-sec timer was used to actuate an event marker on the edge of the record for an accurate time base. The amplification of the strain can be increased to more than two chart divisions per microinch per inch of strain.

Direct Shear and Triaxial Equipment

Modifications were made on the standard direct shear and triaxial equipment to provide a dynamic pressure condition. In each case the type of dynamic pressure was different; however, it is possible that either condition might be applicable to the in-service vibratory condition resulting from vehicular traffic.

Direct Shear.—The dynamic or vibratory pressure was exerted in the direct shear test by varying the normal load. A small electric motor with an eccentric weight was placed on the normal load hanger of the direct shear equipment (Fig. 4). Both the amount of the vibrating load and the frequency could be varied by changing the amount of the eccentricity and the speed of the motor. This vibratory force was superimposed on the usually constant normal load. The rate of application of the shear load remained constant as in the static test. The remainder of the procedure used in this experiment was identical to that used in a static direct shear test (9).

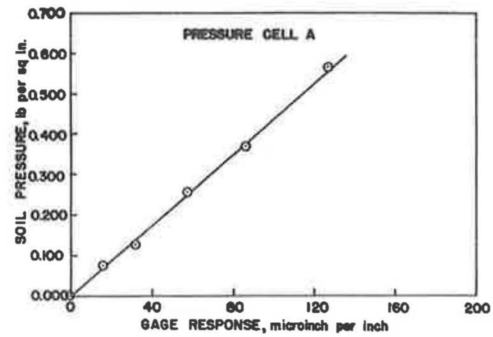


Figure 2. Response of pressure cell A.

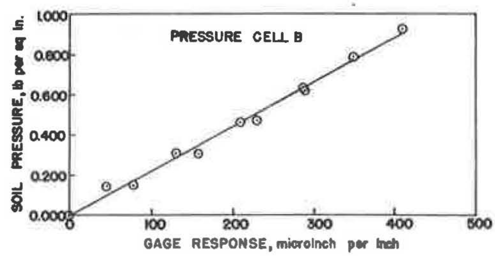


Figure 3. Response of pressure cell B.

Triaxial Test.—In the triaxial test, the hydrostatic pressure which is exerted laterally on the specimen and also adds to the normal applied load was modified to be applied dynamically. This was done by the use of an underwater loudspeaker. This device was coupled with the hydrostatic pressure fluid by a length of ¼-in. tubing and is shown mounted with the triaxial equipment in Figure 5. The power was supplied to the loudspeaker by means of an audio-oscillator and amplifier. In this experiment the

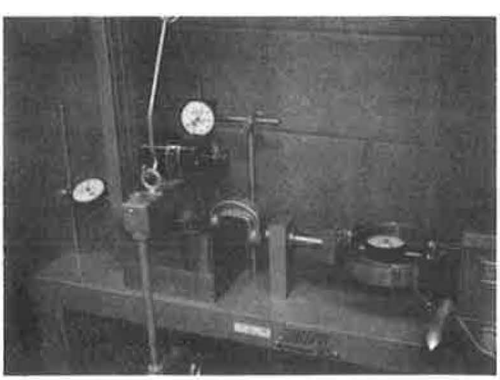


Figure 4. Direct shear equipment with pulsating normal load.

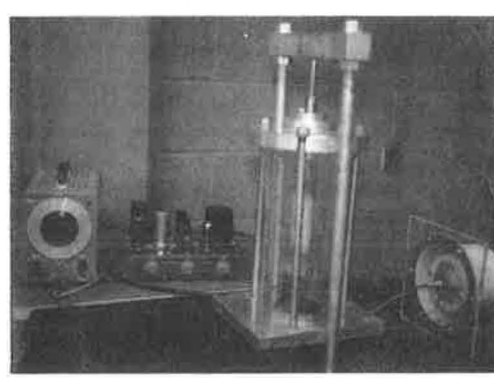
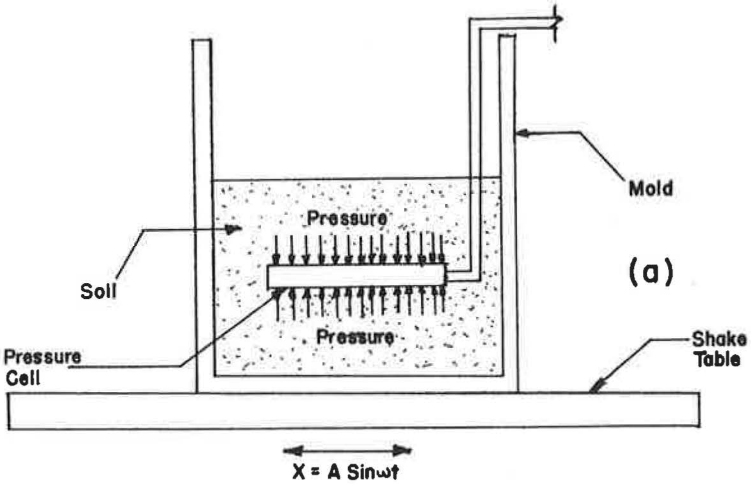


Figure 5. Triaxial equipment with pulsating hydrostatic pressure.



