SONIC RESONANCE AND RELATED ENGINEERING PROPERTIES OF SELECTED SOILS AND ROCK

by

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ABSTRACT

This investigation describes the resonance behavior of selected soils in response to sonic vibrations. Resonance of caliche and water are also measured, given special attention to the effect of sample size and amplitude of vibration on the resonance frequency.

The range of resonance frequency of the studied materials ranges between 20 and 60 cycles per second depending on: type of material, density, moisture content, degree of cohesion or cementation, size of the sample, and presence or absence of a container. The relative effects of each of these variables on the resonance frequency are discussed.

A new method for the determination of the liquid limits on undisturbed samples of soils based on the resonance frequency is tentatively presented. It is supported by observations that resonance frequency increases gradually with moisture content, provided that liquid limit is not exceeded. This method would permit determinations on undisturbed samples without previous selection of grain size. The values obtained by this method may not coincide exactly with the values obtained by the standard method, but would be strongly indicative of in situ soil behaviour.

INTRODUCTION

Statement of the Problem

This study investigated resonance frequencies of certain natural soils and rocks. The importance of these determinations are not only of academic interest, but is also of a direct practical significance.

Compaction of soils by vibratory equipment has been successfully used in many construction works. Experimental studies have shown that when compacting with vibratory equipment greater densities can be obtained at specific critical frequencies of each soil. These frequencies correspond to the natural frequency of the soil which, by superimposing a vibration of the same frequency, results in a resonance wave of larger amplitude and compaction power.

This resonance situation is highly desirable when compaction has to be achieved, but when the superimposed vibration is a product of working machinery farther compaction would cause differential settlement and might result in a disastrous situation. Generally when foundations with dynamic loading are placed on loose gravel or sandy soils they are pre-vibrated or pre-compacted to eliminate settlement or possible reduction on bearing capacity as consequence of vibrations. Eastwood (1953), Mencl and Kazda (1957), Wen-Xi and Peking (1961) and others described the effect of dynamic loads on the bearing power of soils. Principles for designing foundations of vibratory equipment are described by: Terzaghi (1943), Tschebotarioff and Ward (1948), and Tschebotarioff (1952, 1953, 1964).

Other practical applications where resonance frequency has been shown advantageous are:

Drilling (Barkan, 1957),

Sinking of piles (Savinov and Looskin, 1960), and

Determination of elastic constants of materials if shape, dimensions and weight are known (A. S. T. M. Designation:C215-60, 1964).

If total shear strength is reduced during vibration (Mogami and Kubo, 1953), vibration could also be used as an aid to earth excavations.

Many studies have been carried out concerning the behavior of soils and soils-foundation systems during vibrations. All of these studies were made by placing a mechanical oscillator directly on the soil surface, on scale models of foundation footings, or on the measuring equipment. Description of several of these instruments, of which the two-mass oscillator is the most common, can be found in: Bernhard (1949), Tschebotarioff (1952), Bendel and Boret (1961), and Linger (1963).

Natural frequencies obtained with these instruments can be referred to the vibrator-soil system, or vibrator-soil-foundation system; examples of these are given in Tschebotarioff (1952) for different types of soils utilizing a two-mass type vibrator. However, little information is available on either the natural frequency (resonance frequency) of the soil itself, or how these frequencies vary with the change of the "in situ" engineering properties of soils.

Scope and Limitations

The aim of this thesis is to approach as much as possible, the real resonance frequencies of soils in an undisturbed state and determine how they vary with the "in situ" engineering properties of the soil. As it will be seen, the difficulty to achieve this goal entails the problem of dealing with cohesionless soils which are very difficult to take undisturbed or test without a container.

During the four months time devoted to this thesis, it was possible to study six different types of soils and one type of rock collected in the Tucson area. Therefore, the results are representative only of these soils, with no statistical significance. It is hoped, however, that this represents at least another step toward the understanding of this subject.

LITERATURE REVIEW

A great deal of research on the effect of mechanical vibrators on the behavior of soils and soil-foundation systems have been reported through the literature. Only the work directly related to this study will be summarized here.

Converse (1953) describes the effect of operating at the resonance frequency in the compaction of sand with a surface vibrator; he presented principles for determining the resonance frequency of soil-oscillator systems. The depth where the compaction is effective is determined to be about twice the width of the oscillator. In (1956) he explains and gives basic rules for compaction of cohesive soils by low frequency vibrators. One of these rules is to ". . . operate at or near resonant frequency of the soil oscillator mass." The reason for this, he explains is that ". . . the dynamic magnification at resonance frequency may be quite large." This produces greater contact pressure between the base plate of the oscillator and the soil. Another reason given is that ". . . between applications of high pressure the soil is subjected to a pulsating wave of compression and relief of pressure (possibly even tension) which undoubtedly has a marked effect on decreasing the bond between the clay particles." The same author (1961) points out that for soft mud the frequency of oscillation is one of the major factors that affects the shearing modulus; but within frequency of 1 to 5 cycles per second, such as usually occur during strong earthquakes, the amplitude of vibration has the primary influence.

Bernhard (1956) investigates the dynamic characteristic of a stratified soils of several gradations by vibrating it with a mechanical oscillator placed on top of the soil and receiving the wave by a seismometer on the surface and pressure cells below the surface of the soil. The resultant frequency of vibration is related to: the vertical wave displacement at different distances from the disturbing face, the pressure transferred at different depths below surface, and to other parameters. This study permitted him to establish the validity of applying methods used in "macroseismic" to the "microseismic" investigations. Bernhard (1959) studies the "in situ" dynamic soil characteristics by sinusoidal and impact excitations. The results obtained are considered to be in a rather close agreement with the theoretical considerations, and similar for both methods. Bernhard (1961) describes "in situ" measurements of normal stresses for noncohesive soils subjected to vibratory loads.

Viering (1961) was able to relate the coefficient of swelling of soils and its angle of internal friction with the resonance frequency.

He also mentioned that if relative densities are less than 70 per cent the vibrational behavior of the soil may change with time.

Gomes and Graves (1962) investigate the compaction of sand by vibratory methods. One of their conclusions was that ". . . Compaction of dray sand by vibration is controlled by the frequency of vibration"; they defined critical frequency as the one that gives the greatest compaction.

Honigs, Valente and Graves (1963) presented the theory that ". . . compaction in clean sand can best be accomplished by applying the correct amount of shearing strain." Static compressional loading builds large normal stresses between the grains which will resist the rearrangement of grains, thus limits compaction. If vibrations and low compressional loading permit enough strain to occur the sand may reach the lowest possible void ratio. However, this lower void ratio was not obtained by the authors. They also stated that higher compactions are more easily reached in well-graded sand than in uniformly sized sand and in rounded grains than in angular grains.

Linger (1963) studied the response of a clean sand to vibratory pressures and motions. It was shown that while vibration increased the angle of internal friction it decreased the effective cohesion. It was also noted that even small amplitudes of vibration, particularly near the resonance frequency, produced large settlement; this occured principally during the first ten second of vibrations and was larger for coarser materials. The frequency of vibration was found to affect the soil to a much greater extent than its amplitude; this draws attention to the importance of determining the critical frequency for each soil. The optimum moisture content for a maximum dray density in the static and dynamic compaction test were also found to be very similar.

A different aspect, but also related to the subject, is the change of natural frequency of foundation soils to improve foundations characteristics. Gnaedinger (1961) and Tschebotarioff (1964) report instances where machines that vibrated at excessive amplitudes were treated to reduce these vibrations to a tolerable amount by changing the natural frequency of the foundation soil. This change was accomplished by grouting of the soil. Naturally this approach is only possible when the foundation soil is pervious enough to permit the introduction of chemical or cement grouts. In these instances grout changed the elastic properties of the soils, thus changing their natural frequencies.

Finally, the text-books of Terzaghi (1943), Tschebotarioff (1952) and Leonards (1962), that dedicate many pages to vibration problems in the design of foundations for machinery and describe principles of compaction by vibratory methods, are worthy of mention. The fundamental principles on which theories of vibration are based are also given in these texts.

APPROACH TO THE RESEARCH

Equipment

The research on sonic resonance of soils was accomplished by studying representative samples in the laboratory. The equipment required for these studies consisted of regular soil mechanics testing equipment and an electro sonometer provided with a cathode ray oscilloscope. Special description of the equipment is believed to be necessary only for the electro sonometer, used for the determinations of the resonance properties of the samples.

The electro sonometer was designed by the "Electro Products Laboratories, Inc., Chicago, Illinois," for the primary purpose of testing the elastic constants of concrete as given by its resonance characteristics. Basically it consists of two sections:

a-. The generating section equipped of an oscillator, a power amplifer, and a driver.

b-. The sensing section which include the pickup and the pickup amplifer.

The general layout of this equipment with the additional cathode ray oscilloscope is shown in Fig. 1. The oscilloscope furnishes a visual comparison of the magnitude, frequency and phase relationship between the driver and the receiver vibrations.

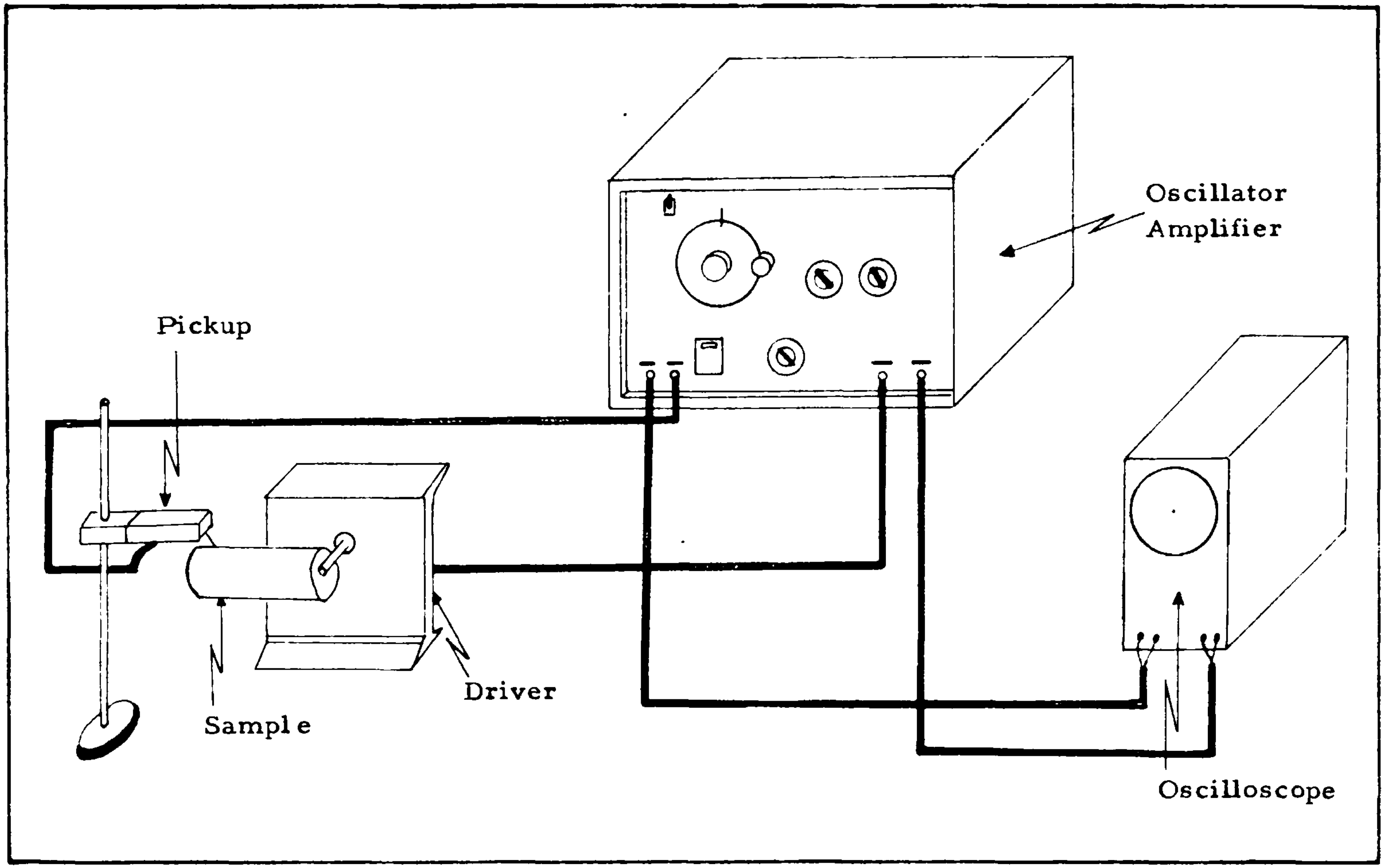

Fig. 1. General setup of electro sonometer and additional oscilloscope

The oscillator of the electro sonometer generates electrical audio frequency voltage which, after being amplified, feeds the driver. The frequency output of this oscillator ranges between 17.3 to 20,000 cycles per second (cps.), with an accuracy of 2 per cent. Fig. 2 shows the oscillator amplifier controls which permit selection of the desired frequency and relative amplitude of the imput vibration.

The driver mechanism converts the electrical audio frequency voltage of the oscillator into mechanical vibrations of the same frequency. This mechanical vibration is transmitted to the sample to be tested.

The mechanical vibrations are sensed from any point on the sample by a piezo-electric crystal pickup provided with a steel needle, which operate similar to a phonograph pickup. These mechanical vibrations are thus converted into low level electrical vibrations. These low level impulses are raised through the pickup amplifier unit to a value that can be detected on a meter. The sensitivity of this amplification can also be selected in order to permit a clear deflection of the resonance indicator of Fig. 2.

