VELOCITY OF SHEAR WAVES THROUGH
UNCONSOLIDATED MATERIALS

by

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ABSTRACT

The elastic properties of the unconsolidated materials which cover most of the earth are, in general, unknown. In this paper, an attempt was made to measure, in the field, the shear and compressional wave velocities, with the emphasis on those for shear waves. For this purpose, a simple source was devised which produced fairly pure shear waves. A portable refraction seismograph of standard design was used to record the seismic waves. With the extremely short spreads used, normally from 40 to 80 feet, it was found that the shear wave velocities for a variety of unconsolidated materials ranged from 300 ft/sec to 825 ft/sec.

The results obtained were compared, whenever possible, to previous work done on similar types of materials. These comparisons generally showed good agreement when the differences in materials and methods of measurement were taken into consideration.

The modulii of rigidity of the various materials were computed on the basis of isotropic elastic theory. These values were then compared to tabulated values for such things as steel and copper. The unconsolidated materials had modulii of rigidity whose orders of magnitude were one thousandth of the tabulated value. These results seemed reasonable.

Finally, some suggestions were made on a few of the problems which arose and which offered the possibility of further research.

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INTRODUCTION

The studies of the elastic properties of the earth, whether in the field or in the laboratory, have been generally concerned with lithified materials. This is to be expected as these materials comprise the major component of the earth's crust. It ignores, however, the very thin layer of materials which cover a major portion of the land mass. These are the unconsolidated materials. This paper is a preliminary study of some representative samples of these materials.

The elastic theory for isotropic material shows that if any two elastic parameters are known, the others may be computed. This has suggested the possibility of using two separately determined sets of parameters as checks on one another and so on the theory. One set of parameters commonly found consists of the shear and compressional wave velocities. These values are obtained by field work and are then compared to the results of laboratory work in which two other parameters have been measured. The present work is a study of velocities, with special emphasis on the velocity of shear waves, and a comparison of the results with the very scattered findings of laboratory experiments.

A study of the elastic properties of unconsolidated materials is of interest in connection with the low velocity surface layer and the characteristics of surface waves in seismic exploration. There is also the possibility that such

a study might show the existence of significant elastic
wave coupling between the earth and the atmosphere.

THEORY

Much work has been done in the study of vibrations in elastic material. And, as is normal in most things, it started with the easiest cases and then progressed toward the more difficult ones. Thus, the two dimensional case is nearer complete solution than is the, infinitely more difficult, three dimensional case. The problem of this paper is concerned with, just about, the most general three dimensional case there is, elastic waves in unconsolidated material. Such a material as beach sand is not homogeneous or isotropic and may not obey Hooke's Law. But, practically always these conditions have been assumed in the development of a usuable theory. As an example of what happens when only one of these assumptions is not made, assume that the material is non-isotropic, but still homogeneous and perfectly elastic. In this case there may be twenty-one elastic parameters in place of the two which are sufficient if the material is isotropic. It is obvious that it is a practical impossibility for anyone to measure twenty-one parameters for most materials, although it has been done for single crystals. In order, therefore, that any practical application be made of elastic theory, it is a necessity that some simplifying assumptions be made. The commonest ones are those mentioned above. That is, the material is homogeneous, isotropic and perfectly elastic. These assumptions will be made, in general, in this paper although it is obvious they are, to some degree, false. It

is hoped that the results obtained will give an estimate of the degree of falsification.

Assuming a material that is homogeneous, isotropic, and infinitely extended which obeys Hooke's Law, it can be shown that:

$$(1) \qquad \rho \frac{\partial^2 u_i}{\partial t^2} = (\lambda + \mu) \frac{\partial \theta}{\partial x_i} + \mu \nabla^2 u_i$$

where u_i is particle displacement

λ, μ are elastic parameters (Lames's constants)

θ is $\frac{\partial u_i}{\partial x_i}$

ρ is density

There are the relevant equations of motion for the above assumptions. By differentiating both sides of (1) with respect to x_i and then adding the results, we get:

$$(2) \qquad \rho \frac{\partial^2 \theta}{\partial t^2} = (\lambda + 2\mu) \nabla^2 \theta$$

By taking the curl of (1), we get:

$$(3) \qquad \rho \frac{\partial^2}{\partial t^2} curl(u_i) = \mu \nabla^2 curl(u_i)$$

Equations (2) and (3) are of the form $\frac{\partial^2 \phi}{\partial t^2} = C^2 \nabla^2 \phi$ where C is the velocity of the wave traveling through the medium. This equation is known as The Wave Equation. In the case of equations (2), we can see that a pure dilitational (or irrotational or compressional or longitudinal) wave will have a velocity, $v_c = \left[(\lambda + 2\mu)/\rho \right]^{1/2}$. By equations (3), we have a pure rotational (or equivoluminal or shear or transverse) wave with a velocity, $v_s = \left[\mu/\rho \right]^{1/2}$. These velocities, and especially the latter, are the velocities which I attempted to find by actual measurement. (Note: In this paper, v_c and v_s are commonly called compressional velocity and shear velocity respectively. Technically this is incorrect as they should be compressional wave velocity and shear wave velocity, but the shorter names will be used as they entail no ambiguity.)

In this special case, the two required elastic parameters may be written in many forms. In the equations above, they appear as Lame's constants where μ is rigidity, where λ has, in general, no physical significance in the sense that μ has. Other parameters are; K,σ, E where K is the bulk modulus, σ is Poisson's ratio and E is Young's modulus. These constants are all expressible in terms of any other pair. So that:

$$\lambda = E\sigma/(1+\sigma)(1-2\sigma)$$
$$\mu = E/2(1+\sigma)$$
$$K = E/3(1-2\sigma) = \lambda + 2\mu/3$$
$$\sigma = \lambda/2(\lambda+\mu)$$
$$E = \mu(3\lambda+2\mu)/(\lambda+\mu)$$

Experimentally, it has been found that some of these constants are more easily found than others. Thus, Young's modulus and bulk modulus are, in general, more easily determined experimentally, in sofar as rocks are concerned, than are rigidity, Poisson's ratio and λ. Furthermore, it is to be noted, that if the shear and compressional velocities, and the density are measured, it is possible to compute the elastic constants. If, therefore, two sets of measurements can be made which give two elastic parameters and the two velocities independently, it would be possible to check the accuracy of the original assumptions, as applicable to the given material. This has been done, and will be discussed later.

For this paper, it would be desirable to have a somewhat more general theory which would take into consideration the facts that unconsolidated materials are neither homogeneous nor isotropic. Unfortunately, usable theories for these materials are very rare and even these are for rather special conditions. T. Takohashi and Y. Sato[1949] have developed a

theory for elastic waves in granular substance, but, unfortunately, their notation is extremely abstruse so that I have been unable to follow their mathematics or to find anyone else who could. Their results, however, appear to be much the same as those developed by F. Gassmann[1951], although somewhat more general. He (Gassmann) has developed a theory of elastic waves through homogeneous, isotropic spheres with hexagonal packing. This is still a very special theory for elastic waves, but it is more general than the one which assumes isotropy. If this theory is valid, it should, for quartz spheres, give velocities of the same order of magnitude as those measured in a sand.

Gassmann's theory, as it concerns an anisotropic material, yields three velocities, v_1, v_2, v_3. Of these, only v_3 has a direction of displacement which is simply determined for all directions of propagation. It is a SH wave (i.e. a shear wave polarised in the horizontal plane). The displacements associated with the velocities v_1, and v_2 are combinations of SV and P waves (i.e. a shear wave polarised in vertical plane and a compressional wave, respectively) which will depend, in a complicated manner, on the elastic constants of the material and the direction of propagation. For horizontal or vertical propagation, however, it is possible to give a simple interpretation to v_1 and v_2. For horizontal propagation, v_1 is associated with a P wave and v_2 with a SV wave. For vertical propagation, v_1 is associated with a SH

wave and v_2 with a P wave.

For the study involved in this paper, the direction of propagation of the wave was essentially horizontal. Substituting this fact into Gassmann's equations gives:

$$v_3 = 0$$

$$v_1^2 = C_1 / \rho$$

$$v_2^2 = C_4 / \rho$$

where

$$C_1 = \beta \sqrt[3]{z} + \frac{\alpha}{D} b_1^2$$
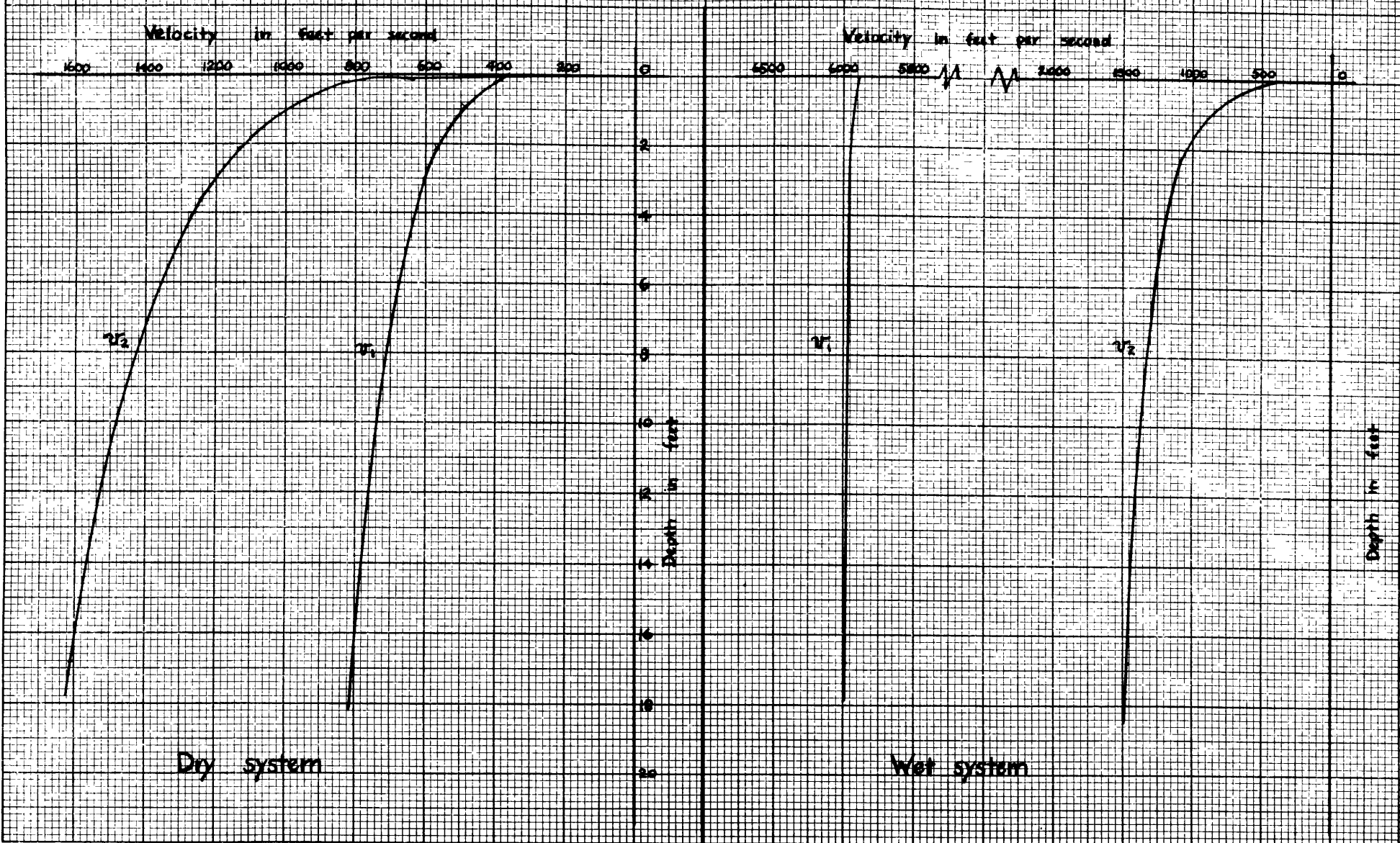
$$C_4 = 4 \beta \sqrt[3]{z}$$

$$\rho = \text{apparent density}$$

and where β is a function of Young's modulus, density, gravity and Poisson's ratio, Z is depth below surface, and α, D and b_1 are functions of the bulk moduli of the spheres and the pore spaces, β, and the depth, Z. Plate I shows plots of v_1 and v_2 for quartz spheres, both dry and saturated with water for the case of horizontal propagation.

As v_1 and v_2 cannot normally be correlated with any measured velocities, it might be well to look at v_3 more closely, as it is with SH waves that the present work is

VELOCITIES COMPUTED FROM GASSMANN'S THEORY
DIRECTION OF PROPAGATION — HORIZONTAL

Velocity in feet per second

1600 1400 1200 1000 800 600 400 200 0

v_2

v_1

Dry system

Velocity in feet per second

6500 6000 5500 2000 1500 500 0

v_1

v_2

Wet system

Depth in feet

Plate I

principally concerned. If the direction of propagation is below the horizontal, $v_3 = C_4/\Delta \rho$ where Δ is a constant for any given direction of propagation, but which approaches infinity as the direction of propagation approaches the horizontal. Thus, the curve for v_3 should have the same form as that for v_2 in Plate I, with the exception that it is always smaller, until the direction of propagation is vertical when they become equal. (Note: The v_2 has this form only for horizontal propagation while v_3 has it for any direction of propagation.) As an example, assuming the direction of propagation to be 5° $42'$ below the horizontal, then $\Delta = 101$.

PREVIOUS WORK

Because it was recognized early in the study of seismic data that knowledge of the elastic wave velocities through various rock types would be of invaluable aid for the investigations of the earth, the literature is rich in work on the subject. But, as might be expected, the emphasis has been almost entirely on elastic waves through igneous rocks and the effects of temperature and pressure on them. The reason for this is twofold. First, the study of earthquakes, and the resultant work on the interior of the earth, has to do entirely with igneous material, most of which is at extremely high pressures and temperatures. Secondly, the laboratory study of the elastic properties of consolidated rocks can be done, in theory anyway, with much the same techniques as have been developed for testing such material as steel. Thus, theoretical problems of interest, combined with known laboratory techniques, have lead the academicians to ignore sedimentary rocks in general, and the top few feet of unconsolidated materials, which cover so much of the earth's surface, in particular. The professional exploration geophysicists, on the other hand, have a definite interest in these materials, but they have always seemed to consider the unconsolidated portion too insignificant as compared to other indeterminate factors involved in their work.

About 50 years ago, H. Nagaoka (1900) did what was probably the first laboratory experiments to determine the

elastic constants of rocks. In particular, he was attempting to find the velocity of seismic waves by computations from the elastic parameters. By a couple of rather ingenious experiments, he measured Young's modulus (by a flexure experiment) and rigidity or modulus of shear (by a torsion produced by a couple). He discovered very early in his experimentation that Hooke's Law did not hold for rocks even for a very small flexure or torsion. This he believed was due to lack of isotropy in the material. Nonetheless, he computed $v_c = \sqrt{E/\rho}$ and $v_s = \sqrt{\mu/\rho}$ which he felt would give a rough estimate of the velocities.

Some years later, Adams and Coker (1906) determined Young's modulus and poisson's ratio for a number of igneous rocks by direct compression methods. They did very careful laboratory work and some of their results are still accepted, although Zisman (1933b) questions the value of three separate experiments done with three samples, three inches long and one inch square, all taken from the same hand speciman and all giving varied results. These variations were especially noticeable in the Quincy granite samples and were blamed on the aeleotropic properties of the material.

Ide (1935), Zisman (1933a), Birch and Bancroft (1938) are but a few who have attempted to find the elastic constants of rocks by laboratory technique. They found out how pressure and temperature effected Young's modulus, Poisson's ratio, et al, but, in general, their work was most notable for its

lack of agreement with anyone else, especially at low pressures. This was not usually the fault of the experimenters, but was due to the inherent characteristics of the material. Unfortunately, nobody seems to be able to devise either theory or experiment which will describe these characteristics and so make these various results compatable. From the results of his experiments, Ide (1936) notes that, "We can also make a reasonable guess that disagreement between theory and experiment will be still larger for the less compact sedimentary rocks such as shales, conglomerates, and soft sandstone". This may be an unduly pessimistic outlook. Perhaps the fault lies in the unnatural conditions in the laboratory and that, therefore, measurements to have any meaning must be made in the field where variations may average out and produce a closer agreement between theory and actual measurements.