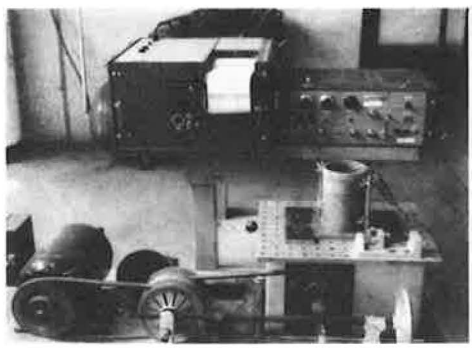


Figure 6. Vibrating table used for settlement, density, and vibration pressure tests: (a) schematic of vibratory motion and recorded pressure; (b) vibration equipment.

pulsating vibratory pressure was superimposed on both the lateral or confining pressure and on the normal applied load. This experiment was conducted as a typical triaxial test in which a precast specimen is placed in the chamber and tested (9).

Settlement, Density and Vibration Pressure Equipment and Procedures

The effect of vibration on the settlement, density, and vibration pressure of soil was determined by the use of a vibrating table (Fig. 6). This vibrating table is motor driven in the horizontal plane by an eccentric drive. The amplitude is variable from 0 to 0.25 in. and the frequency can be varied from approximately 20 to 90 cycles per second (cps). Therefore, a relatively large range of amplitudes and frequencies is available.

Soil Settlement.—The effect of vibration on the settlement of soil was determined for a vibratory motion of the soil. That is, the soil was placed in a $^1/_{30}$-cu ft mold with a surcharge weight on the soil surface and the entire mold vibrated horizontally. The soil was placed in the mold at a minimum relative density and during vibration the settlement was determined by continuously measuring the height of the soil surface. The densities were then computed by using the known weight and volume of soil. The relative minimum density of the soil at the beginning of the test was obtained by placing a known weight of material in the mold loosely and then inverting the mold once very slowly. The resulting soil was considered to be at the minimum relative density. The surcharge weight was then placed on the soil surface and the vibration test begun.

Vibration Pressure.— The effect of vibration of soil on the amount of vibration pressure transmitted through the soil was investigated by a method very similar to the previous settlement procedure. The mold was filled with the soil and a soil pressure cell was placed in the soil near the bottom of the mold. The entire system of the mold, pressure cell, and surcharge weight was then attached to the vibrating table. The vertical pressure of the soil and surcharge weights was recorded continuously as the frequency of the horizontally vibrating table was varied. The frequency was recorded on the soil pressure chart so that a permanent record of the soil pressure oscillations vs soil vibration frequency was obtained.

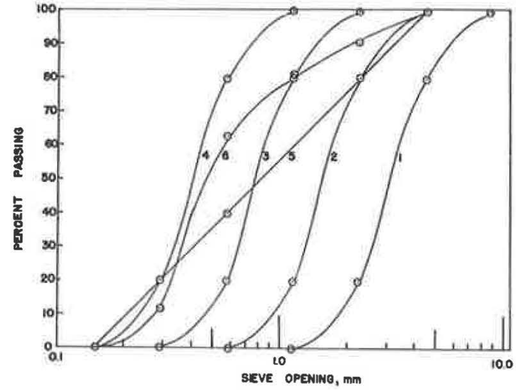


Figure 7. Soil gradations.

Soil Investigated

The soil investigated was a clean, medium sand and therefore, the results represent the effect of vibration on a granular type of soil. This sand is a natural, subrounded, washed material and represents an ideal granular soil. The gradation curve for the natural sand used is indicated by curve 6 on the gradation curve (Fig. 7). The other soil gradations used in this study were obtained by artificially grading this natural sand. These other gradations (curves 1 through 5) were used to determine the effect of gradation on the susceptibility of granular soils to vibration.

TEST RESULTS

Apparent Cohesion and Internal Friction

A good indication of the susceptibility of soil to vibration can be obtained by determining any change in the basic soil properties which occurs when the soil is tested under vibratory conditions. However, the nature of the vibratory condition may affect the results. Therefore, a study of the dynamic response of the "apparent cohesion" and the "angle of internal friction" was made by two different methods. These two methods (the triaxial and the direct shear tests) are commonly used to obtain the basic properties of soils for the usual static condition.

Triaxial Test.— In the triaxial test, samples of soil gradation No. 6 were compacted in a Harvard miniature compaction mold at the optimum moisture content and then stored in a 100 percent humidity moisture room for 24 hr.

The specimens were then placed in the triaxial chamber and tested in a wet but yet unsaturated condition. The tests were conducted by the usual triaxial procedure (9). The only variation required to conduct the dynamic tests was the addition of a vibratory pressure which was applied to both the lateral and normal stresses by means of pulsing the hydrostatic pressure fluid. This vibratory pressure was approximately ± 0.050 psi at a frequency of 50 cps.