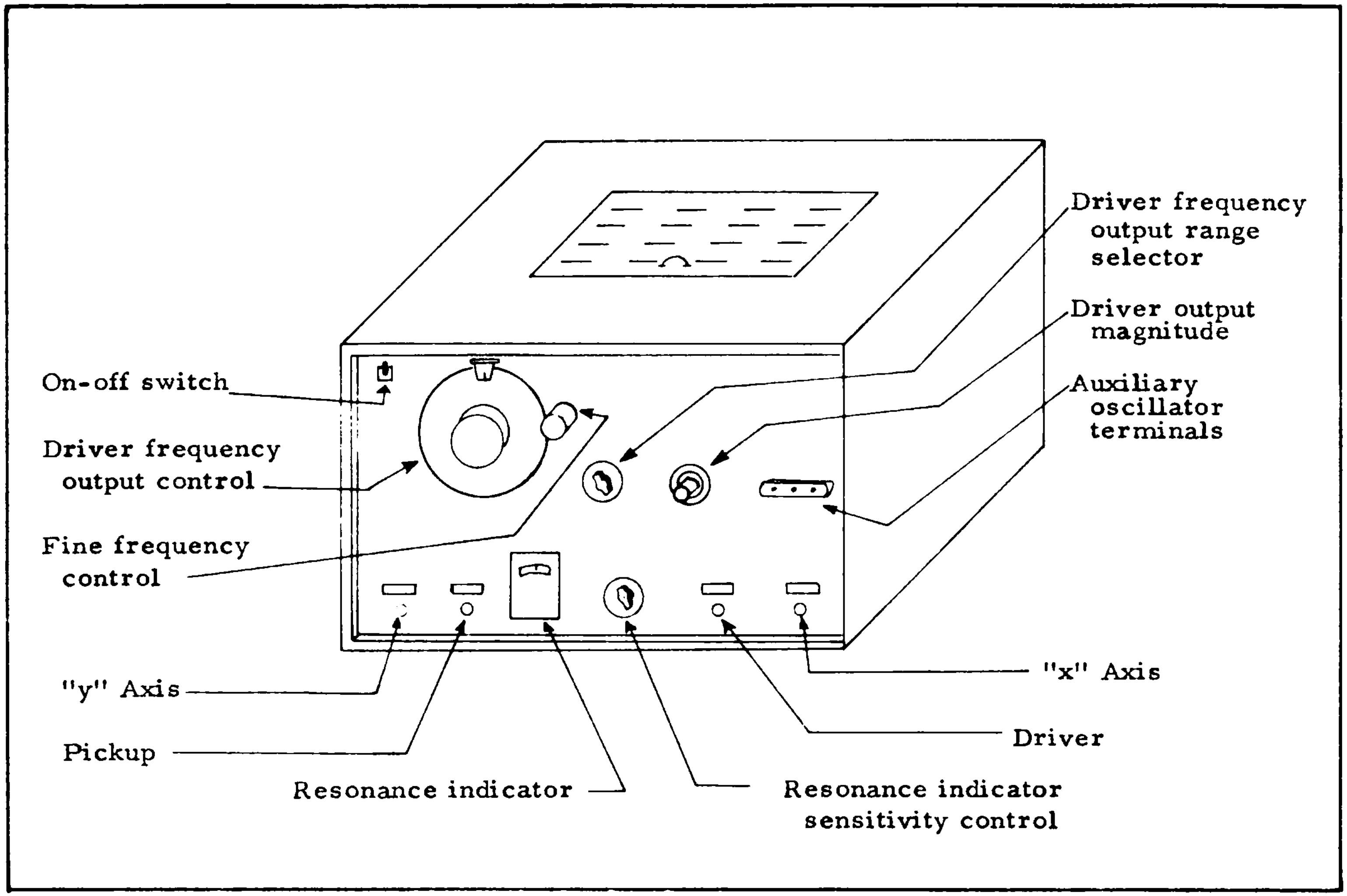

Fig. 2. Oscillator amplifier controls

Procedures

The investigation comprised field and laboratory works.

Field

The field procedure included the collection of samples for laboratory determinations and the measurement of the natural density of the soil.

The selection of soils was arbitrary. The samples were taken in an undisturbed state by following the instruction given in Krynine and Judd (1957). Some of the samples, especially the cohesionless ones, were placed in cardboard cans with the purpose of keeping them as much undisturbed as possible for the laboratory research.

For the field density a hole was dug in the soil of about 7 inches in diameter and 10 inches deep. All the material removed was carefully recovered and weighed at natural moisture content. Then the volume of the hole, which corresponded to the volume of the removed soil in its undisturbed state before removal, was measured by placing into it a thin plastic bag which permitted one to fill the hole with water. The weight of the removed soil divided by the volume of the water needed to fill the hole determined the field density of the soil at its natural moisture content.

Laboratory

Laboratory investigations consisted of two parts: tests for the determination of soil condition and classification, and tests for resonance properties.

Classification of soils

The tests for the classification and determination of soil conditions included: determination of natural moisture content, Atterberg limits, grain size analysis, and direct shear tests to undisturbed specimens at natural moisture content.

All these tests were performed in accordance with the standard procedures described in the soil mechanic literature.

Sieve analysis for grain size distribution was carried down to the 200 mesh only, because, as pointed out by Means and Parcher (1963), the size distribution of smaller fractions is of little importance in the solution of engineering problems. The Atterberg limits are of a more practical significance in determining the engineering properties of the finer fractions.

The direct shear test, performed on each soil type, was done to determine the "in situ" shear conditions as indicated by the angle of internal friction and the cohesion. This test was run at an approximate strain rate of 0.04 inches per minute, with normal stresses ranging between 0.43 Kg/cm^2 and 2.7 Kg/cm^2. No drainage was required.

Two types of soils studied could not be tested by the direct shear test in an undisturbed state. Samples S-1 and S-2, consisting of poorly graded gravelly sand (SP) and poorly graded sand (SP), were too friable and it was impossible to keep them undisturbed while cutting them to the size of the shear box. The natural densities of these soils were approximated by weighing the specimen and compressing it to the volume that would satisfy the field density. If an evaluation of the shear tests is to be made, it should be considered relative to the density of the soil for each shear test run--particularly for the (SP) soils where the shear strength is primarily due to internal friction.

Sonic-resonance determinations

The set up for the determinations of the resonance frequency is shown in Fig. 1. During vibration the samples were mounted on a sponge pad held by a heavy-base stand, not shown in the Fig. 1. The sponge pad acted as a spring in decreasing the effect of damping.

The frequency of the vibration was varied using the "driver frequency output control" and the "fine frequency control" shown in Fig. 2. It was started at lower frequency and gradually increased recording all the resonances encountered. The frequency of resonance was indicated by a strong deflection of the needle in the "resonance indicator" of Fig. 2. The highest resonance was taken as the fundamental resonance frequency, and the others as harmonics. Fig. 3, shows the resonance deflections for each frequency sensed in one point on a caliche sample. In this instance the higher deflection is at 66 cycles per second, and that was taken as the resonance frequency for that point and that sample. As it can be seen from this figure, the distribution of harmonics was not at regular multiples of the fundamental resonance frequency, as observed for a vibrating rod, but they follow an irregular distribution. This pattern was observed for all the samples tested.

Resonance was also noted by a higher amplitude of the sine wave shown on the oscilloscope. During non-resonance vibration frequency the oscilloscope showed irregular shaped waves which varied with: the material tested, the frequency of vibration and the degree of contact of the driver and pickup with the sample. However, it was not possible to see any relation between the different shapes of waves and their causes. Sometimes it was also possible to see two waves in the oscilloscope. Only when the sample underwent resonance did the oscilloscope show a regular sine wave of higher amplitude.

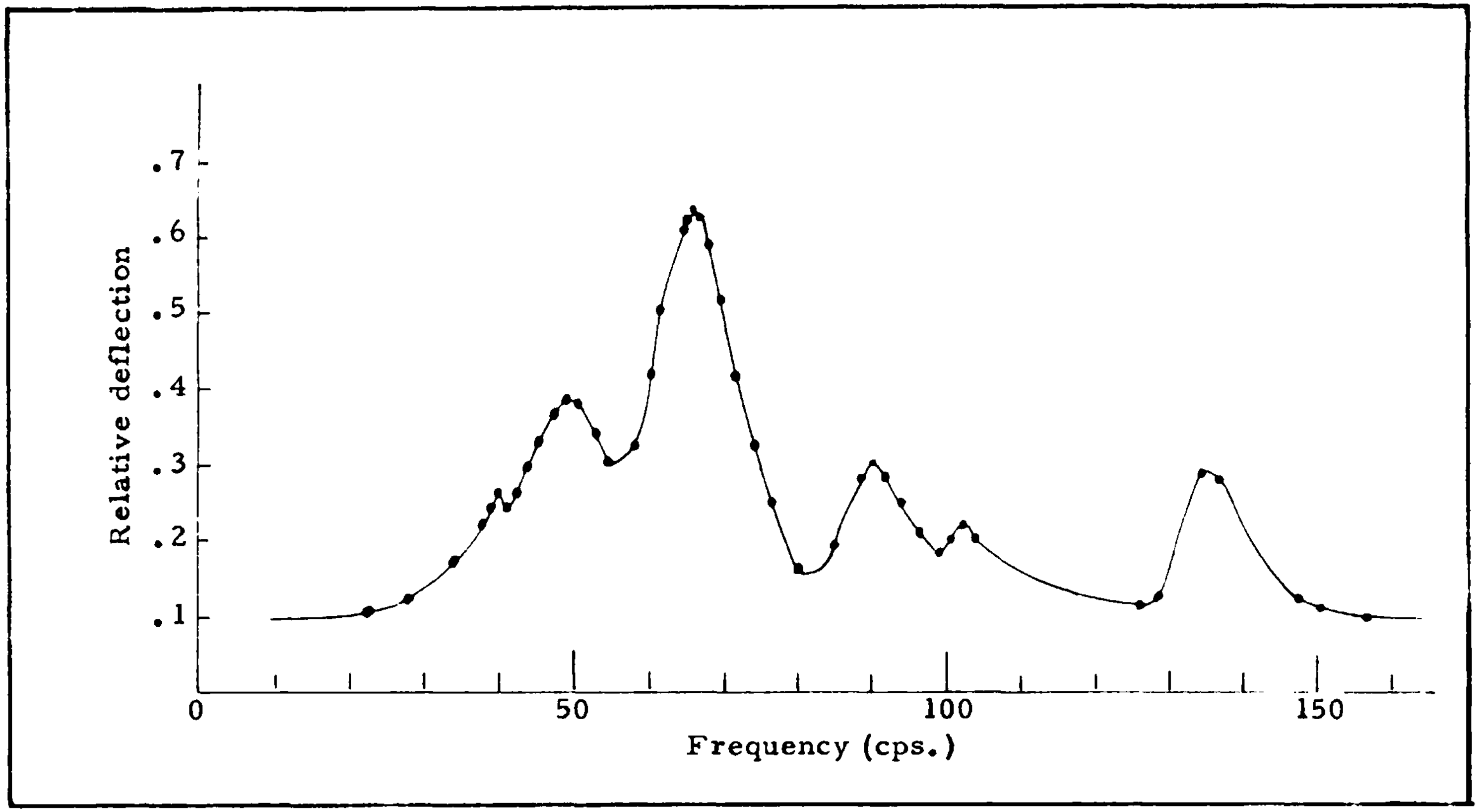

Fig. 3. Intensities of resonance deflections for differents frequencies of vibration

It was sensed at 2.7" from the driver in a caliche sample of 0.7" wide, 0.8" high and 2.7" long. No appreciable resonance was detected above 150 cps.

All the samples were vibrated in an undisturbed state, at their natural moisture content, air dried, and saturated. Some of them were placed in cardboard cans to prevent their disintegration, particularly during saturation. However, although some of them were in these cans, the driver and the pickup were always placed in direct contact with the sample, not with the can. By doing this it was hoped to decrease the effect of the can on the resonant frequency of the soil. Whenever possible the same sample was vibrated inside and outside of the can to determine these effects.

The vibration was sensed at various distances from the driver--from 0 to the total length of the sample. This permitted establishment of the relationship between the resonance frequency and the distance from the disturbance.

Resonance determinations of caliche were performed on regularly cut samples of different sizes and on samples of irregular shape. This was done to determine the size effect on the resonance frequency. Samples were tested air dried without the cardboard can.

The resonance frequency of water was also measured. This was done to determine the resonance wave form of water shown on the oscilloscope, and the influence of the amplitude of the vibration used on the resonance frequency. The amplitude of the input wave was varied 100 per cent in order to check this last point.

CLASSIFICATION AND SHEAR PARAMETERS OF STUDIED SOILS

The soil classification adopted in this thesis is based on the "Unified Soil Classification System." In this system, soils are classified according to their grain size distribution and Atterberg limits. This method permits classification of the soils into groups with similar behavior which, if they are accompanied by a brief description of the particular soil, the density and the shear parameters, furnish the basic engineering properties of the soil.

The field densities, natural moisture content and the Atterberg limits are presented in Table I.

The results of the grain size analysis are summarized in Fig. 4. To enable a better understanding of this figure, the grain size classification of the Massachusetts Institute of Technology (M.I.T.), one of the three in most common use, is provided. The extrapolated grain size distribution of the fraction finer than 200 mesh, given in dashed lines, is presented only for the integrity of the figure, and is based on the per cent of this finer fraction and its plasticity.

TABLE I: Field density, natural moisture content and Atterberg limits of studied soils

Soil Type	Sample No.	Field Density gr/cc	Natural Moisture Content %	Liquid Limit %	Plastic Limit %	Plasticity index
Poorly graded gravelly sand (SP)	S-1	1.86	5.3	16.0	-	0
Poorly graded sand (SP)	S-2	1.76	5.1	14.8	-	0
Silty sand (SM)	S-3	1.85	11.4	41.5	21.3	20.2
Inorganic sandy silt (ML)	S-4	1.51	8.1	25.3	23.8	1.5
Organic clay (OH)	S-5	1.75	27.1	71.0	40.0	31.0
Silty sand (SM)*(1)	S-6	2.02	10.3	28.1	19.4	8.7

(1) Asterisk is to differentiate this silty sand from the previous one of sample S-3.