As a matter of fact, work has been done in the field. This consists of measuring seismic velocities, usually only v_c, but sometimes v_s, and comparing the results with those obtained in the laboratory. Leet (1933) and Gutenberg (1937) are just two of many who have determined seismic velocities with field methods. Leet's work is of special interest because he worked on the Quincy granite which had been studied by Adams and Coker and was to be studied again by Ide. There was a variation of 19% between Ide's laboratory results and Leet's field results.

Of some special interest is the work of Weatherly, Born, and ᴴarding (1934) on their study of granite. With special recording instruments which gave records readable to .0006 seconds and carefully matched geophones and amplifiers, they made shots with spreads as small as 400 ft. With this abnormally small spread they measured both v_c and v_s for Tishomingo granite and found, as to be expected, that the velocities increased with an increase in the spread (i.e. increasing penetration). There was also a slight increase in v_c/v_s from 2.12 to 2.16.

Ewing and Crary (1934) used a technique somewhat similar to the one used in this paper to measure v_s in ice. They used the geophones on their sides to measure horizontal motion at right angles to the direction of propagation. However, they used a blasting cap buried in the ice as a source and a spread of 2,000 ft. By the method of least squares, they determined v_s to be 6057 ft/sec. It is of interest to note, that they did not pick first breaks, but attempted to follow wave form through the record.

The only work that has been done on elastic waves in unconsolidated materials was done, originally, by Ishimoto and Iida (1936) and later Iida (1938) alone. The method used was a variation of the one developed by Ide in his study. Basically the equipment consisted of a thin steel plate which was made to vibrate by an alternating current coil. The

specimens were placed on this plate, being held in form
either by first being packed in a box or by being supported
with a cellophane cylinder. When the plate vibrated, longi-
tudinal waves moved up through the specimen and were detected
by a suitable device at the top. As the frequency of the
vibrating plate was changed, the amplitude of the recorded
wave varied and reached a maximum at resonance (i.e. when the
frequency of the vibrating plate equaled the natural frequency
of the specimen). This gave the value of T, the period of
free vibration of the specimen. From this, Young's modulus
was computed from the equation.

$$T = 4h \bigg/ \sqrt{E/\rho}$$

where h is height of specimen

ρ is density of specimen

E is Young's modulus

This then gave v_c as $v_c = \sqrt{E/\rho}$ for a bar fastened at one
end and free at the other, which corresponds to the form of
the specimen used. In later work (1937), they developed a
simple piece of apparatus which generated torsional vibrations.
This permitted the calculation of rigidity and from it, $v_s = \sqrt{\mu/\rho}$.

With these two pieces of equipment, studies were made of
sand, clay, silt, loam, rubber, etc. to determine relations
between water content, porosity, height of columns and the
velocities. They got compressional velocities of clay that
ranged from 368 ft/sec to 1050 ft/sec and shear velocities

from 97 ft/sec to 433 ft/sec. (The testing of sands were done on sieved material so that the specimens were rather artificial.) It was found that compressional velocities decreased for a time with increasing moisture content and then increased as the moisture content became greater. The shear velocities continually decreased and approached zero. For medium grained sand, v_c was 590 ft/sec to 302 ft/sec and v_s was 358 ft/sec to 174 ft/sec as moisture content went from 4.1% to 22.9%. It was also shown that both velocities decreased with increasing porosity.

Later work by Iida (1939) on granular substances showed that the velocities increased as the height of the specimen increased, as might be expected. There was also a slight increase in velocities as the radius of the spheres increased under conditions of identical packing. This disagrees with the results obtained in the theory of Gassmann, but the disagreement is small.

Iida concludes that, "the wave velocity through a granular mass is proportional to the sixth root of the height, to the cube root of the ratio of the elastic constant to the density of the grains, and to the constant due to the conditions of packing".

EQUIPMENT AND PROCEDURE

In all of the work done for this paper, it was necessary to adjust the experiments to fit the equipment instead of the other way around. This is probably not the ideal method for experimental work, but in the present case, these economic restrictions were, in the main, probably not too important.

The recording apparatus was a "12 - Trace Portable Refraction Seismic Equipment" built by the Century Geophysical Corporation of Tulsa, Oklahoma and is standard gear. It consists of 12 seismometers, a bank of 12 amplifiers, an oscillograph (or camera) and the necessary cables and power supplies. The equipment is divided into a number of small components which are individually portable. There are, however, too many components for the equipment to be suitable for one man operation.

In order to make the equipment portable, certain features, which are normally incorporated in exploration seismic gear, were omitted. In the present work, however, their omission was not especially noticeable. It was unfortunate, however, that the amplifiers and geophones were not matched and that the amplification controls could not be re-set accurately.

In normal operation with this equipment, dynamite is used as the source of energy to produce the recorded signals. For measuring the velocities of shear waves, however, it was necessary to use a different type of source for two reasons.

First and most important, dynamite produces a large compressional component which, because it travels faster, covers up the later shear component, if any exists, so completely that it is impossible to separate the two components on the record. Secondly, dynamite may only be used under special conditions in Massachusetts and these would have been too difficult to fulfill for this work.

Therefore, what was needed was a source of energy which would produce, primarily, shear waves and which would require no high-explosives. In addition to this there were added the further requirements that the equipment be inexpensive, relatively portable and simple enough in operation for one man to manipulate. The equipment produced satisfied all of these requirements in spite of the fact that it was extremely crude. It consisted merely of a 5 foot length of 2 x 4 with a 2 x 16 x 10 board attached under one end of it with four iron straps. The other end of the 2 x 4 had a simple plug contact which could be broken by a sharp blow and which would, therefore, produce a time break on the record. In operation, a narrow trench about 2 inches wide, 6 to 8 inches deep and 1.5 feet long was dug with a special hoe made for the purpose. The board at the end of the 2 x 4 was placed in this trench so that the 2 x 4 was parallel and about 2 inches above the ground. Material was then tamped into the trench so that the board was held firmly in place. The far end of the 2 x 4 was hit rather "gently" by a 6 lb. sledge hammer. This produced

both the time break on the record and the desired shear
waves. It was found by trial and error, that a more nearly
pure shear wave was produced along the direction of the 2 x 4
than perpendicular to it. (see Fig. 1)

For the tests where shear velocities were measured, the
geophones were placed on their sides with the bases parallel
to the length of the 2 x 4. In this position, they were more
sensitive to the shear wave than to the compressional wave,
although they did give some indications of the latter. When
compressional waves were to be measured, the geophones were
set upright and the plank was hit a downward blow instead of
a sideward one.

In spite of the seeming crudity of this equipment as a
source of energy, the results produced were extremely repro-
ducible as shown by two records made at the same place.
(see Fig. 2)

SCHEMATIC DIAGRAM OF TYPICAL SET-UP
(Plan View)

Plank

Time break

(Buried section)

Geophones

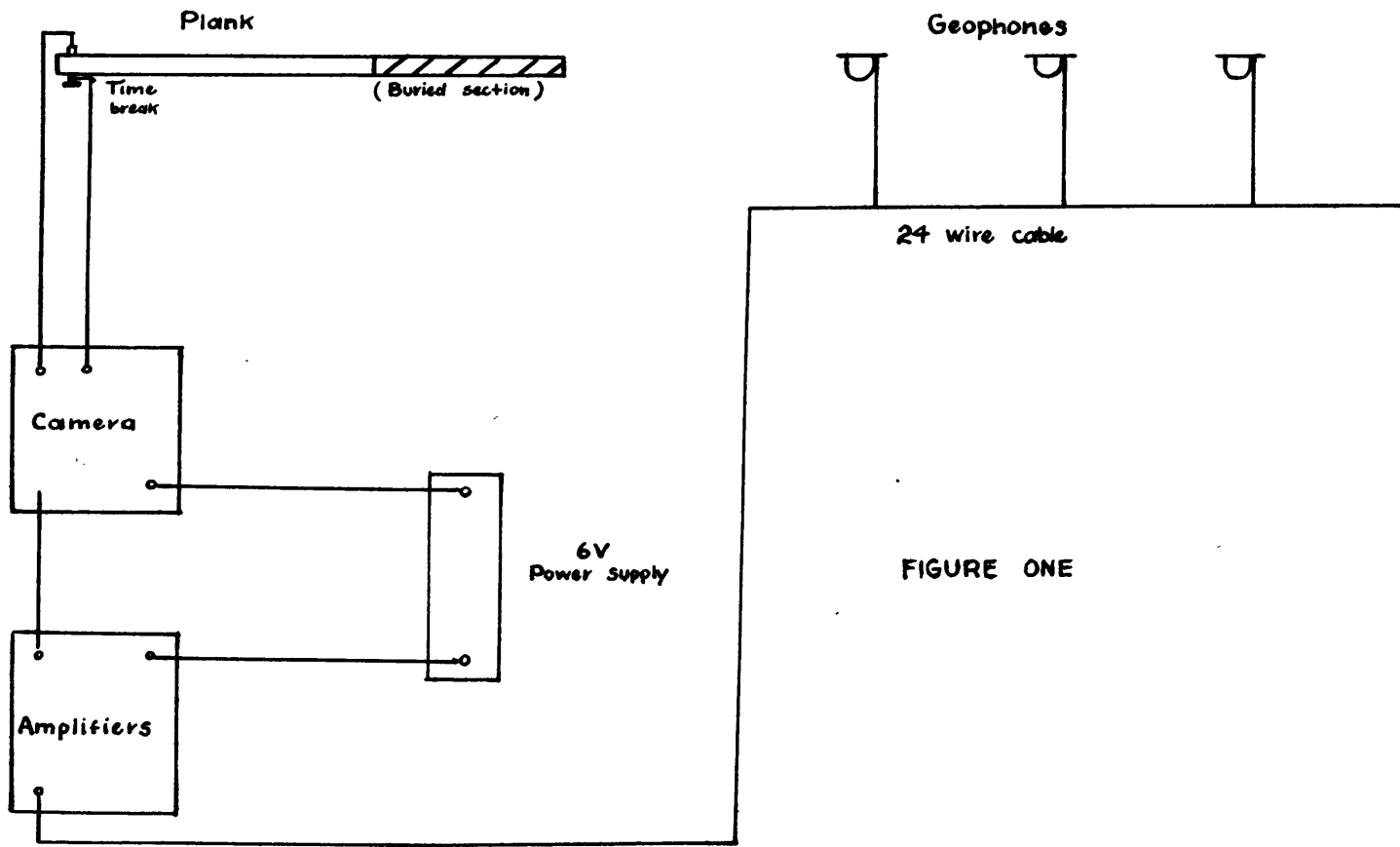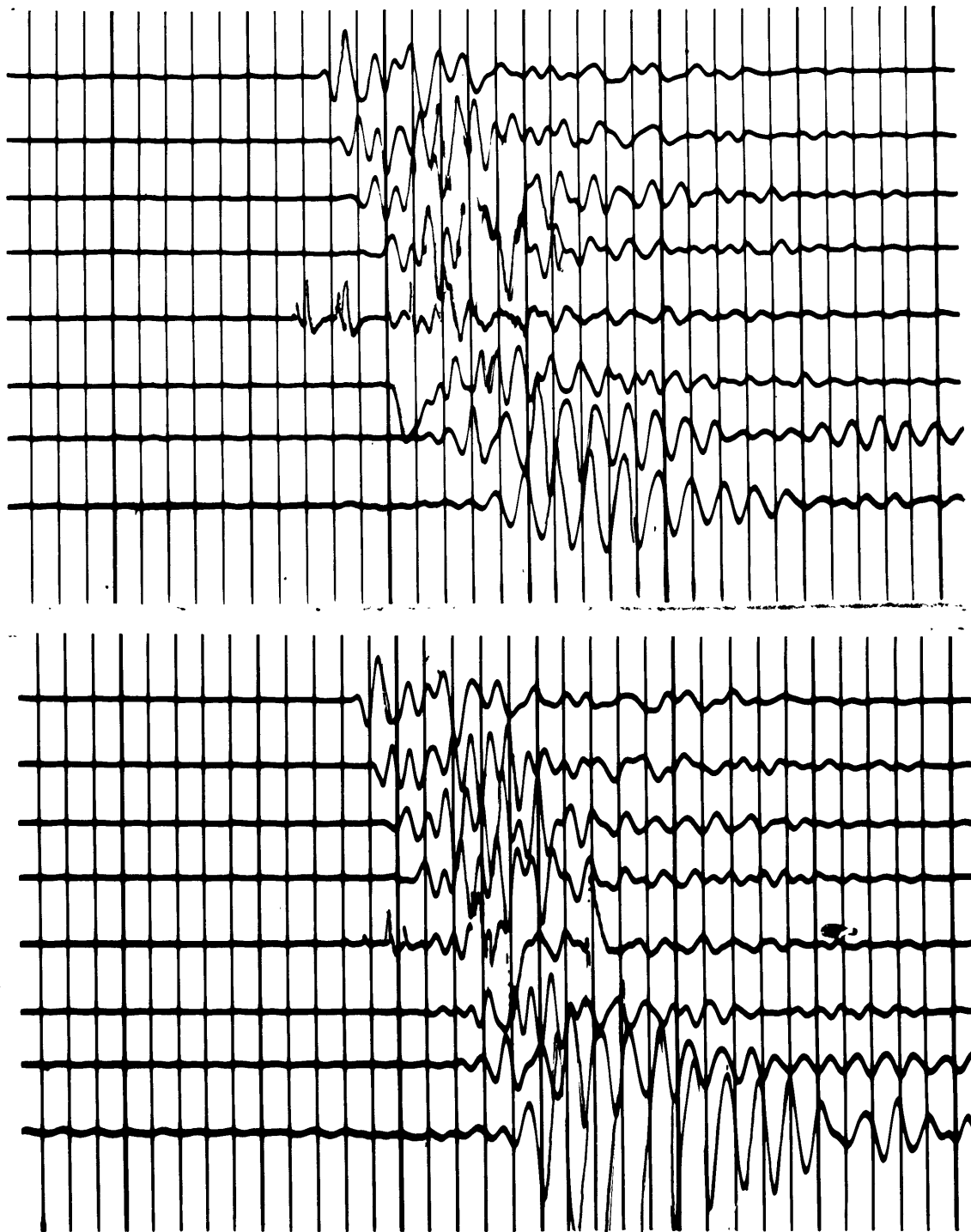24 wire cable

Camera

6V
Power Supply

Amplifiers

FIGURE ONE

Records from Rockwell Cage showing reproducibility.
Note especially the similarity between the first three
corresponding traces.

Fig. 2

RESULTS

It was found in the work done for this paper, that a method which would appear to give good results one day in one place would not do so the next day in another place. There was, therefore, a constant varying of minor points in technique in an effort to find one which would give consistant, legible results. It is thought desirable, therefore, that the results be explained in more detail than would be possible in a simple tabulation of results.

Fletcher's Quarry

The original work was done at Fletcher's Quarry at Chelmsford, Massachusetts. At this time it was unknown whether or not any recordable vibrations could be produced with the simple apparatus used. And so, the geophones were lain out in two groups. The first group, consisting of four geophones, on their sides, was placed in line with the plank with a five foot interval between geophones. The second group, consisting of eight geophones, also on their sides, was placed perpendicular to the plank, but with ten foot spacings. The material being studied was fresh granite sand (the result of quarrying operations) which had been used as fill to make a roadway.

The main results of this test were to show that the plank was a sufficient source and, more important, the energy moving parallel to the plank had a relatively larger component of

shear waves than did the energy moving perpendicular to the plank. No further results were obtained from these records because in addition to the poor techniques used, microphonics in the amplifier completely blotted out a number of traces. Thus, while a general tend is noticeable, giving a shear velocity of about 300 ft/sec, it is impossible to pick the records closely enough to give any value to a time-distance curve.

Rockwell Cage

The floor of Rockwell Cage, the athletic field house of M. I. T., is composed of hard-packed clay containing numerous small pebbles. It is intermittently plowed up and then rolled smooth whenever it becomes too hard and uneven. Tests were made of this material a few days before it was plowed, so that it was probably at or near a condition of maximum packing.

The geophones were placed on their sides in line with the plank, there being nine geophones in all. The spacing was five feet from the end of the plank to the first geophones and five feet between adjacent geophones. The plank was buried only about six inches, which was less than the depth normally used in later tests, but in this case the material became more pebbly with depth and the digging of the necessary trench became impossible.