Figure 8 shows the results of the triaxial test. The failure envelope for the static tests is indicated by the solid line, and the failure envelope for the dynamic tests is indicated by the dotted line. The dynamic tests were not continued beyond the pressure shown due to the limitations of the underwater loudspeaker. The angle of internal friction determined from the static test results was 30.5^0 and the effective cohesion 5.25 psi. In the dynamic test the effective cohesion was reduced to zero and the angle of internal friction increased to 37.5^0.

Direct Shear Test.—The direct shear test was conducted on soil samples of gradation No. 6 compacted in the direct shear box at an optimum moisture content of approximately 6 percent. The compaction was obtained by a static force of 1,000 lb applied as a normal force on the soil sample. The same degree of compaction was therefore not

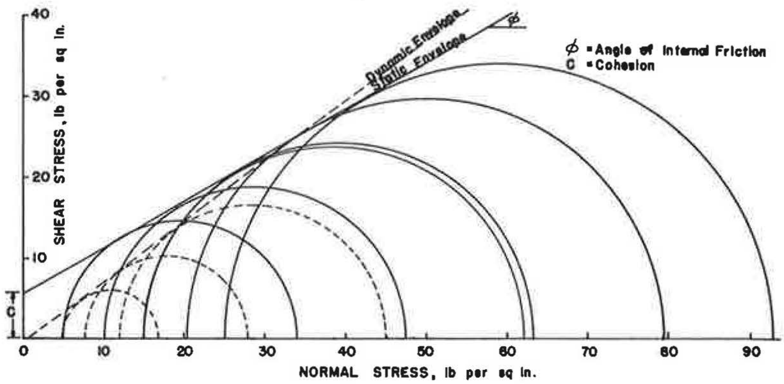


Figure 8. Failure envelope for triaxial test.

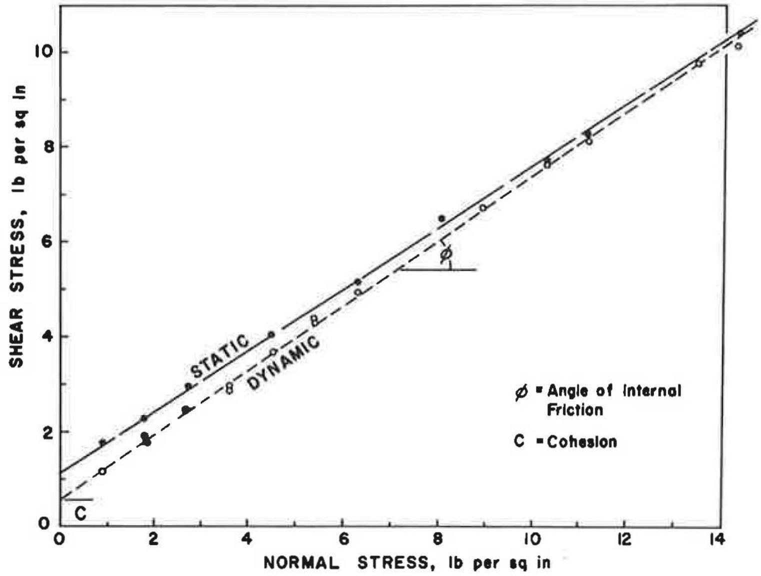


Figure 9. Failure envelope for direct shear test.

necessarily obtained on the direct shear and triaxial samples. Moreover, the direct shear specimens were used immediately after compaction. The testing of the specimens for the direct shear tests was done by the usual procedures except in the case of the dynamic tests where a vibratory pressure was applied to the normal load by means of a small motor with an eccentric weight.

Figure 9 shows the results of the direct shear tests. The vibratory pressure used in this test was approximately ±0.150 psi at a frequency of 58 cps. The resulting angle of internal friction and effective cohesion determined by the dynamic test was 35.6^0 and 0.55 psi, respectively. The corresponding static tests resulted in an angle of internal friction of 33.4^0 and an effective cohesion of 1.1 psi. The dynamic test results, indicated by the dotted line, show the increase in the angle of internal friction and the decrease in the effective cohesion which resulted from the direct shear test.