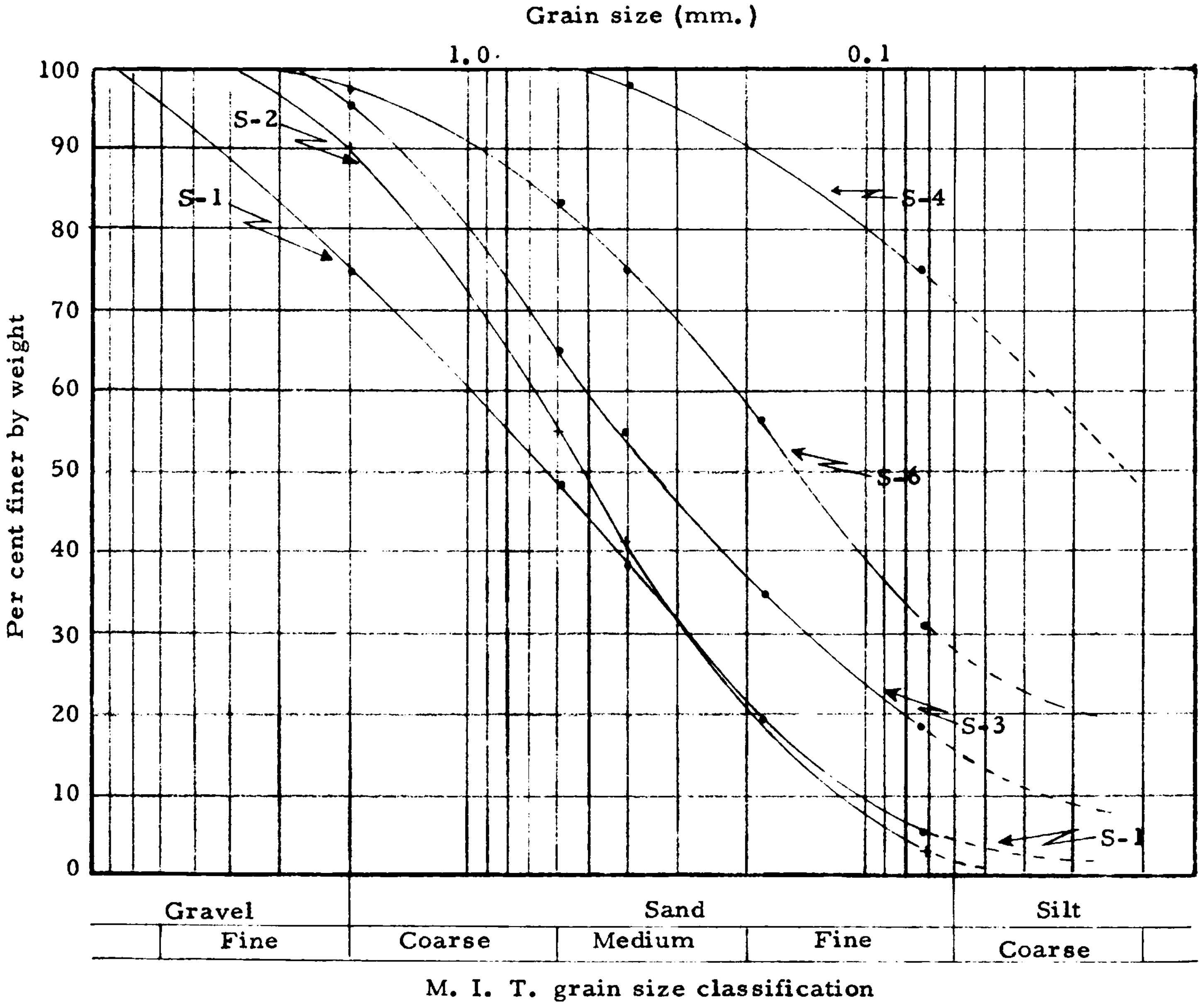

Fig. 4. Grain size distribution of studied soils

With the data presented in Table I and Fig. 4, it is possible to classify the soils into the following groups:

S-1 Poorly graded gravelly sand (SP). Soil is friable containing about 25 per cent of fine gravel particles, with maximum size of 0.8 cm., about 70 per cent of coarse to fine sand of round and sub-rounded grains, and about 5 per cent of non-plastic to slightly plastic fine fraction.

S-2 Poorly graded sand (SP). Soil is friable containing about 10 per cent of fine gravel, with particles of maximum size of 0.4 cm., 88 per cent of coarse to fine sand of round to sub-round grains, and about 2 per cent of a non-plastic fine fraction.

S-3 Silty sand (SM). This soil is fairly well consolidated containing about 5 per cent of fine gravel, with a maximum size of 2.5 mm., 77 per cent of coarse to fine sand with rounded grains, and around 18 per cent of a moderately plastic to plastic fine fraction.

S-4 Inorganic sandy silt (ML). Soil is moderately consolidated containing about 25 per cent of medium to fine sand, and the rest is a non-plastic fine fraction.

S-5 Organic clay (OH). A fairly well consolidated soil with a low content of silt, highly plastic, and possessing high dry strength.

S-6 Silty sand (SM)*. Consolidated soil with less than 5 per cent of very fine gravel, 70 per cent of coarse to fine sand with round grains, and about 25 per cent of a plastic fine fraction.

This classification and description of each soil can be further complimented with the corresponding shear characteristics.

In Table II is given the values of the normal and shear stress at failure from the several shear tests performed on each soil type. The specimen density before testing and its moisture content after testing are also presented because they show slight variations from the field conditions reported in Table I, and between various tests.

The variations between field and test densities of the two friable soils (SP) have already been explained under the procedures of testing--they were not tested in their undisturbed state. The other soils, although tested undisturbed, show slight variations between the field and test densities; usually test densities are higher than field densities. This can be explained as follows:

a.- The field density was determined on a larger sample, which would give a more representative value of the average "in situ" density.

b.- When the sample was cut to the size of the direct shear box usually the looser part of it was cut off and only the denser remained in a compact undisturbed state.

TABLE II: Failure stresses with soil density and moisture content for each direct shear test

Soil Type	Sample No.	Test No.	Specimen Density before Testing (gr./cc.)	Moisture Content after Testing (%)	Failure stresses in (Kg/cm.^{2})	
					Normal stress	Shear stress
Poorly graded gravelly sand (SP)	S-1	1	1.83	5.2	.683	.458
		2	1.87	5.0	1.185	.657
		3	1.81	5.1	1.69	.89
		4	1.90	5.1	2.19	1.09
		5	1.89	4.9	2.70	1.31
Poorly graded sand (SP)	S-2	1	1.82	5.0	.683	.52
		2	1.98	5.1	1.185	.98
		3	1.95	4.9	1.69	1.40
		4	1.93	4.5	2.19	1.90
		5	1.97	4.8	2.70	2.26
Silty sand (SM)	S-3	1	1.86	11.0	.43	.76
		2	1.87	11.0	.683	.99
		3	1.87	11.0	1.185	1.39
Inorganic sandy silt (ML)	S-4	1	1.64	8.0	.683	.28
		2	1.71	7.9	1.185	.485
		3	1.65	8.1	1.69	.56
		4	1.68	8.1	2.19	.78

TABLE II: Continued.

Organic clay (OH)	S-5	1	1.82	27.2	.683	.825
		2	1.80	28.0	1.185	.91
		3	1.84	27.9	1.69	1.03
		4	1.81	27.5	2.19	1.09
Silty sand (SM)*	S-6	1	2.0	10.0	.683	1.81
		2	1.99	10.0	1.44	2.18
		3	2.04	10.0	2.45	2.74
		4	2.06	10.0	.68	1.82
		5	2.02	10.0	1.08	2.0

c.- The field density could also be subject to errors, particularly in the measurement of the volume of the soil (volume of the hole). The volumes of the shear test specimens, were determined by mercury displacement. This measurement is probably more correct; however, it is representative of only a small specimen.

The deviations of the moisture content from the natural state is probably due to evaporation during the test. The ambient temperature of the laboratory favored high evaporation. The different duration of each test was probably the cause of the slight difference in moisture content between one test and the other.

The shear diagrams for each soil type are presented in Fig. 5 and Fig. 6. They were obtained by plotting the normal stresses vs. the shear stresses of Table II. Values of internal friction and cohesion obtained from these figures are summarized in Table III.

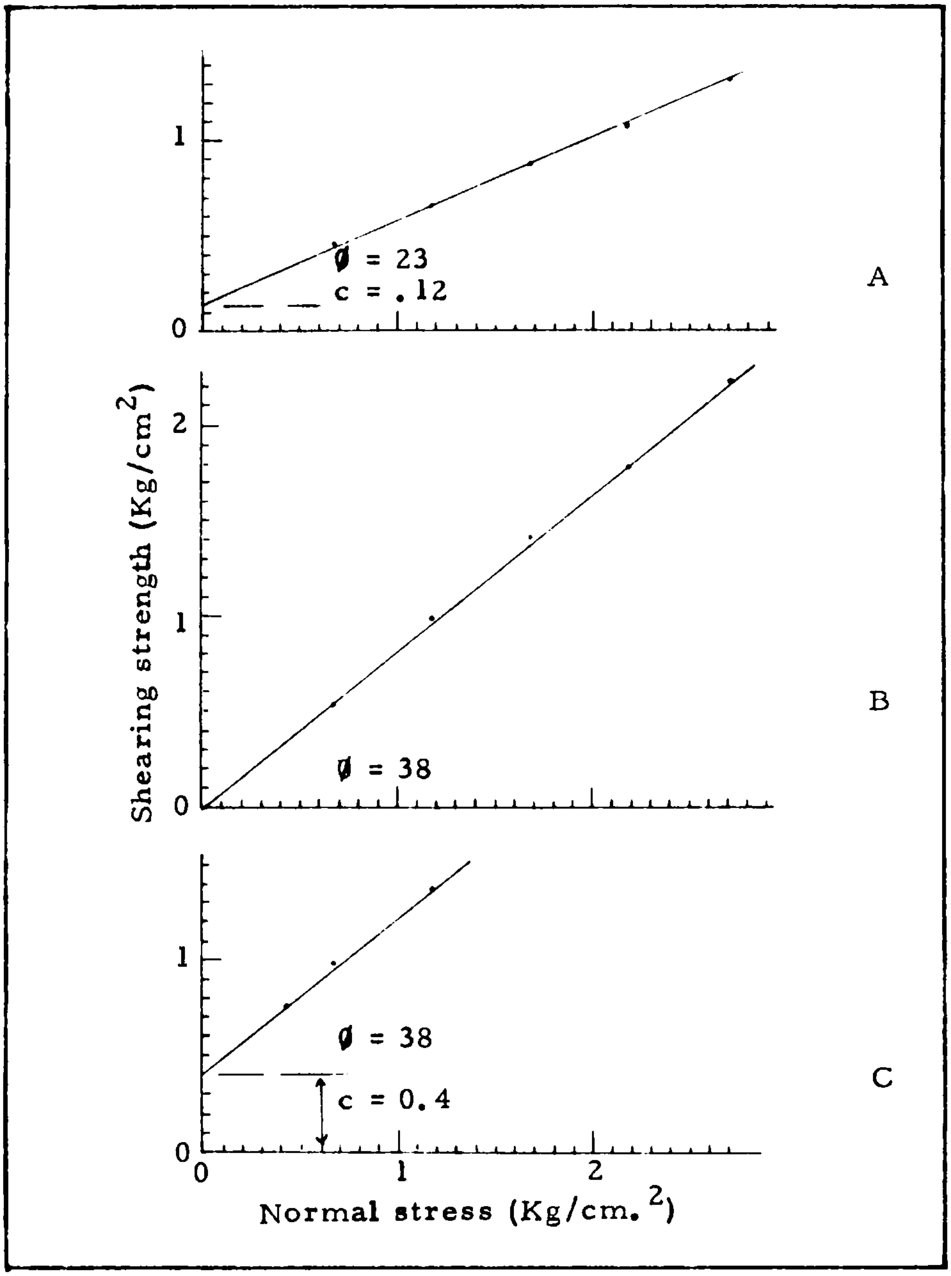

Fig. 5. Shear diagram of studied soils

A. Poorly graded gravelly sand (SP)
B. Poorly graded sand (SP)
C. Silty sand (SM)

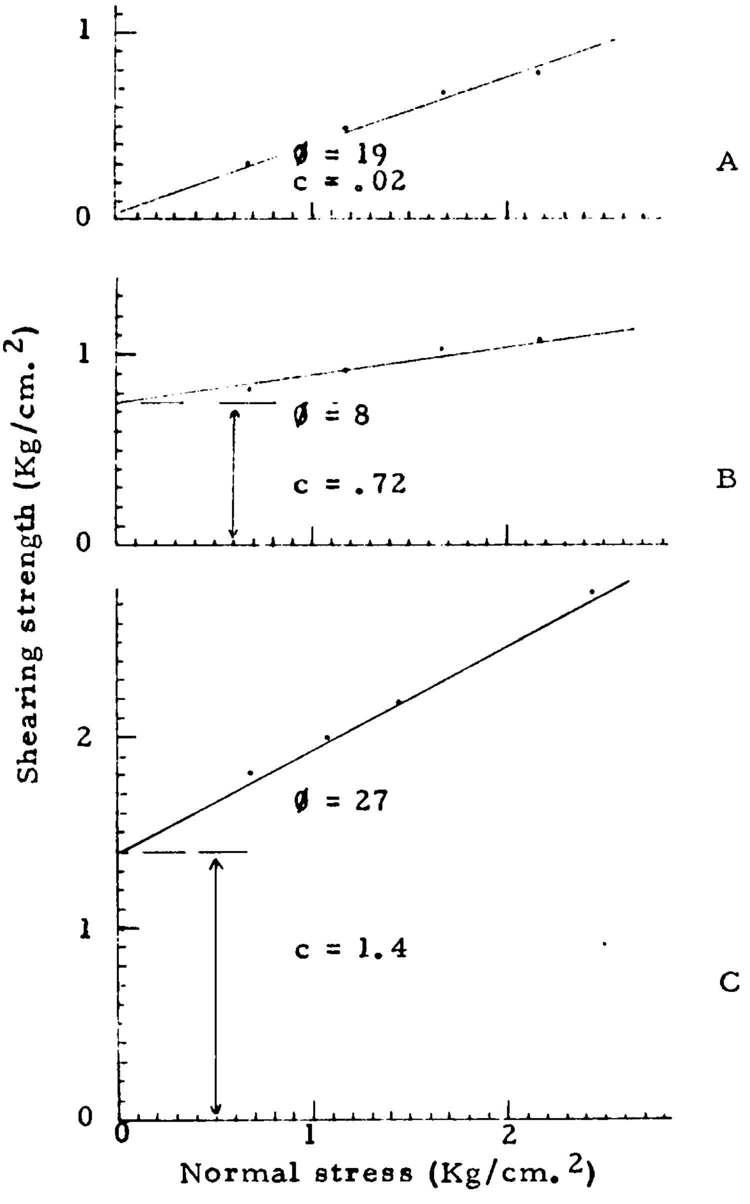

Fig. 6. Shear diagram of studied soils

A. Inorganic sandy silt (ML)
B. Organic clay (OH)
C. Silty sand (SM)*

TABLE III: Shear parameters of studied soils

Soil Type	Angle of Internal Friction (Ø)	Cohesion (c) in Kg/cm.^{2}
Poorly graded gravelly sand (SP)	23	0.12
Poorly graded sand (SP)	38	-
Silty sand (SM)	38	0.40
Inorganic sandy silt (ML)	19	0.02
Organic clay (OH)	8	0.72
Silty sand (SM)*	27	1.40

RESONANCE RESULTS AND ANALYSIS

As might be expected the response to vibration was different for each material tested. Therefore, the data obtained from the resonance frequency determination will best be analyzed independently for each material type.