The records resulting from this test, in general, fail to show clean first breaks. This was later to be recognized

as normal in all of the records, regardless of variations in spacing or positioning of the geophones. At first glance, what appeared to be the first break was, in fact, the arrival of a later, larger wave. When the amplification of the instrument was increased greatly, the true first breaks became more apparent, but these were followed shortly by a large increase in energy which often drove the traces clean off of the recording paper. It seemed obvious, therefore, that what was being received was a combined compressional-whear wave in which the compressional component was very small compared with the shear component. Thus, the first little ripple on the record indicated the arrival of the compressional wave and the first large ripple indicated the arrival of the shear wave. It would thus appear that both velocities could be measured on the same record. This was felt to be desirable. As has already been explained, there are very few velocities of shear waves recorded so that there is no good way to check results. With both velocities known, however, the velocities of the compressional waves could be compared, in magnitude at least, with velocities found by other workers in the field. A good check for these velocities would indicate that the velocities for shear waves were probably also correct.

In addition to the "smearing" of the first breaks produced by the earlier arriving compressional waves, there are the added effects of dispersion and multiple refractions.

In this work, the recorded frequencies go from about 140 cycles
per second at the first geophone to about 80 cycles per second
at the last geophone. The attenuation of the high frequencies
also produces a change in the apparent group velocities being
measured. The relationship between frequencies and veloci-
ties will not be gone into here, but it offers opportunity
for future work.

Plate II shows the time-distance curves for a number of
records taken in Rockwell Cage. Both shear and compressional
velocities were taken from a couple of the records, but as
the first breaks for the compressional velocity are extremely
small, especially on the last few traces, they could only be
picked on those records where the amplification was reasonably
high. On the other hand, the shear waves were picked on wave
form, so that it was desirable for the amplification to be
relatively low in order that the wave forms of the individual
traces could be recognized and separated from one another.
The ideal amplification which would give both velocities was
only found by much trial and error. It will be noted that
Plate II shows a couple of cases where the shear velocities
are plotted from two separate wave forms on the same record.
This was done as a check to help eliminate the possibility of
reading something into the records which was not there, and
became standard procedure whenever possible.

The curves through the plotted points are average curves
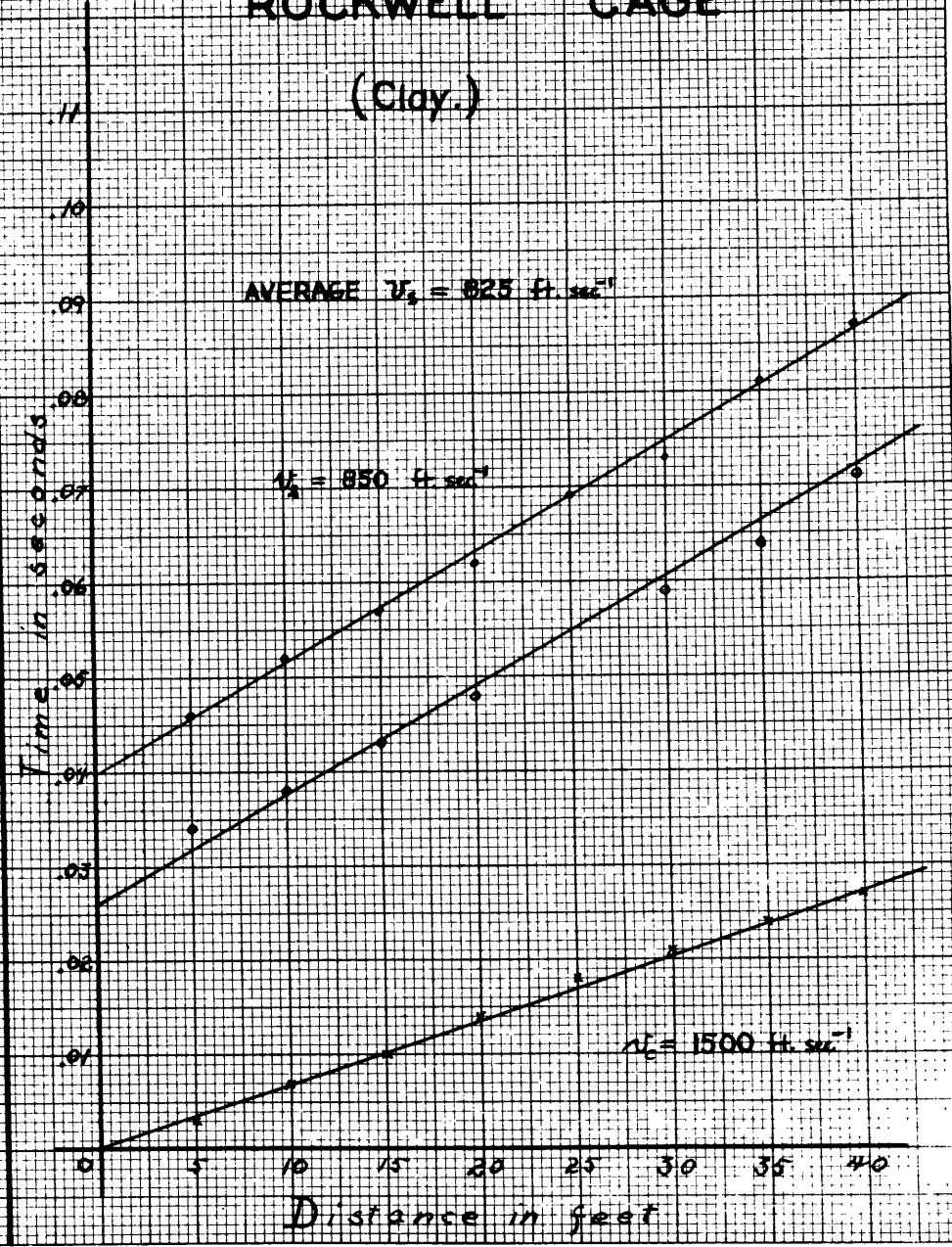which were drawn by eye. It is reasonable to expect, therefore,

ROCKWELL CAGE
(Clay.)

ROCKWELL CAGE
(Clay.)

plate II
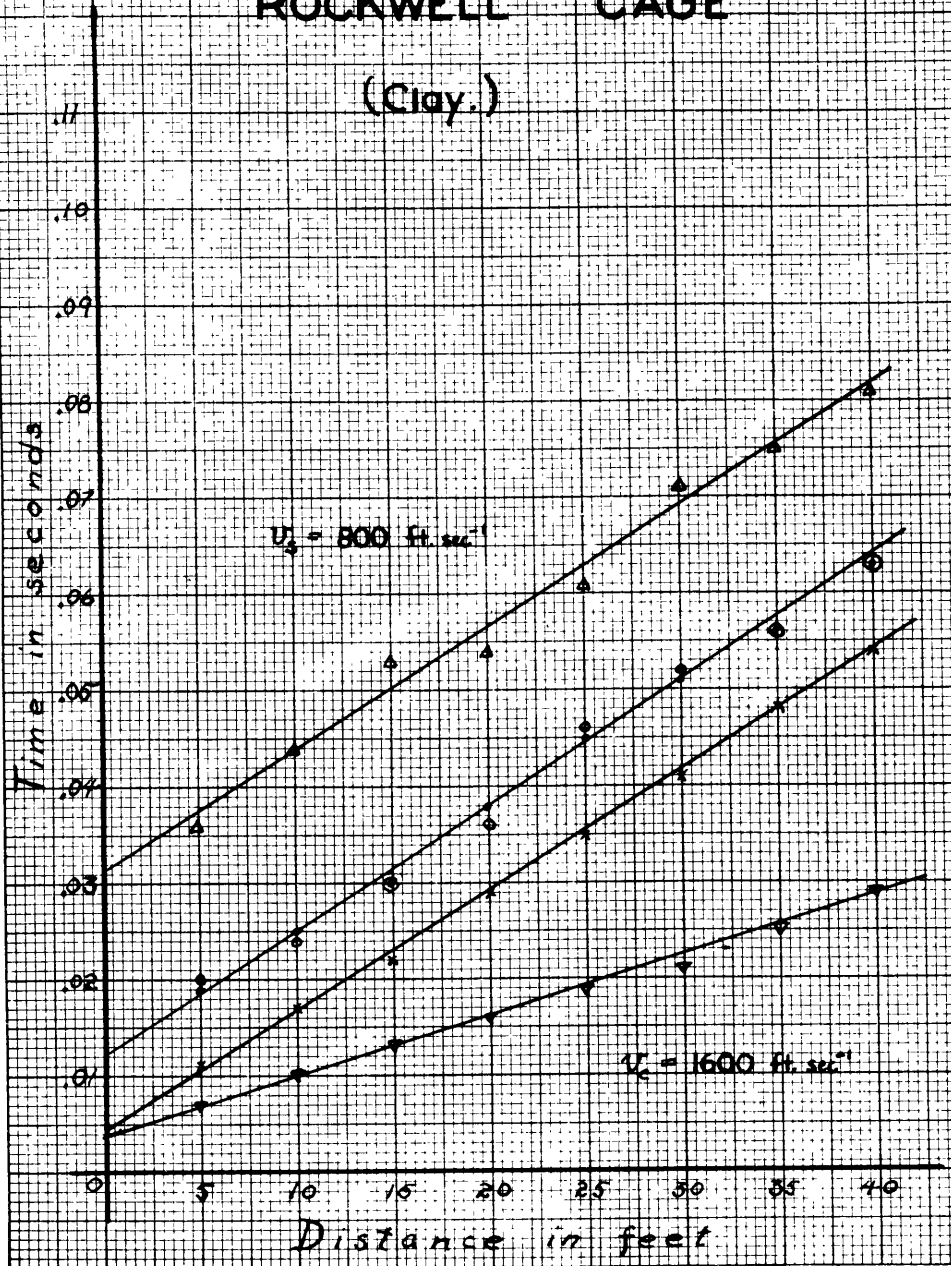
that there would be some variation in the resulting veloci-
ties. In both sets of velocities there is about 6% deviation.
Taking into consideration the variations in reading the record
(an error of .002 seconds in reading the record might give a
4% deviation), errors in plotting the points and drawing the
curves, the resulting velocities are essentially identical.

In order to further check the accuracy of the curves as
drawn by eye, some of them were computed by the method of
least squares. From one of the better records, two sets of
points were taken for shear waves, one giving a velocity of
815 ft/sec and the other giving 780 ft/sec. Both of these
were computed by the method of least squares and the resulting
values were both 795 ft/sec. A third check was made for
another record which gave 850 ft/sec from the curve. In
this case, computation gave 860 ft/sec. However, when the
times picked on the sixth and eighth traces were increased
by .001 second, the velocity decreased to 840 ft/sec. This
gives more than 2% deviation. When it is remembered that,
even ideally, a trace may be picked only to ± .001 second,
and more likely only to ± .002 second, it becomes apparent
that a curve drawn by eye is essentially as accurate as one
computed, although the method of least squares may give the
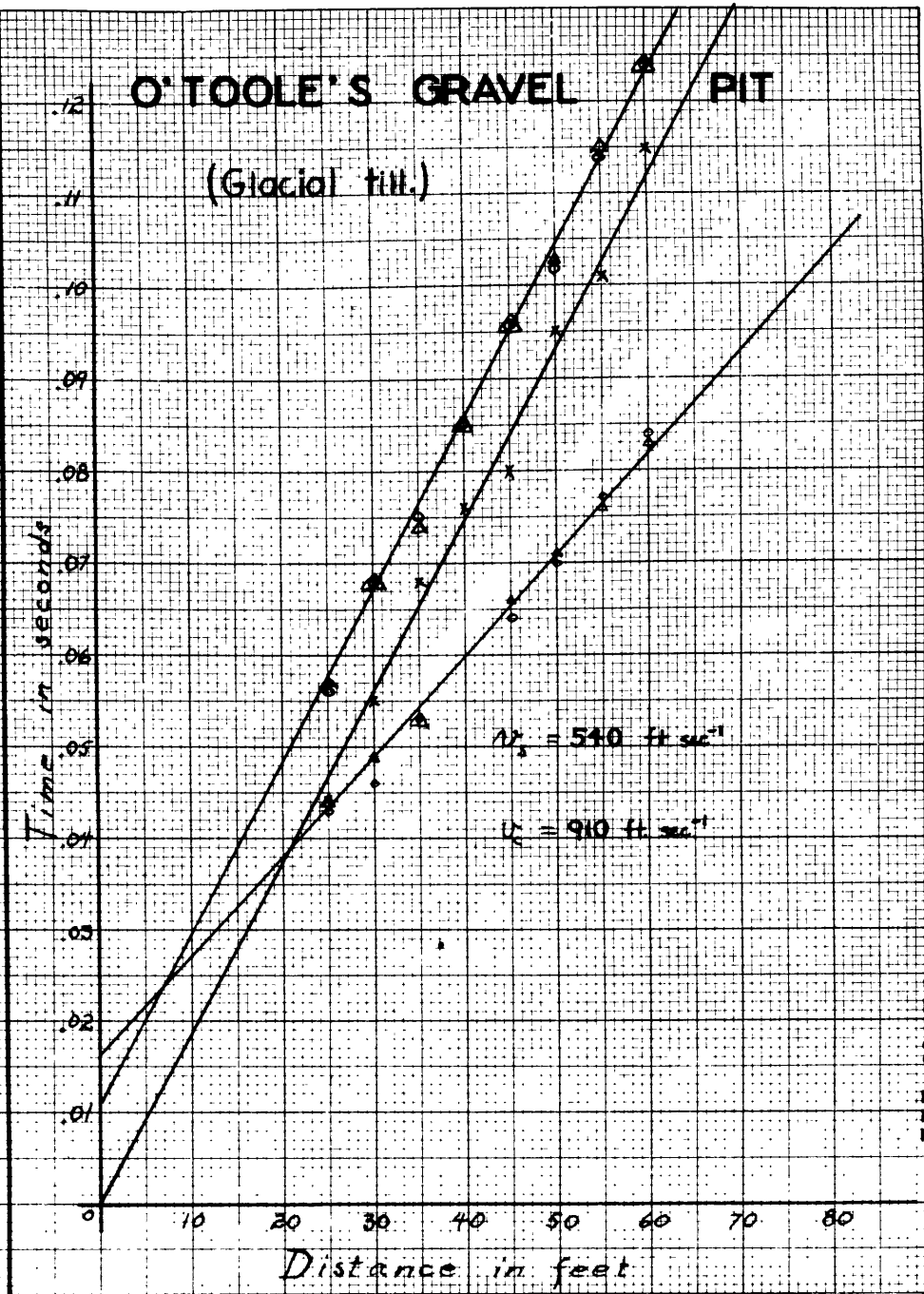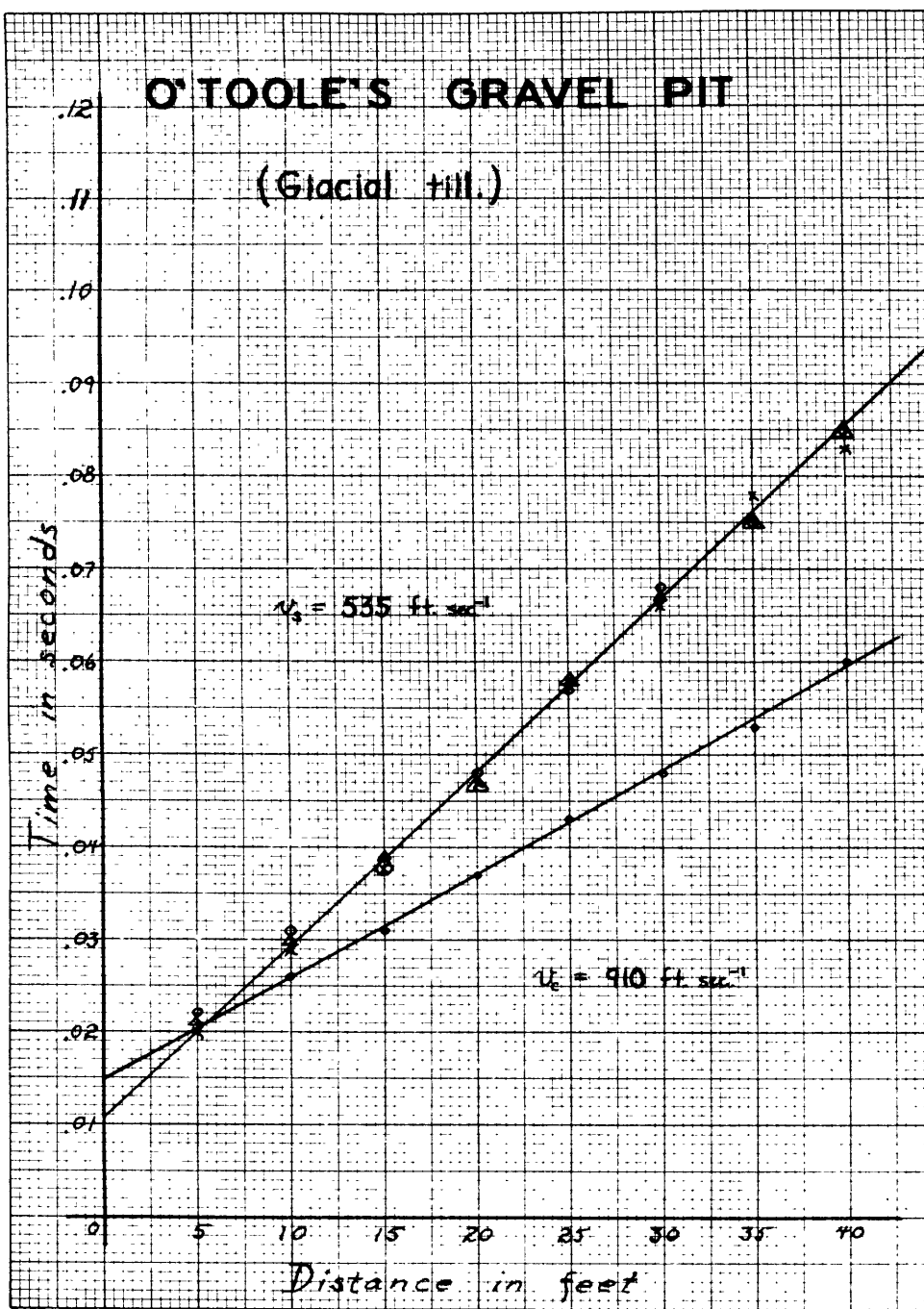false impression of greater accuracy.