Settlement and Density

The effect of vibration on the settlement and compaction of soils has resulted in a large amount of interest in soil vibration. This portion of the study was made to help

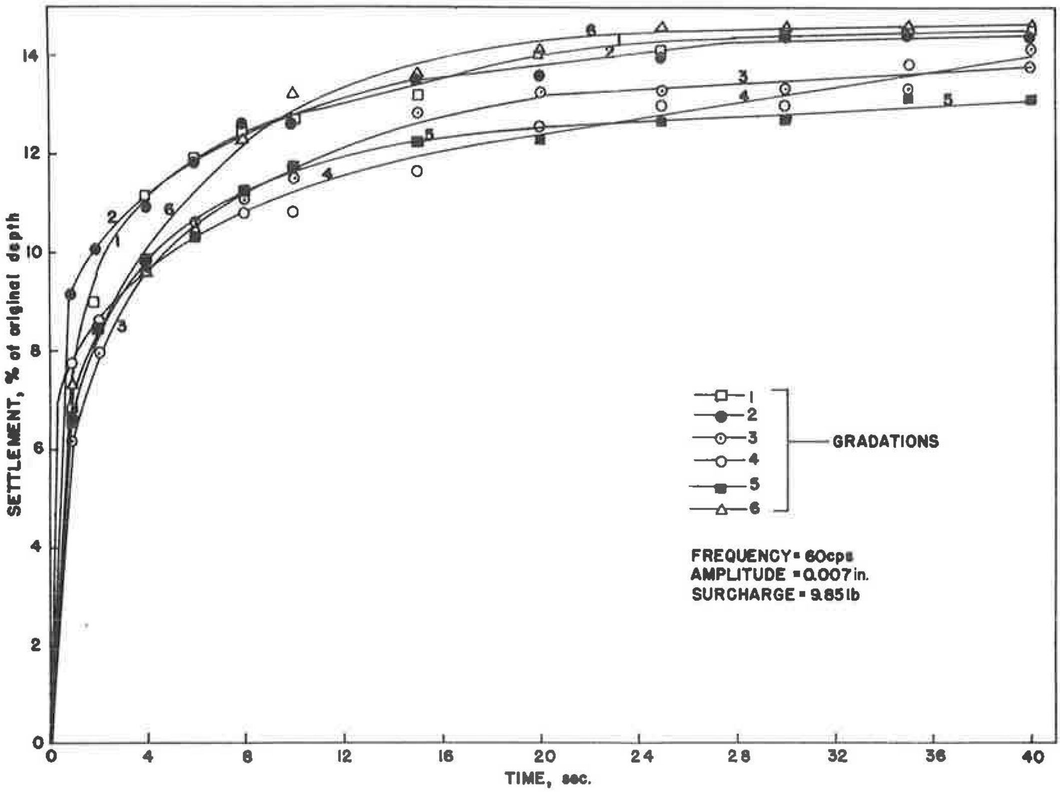


Figure 10. Time-settlement relationship for each soil gradation.

isolate the basic parameters that might affect soil settlement and compaction by vibration.

The susceptibility of a soil to vibratory loads is exemplified by the volume change relationships of the soil. These relationships can be determined in a number of ways. In this research the volume change was measured by the change in height of the sample as a percentage of the original height and also in absolute terms, as the dry density and the change in dry density of the soil. Different gradations of soil were studied to determine the effect of soil gradation, frequency of vibration, amplitude of vibration, time, and moisture content on the dynamic volume change relationships of soils.

Vibration.— The effect of vibration on soil settlement was determined by both the percentage settlement and the change in dry density relationships previously discussed. The soil was vibrated by a horizontal motion and the resulting vertical settlement of the soil recorded continuously during the vibration. The resulting time-settlement and time-dry density curves are shown in Figures 10, 11, 12, and 13. The largest settlement and change in density occurred during the first 10 sec of vibration. After 30 to 40 sec of vibration, the settlement and density reached their maximum values. This was true of all frequencies, amplitudes of vibration, and soil gradations.

Gradation.— To isolate the effect of soil gradation on the settlement response of soils to vibration, four gradations of soil (1 through 4 in Fig. 7) were investigated. The gradation curves for these soils are parallel, and for any given percent passing the particle size is double that of the next smaller gradation. The uniformity coefficient for these gradations are the same (1.88). The effective soil particle size is 1.80, 0.90, 0.46, and 0.23 mm for gradations 1, 2, 3, and 4, respectively.

These four gradations were studied to obtain the characteristics of each when subjected to a vibratory motion. The variations in density of each gradation present at the