Poorly Graded Gravelly Sand (SP)

The data shown in Fig. 7 were obtained on vibrating, at different time intervals, an undisturbed sample of poorly graded gravelly sand at natural moisture content in a cardboard can. In this figure the resonance frequency was plotted versus the distance of sensing it from the driver.

The tests were conducted in the following order: the first point sensed was of curve a at 3.8 inches from the driver. After this point was sensed, the determination was repeated for all the points marked in curve a, gradually from 3.8 inches to 0 inches. In the same order, and immediately later, the points of curves b and c respectively were determined. Curve d was obtained in the same manner, but measurements were made two days later; no

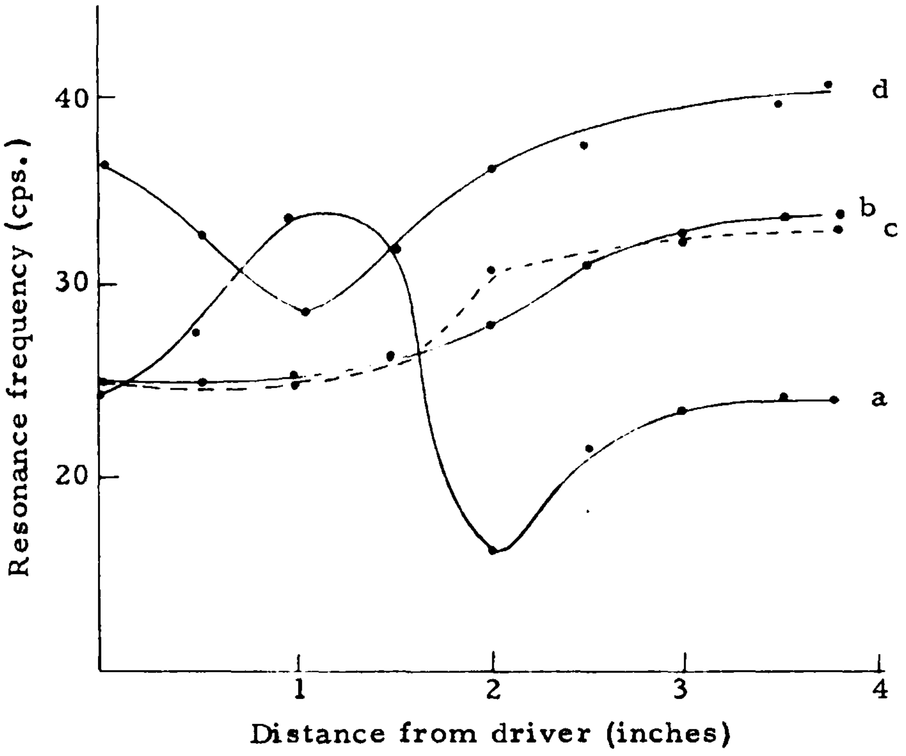

Fig. 7. Resonance behavior, at different time intervals and distances from the driver, of poorly graded gravelly sand (SP)

Curves a, b and c were measured in this same order one after the other. Curve d was measured two days later, but at the same moisture content.

appreciable change in the moisture content was permitted during this time.

The irregular shape of these curves seems to be due to a component effect of: history of previous vibration and distance between the driver and the sensed point related to the length of the sample. However, it was not possible to distinguish how much was due to one cause and how much to the other.

The change in resonance due to the previous vibration history can be explained in terms of change in the density and intergranular linking of the soil. As it can be seen from the classification of this soil, it corresponds to a friable type of soil with almost no cohesion. Consequently, it is probable that as soon as vibration of the soil is started there is grain rearrangement toward a denser state thus changing the resonance frequency. The rate of this densification was not determined, but, as it can be seen from the relative position of curves a, b, c, and d, and the interval of time between one determination and the other, the greater percentage of the change in density occurred at the beginning of vibration. Later curves b and c remained more or less close together.

The higher frequencies obtained two days later (curve d), may be explained as due to an increase of effectiveness of the cohesion in the finer material to link the particles of the soil, now that they are more closely packed. Effectively there is an increase of strength of the material as consequence of densification and time. A similar effect was observed when this sample was air dried after saturation. If this increase of strength is related to thixotropy, resonance measurements could also be useful in the determination of the degree of thixotropy of soils. For this purpose it will be necessary to investigate the relation between the increase of resonance frequency and the increase of strength in different soils.

Although curve d shows higher resonances frequencies, its shape is almost parallel to curve c (only the resonance at 0 distance is different). In other words, there is a gradual change in the shape of the curves from a toward d, which is interpreted to be a consequence of a gradual increase in density and then linking between particles.

The general effect that distance of sensing from the driver has on the resonance frequency is related to the length of the sample, but is not yet clear. In almost all the samples, particularly in small ones, the resonance frequency is usually smaller around the middle distance range. See Figures 9, 12 and 13. However, for larger samples, as will be seen later, when the frequency is plotted versus the distance of sensing from the driver it produces a curve whose shape is similar to a sine wave. See Figure 19.

The only conclusive fact is that the resonance frequency is affected by at least: density, linking of particles (cohesion or cementation) and distance from the driver. These **variables** are all interrelated and are reflected in the shape of curves in Fig. 7 and the following figures. The determination of the real meaning of distance on the shape of these curves is not possible unless each variable is studied independently by keeping constant all the others.

After the results of Fig. 7 were obtained, the sample was saturated with water and then vibrated, always inside of the cardboard can. The results are presented in Fig. 8, where the curve e was obtained in the first set of measurements and curve f immediately later.

It can be seen that in this case also there was a change of shape of the curves e and f. The shape of curve f tends to resemble the shape of curve a of Fig. 7, but resonance values are not the same. In curve a (Fig. 7) the lowest value is at 2.0 inches from the driver and the higher at 1.2 inches, and in curve f (Fig. 8) these values are at 3.0 inches and 1.5 inches, respectively. The difference in resonance values could be due to the difference in moisture content of each sample during resonance determinations; one was saturated and the other was at natural moisture content.

Fig. 8. Resonance behavior of saturated poorly graded gravelly sand (SP)

Measurements were taken first for curve e followed immediately for curve f.

The similarity between curve f and curve a can be explained as follows: the moisture content of the saturated sample was 22 per cent, thus higher than the liquid limits of this soil which is 16 per cent. By vibrating this soil in this condition it very probably produces a tendency to a rearrangement of grains toward a looser state. This is probably what is reflected in the change of the shape of curves in Fig. 8. The curve f represents resonance frequencies in a looser state than curve e, thus resembling curve a of Fig. 7.

In fact, desiccation of the sample after saturation caused the sample to develop a relatively high degree of adherence between the grains, higher than in the undisturbed state; and it was possible to take the soil out of the cardboard can and measure the density and the resonance frequency in this new state. The density was 1.78 gr/cc, equivalent to the dry density of the undisturbed state. This similarity of density shows that by vibrating the soil at higher moisture content than the liquid limit, and without confining pressure, the tendency of granular soil is to become less dense. This effect can be related to liquefaction.

The resonance frequency of this soil without cardboard can is presented in Fig. 9. Resonance values for curves g and h were measured at intervals of several days during which the sample was kept under ambient conditions. Both curves show very similar

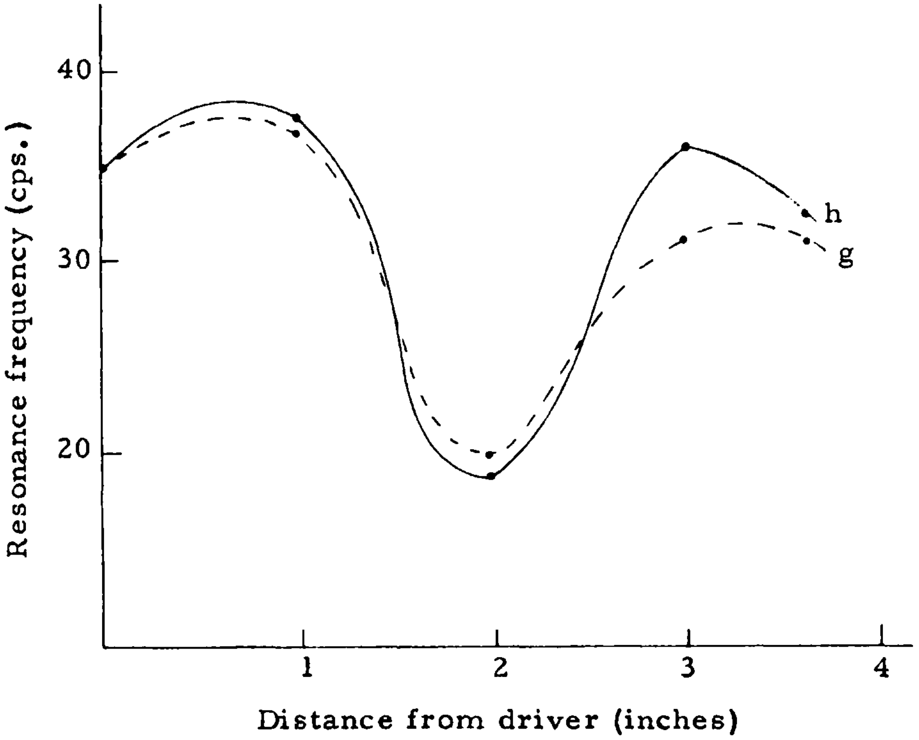

Fig. 9. Resonance behavior of air dried, poorly graded gravelly sand (SP), without cardboard can

Curves g and h were determined at several days of interval.

patterns indicating no additional rearrangement of grains. The small differences between one curve and the other may be the result of minor changes in the sample during the time that it was kept under ambient conditions.

If the shape of the curves in Fig. 9 is examined, it is possible to see a close relationship with curve a of Fig. 7. This similarity can be attributed to the close density of the soil during the test. However, the following differences can be observed: (1) Resonance frequencies of curve a are generally lower, especially around the extremes of the sample than for curve g and h; (2) Curve a is supported with resonance readings at closer intervals.

The difference in resonance frequencies between curve a and curves g and h of Fig. 9 are probably related to the different conditions under which the test was run. Some of these are:

(1) For curve a the test was run with cardboard can. For curves g and h the test was run without cardboard can.

(2) For curve a cohesion between the grains was not enough to link the grains particles together. For curves g and h the cohesion was strong enough to link grains, not permitting rearrangement of grains during and after testing.

(3) Curve a was transitional to curve d (Fig. 7). Curves g and h were stabilized.

(4) Curve a was at natural moisture content. Curve g and h were measured when the sample was air dried.

The preceding discussion shows that for a poorly graded gravelly sand the resonance frequency is a function of variables that can easily change from one test to the other, and sometimes during the same test--density, for example. Consequently, for natural conditions it is not possible to give an absolute value for natural frequency unless all variables are studied and their effects on the resonance frequency clearly established. Therefore, a range of frequencies is given that can produce resonance dependent upon the condition of the soil. For this type of soil the range is between 20 and 40 cycles per second.

Poorly Graded Sand (SP)

The results of resonance determination for a poorly graded sand (SP) are presented in Figs. 10 and 11.

Fig. 10 shows a series of measurement taken on an undisturbed sample inside of a cardboard can. Curves a, b, and c are measurements performed at natural moisture content and curve d under saturated conditions.