O'Toole's Gravel Pit

Plates III, IV, V and VI show the results of tests made

at O'Toole's Gravel Pit in Norwood, Massachusetts. This is
a glacial delta, and so shows much cross-bedding and graded
bedding. In its natural condition, it is relatively hetero-
genous, varying from fine sand to cobbles, but there are also
piles of material which have been separated on a size basis
by the operators of the pit. The floor of the pit has been
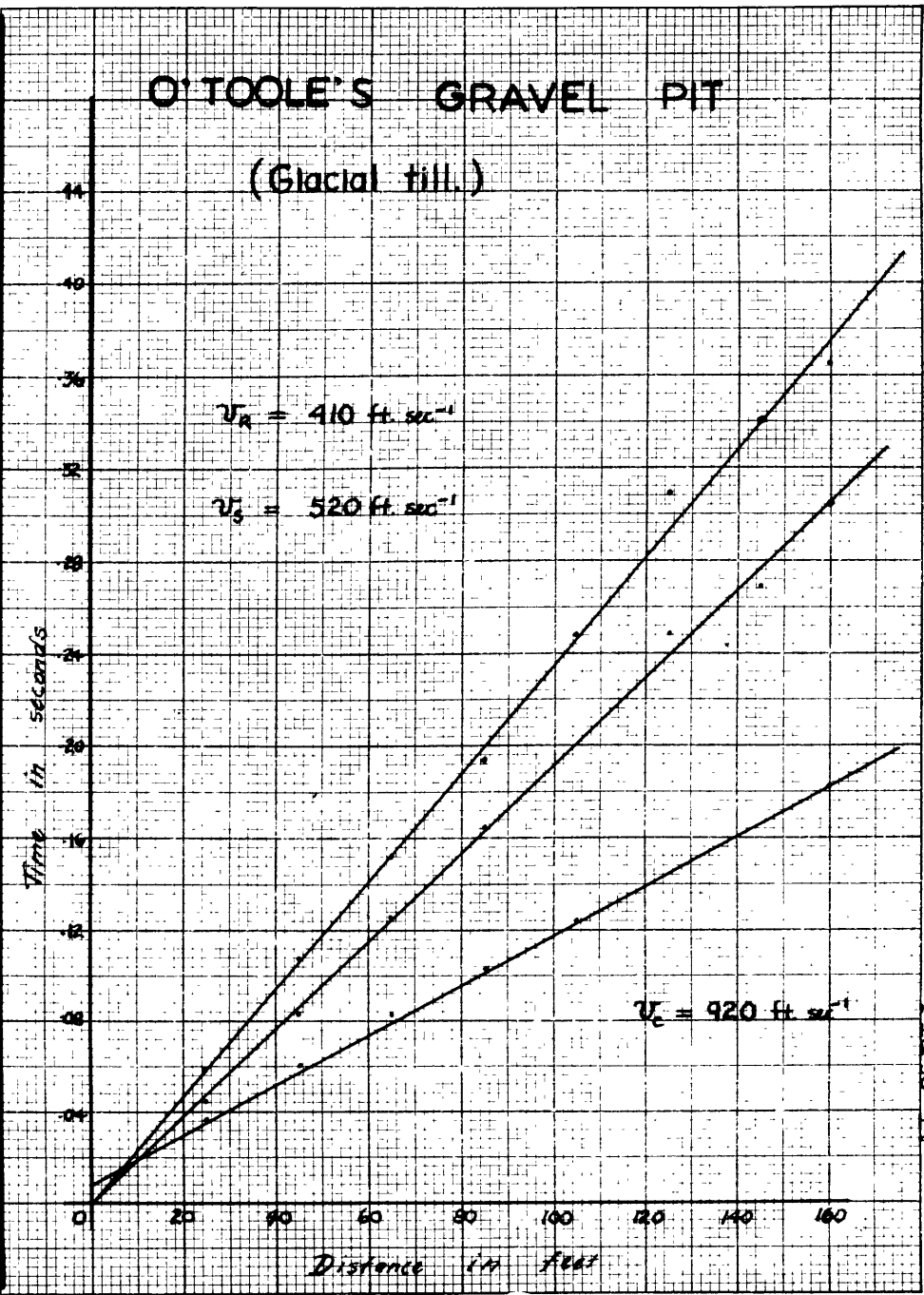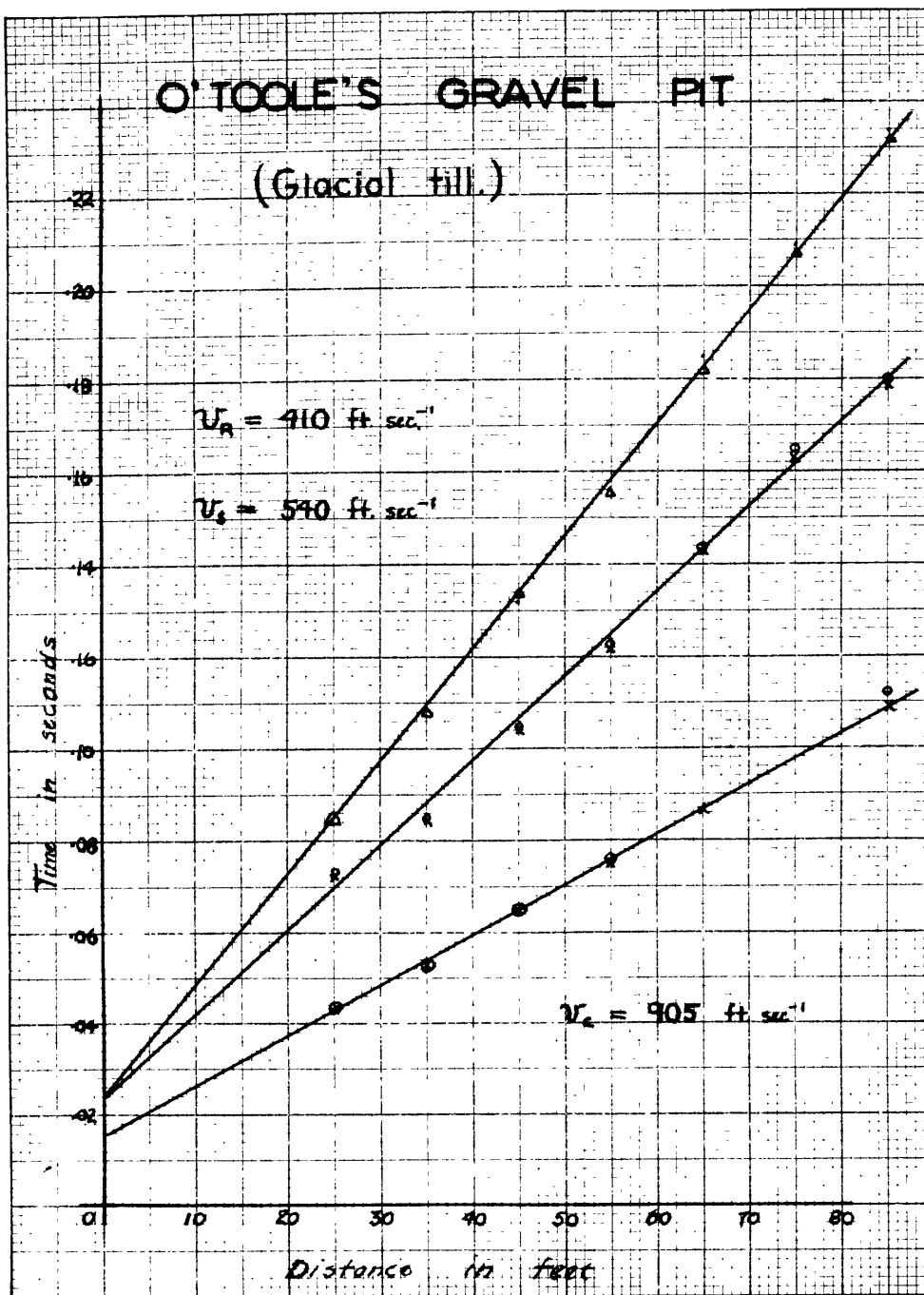dug down to within a foot or so of the underlying glacial till.

The first tests made here were on the floor of the pits.
The top few feet consisted of a heterogenous mixture of sand,
gravel, pebbles and cobbles with the underlying material
being glacial till. The set-up used was the same as in pre-
vious tests, that is, geophones on their sides, five feet
apart and in line with the plank. In this case, however,
the geophones were half buried. The results are plotted on
Plate III. These records showed the arrival of the shear
waves much clearer than the compressional waves when compared
to the records taken at Rockwell Cage. This was due, probably
to the fact that the partial burial of the geophones improved
the coupling between the earth and the geophone proportionately
more for the shear waves than for the compressional waves.
It is of interest to note, that in this case, v_c/v_s =
910/540 = 1.69. As will be recalled from the previous dis-
cussion of elastic theory, this is a very close approximation
to the relationship which holds when $\lambda = \mu$. This is,
moreover, a common assumption used when discussing igneous
rocks. Therefore, this particular set of data would indicate

O'TOOLE'S GRAVEL PIT

(Glacial till.)

$V_s = 535$ ft. sec^{-1}

$V_c = 910$ ft. sec^{-1}

O'TOOLE'S GRAVEL PIT

(Glacial till.)

$V_s = 540$ ft. sec^{-1}

$V_c = 910$ ft. sec^{-1}

Time in seconds

Distance in feet

that $\lambda = \mu$ even for unconsolidated material.

Two more tests were run along the bottom of the pit, in order to determine the effect of increasing the spread. There was also some doubt as to what, if anything, the geophones would pick up when they were vertical and the source produced, primarily, shear waves. Therefore, the spread was increased by moving the first geophones twenty-five feet from the plank with the rest of them at five foot intervals. The results of these trials are shown on Plate III.

As a further test, the above was repeated with a geophone interval of ten feet so that there was a total spread of ninety-five feet. Shear waves were recorded for this spread with the geophones both vertical and horizontal. After this, the geophone interval was increased to twenty feet and the geophones were placed horizontally. In all cases, records were produced, but as the spread increased, it became more and more difficult to pick the last few traces. In spite of this, however, there were a couple of records of interest. Plate IV shows the results of these tests and as can be seen, there is a third velocity. This velocity only became really apparent on the records produced when the geophones were upright and the source contained a SV component. This is the set up for receiving Rayleigh waves, so that is probably what this third velocity is. As a check on this idea, it will be remembered that in isotropic elastic theory, if $\lambda = \mu$ (Poisson's or Cauchy's relation), the Rayleigh wave will have

O'TOOLE'S GRAVEL PIT

(Glacial till.)

$V_R = 410$ ft. sec.$^{-1}$

$V_s = 540$ ft. sec.$^{-1}$

$V_c = 905$ ft. sec.$^{-1}$

Time in seconds

Distance in feet

O'TOOLE'S GRAVEL PIT

(Glacial till.)

$V_R = 410$ ft. sec.$^{-1}$

$V_s = 520$ ft. sec.$^{-1}$

$V_c = 920$ ft. sec.$^{-1}$

Time in seconds

Distance in feet

a velocity equal to 0.92 of the shear wave velocity. In
the present case, this third velocity is about 0.83 times the
shear velocity. This is very roughly the theoretical value,
considering that λ undoubtedly does not equal μ exactly
for unconsolidated material.

The second half of Plate IV which shows all three veloci-
ties from one record has a certain amount of interest. This
is the only record from which these three velocities could be
picked, although they probably occur, in an illegible form,
on others. (See Fig. 3)