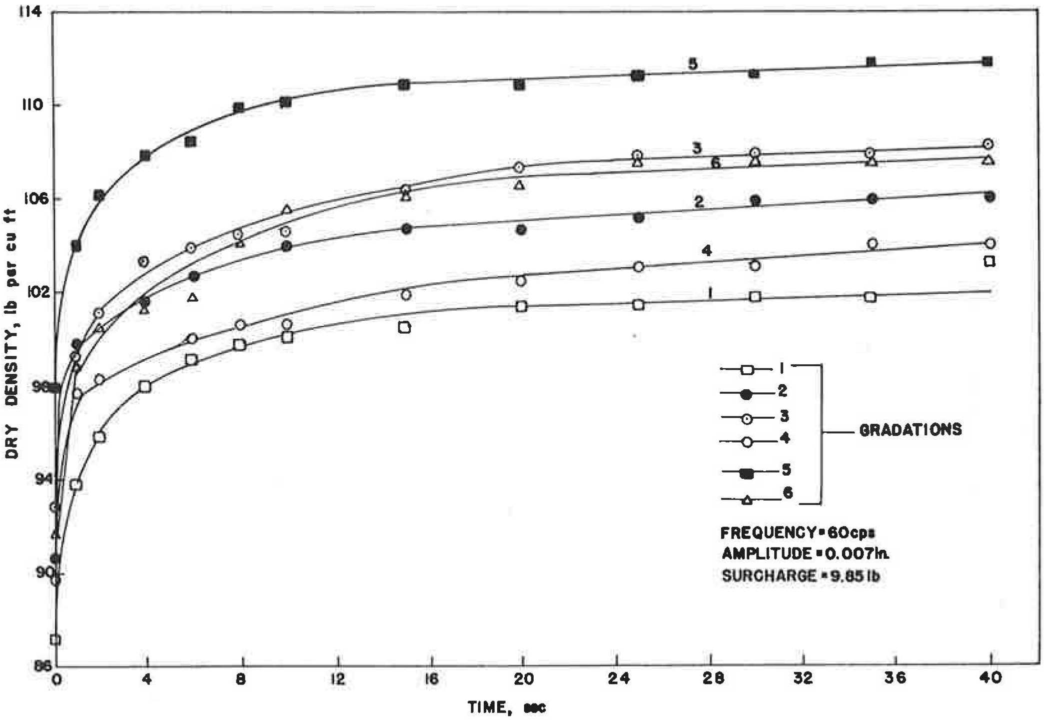


Figure 11. Time-dry density relationship for each soil gradation.

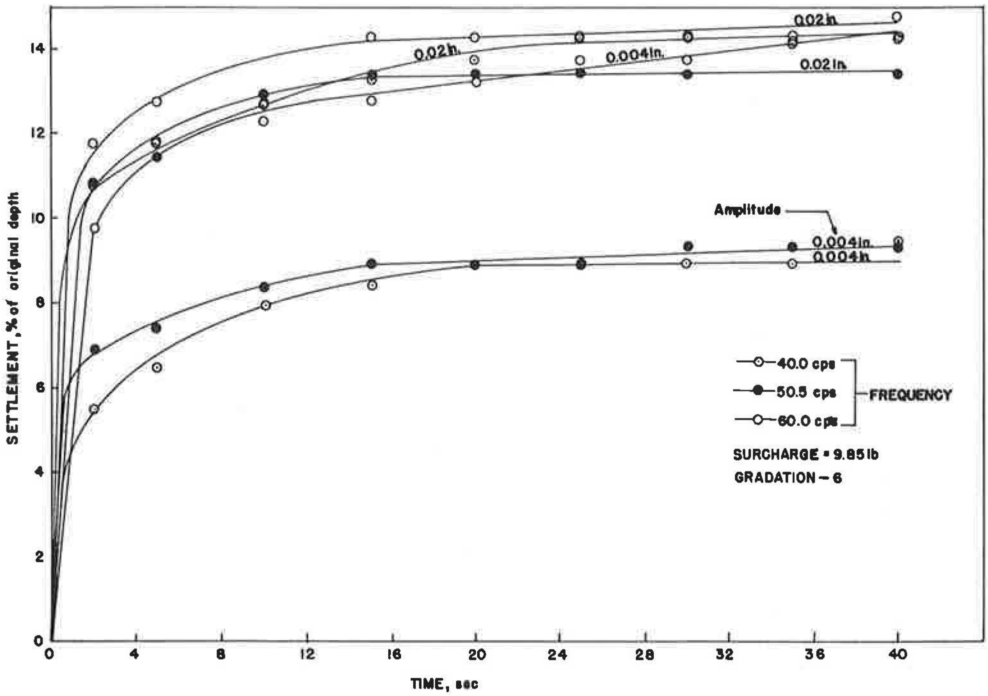


Figure 12. Time-settlement relationship for different amplitudes and frequencies.