The sequence of measurements was the same as in the previous soil sample starting from a distance of 3.8 inches and gradually

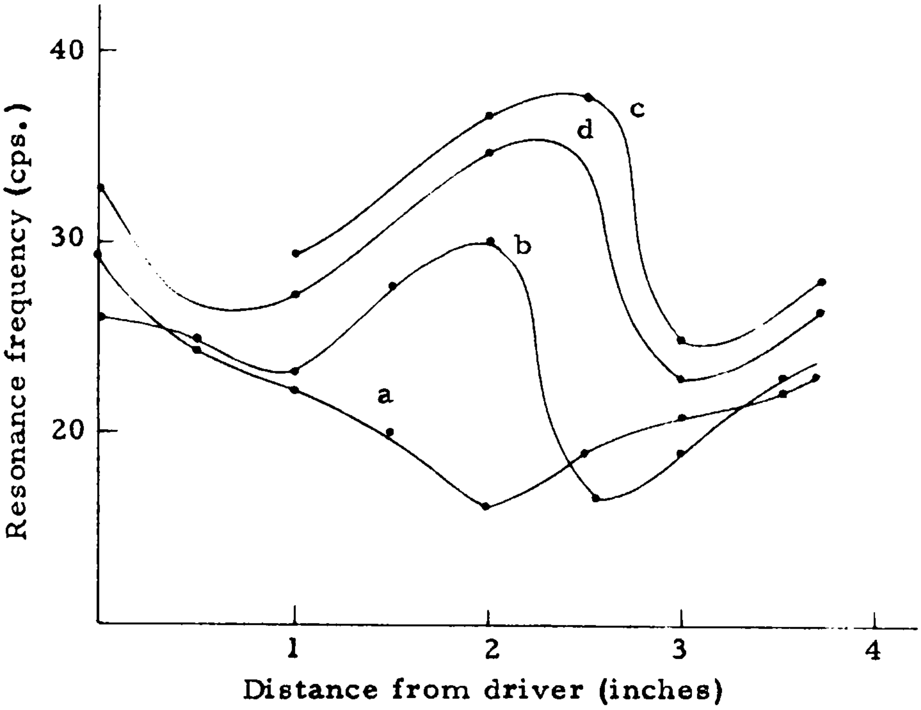

Fig. 10. Resonance behavior of poorly graded sand (SP)

Curves a, b and c were consecutive measurements at natural moisture content; c, two days later. Curve d was determined under saturation conditions.

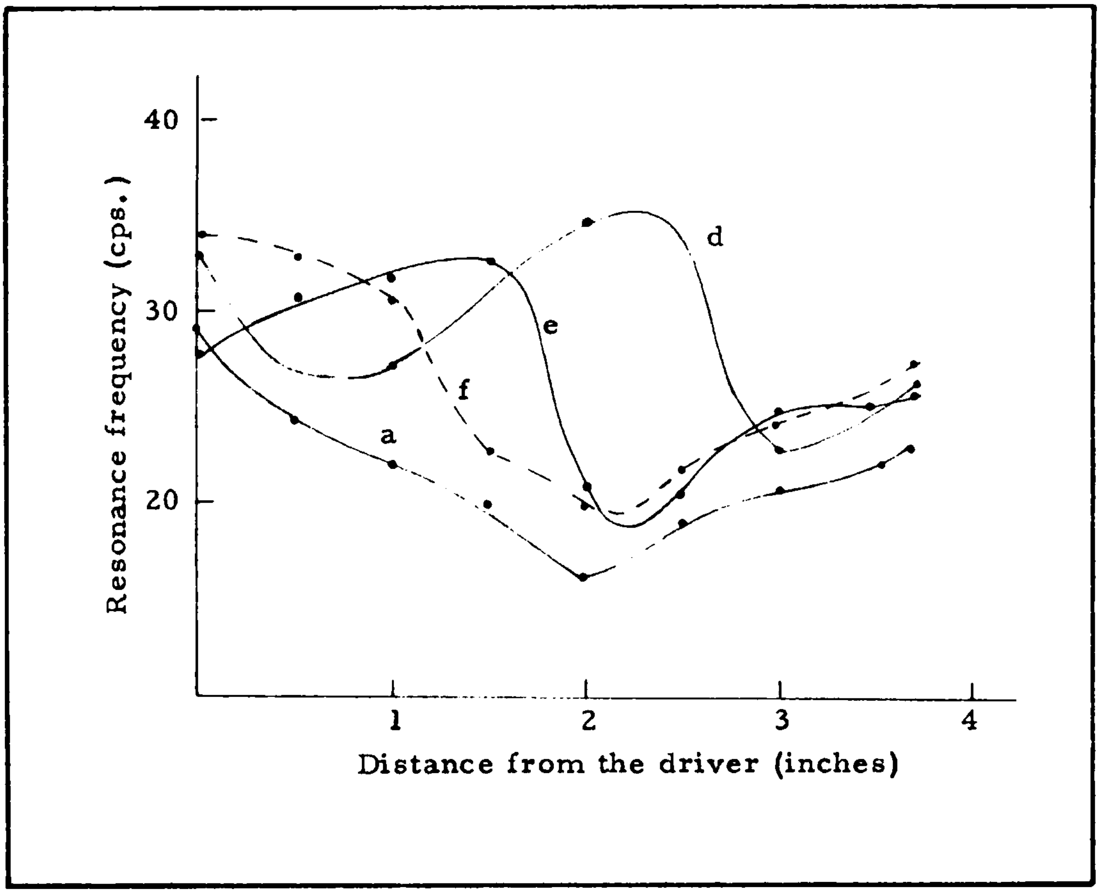

Fig. 11. Resonance behavior of saturated, poorly graded sand (SP)

Curve a is for comparison with curve f. Curves d, e and f are consecutive measurements on the sample in a saturated condition. (Saturation moisture content = 24.5%, liquid limit = 14.8%)

approaching 0 distance from the driver. Curves a and b were determined one after the other, and curve c two days later, during which the natural moisture content was carefully preserved.

It is possible to observe that there is a gradual change of the resonance frequency during vibrations from curve a to curve b, and two days later to curve c. This soil also has been classified as a friable granular type, with a weak intergranular adhesion. In fact, as measured by the direct shear test, the cohesion is nil. Consequently, these resonance changes can also be explained in the same manner as those for the first soil analyzed.

The shape of the curves for this soil are different from the first, but the soil also is different--especially in the percentage of the coarse and fine fraction. Resonance frequency for poorly graded sand are in general lower than for the poorly graded gravelly sand, but also the field density and the amount of cohesion is lower in the poorly graded sand. An important point is that in both instances there is evident an immediate change in the resonance frequency toward higher values as soon as the sample is vibrated. This change reflects the densification that the sample undergoes during vibration under the test conditions.

Another phenomena common to these two similar soils is the general decrease of the resonance frequency when the sample is saturated. The moisture content during saturation was 24.5 per cent and the liquid limit of the soil is 14.8 per cent; as in the previous soil the sample was saturated inside of the cardboard can. Curve d in Fig. 10 permits a comparison between the first measurement in the saturated condition and the measurements at the natural moisture content. Resonance values along curve d are less than for curve c although the shapes of both curves are very similar.

In Fig. 11 are presented three consecutive series of measurements of resonance in the sample at saturation, and for comparison, the first measurements in the undisturbed state, curve a. It can be seen that there is a gradual tendency to change the shape of the resonance curves from d to f; curve f being very similar to curve a. In general the similitude of curves for this soil is: curve d with c, curve e with b, and curve f with a. It seems clear then that the effect of vibrating this type of soil at a moisture content above the liquid limit is the opposite to densification which occurred at natural moisture content. It is important to note that these effects would not be noted if resonance frequency is measured only at one point on the sample--the results would be too confusing to enable interpretation.

Unfortunately this soil did not develop sufficient cohesion after desiccation to permit it to be taken from the can to measure its density and resonance behavior without the can. It might be concluded that the relative displacement of resonance frequency as the tests progressed reflected in the shapes and locations of the curves in Figs. 10 and 11, indicates a common behavior of both soils. In other words, the two (SP) soils undergo densification at natural moisture content and dedensification under saturated conditions. However, the range of resonance frequency under each test condition is generally lower for the poorly graded sand which ranges from 20 to 35 cycles per second.

Silty Sand (SM)

A sample of silty sand (SM) was a cohesive soil and it was possible to vibrate it without the cardboard can. Fig. 12 shows the resonance behavior of three specimens of this type of soil, of different densities and sizes, but without an appreciable difference in the moisture content. Curve a represents a specimen 4 inches long, 3 inches high and 3 inches thick, with a density of 1.85 gr/cc. Curve b was determined on a specimen of 2.3 inches in diameter and 1 inch high, with a density of 1.86 gr/cc., and curve c on a specimen used in the direct shear test, of 2.3 inches in diameter and 1/2 inch high, with a density of 1.89 gr/cc.

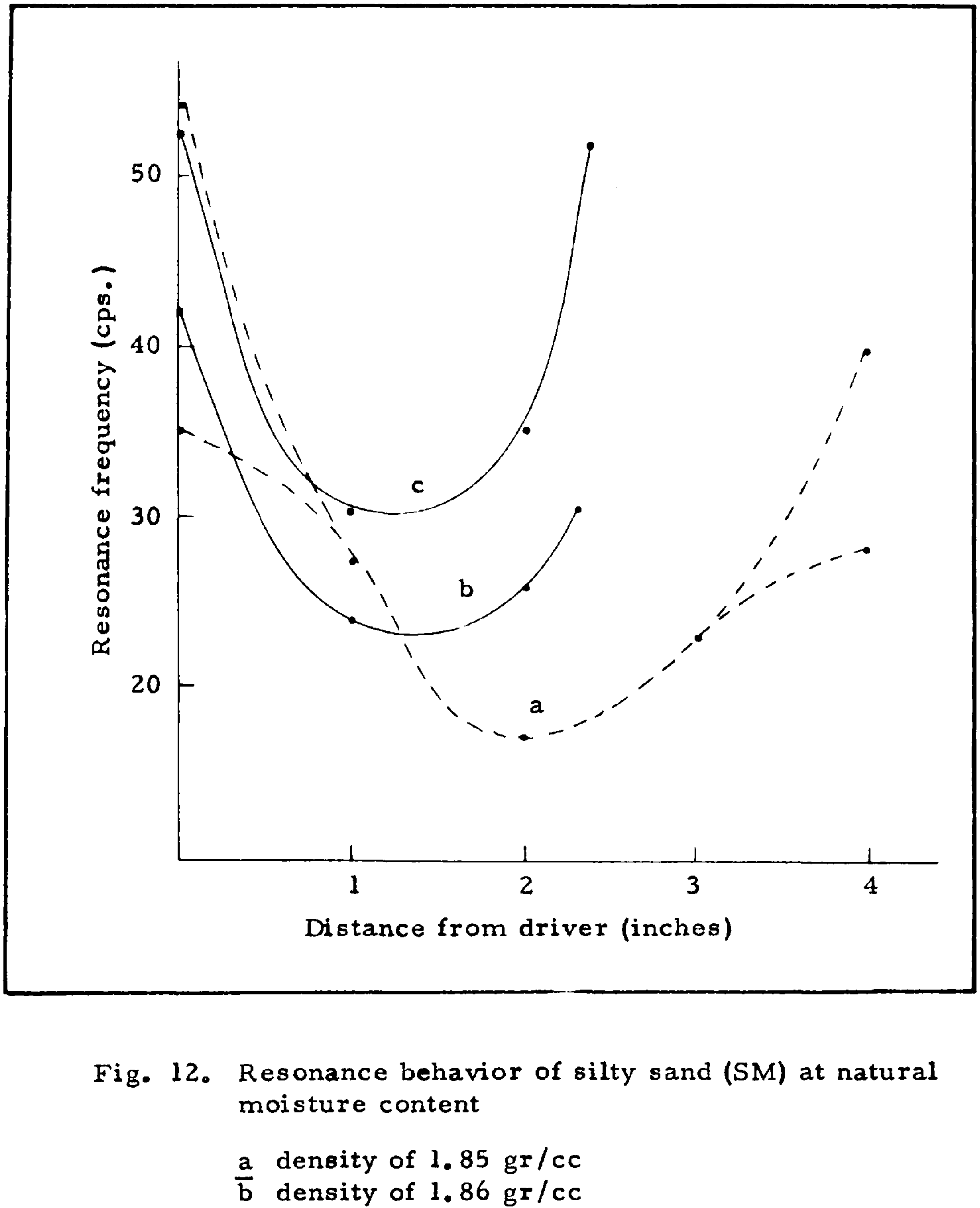

Fig. 12. Resonance behavior of silty sand (SM) at natural moisture content

a density of 1.85 gr/cc
b density of 1.86 gr/cc
c density of 1.89 gr/cc

It is possible to see that these three curves are very similar in shape, although they are displaced with respect to each other. The relative displacement may be partially due to the difference in density and partially to the difference in size of the samples. The general tendency, pointed out previously, of showing lower resonance frequencies toward the middle of the measured range is very accentuated in these examples.

It can also be noted the curve a is divided in two branches at the extremes. In the resonance readings at 0 and 4 inches from the driver there were two resonance frequencies that showed the same deflection on the "resonance indicator" of Fig. 5, and did not permit identification of which was fundamental. This effect may be due to the large size of the sample. In shorter samples lower resonance frequencies are obtained in the middle of the sample, and higher on both extremes; and, the difference between the lower and higher resonance frequencies seems to be greater for shorter specimens. In samples larger than 4 inches, the shape of the curves becomes similar to the sine wave. Curve a of Fig. 12 may probably reflect the transition shape.