A few tests were made on a gravel pile, which was the
result of separation of materials carried on during the opera-
tion of the gravel pit. The gravel was pebble size, with
the maximum dimension being 1 to 2 inches, and was primarily
granite. Tests were made with the geophones on their sides
with five foot intervals between them and also with ten foot
intervals. The records obtained in both cases were practically
meaningless. The wave may be followed for only very short
distances. In less than twenty feet, the wave form has changed
so radically that it is impossible to pick it out of the
record. This is undoubtedly due to two factors. The first
is the poor coupling between the pebbles and the geophones,
which lowered the efficiency of the geophones by an unknown
but appreciable amount. The second factor, and probably the
more important one, is that a pile of pebbles is a highly
dispersive medium. This means that the velocity is dependent
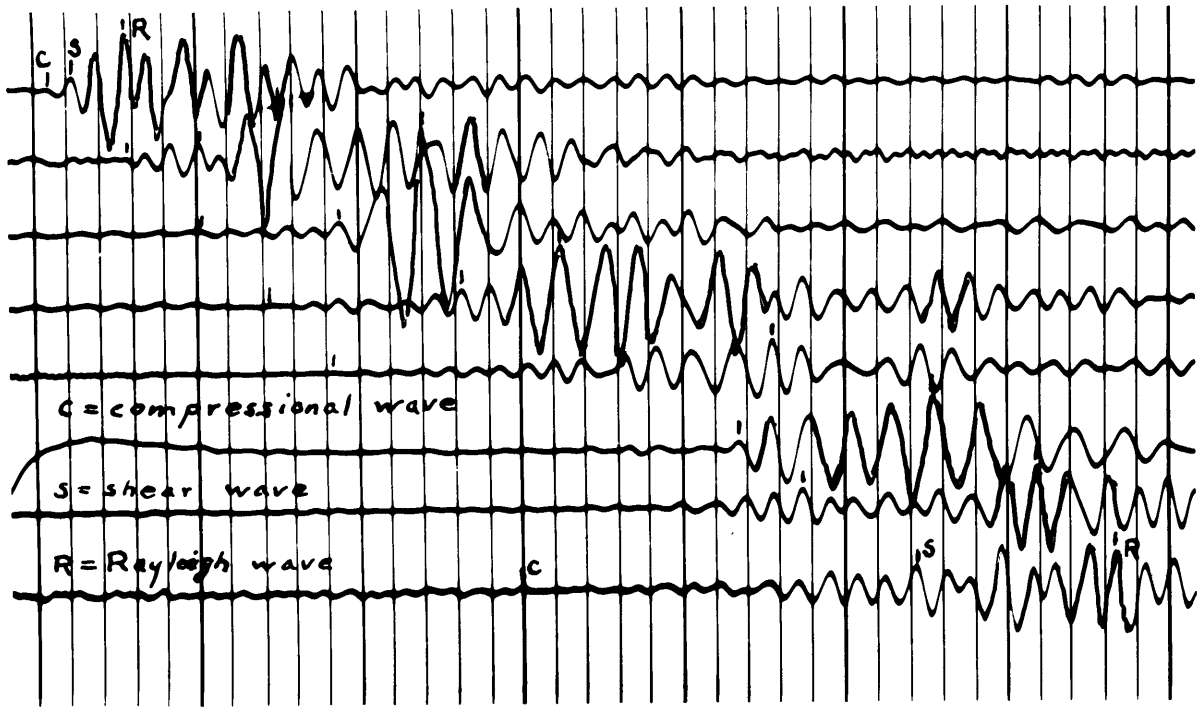
Record from O'Toole's Gravel Pit showing all three
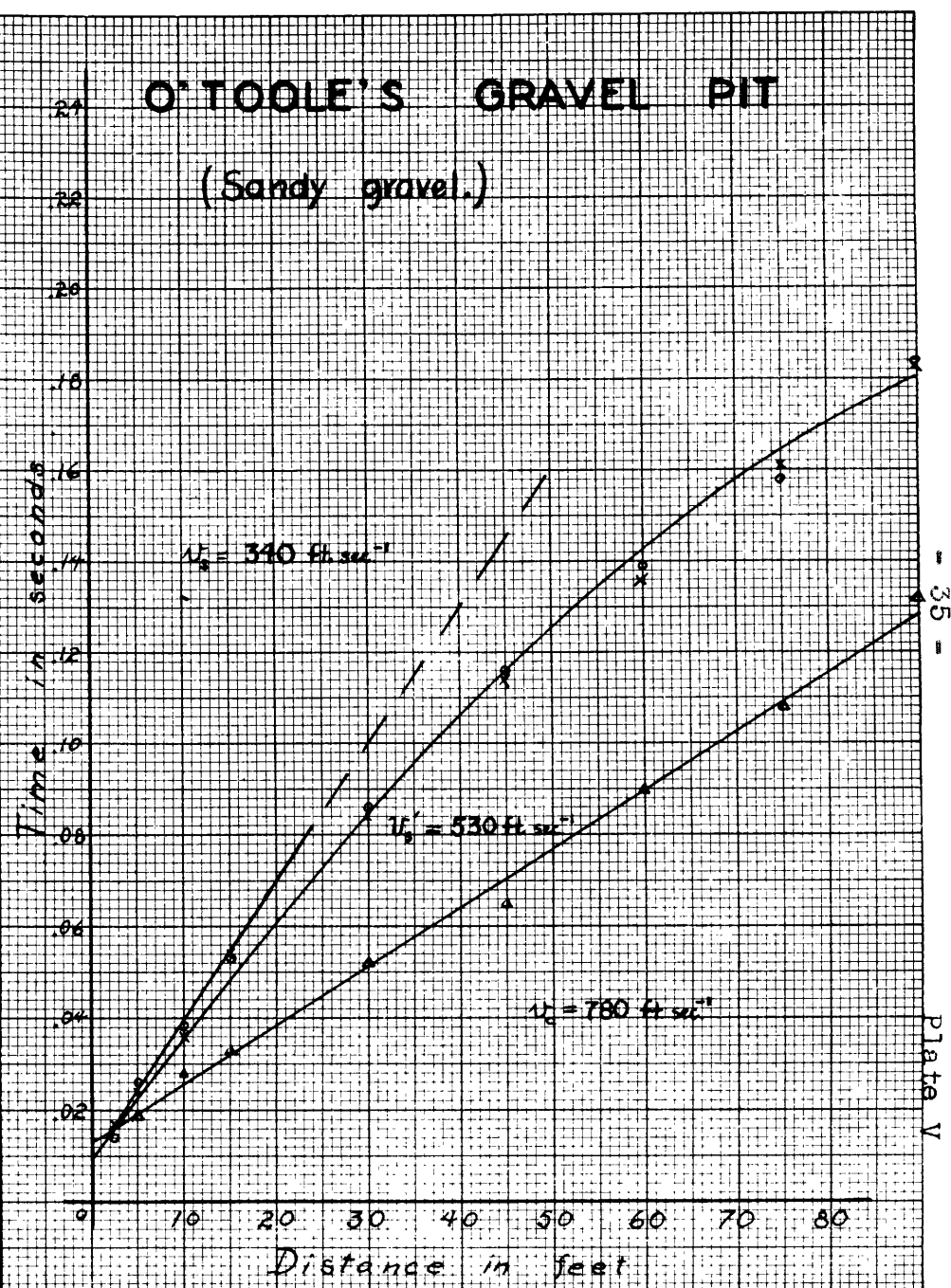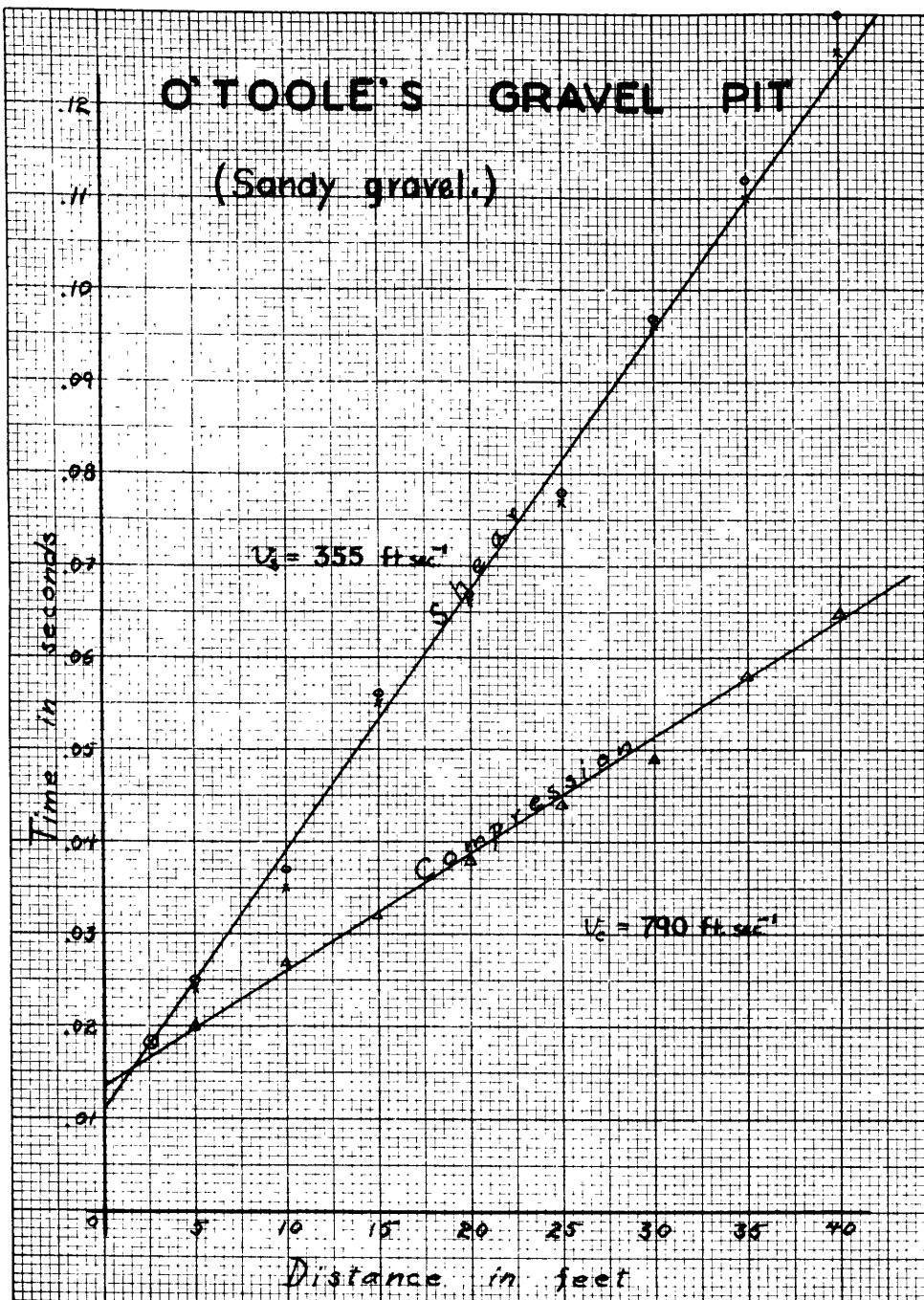waves: compressional, shear and Rayleigh.
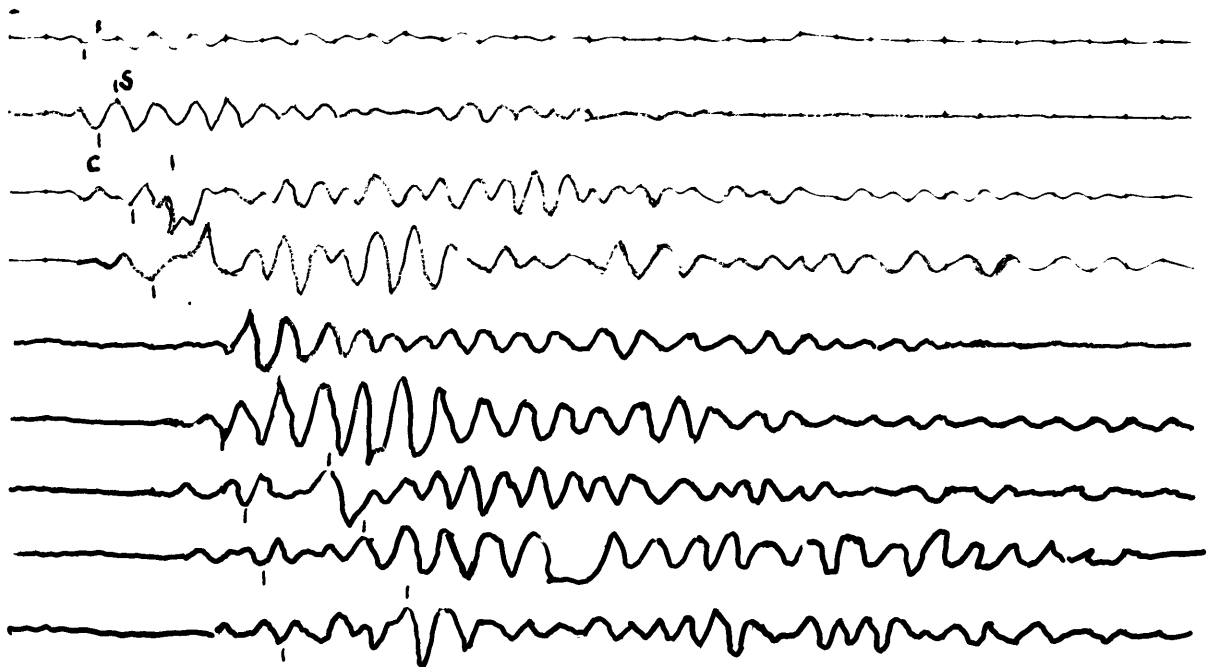
Normal record, from Lexington Sand and Gravel Company Pit.

Fig. 3

on the frequency. Thus, a pulse source, composed of many
frequencies, quickly turns into a band of separate waves,
each with its own frequency and velocity. The result is that
the energy is so dissipated that no translatable results are
recorded. The only velocity obtainable from these records
comes from only two or three traces and so, the resulting
600 ft/sec is just a rather vague trend.

A third test was made near the top of the glacial delta
which is now O'Toole's Gravel Pit. The surface material (i.e.
down at least two feet) consisted of a very sandy gravel
which ranged in size from a medium sand through pebbles to a
few cobbles. All tests were made along the strike of the
surface layer, which was easily traced along the face of the
pit some fifteen or twenty feet away. The geophone spacing
was the standard one, except that an extra geophone was
placed two and a half feet from the plank. This was done
in an attempt to improve control in reading the records as
experience had shown that, in general, the first few traces
could be picked with more confidence than could the last few.

Additional tests were made with the spacing between the
geophones changed. The first four geophones were left as in
the previous tests, but the rest were all moved so that the
interval between them was fifteen feet. Plate V shows the
results of both test sets. For both arrangements of geophones,
the compressional velocity was constant, but the shear velocity
showed an appreciable increase as the spread was increased

O'TOOLE'S GRAVEL PIT

(Sandy gravel.)

$V_1 = 355$ ft sec⁻¹

Compression

$V_c = 790$ ft sec⁻¹

Time in seconds

Distance in feet

O'TOOLE'S GRAVEL PIT

(Sandy gravel.)

$V_3 = 340$ ft sec⁻¹

$V_2' = 530$ ft sec⁻¹

$V_c = 780$ ft sec⁻¹

Time in seconds

Distance in feet

= 35 =

Plate V

over forty feet. This would indicate that the velocity of
shear waves increases with depth more rapidly than does the
velocity of compressional waves. The method of least squares
gives an average velocity of 530 ft/sec for shear waves which
travel less than ten feet below the surface.

It should be noted here, that the records used to find
the compressional wave velocity were made especially for this
purpose. For these records, the geophones were set upright
and the plank was hit a downward blow near its center. The
resulting velocity was determined by reading the first breaks
which were, in general, rather sharp. In this particular
case, $v_c = 2.24$ instead of 1.73 as Poisson's relation re-
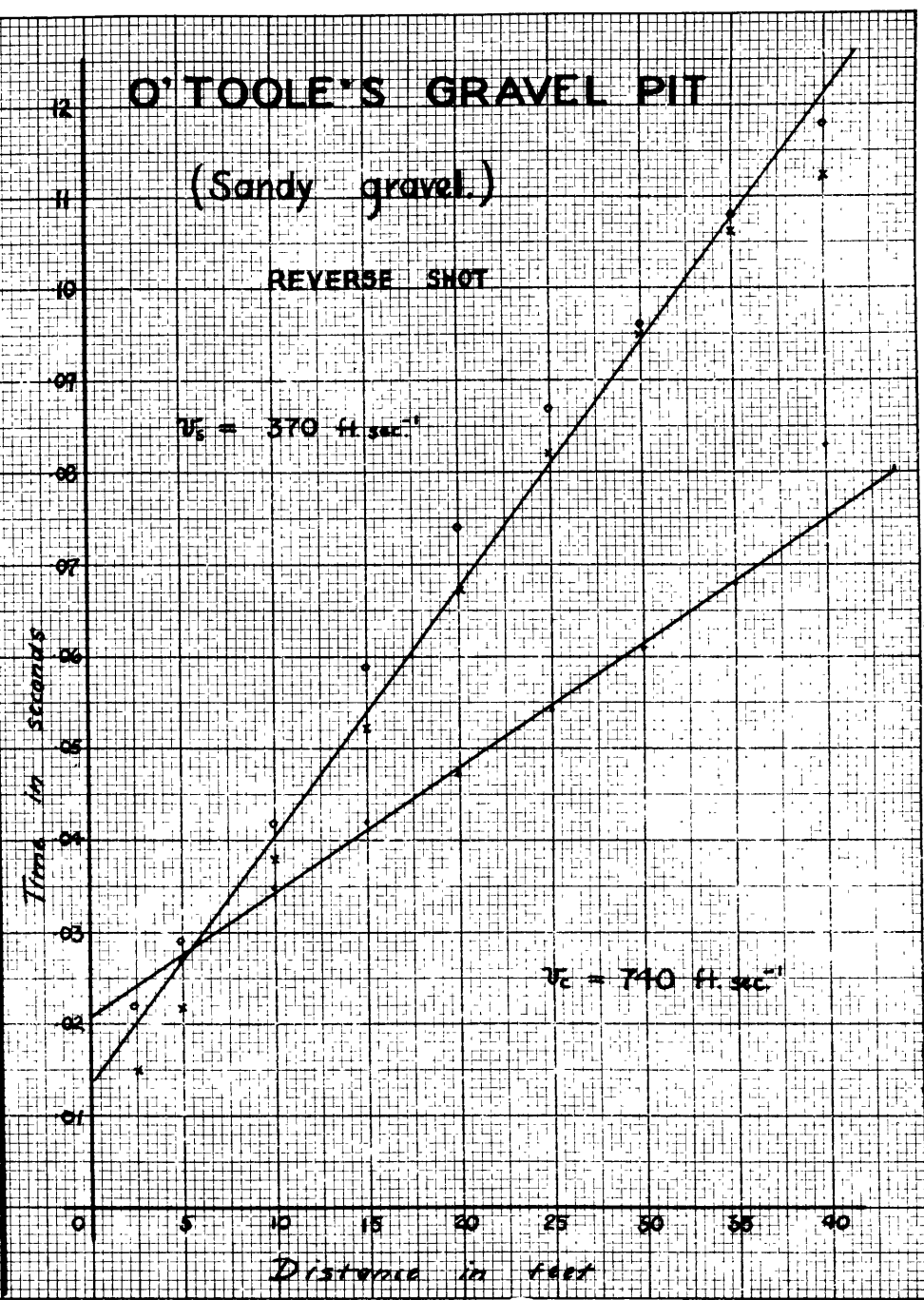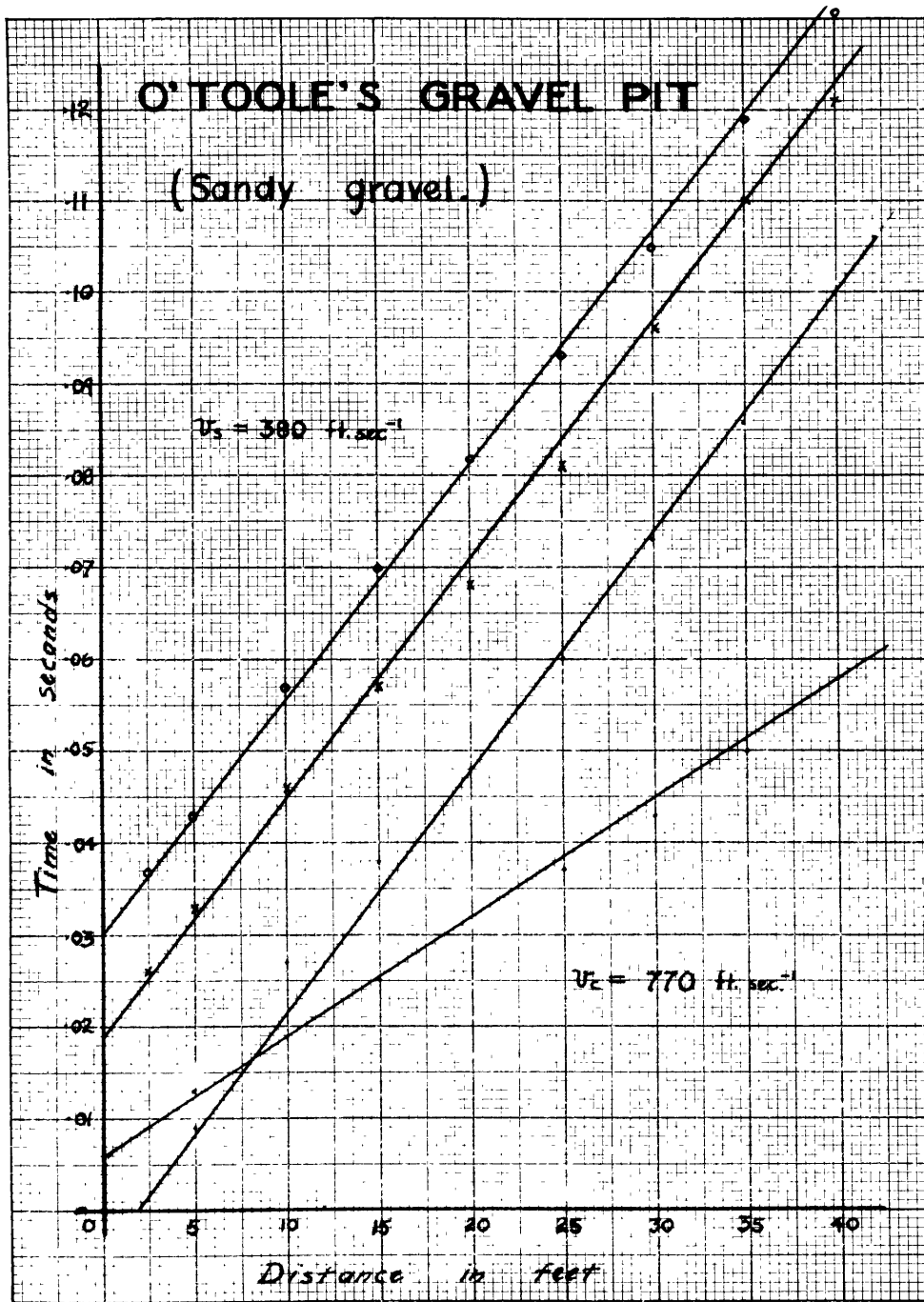quires.