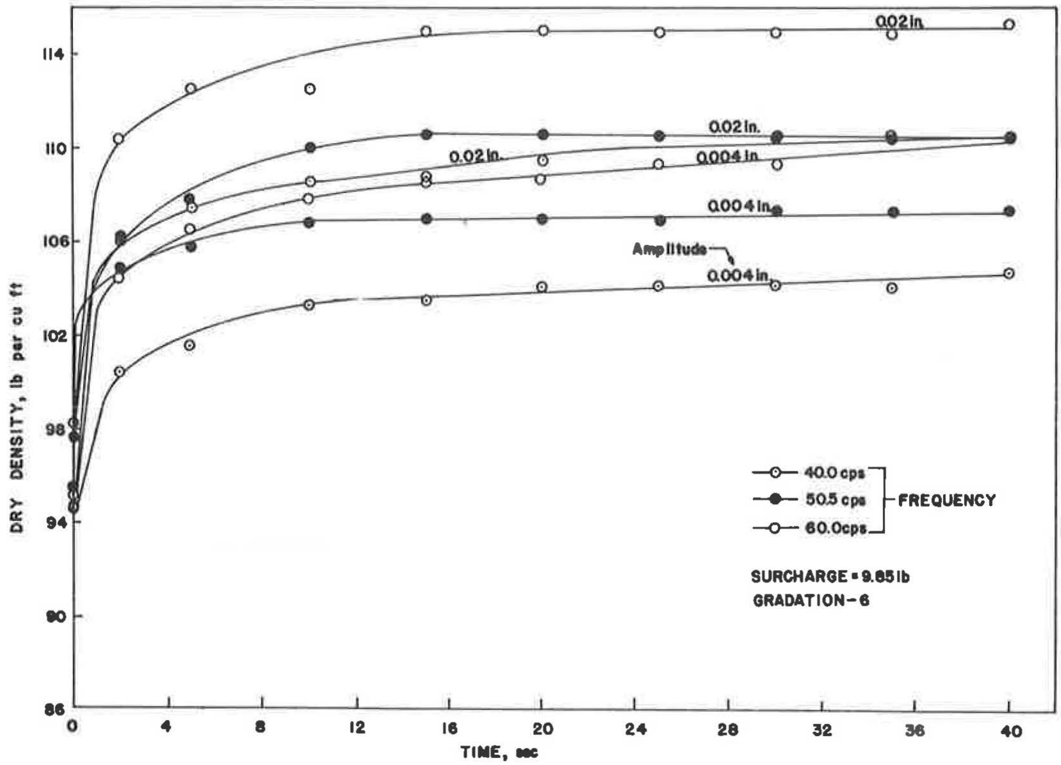


Figure 13. Time-dry density relationship for different amplitudes and frequencies.

beginning of the vibration were also present during and following the vibration. The solid line curves in Figure 14 show the dry densities for each gradation at the beginning of the test and at the end of 10, 20, 30, and 40 sec. The percent change in dry density is shown by dotted lines and indicates that the coarsest material had the greatest change in density.

The effect of the uniformity of gradation of soil could not be established because there was not enough variation in the uniformity coefficients of the soils studied. However, the variation of the uniformity coefficients of gradations 5 and 6 (5.55 and 2.03, respectively) is large enough to obtain an indication of this effect. The response of these two gradations indicates that the gradation with the largest uniformity coefficient (gradation 5) obtained the greatest density, as might be expected. This is shown in Figure 11 by the position of curves 5 and 6. However, the greatest change in density or percent settlement occurred in soil 6, as shown by the position of curves 5 and 6 in Figure 10.

Frequency and Amplitude.—The results of the second series of tests to study the effect of frequency and amplitude are shown in Figures 12 and 13. In this study, only the natural gradation was studied (gradation 6). The effect of frequency and amplitude is very apparent in these results. Figure 12 shows that significant changes in settlement occurred as the amplitude of vibration was increased. However, it is apparent that both amplitude and frequency affected the settlement and density. The 60-cps vibration was much more effective in settling the soil, even at the small amplitude, than was either the 40- or 50-cps vibration. This significant difference, as shown later, is the result of a resonance in the soil at this frequency. This indicates that even small amplitudes of vibration can produce large settlements if the frequency of vibration is near a resonant frequency of the soil.

Frequency-Dry Density Relationship.—The effect of the frequency of vibration on the dry density was studied for the natural soil gradation (gradation 6). The effect of

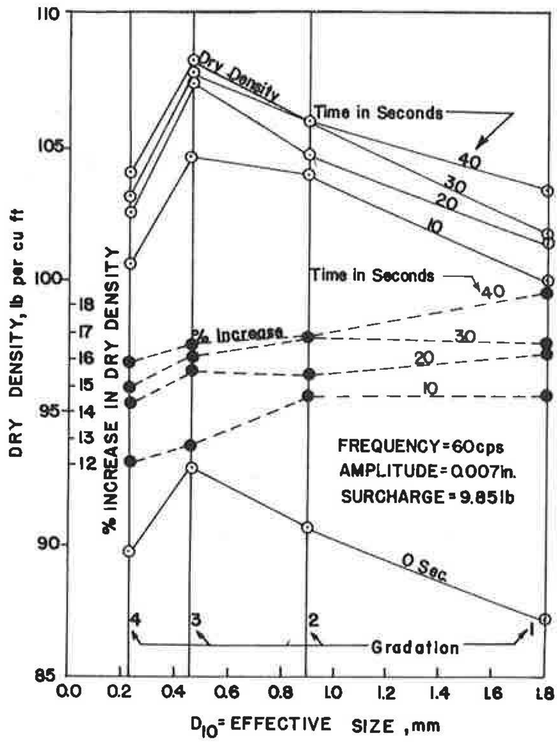


Figure 14. Soil size-density relationship for each gradation including effect of time.