In Fig. 13 it is possible to compare curve c, obtained at natural moisture content, with curves d and e, obtained in the same sample after it was air dried. Although curve e was determined

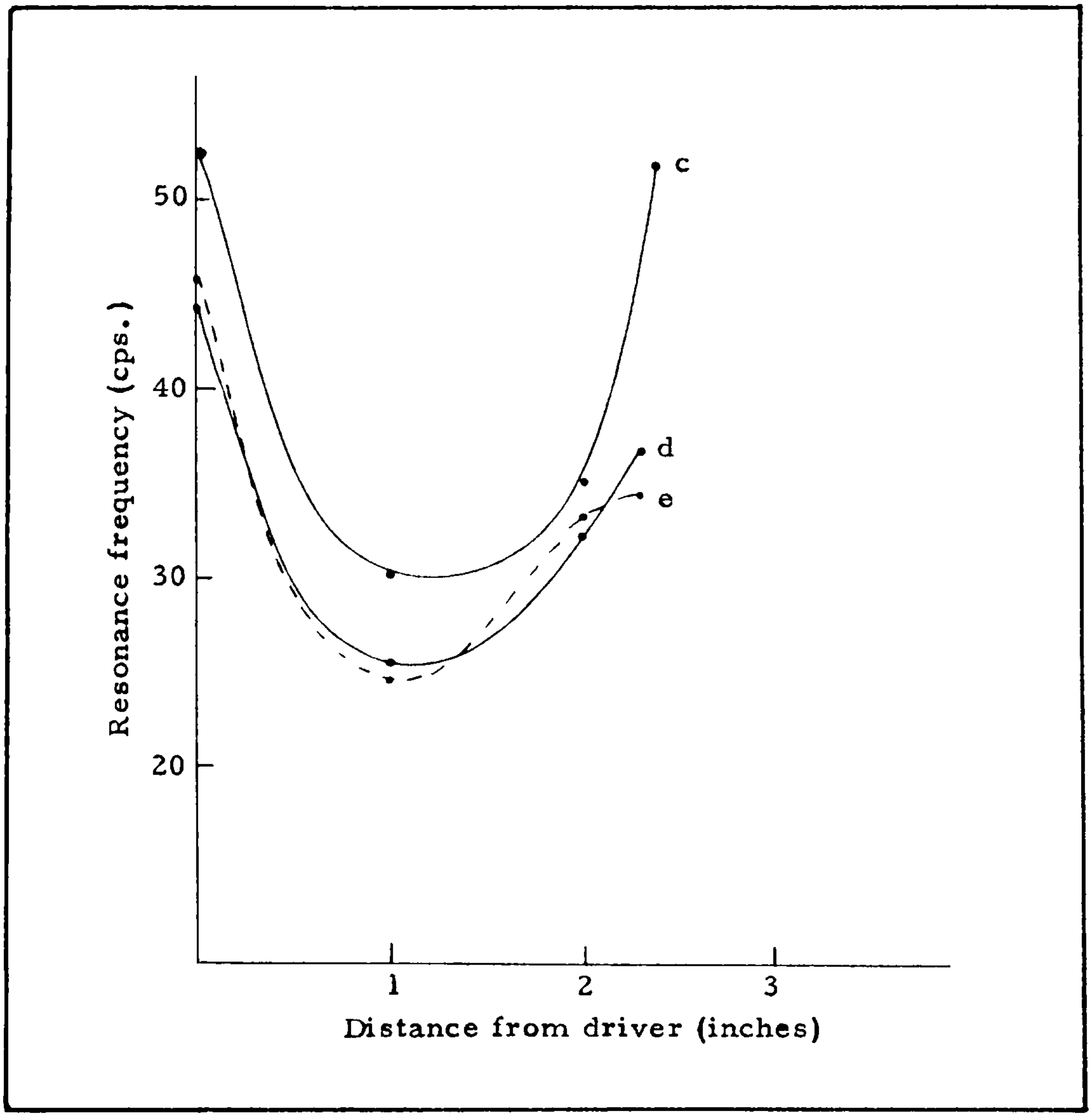

Fig. 13. Resonance behavior of silty sand (SM), with change of moisture content

c moisture content = 11.4%
d and e = air dried

5 days after curve d the resonance frequency curve is very similar. From curves of Fig. 13 it is possible to appreciate the general decrease of resonance frequency due to the decrease of moisture content. This effect is very important and will be seen in other samples.

Although it was attempted to determine the resonance behavior of this soil under saturation conditions, it was not achieved because the sample took the consistency of a liquid suspension and was not representative of the solid soil.

For this soil it can be concluded that resonance increases with increase of density and moisture content within limits. The shape of the curves, when plotting resonance versus distance from the driver, are a function of the length of the sample. The general range of resonance frequencies is between 20 and 50 cycles per second, depending upon the above named variables and being very high at the extremes of the sample. Fig. 12 and 13 illustrate these variations.

Inorganic Sandy Silt (ML)

Two undisturbed specimens of inorganic sandy silt (ML) were vibrated in cardboard cans. Vibration procedure and presentation of results is the same as described for previous soils.

Fig. 14 shows the resonance behavior of these two specimens. Resonance frequencies were determined twice for each curve of the figure, and no appreciable change was observed between one trial and the other. This indicates that vibration did not produce further densification of the soil. In other words, the soil is at a higher density than the one that vibration could produce at its natural moisture content, or cohesion was sufficient to prevent rearrangement of grains.

The difference in resonance frequency between one sample and the other may be due to variations of the natural characteristics of both samples or differences in the cans. However, the shape of both curves is very similar, as usual,both show lower resonance frequencies around the middle of the measured traverse across the sample. In this instance the sample length seems to be approaching the transition where the shape of the curve starts to resemble a sine wave, with some damping effects at an increasing distance from the driver. This effect will be clearly seen in a 14 inches long sample of caliche.

The sample used to determine the resonance frequencies of curve a Fig. 14 was also tested at different moisture contents--above and below the liquid limit of 25.3 per cent. The results are given in Fig. 15a in which curve a is also shown for comparison.

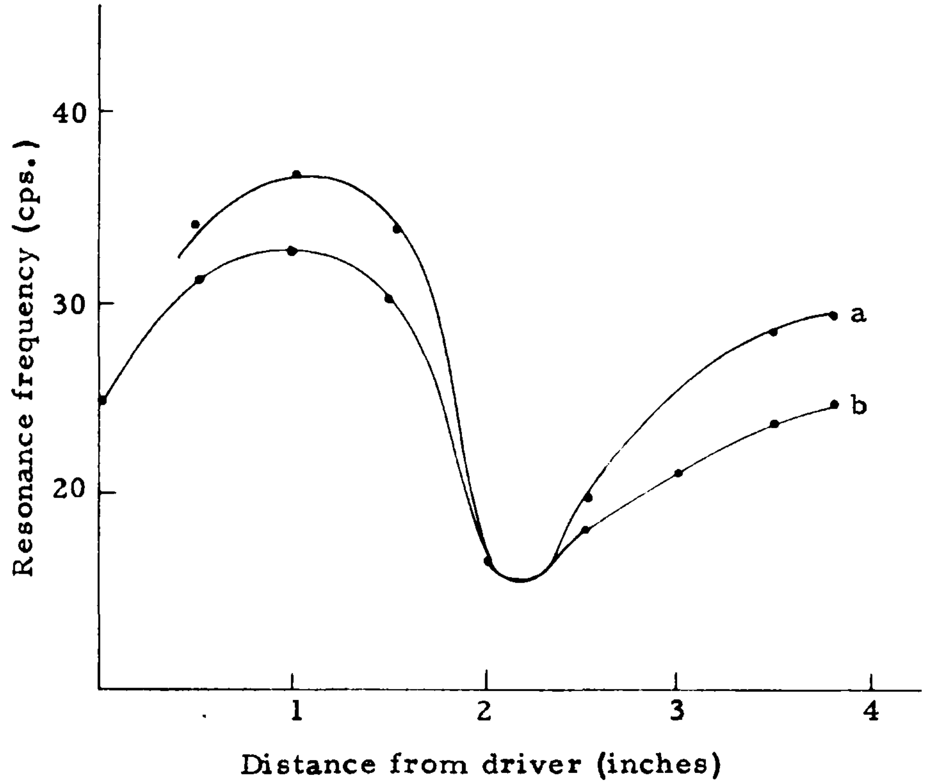

Fig. 14. Resonance behavior of inorganic sandy silt (ML)

Two undisturbed samples were measured at natural moisture content; a is for one sample and b, for the other.

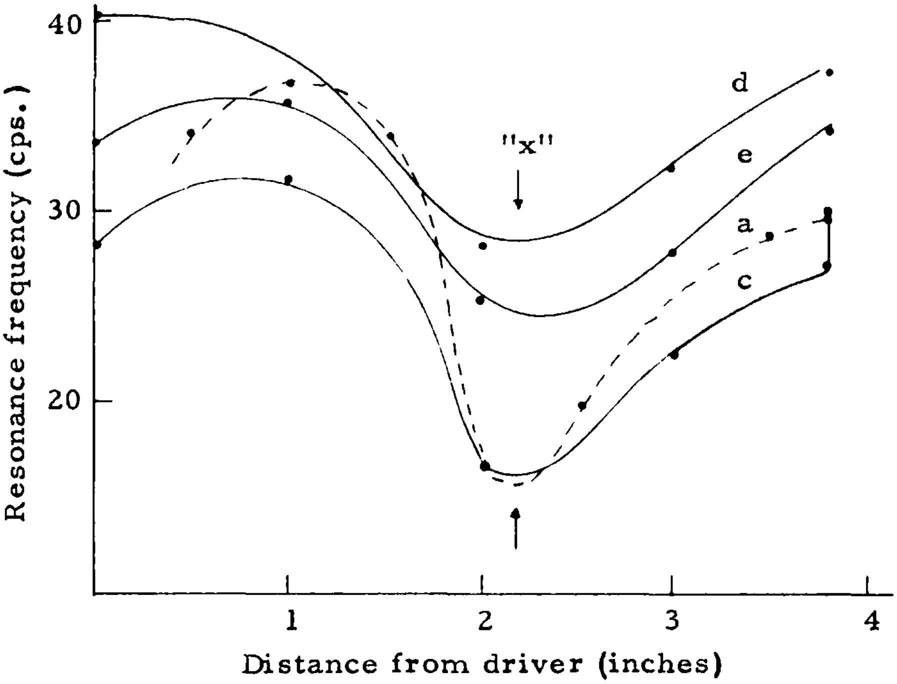

Fig. 15a. Resonance behavior of inorganic sandy silt (ML), at different moisture contents

a- undisturbed and at natural moisture content-8.1%
c- moisture content at saturation--32.8%
d- moisture content--18%
e- moisture content--10.4%

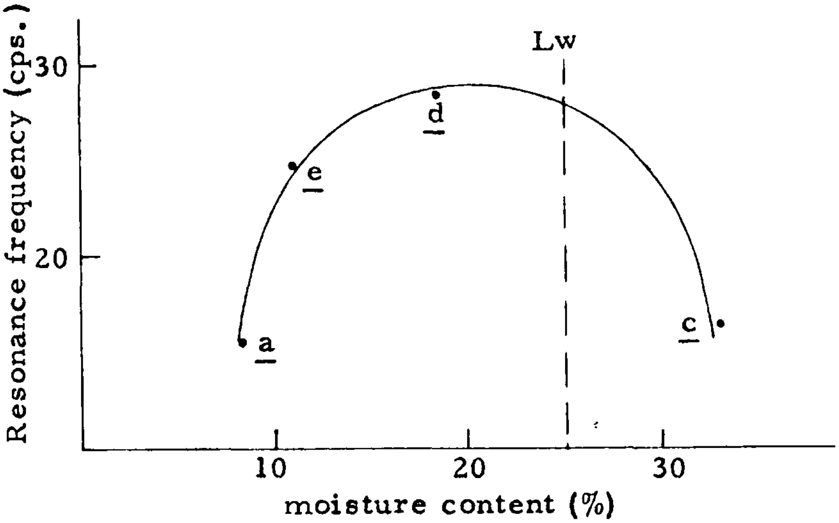

Fig. 15b. Effect of water on resonance frequency at point "x" of Fig. 15a

Lw = liquid limit of the soil--25.3%

The order of the determination was: first, curve c at moisture content of 32.8 per cent; then, curves d and e, respectively, at moisture contents of 18 per cent and 10.4 per cent.

It can be seen that curve c (Fig. 15a), shows a sharp drop of resonance frequency from 30 cycles per second to 27 cycles per second immediately after starting vibration. This probably indicates a rearrangement of grains towards a looser state than the natural. It can also be clearly observed that at higher moisture content there is a general higher resonance until the liquid limit is exceded. The general range of resonance frequency for this soil is between 20 and 40 cycles per second.

Observations indicate that at moisture content less than the liquid limits, the resonance frequency increases with the increase of the moisture content. And, at moisture content above the liquid limit, the resonance frequency decreases. The point at which the resonance frequency starts to decrease with the increase of moisture content has not been determined, but it is believed that it corresponds with the liquid limit of the soil, especially for granular soils (Figure 15b).

Supporting this theory are the observations on the (SP) type of soils where vibration at moisture above the liquid limit of the soil, and without confining pressure, decrease the resonance frequency. This may be related to liquefaction. At the same time, it is observed in Fig. 13, that resonance frequency of the same sample is higher at natural moisture content than when air dried. The same relation is also observed in Fig. 15a where resonance frequencies of curve d are higher than for curve e, and curve e higher than curve a--the same relation as their moisture content.

Consequently, it seems that the increase of the resonance frequency of a soil with an increase in moisture content can be related to the liquid limit. The liquid limit is supposed to indicate the water content of a soil that causes a change from plastic solid to viscous liquid behavior, consequently there is a change in the physical properties of the soil.

If it can be proven that resonance frequency of the soils, at least cohesionless soils, increases with increasing moisture content up to a point where the available moisture changes the resonance frequency toward a gradual or sharp decline, it would determine a point at which there is a change in physical properties of the soil. This point may not exactly coincide with the rather empirical value of the liquid limit determined by the standard procedure, but it would have a real physical meaning. It would represent a point where at least one physical property of the soil changes. At the same time it might enable definition of the liquid limit of a soil by another method, and would permit its determination in the undisturbed soil without a previous selection of grain size. The test could be performed by gradually increasing the moisture content of the soil while measuring resonance.

Organic Clay (OH)

Two undisturbed samples of an organic clay (OH) were taken for resonance measurements--one in a cardboard can and the other without it. Resonance measurements under saturation conditions were not obtained.

Fig. 16 summarizes the results of these determinations. Curve a was obtained on the sample without the cardboard can at its natural moisture content of 27.1 per cent. The resonances obtained on the specimen within the cardboard can are shown in curves b and c; curve b at natural moisture content and curve c at a moisture content less than the natural, but not determined. The sample was allowed to dry for two days but was not completely air dried.