The question arose as to how sensitive the geophones
were to the (essentially) shear waves when they were in a
vertical position. Tests were, therefore, made in this area
which were repetitions of the previous ones except that the
geophones were placed vertical instead of horizontal. It
must be remembered, however, that the source was not a pure
shear wave, but had an appreciable compressional component.
Thus, the best that could be hoped for in these tests was a
quantitative measurement of the geophones sensitivity.

In normal seismic work, reverse shots are made as normal
procedure. In the present work, however, it was assumed that,
for the materials tested and with the short spreads used, the
errors in the velocities due to dipping beds would be within

the experimental error. In the tests being discussed here, however, beds were thin and, in some places at least, fairly steep. Therefore, reverse shots were made to check any variations due to dip or to the fact that the geophones had been slightly displaced during previous tests.

The results of these last two sets are shown in Plate VI. When the geophones were vertical, the velocity of the shear waves was slightly higher, but only about 8%. The records, however, were somewhat more difficult to read as the compressional component was almost as large as the shear component. It was possible, none the less, to pick the trend which occurred on the arrival of the shear wave. But the actual picking of individual points becomes more critically dependent on the amplification of the recording instrument then in previous records. The general appearance of the records seems to indicate that the geophones have an appreciable increase in sensitivity to SH shear waves when they are in a horizontal position as compared to what they have in a vertical position.

The reverse shots show that the tests were made along the strike of the formation as there are no variations in the velocities greater than the experimental error. They also show that slight re-positioning of the individual geophones has no noticeable effect. The most interesting record resulting from this test is one which shows no recognizable shear wave although the compression wave can be picked rather easily.

O'TOOLE'S GRAVEL PIT

(Sandy gravel.)

$v_s = 380$ ft. sec.$^{-1}$

$v_c = 770$ ft. sec.$^{-1}$

Time in seconds

Distance in feet

O'TOOLE'S GRAVEL PIT

(Sandy gravel.)

REVERSE SHOT

$v_s = 370$ ft. sec.$^{-1}$

$v_c = 740$ ft. sec.$^{-1}$

Time in seconds

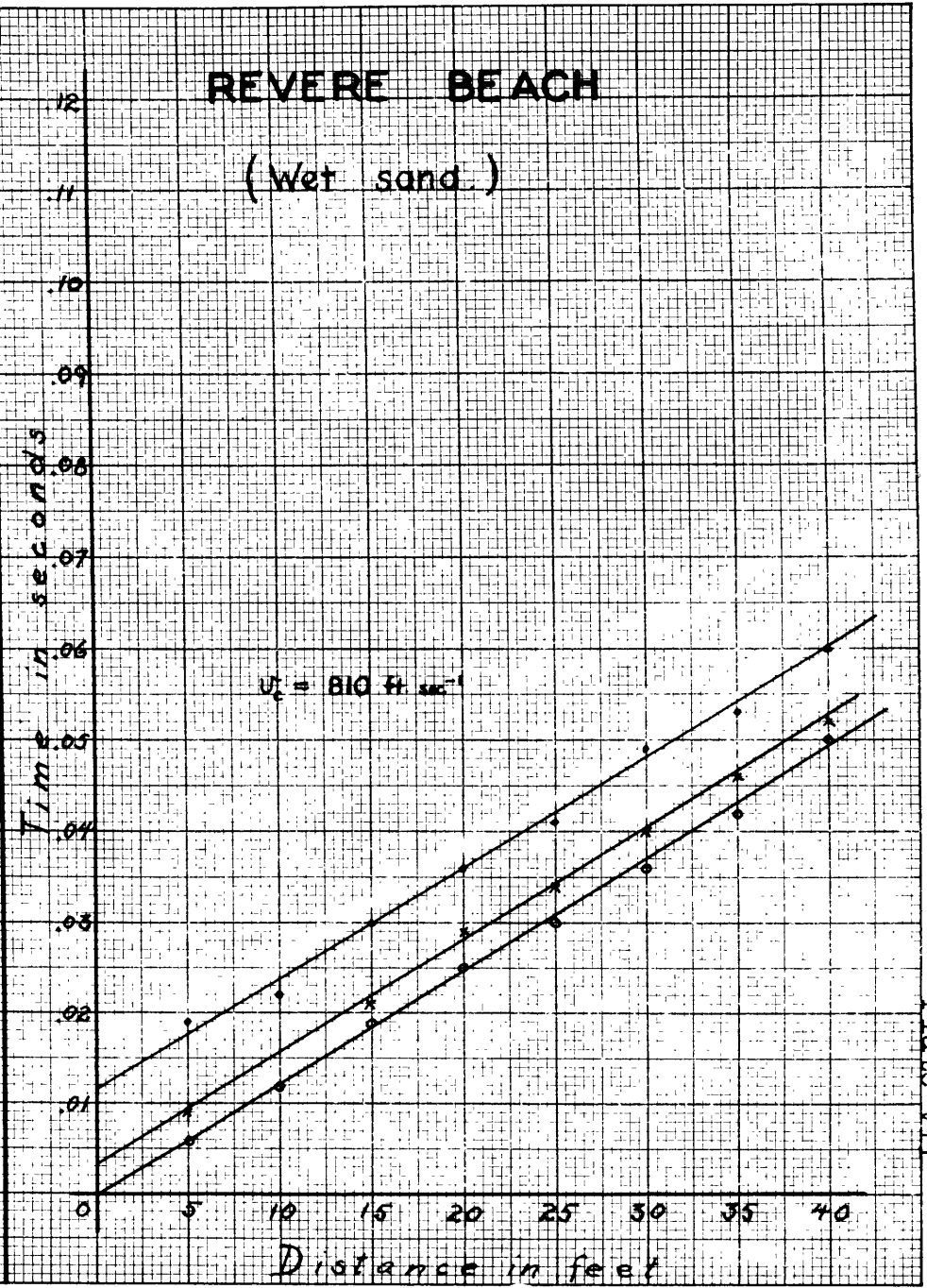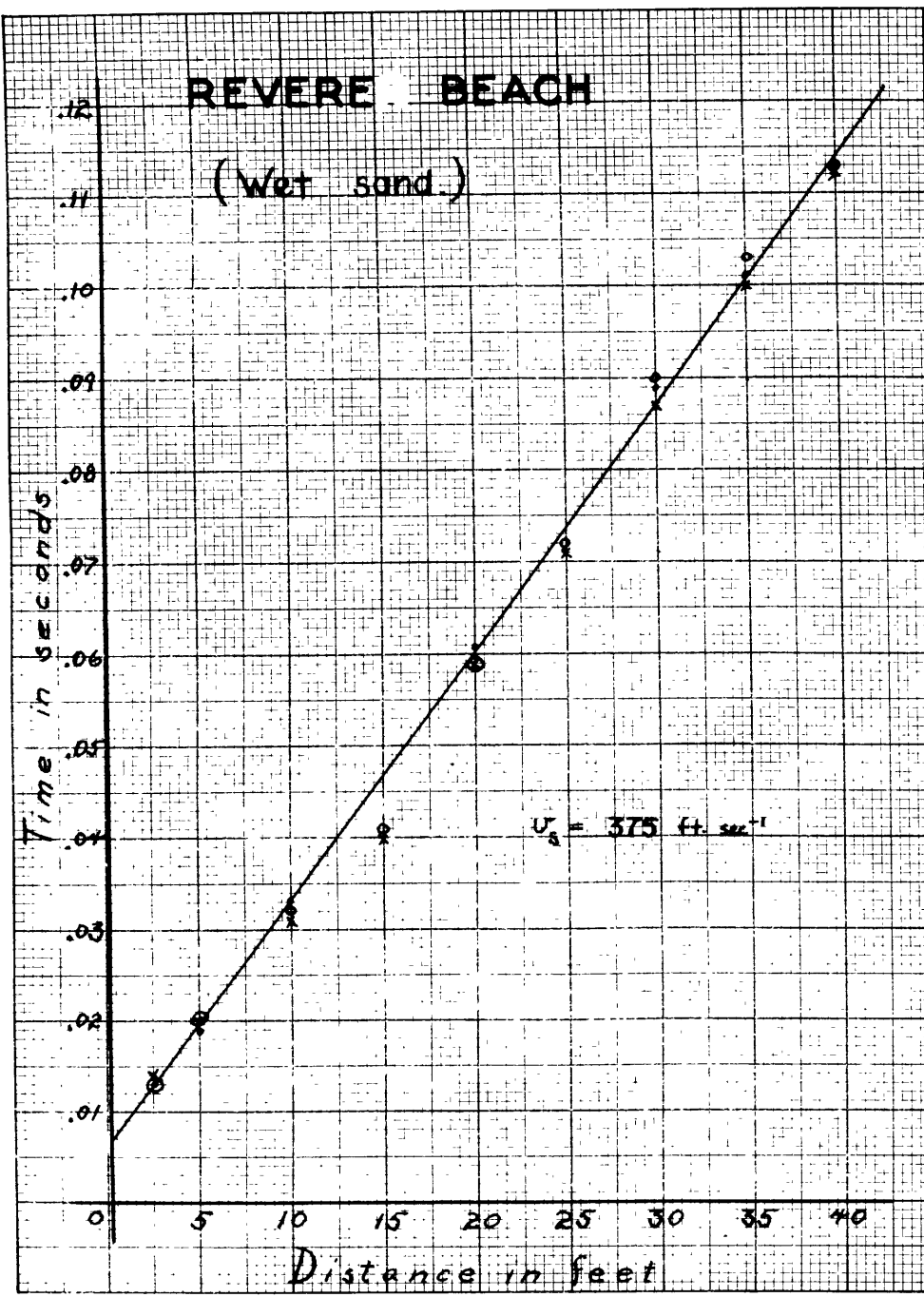Distance in feet