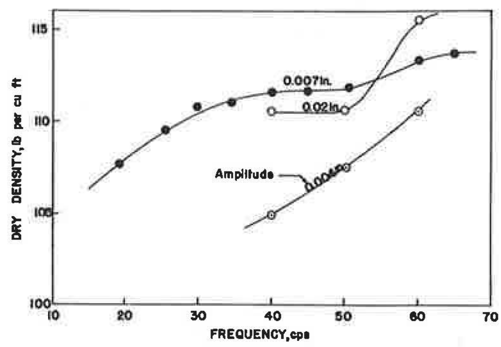


Figure 15. Effect of vibratory frequency on soil density for various amplitudes.

the frequency of vibration on the resulting dry density of the soil is shown in Figure 15. These results indicate the increased effectiveness of the critical frequencies in compacting soil. The critical frequency of the soil, or the resonance condition, is indicated by an abrupt change in density. Moreover, the smaller amplitudes of vibration were affected more by the critical frequency but less abruptly than the larger amplitudes.

Moisture Content.— The previous studies of the effect of vibration on density were conducted with the soil in a dry condition. The moisture content of the soil was approximately 0.5 percent during all the previous tests. As a result, a study was made to determine the relationship between moisture content and density for a soil compacted by vibration. This relationship was obtained by placing the loose moist soil, at each moisture content, in a $^1/_{30}$-cu ft mold without any surcharge weight. The mold and soil were then vibrated at a frequency of 60 cps and an amplitude of 0.003 in. for 40 sec. This test was run in conjunction with a Harvard miniature compaction test (16) and the results are shown in Figure 16. The Harvard miniature apparatus had been previously correlated with the standard AASHO compaction procedure for this soil. Therefore, a standard AASHO moisture-density curve is also shown for this soil (Fig. 16). The maximum dry density resulting from the vibratory compaction is 100 pcf at a moisture content of 5.2 percent. The Harvard miniature curve is very

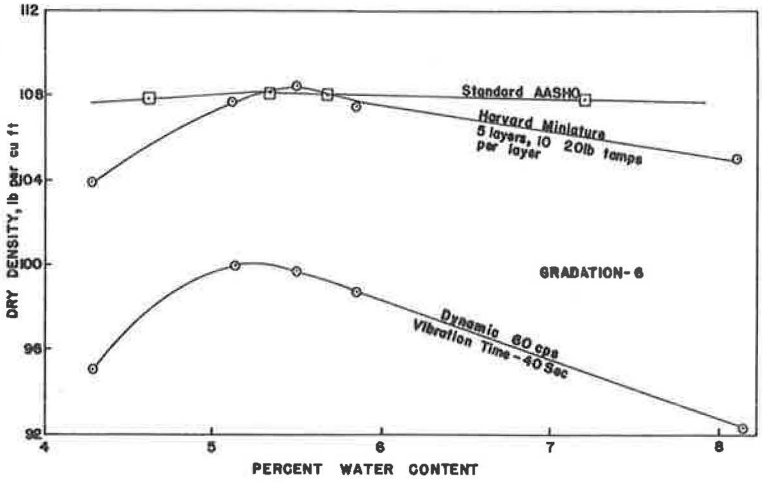


Figure 16. Dynamic and static moisture-density relationships.

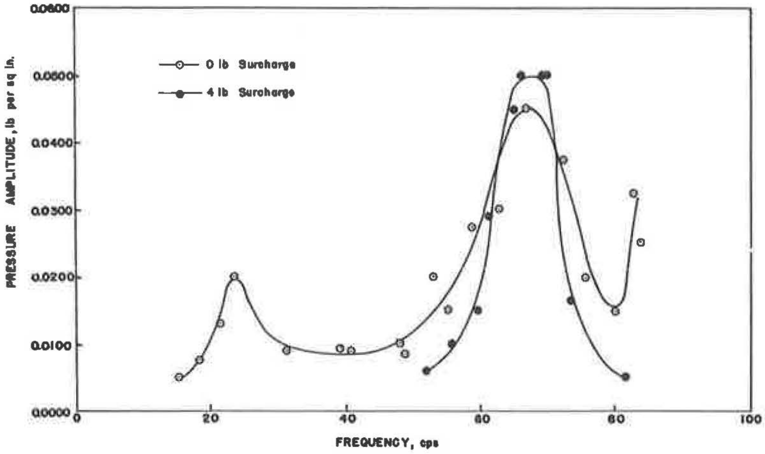


Figure 17. Vibratory pressure characteristics of natural soil (gradation 6).

similar to the vibratory compaction curve, except that a maximum dry density of 108.3 pcf was obtained at a moisture content of 5.5 percent. The standard AASHO moisture-density curve has a similar maximum dry density; however, the curve is much flatter and is almost horizontal for this soil for a moisture content of 5 to 8 percent. These results, primarily the form of the curve, indicate a correlation between vibratory compaction and the Harvard miniature compaction results.