From the results it can be observed that the lower resonance frequency around the middle of the resonance traverse is persistent also for this soil. The difference in resonance frequencies between curves a and b are probably not entirely due to the cardboard can used in the determination of curve b. It must be kept in mind that they were determined on two different specimens and conditions of

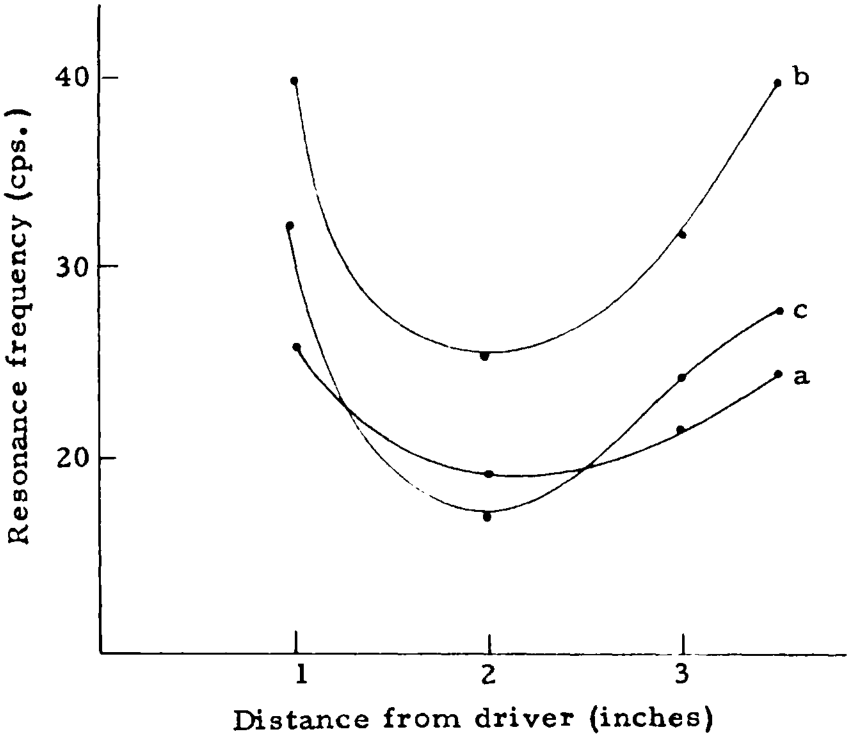

Fig. 16. Resonance behavior of organic clay (OH)

a - Sample without cardboard can, at natural moisture content
b - Sample with cardboard can, at natural moisture content
c - Sample with cardboard can, at lower moisture content than natural

density, moisture content and disturbance of the sample may vary within limits. The general increase of resonance frequency with the increase of moisture content can be observed in the relations of curves b and c. The average range of resonant frequency of this soil can be considered between 20 and 40 cycles per second.

Silty Sand (SM)*

The resonance results of two specimen of silty sand (SM)*, at natural density and moisture content, are presented in Fig. 17. Cardboard can containers were not used for these determinations. The typical low resonance frequency at the middle of the traverse is strongly accentuated in this soil; probably due to the short length of the sample. The small difference of resonance frequencies between curves a and b are probable consequences, as in the previous soil, of differences between the two specimens. In this instance even the size of the specimens is different.

The specimen used for the determination of curve a was placed in a can which permitted measurement of the resonant frequencies at various moisture contents. The results are shown in Fig. 18a. Curve b is repeated from Fig. 17 for comparison with curve c which represents the same specimen, but vibrated in the can. The general difference between curve b and c is of the order

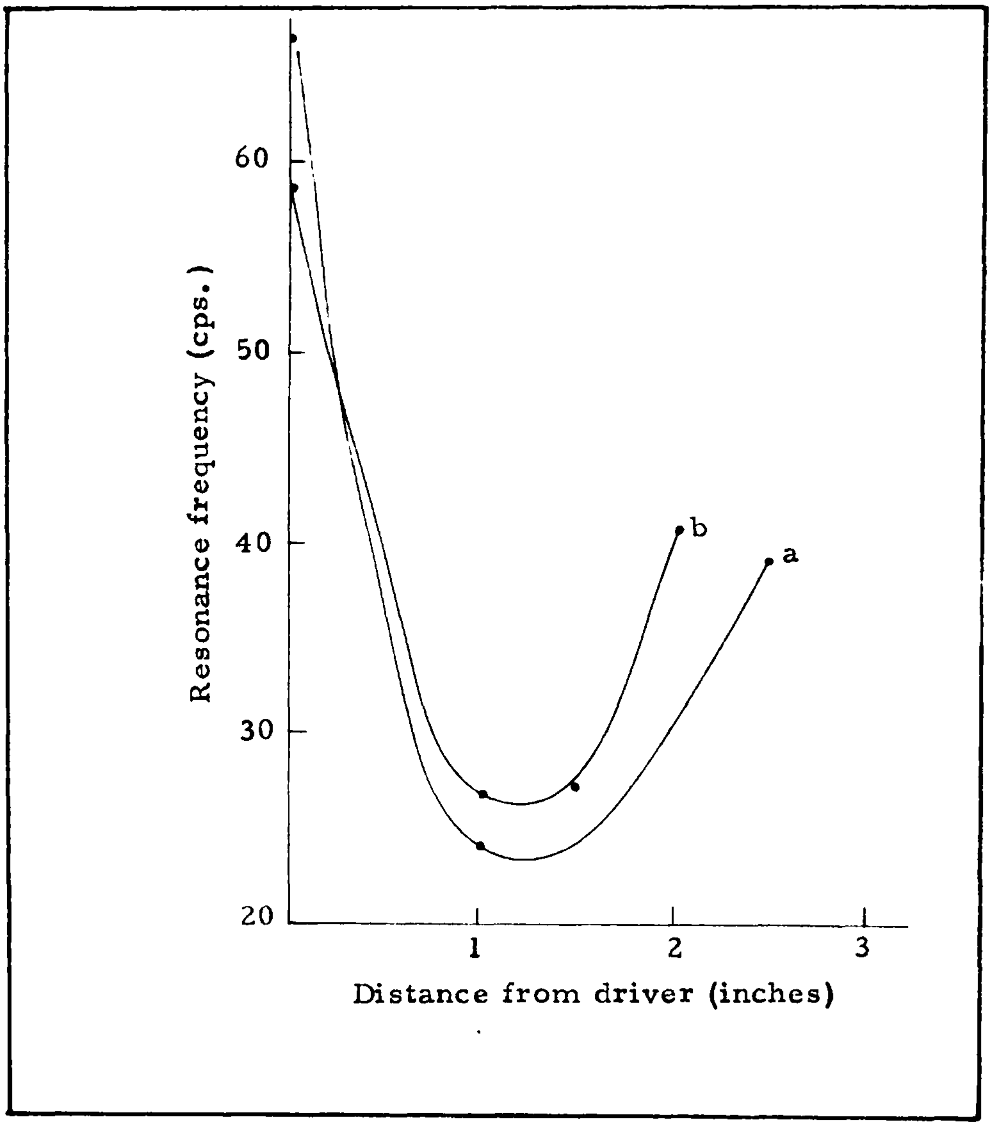

Fig. 17. Resonance behavior of silty sand (SM)* in its natural state

a - Specimen of 2.5" long, undisturbed and at natural moisture content

b - Specimen of 2" in diameter, undisturbed and at natural moisture content

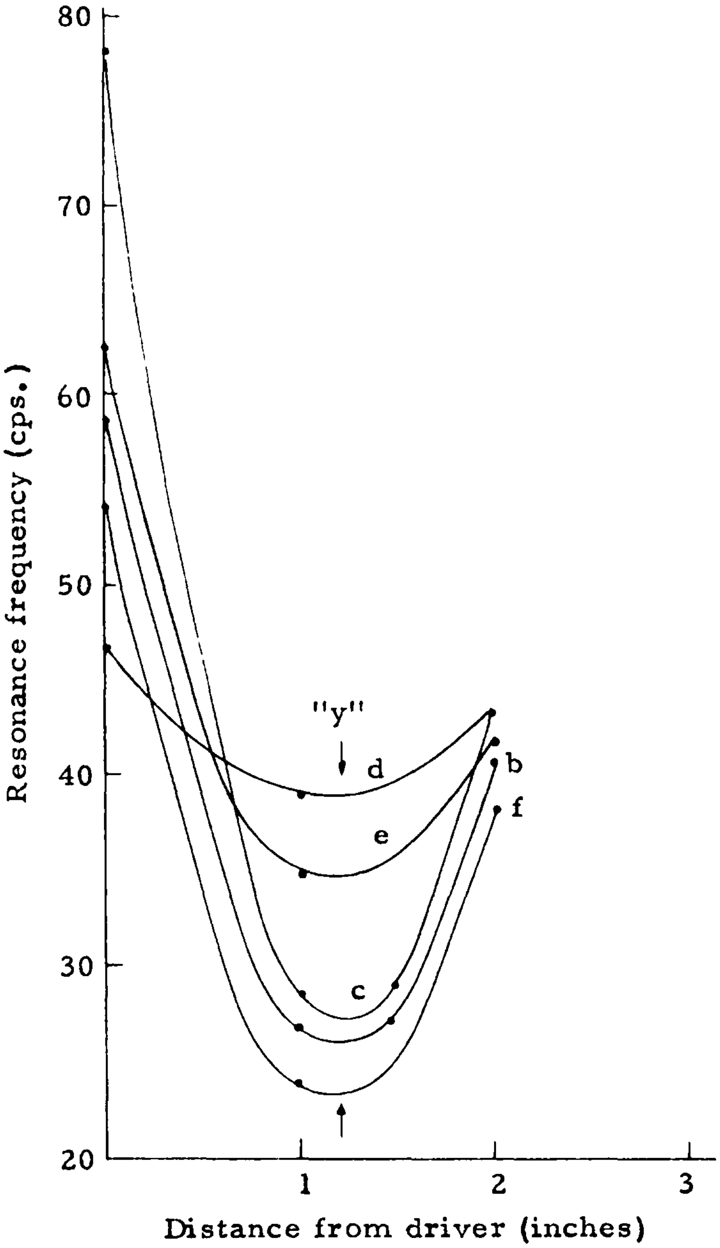

Fig. 18a. Resonance behavior of silty sand (SM)* at various moisture contents

b - without can, undisturbed, at natural moisture content
c - in the can, undisturbed, at natural moisture content
d - saturated, in the can, at 28.1% of moisture content
e - in the can, at 10.8% of moisture content
f - oven dry (after it has been saturated)

of 2 cycles per second higher when the sample was vibrated in the can. In this instance the difference between curves *b* and *c* is probably entirely due to the presence of the can.

When the sample was saturated the moisture content turned out to be 28.1, equal to the liquid limit of the sample. Resonance frequencies in this conditions are shown by curve *d* (Fig. 18a). It can be observed that in this case, where by coincidence a resonance measurement was made at liquid limit, the curve of resonance is relatively high. It shows higher values except close to the driver.

Unfortunately no measurements of this soil was taken at moisture contents above the liquid limit, which would permit one to see if resonance frequencies would decrease. But, curves *e*, *c* and *f*, all of them from samples having a lower moisture content than the sample condition giving curve *d* are in accordance with the theory that decreasing moisture content results in a decrease in resonance frequency or vice versa. Fig. 18b illustrates this situation. The resonance frequencies for this curve were taken from curves *d*, *e* and *f* (Fig. 18a) at 1.2 inches from the driver. In this instance the resonance frequencies of curves *c* and *d* were not considered because they were obtained before the sample was saturated; during saturation part of the sample was lost; consequently, the resonance values are not representative of change in moisture

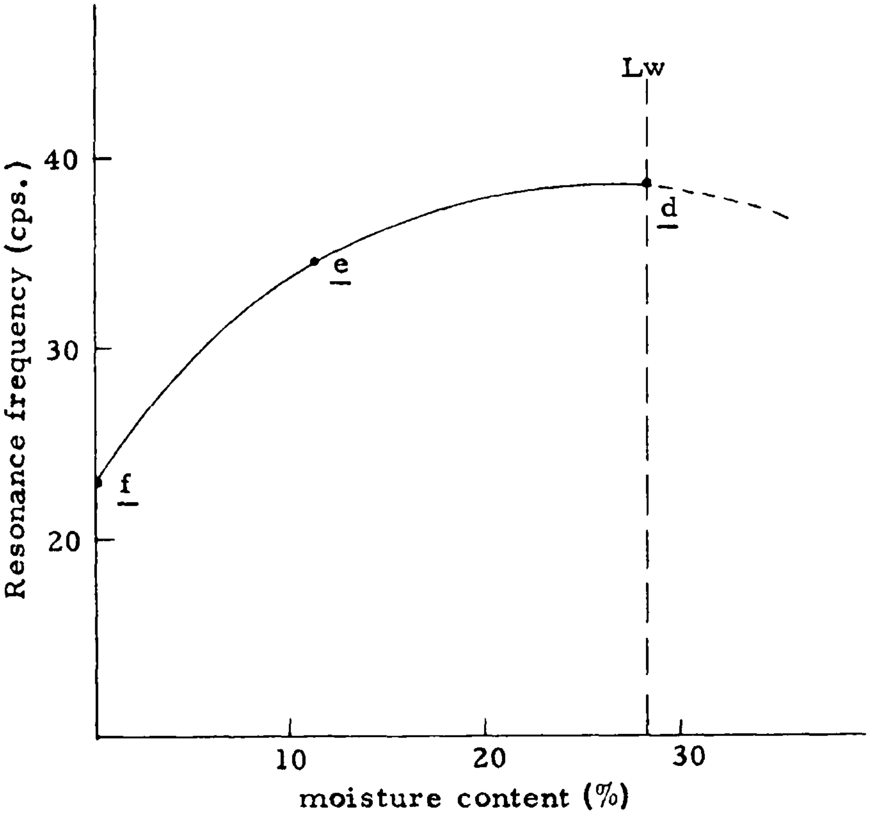

Fig. 18b. Effect of water on resonance frequency at point "y" of Fig. 18a

Lw = liquid limit of the soil--28.1%

only. It can be seen this theory also seems to have some validity for cohesive soils.