Plate VI

- 38 -

This may possibly be due to the fact that the low degree of amplification failed to emphasize sufficiently the slight variation produced by the arrival of the shear wave. On the other hand, this record does not repeat the previous records to any such degree, as is usual which indicates that for some reason or other it is spurious.
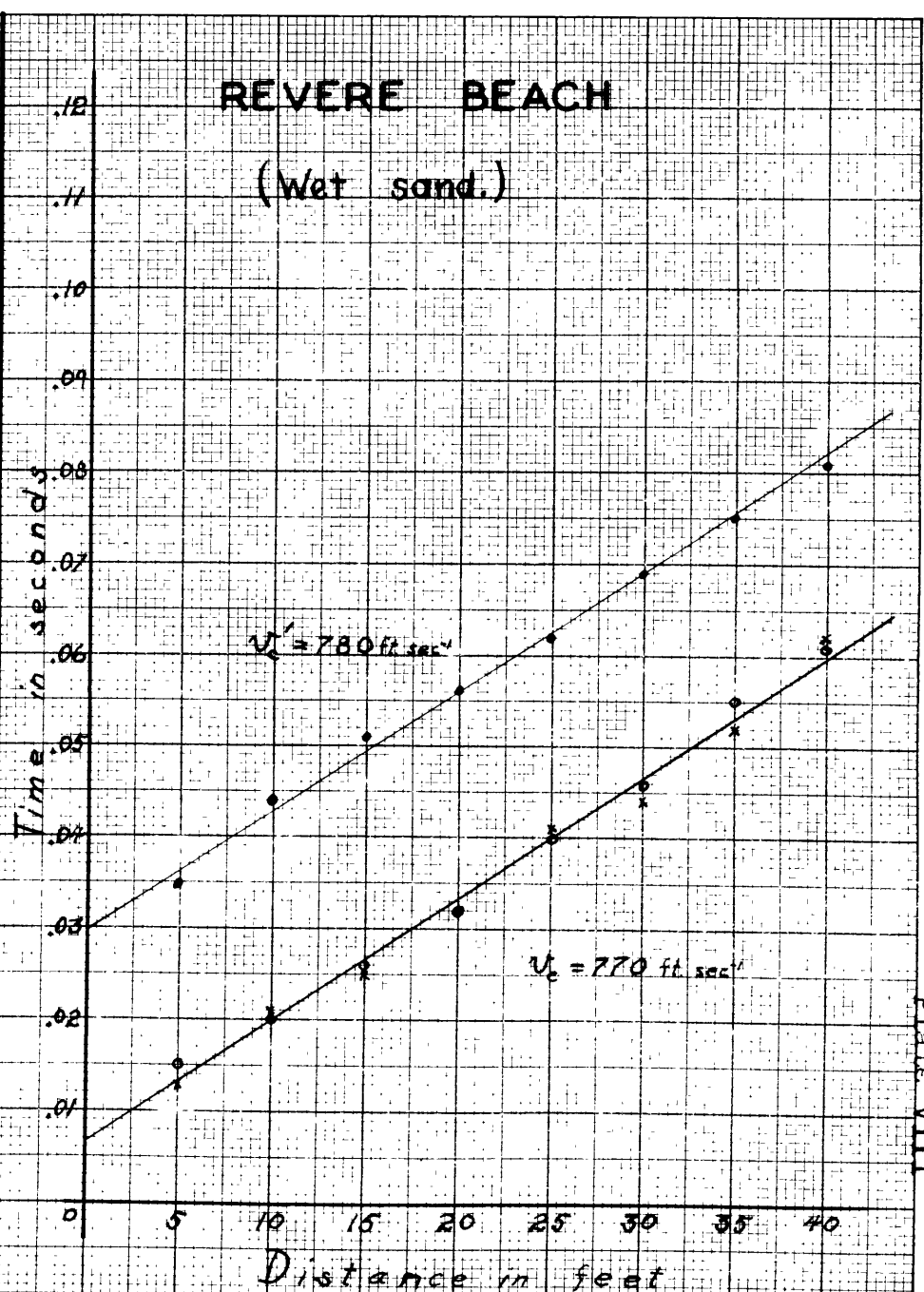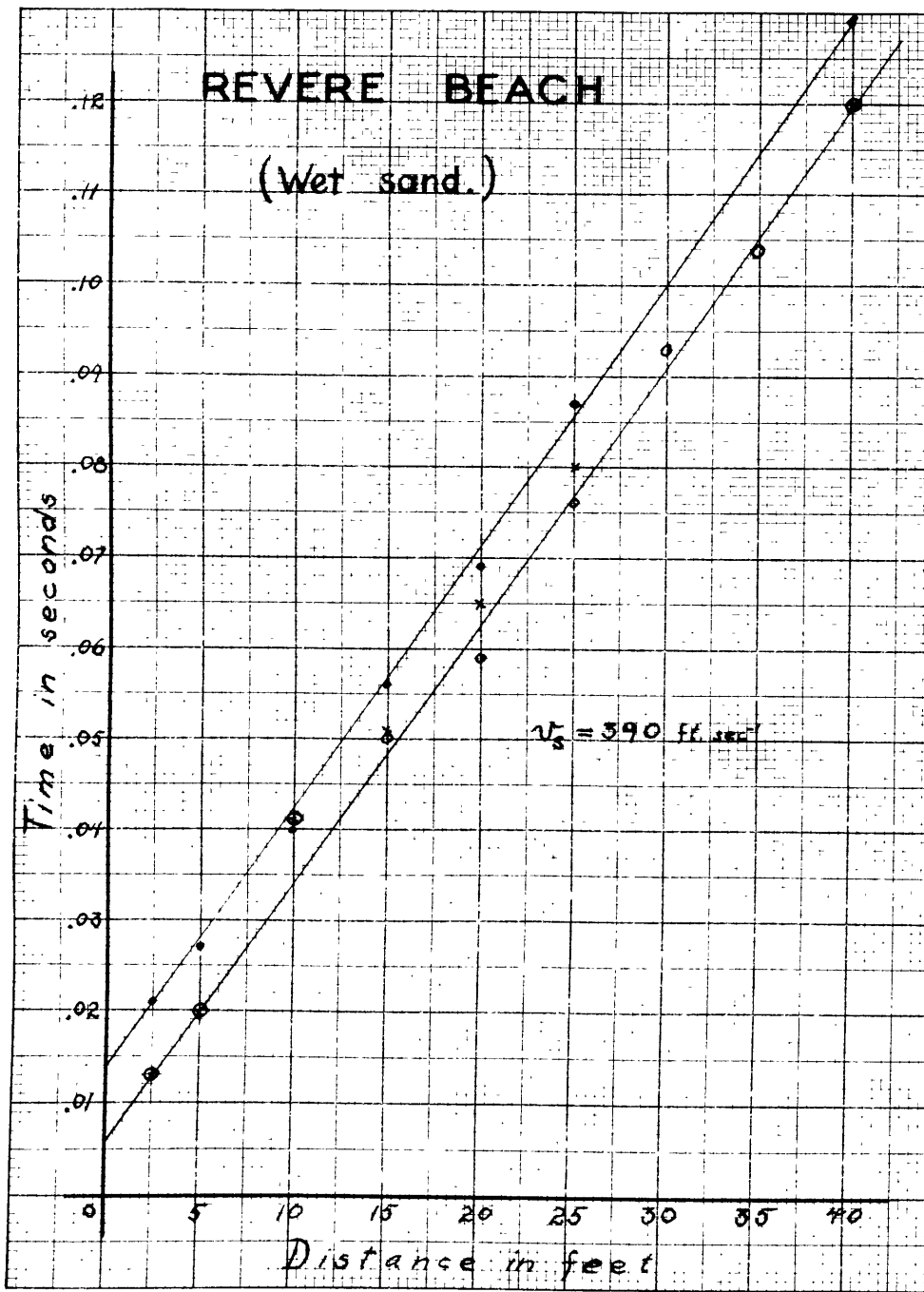
Revere Beach

Plates VII, VIII, and IX show the results of tests made on Revere Beach. These tests were all made on the southern end of the beach and parallel to the water. Results shown in Plates VII and VIII were made in the early winter while those on Plate IX were made in the early part of the following spring. As can be seen by the results, the winter storms, or something else, had a very noticeable effect on the elastic properties of the beach.

In the earlier tests, records were taken both at the high tide level and at the waters edge as the tide was going out. This was an attempt to determine the effect, if any, of saturating water. In both places the beach was a normal ocean beach with an upper layer of sand which graded downward, rather rapidly, to gravel. The geophone spacing was the same in both places and the tests made were also the same. And so were the results, essentially.

The two shear velocities are so nearly the identical that nothing can be proven from them. The slight increase of

REVERE BEACH
(Wet sand.)

$U_s = 375$ ft. sec^{-1}

REVERE BEACH
(Wet sand.)

$U_c = 810$ ft. sec^{-1}

Time in seconds

Distance in feet

Plate VII

REVERE BEACH

(Wet sand.)

$V_s = 390 \text{ ft. sec}^{-1}$

Time in seconds

Distance in feet

REVERE BEACH

(Wet sand.)

$V_c' = 780 \text{ ft. sec}^{-1}$

$V_c = 770 \text{ ft. sec}^{-1}$

Time in seconds

Distance in feet

Plate VIII

velocity in the wet sand may well be only an apparent increase.
On the otherhand, the compressional velocities seem to be a
little more conclusive. These would indicate that the com-
ressional velocity is slightly greater in dry sand than in
wet sand. It is a well known fact, however, that the com-
pressional velocity increases sharply at the water table. In
both cases, there was a record from which it was possible to
find the compressional velocities from two separate sets of
points. The agreement here does much to eliminate the pos-
sibility of an error in velocity due to having picked the
records incorrectly.

In the early spring, another test was made in approxi-
mately the same place, but at this time a week of rain had
wet the whole beach so that all of it was damp if not satur-
ated. At this time, a few variations were made in procedure.
For some of the records a lead weight of about five pounds
was attached to the end of the plank at the point where it
was hit with the hammer. This was done to change the natural
frequency of the plank to test whether or not that would have
any effect on the record. It had no noticeable effect.
Records were also made with the geophone spacing reduced by
a factor of two. The results of these tests are shown in
Plate IX. When the spread is halved, both velocities are
slightly decreased. This is to be expected as the waves will
travel nearer the surface for the shorter spread and so its
average velocity will be less.

REVERE BEACH

(Damp sand.)

$V_s = 565$ ft sec^{-1}

Shear

Compression

$V_c = 1200$ ft sec^{-1}

Time in seconds

Distance in feet

REVERE BEACH

(Damp sand.)

$V_s = 530$ ft sec^{-1}

Shear

Compression

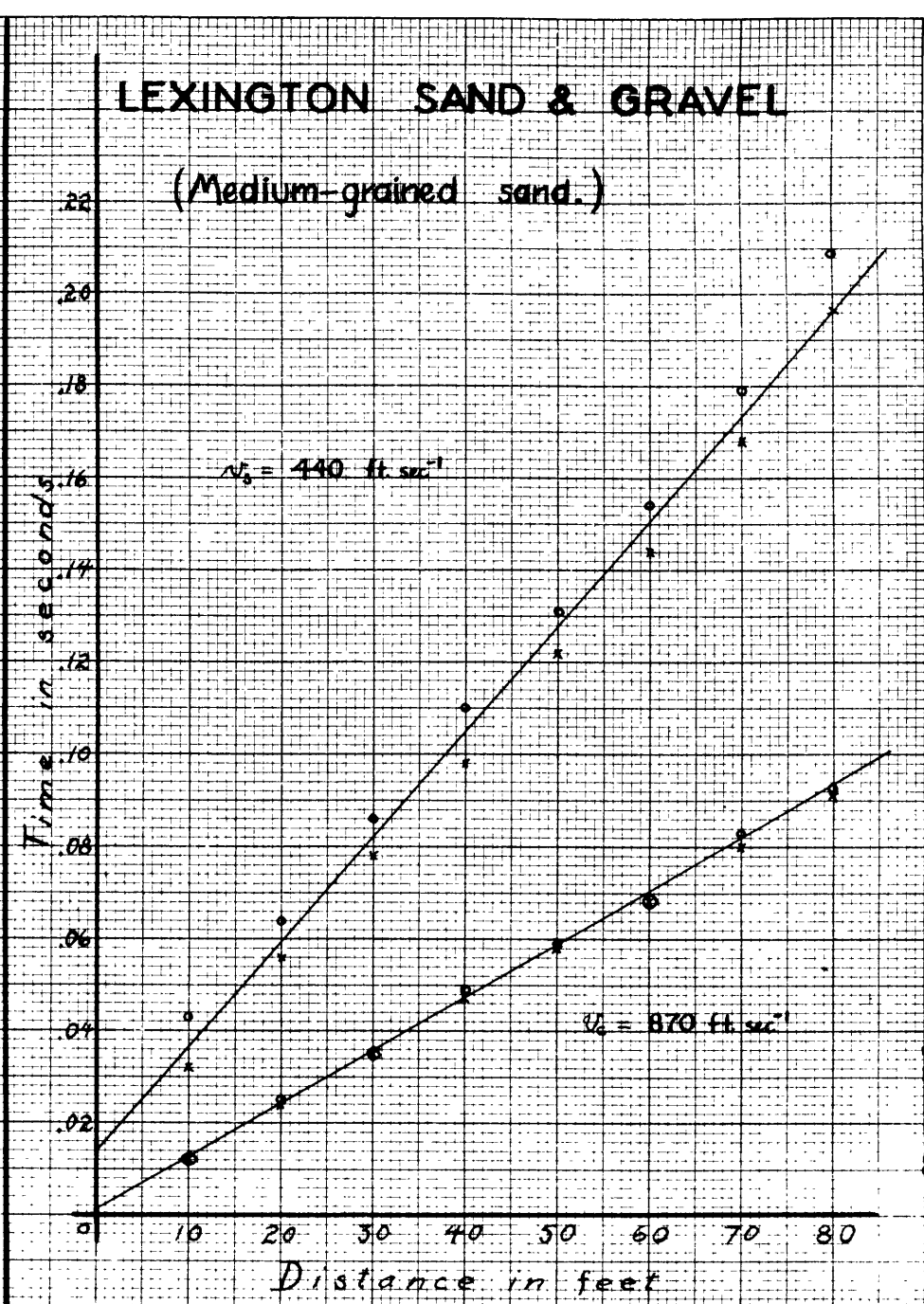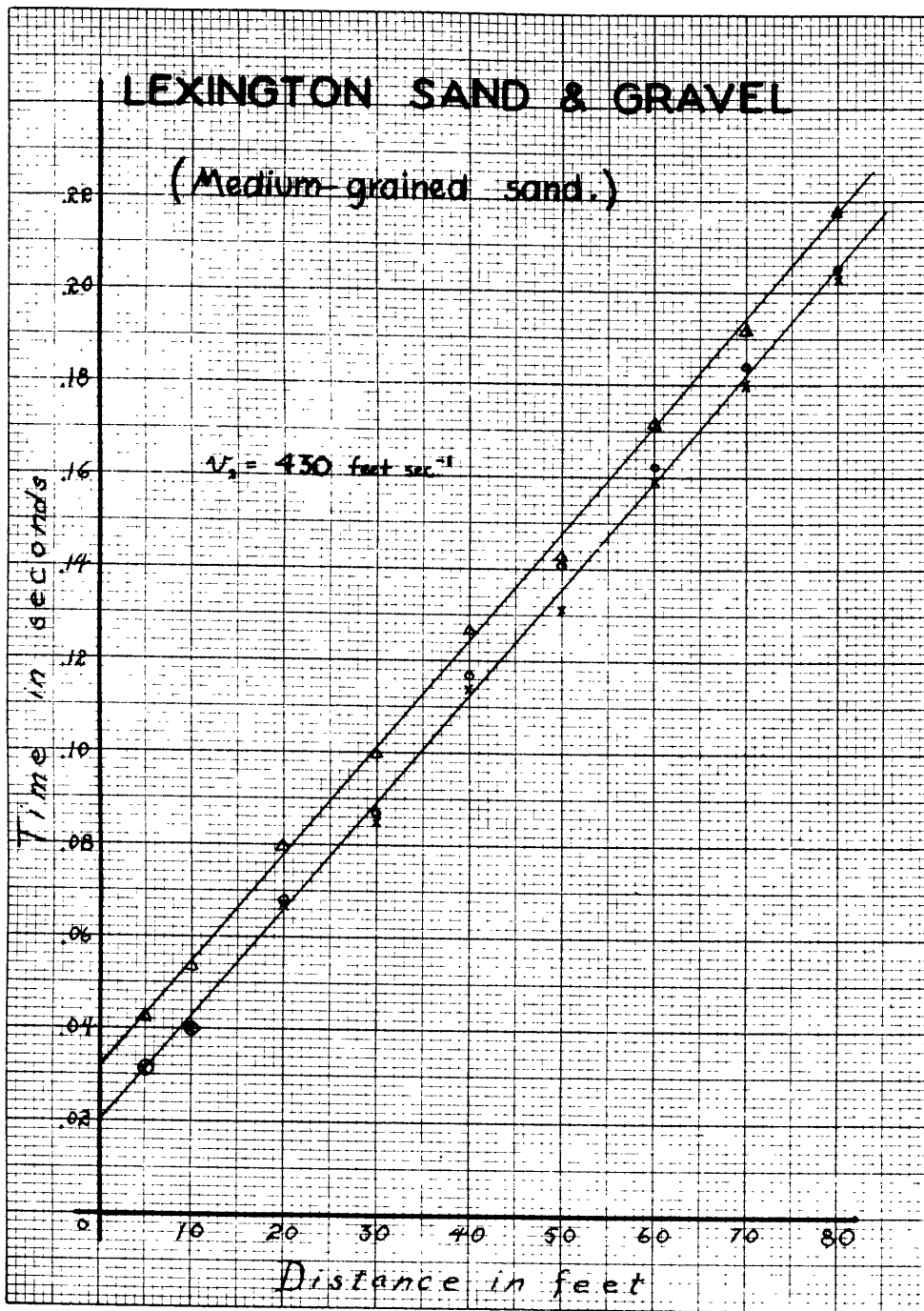$V_c = 1180$ ft sec^{-1}