Vibration Pressure

Many investigators have studied the resonance condition in soils by the use of vibrators placed on the surface of the soil. The response of the soil, in this type of analysis, is dependent on the kind of soil, as well as the weight and dimensions of the vibrator. However, it is reasonable to assume that soil particles have a resonance condition that is a function of the gradation, effective size, and type of soil. Therefore, a study was made of the effect of vibration on a soil that would yield results dependent only on the properties of the soil. The resulting procedure was an attempt to isolate this effect by a vibration pressure study of the soil. In this procedure the soil was placed in the $^1/_{30}$-cu ft mold and vibrated horizontally while the pressure cell measured the vertical pressure of the soil. Figure 6 shows the direction of vibratory motion of the mold and soil and the type of soil pressure measured by the pressure cell. The amplitude of the soil vibration pressure is shown in Figure 17 for various frequencies of vibration. Maximum vibration pressures occurred at two frequencies, and possibly a third. However, above 80 cps the vibrating table had a large amount of random vibration and, therefore, frequencies near and above 80 cps are very inconclusive.

The addition of surcharge weights to the vibrating soil system resulted in an increase in the maximum pressure amplitude at the resonant frequencies with very little, if any, change in the resonant frequency. This indicates the independence of the resonance or critical frequency from the loading conditions.

SUMMARY AND CONCLUSIONS

The application of any results obtained from this research must be tempered by the knowledge that the material used in these experiments was a clean granular sand. In addition to this, these experiments and tests were performed to obtain a comprehensive qualitative indication of the response of soils to vibratory pressure, and are not nearly complete enough to yield quantitative results. A complete investigation of the variables considered in this study would entail a much larger program than the current project. However, the complexity of the problem indicates that there is a necessity for basic research in the area of soil vibration. It is also very important to determine the type of vibration that results from vehicular traffic loadings to apply any results obtained from a basic research program properly.

Apparent Cohesion and Angle of Internal Friction

Two experimental procedures were used to determine the effect of vibratory loads on the basic constants of cohesion and friction angle, which make up Coulomb's Law. These two properties are basic in evaluating a soil.

The vibratory normal load in the direct shear test resulted in an increase in the angle of internal friction and a decrease in the apparent cohesion, similar to the effect of the vibratory pressure in the triaxial test results. The vibratory pressure caused a premature failure in both cases, with a decreasing effect as the normal and applied pressure increased. This probably resulted from the ratio of dynamic to applied pressure decreasing and therefore reducing the significance of the superimposed vibratory pressure.

These results are indicative of the variation in effect which different types of vibratory loadings had on the basic soil properties. From these results it is apparent that the type of vibratory pressure must be known before its effect can be predicted. This will be especially important in the case of vehicular traffic vibrations.

Vibratory Volume Change

The effect of a vibratory motion on the volume change characteristics of a granular soil has been studied for various frequencies, amplitudes, moisture contents, and soil gradations. These results indicate that a relatively insignificant vibratory motion can cause a large volume change in granular soils.

The maximum density occurred in the soil gradation with the largest uniformity coefficient, although the largest change in density occurred in the soils with the smaller coefficient. For the soil gradations with the same uniformity coefficient, the largest increase in density occurred in the soil with the largest grain size.

An increase in the amplitude of vibratory motion increased the settlement and maximum density of the granular soil, although the increase in density was small compared to the increase in the amplitude used. These results seem to indicate that soils will respond to very small amplitudes of vibration with changes in density almost as large as those resulting from larger amplitudes of vibration.

The vibration frequency affected the soil to a much greater extent than the vibration amplitude. The susceptibility of soils to certain frequencies is very evident and indicates the importance of determining the critical frequency of the soil per se. The resonant condition of a certain loading cannot be construed to be the critical frequency of the soil. Moreover, when the soil was vibrated at its critical frequency, the effect of moisture was consistent with the usual moisture-density relationship. However, this relationship cannot be compared with the vibration of soil in the quick condition because no correlation of this type was made.

Soil Vibration Pressures

A knowledge of soil vibration pressures could be very important in the study of active soil pressures in highway soil structures. The pressure that results from the vibratory motion of the soil might provide an important insight into the transmission of live load soil pressure through a soil mass.

The variation in the magnitude of the vibratory pressure of the granular soil which occurred for different frequencies of soil vibration indicates a critical frequency or resonance of the soil particles. The natural soil gradation used indicated two well-defined critical frequencies at 24 and 67 cps. The resonance at 67 cps produced a vibratory pressure approximately double the pressure at the lower critical frequency. Moreover, the soil at its lower critical frequency exhibited a "beat-frequency" type of maximum pressure. This might indicate that the lower critical frequency is not the fundamental frequency, or it might be the result of a resonance based on a particular soil particle size. Additional research on the fundamental frequency of soil particles, and on the cause and effect of soil resonances is necessary for an evaluation of this phenomenon.

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