Naturally this theory can only be proven if a series of resonance measurement are performed at various moisture contents in the same specimen of soil and for various soil types. Probably these measurements would have to be taken at various distances from the driver, and the results plotted in a way similar to that done in this study. The behavior of the soil is clearly observed by a comparison of relative shapes and location of curves rather than an average of measurements taken on different parts of the specimen. The average would be good enough to establish the range of resonance frequencies for the particular soil, for example, in the silty sand the average resonance frequency is between 20 and 45 cycles per second, but this is not sufficient to analyze the effects of each variable, such as density, moisture content and size on the resonance behavior. Under what conditions is it 20 cycles per second and under what conditions is it 45 cycles per second?

Caliche

The investigations of the resonance properties of caliche were performed and given special attention to the effect of size of the sample on the resonance frequencies. For this reason caliche was first tested on a large irregular shaped sample and then measured on small cut prisms with different sizes. The general dimensions of the large samples were: 14" x 5" x 2.5" for one, and 14" x 9" x 5" for the other. The size of the small cut prisms were: 3.4" x 1.4" x 1", and 2.7" x 0.8" x 0.7".

The resonance frequency for the larger samples were determined by picking up readings along a straight line at various distance from the driver and scattered readings over the sample. Fig. 19 gives the results taken in the straight line. Curves a and b of this figure look very similar to a sine wave, with a small damping effect at a distance. Readings of resonance frequencies taken from scattered points over the samples ranged between less than 17.5 and 33 cycles per second. If they are plotted versus the distance from the driver they show a curve similar in shape to curves in Fig. 19. This effect was already noted in the discussion of the previous soils. Its meaning could not be determined in the present study; it could be related to node or loop zones in the sample. However, further investigation may probably clarify its real meaning.

For the smaller samples the resonance frequencies were measured along a straight line at different intervals from the driver.

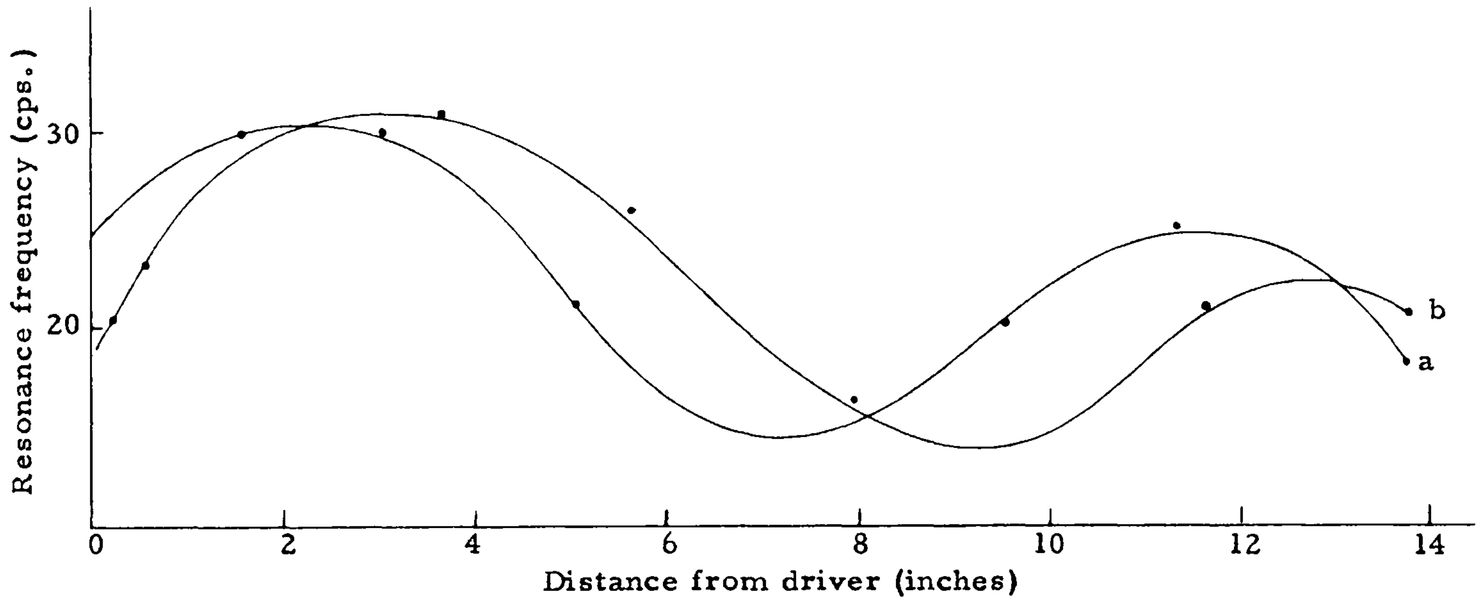

Fig. 19. Resonance behavior of two large samples of caliche

a - Sample of 14" x 9" x 5", air dried
b - Sample of 14" x 5" x 2.5", air dried

The results are shown in Fig. 20. Two determinations for each sample were performed and the shapes of the resultant curves c and d are very similar. A small inclination toward a similarity to a sine wave can be observed especially in curve c, which is measured on a longer sample.

From Figs. 19 and 20 it is possible to see that in general resonance frequencies increase with the decreasing of the size of the sample. And the difference between the maximum and minimum resonance frequency encountered on each sample also increases with the decreasing of the size of the sample.

It is possible to conclude then, also for caliche, that there is a size effect on the behavior of the resonance frequency. The general range of resonance frequencies encountered on small samples of caliche is between 25 and 60 cycles per second.

Water and Metal Can System

Resonance determination of water had two objects: to determine the shape of the curve for water when plotting resonance frequency and distance from the driver and to verify the effect of input wave amplitude on the resonance frequency. For this purpose a water-can system was vibrated at two amplitudes (one double the

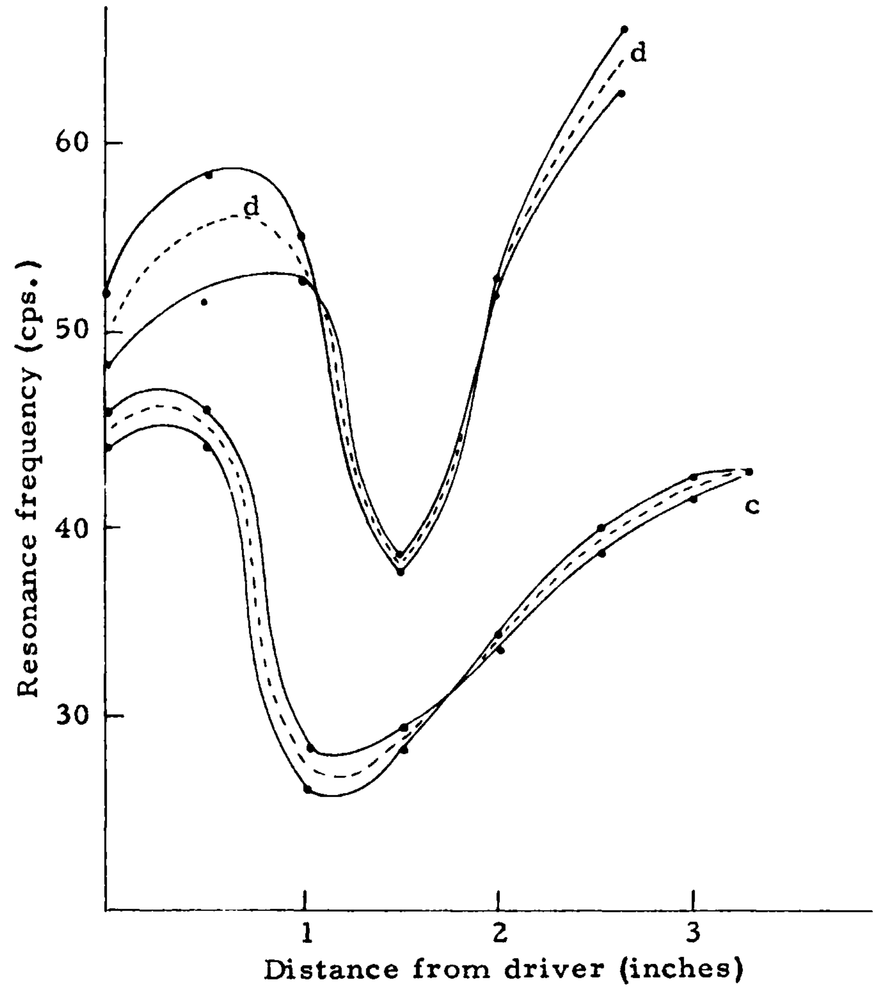

Fig. 20. Resonance behavior of two small samples of caliche

c - Resultant of two determinations on a sample of 3.4" x 1.4" x 1" in size

d - Resultant of two determinations on a sample of 2.7" x 0.8" x 0.7" in size other), and it was sensed at 3 different distances from the driver. The driver was in contact with the can and the pickup was in the water.

Table IV gives the fundamental resonance frequency and the main harmonics under these conditions. It can be observed that variations of 100 per cent amplitude of the input wave does not change the fundamental resonance more than 2 cycles per second. However, it was observed that this change in input amplitude increased, almost proportionally, the amplitude of the resonance deflection. The frequency of the harmonics seems not to change because they were too high to read with accuracy greater than 10 cycles per second. If the fundamental resonance values are plotted versus the distance from the driver, it will show the typical lower frequency in the middle of the sample traverse.

TABLE IV: Resonance frequencies of water-can system

Distance from the driver (inches)	Input amplitude (relative)	Fundamental res. frequency (cps.)	Mains harmonics observed (cps.)
0.2	50	340	3720-4330
	100	338	1230-2200-3710-4330
1.0	50	312	1230-2230
	100	310	640-1240-2230
1.8	50	330	1240-2245
	100	330	1240-2245- 4250

CONCLUSIONS

The following tentative general conclusions may be drawn from the preceding analysis of resonance results:

(1) Resonance frequency was found to vary with the variation of density, moisture content, degree of cohesion or cementation, size of the sample, sample container, and probably other unobserved variables.

(2) Consequently, only a range of resonance frequency values can satisfy the heterogeneous conditions of each _in situ_ soil. Some of the conditions listed change also during testing of the soil. Only a perfectly homogeneous and stabilized soil or rock would have a fixed frequency of resonance.

(3) The range of variation of resonance frequency for the materials studied are:

Poorly graded gravelly sand (SP)	20 - 40 cps.
Poorly graded sand (SP)	20 - 35 cps.
Silty sand (SM)	20 - 50 cps.
Inorganic sandy silt (ML)	20 - 40 cps.
Organic clay (OH)	20 - 40 cps.
Silty sand (SM)*	20 - 45 cps.

Caliche	a. small sample	25 - 60 cps.
	b. large sample	17.5- 60 cps.
Water-can system		310 - 340 cps.

It can be seen that, except for the water, they all may show more or less the same resonance frequency depending on the conditions during vibration.

(4) As a consequence of (3), resonance frequencies may not be a diagnostic criteria for each material unless it is specified under what conditions it was determined. It can be seen that these frequencies overlap for one soil to the other, and for caliche.

(5) As a consequence of (4), the resonance behavior of a soil can best be observed by determining the resonance frequency at various points on the sample, and plotting the values obtained versus the distance of sensing from the driver. The relative position and shape of the resulting curves will permit a better understanding of the soil behavior during vibration. This was the method adopted in this investigation.

(6) Point (5) would be much better accomplished if:

(a) Pickup stand, sample stand and driver unit would be supported on a completely independent base. It was observed that the sensitivity of the pickup unit was enough to sense direct vibrations of the driver unit, through the table and base of the stand where it was mounted. Consequently, it changed the over all resultant detected by the resonance indicator and the oscilloscope.

(b) If it would be possible to provide the sonometer equipment with an extra pickup head that would permit it to sense two points at the same time, this would clearly determine whether the sample vibrates at different resonance frequencies depending on the distance from the driver.

(7) The exact contribution of each variable named in point (1) to the resonance frequency has not been evaluated in this study. However, the general influence was observed to be as follows:

(a) The resonance frequency increases with the increasing of density, cohesion or cementation, and the presence of a sample container.

(b) Smaller samples generally show a higher resonance frequency than the larger one.

(c) If resonance frequencies are measured at various distances from the driver, and the values are plotted versus these distances, the shape of the resulting curve tends to resemble a sine wave with a small damping effect with an increasing distance from the driver. This effect may possibly be related to the nodes and loops of the sample when vibrating. However, deeper investigation is required to see its real meaning.

(d) The moisture content has two effects on the resonance frequency, depending on which side of the liquid limit it falls.

(i) At a moisture content below the liquid limit there is a proportional increase of resonance frequency with an increase of moisture content.

(ii) At a moisture content above the liquid limit there is an apparent reduction of the resonance frequency. For granular soils it was observed that this reduction is accompanied by a decrease of the density of the soil, and it was possibly related to the phenomenon of liquefaction.

(8) Observations of point (7d) indicate that it is very probable that resonance frequency of a soil increases with the increase of moisture content until it reaches the liquid limit, and then it starts to decrease, gradually or sharply, depending on the type of soil.

(9) As a consequence of (8) it appears possible that the liquid limit could be determined on the basis of resonance frequency. The liquid limit determined by this method may not correspond exactly to the liquid limit determined by the standard method, but it might be a closer indication of change in physical properties of the soil. This new method of determining liquid

limit would permit one to perform the test on an undisturbed sample of the soil without previous selection according to grain size; therefore, the liquid limit thus determined would be more indicative of the *in situ* properties of the soil.

(10) In order to verify the previous tentative conclusion, a series of tests should be conducted on the same specimen at various moisture contents. Special attention is needed to ensure that only the moisture content is changed on tested specimen. This test should be repeated for several soil types.

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