Time in seconds

Distance in feet

Plate IX
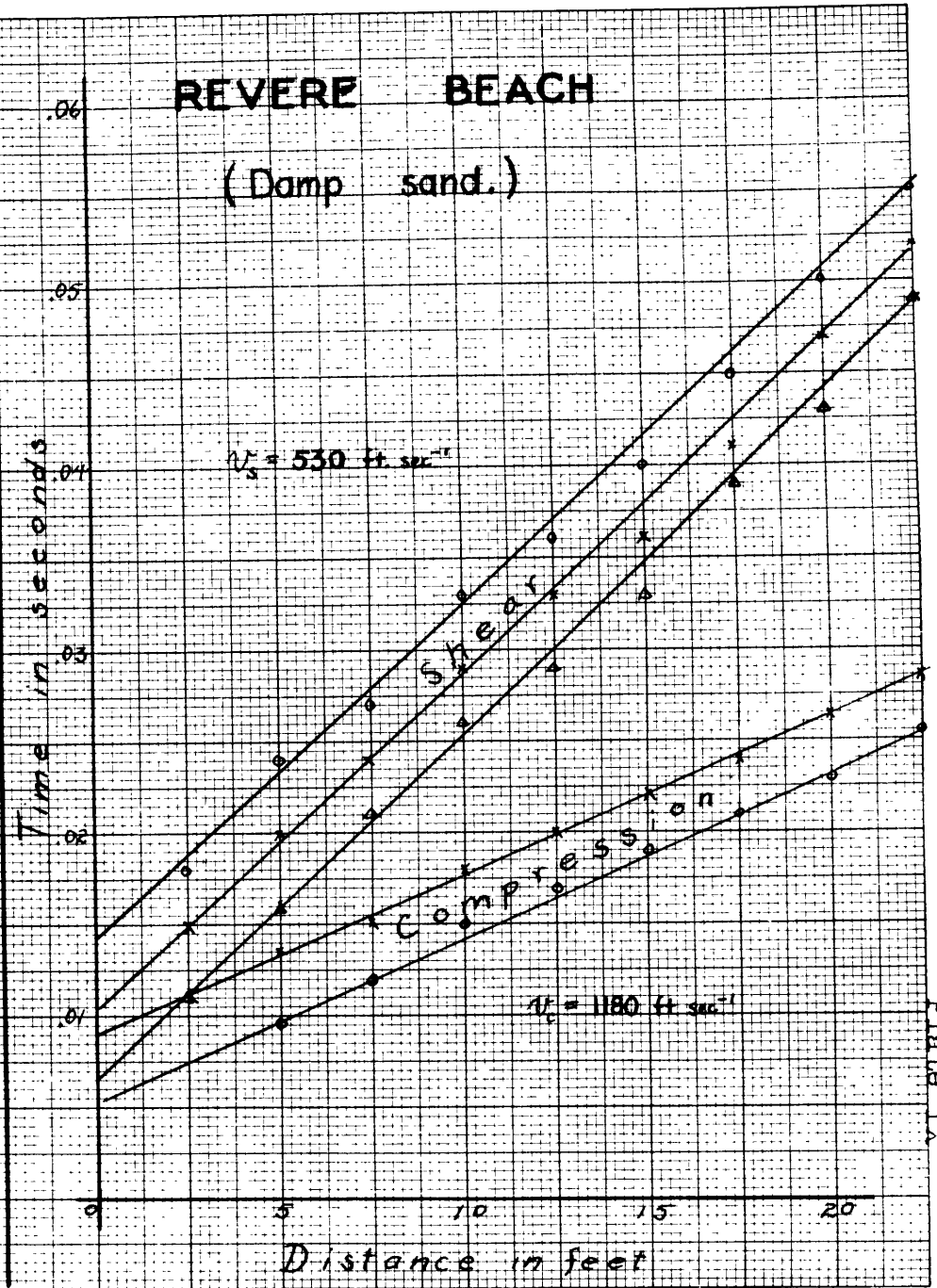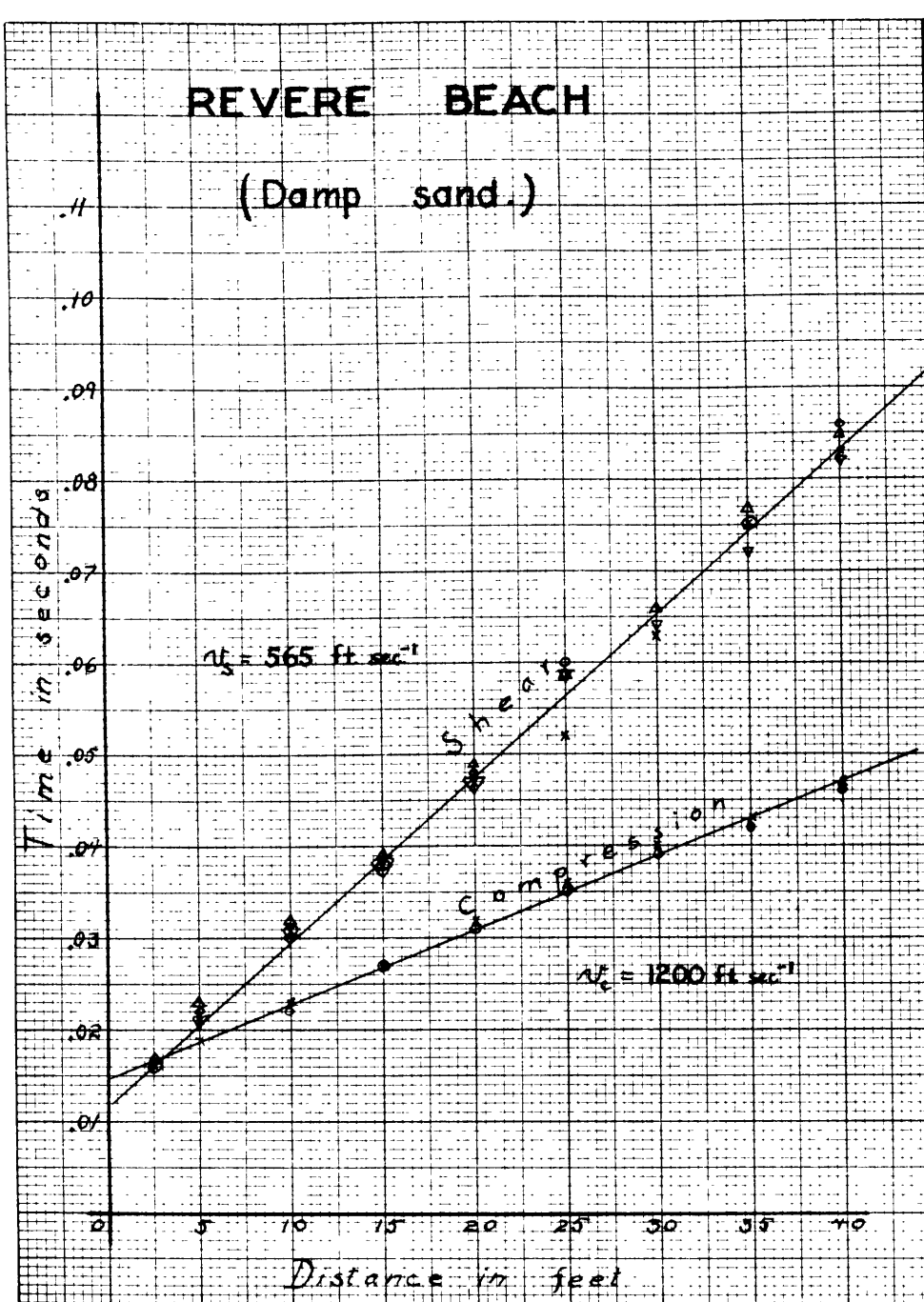
The interesting thing about these two tests at Revere
Beach is the large increase of both velocities which occured
during the winter. These velocities increased uniformly,
that is v_c/v_s ▪ 2.12 for both tests. This consistancy
would seem to indicate that the increases in the velocities
is real and not an apparent one due to mis-interpretation of
the records. The only reasonable explaination of this increase
must be found in some physical change which happened to the
beach during the winter to increase its compaction. A pos-
sible theory to explain this lies in the decomposition of
sea-weed. Storms commonly pile seaweed up on a beach during
summer months and later ones may bury it under a foot or
two of sand. Considering that the wave-lengths are of the
order of three to five feet and that the depth of penetration
is probably less than five feet, it seems reasonable to
believe that a fairly thin layer of seaweed would very effec-
tively aerate the beach so that the wave velocities would be
noticeably lowered. During the winter months a combination
of decomposition with no opportunity of renewal, and the
removal by storm action might conceivably eliminate all or
most of the seaweed. This would increase the compaction of
the beach material, and the wave velocities would also
increase. (This theory has not received universal approval,
but, with the data available, no more satisfactory one has
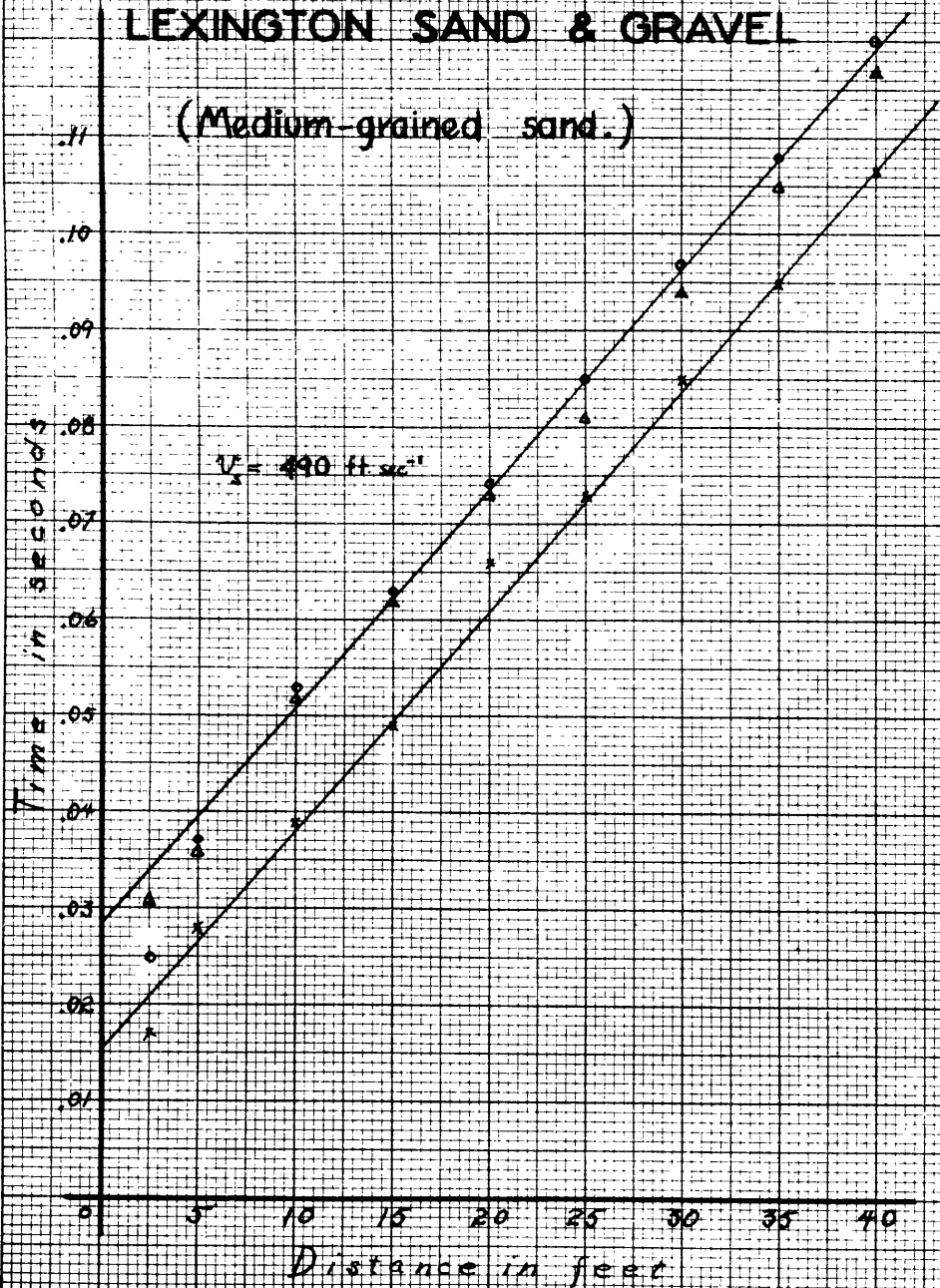been developed.)

Lexington Sand & Gravel Company

Plates X and XI show the results of tests made at the Lexington Sand and Gravel Co. pit in Lexington, Massachusetts. The material was a medium grained sand, well packed and containing a few pebbles. At the surface the material was dry, but it was damp below this. Plate X shows the results of a test with an eighty foot spread while Plate XI shows them for a forty foot spread. The results in both cases are essentially identical. For this material, v_c/v_s ≈ 1.94.

LEXINGTON SAND & GRAVEL
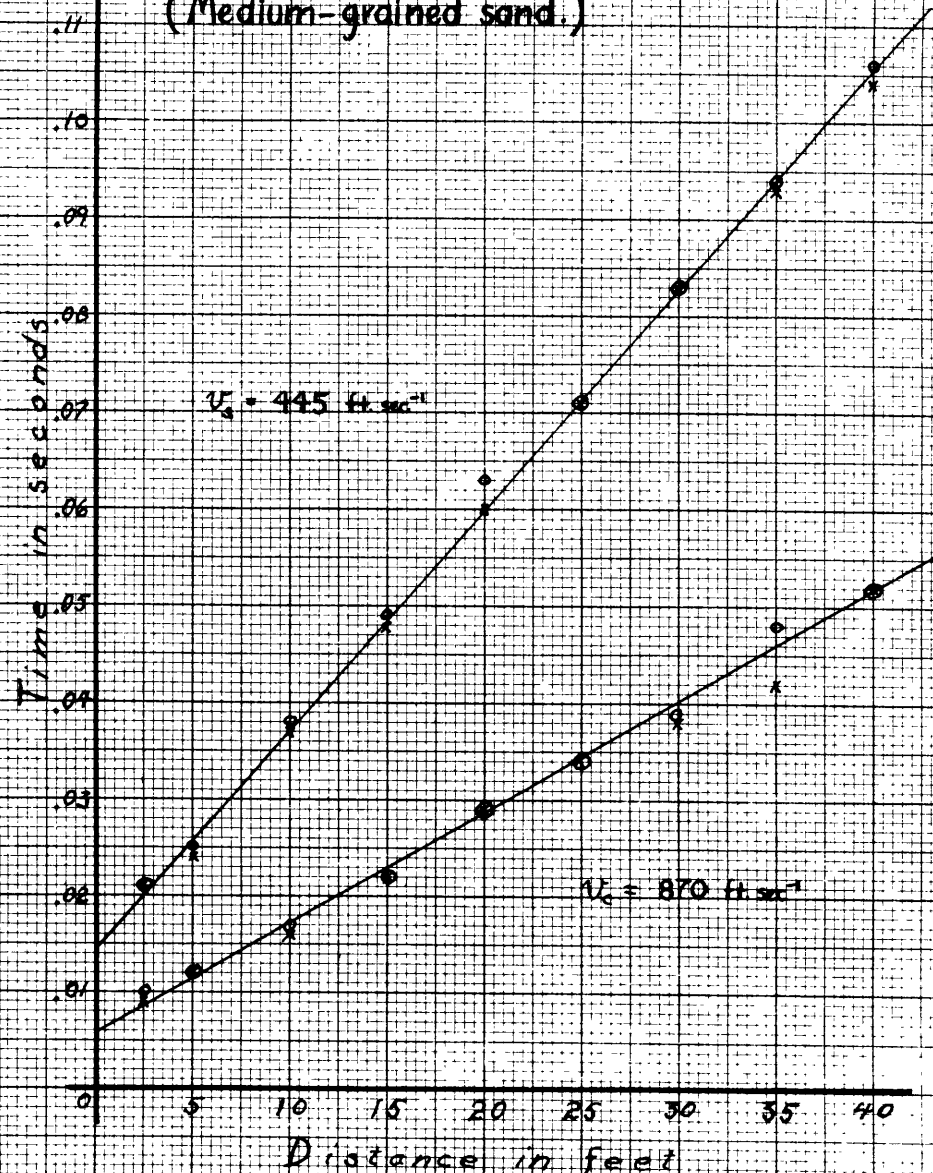(Medium-grained sand.)

$V_2 = 430$ feet sec.$^{-1}$

Time in seconds

Distance in feet

LEXINGTON SAND & GRAVEL
(Medium-grained sand.)

$V_3 = 440$ ft. sec.$^{-1}$

$V_4 = 870$ ft. sec.$^{-1}$

Time in seconds

Distance in feet

Plate X

LEXINGTON SAND & GRAVEL

(Medium-grained sand.)

$V_2 = 490$ ft sec^{-1}

Time in seconds

Distance in feet

LEXINGTON SAND & GRAVEL

(Medium-grained sand.)

$V_4 = 445$ ft sec^{-1}

$V_6 = 870$ ft sec^{-1}

Time in seconds

Distance in feet

CONCLUSIONS

The results obtained for this paper are tabulated in Table I.

TABLE I

Location	Material	v_s	v_c	v_c/v_s
Fletcher's Quarry	granite sand	300	---	----
O'Toole's Gravel Pit	gravel pile	600	---	----
O'Toole's Gravel Pit	sandy gravel	360	775	2.15
Revere Beach (winter)	dry beach sand	370	810	2.19
Revere Beach (winter)	wet beach sand	385	775	2.01
Lexington S. & G. Co.	medium sand	440	870	1.98
O'Toole's Gravel Pit	till	535	910	1.70
Revere Beach (Spring)	beach sand	550	1190	2.16
Rockwell Cage	clay	825	1550	1.88

This tabulation shows that, in a general way, the ratio v_c/v_s becomes smaller (and seems to approach 1.732) as the material becomes more compacted. The apparent inconsistancies could be eliminated by taking into account the $\pm$ 5% error that undoubtedly occurs in the velocities. In this respect, it should be noted that the results for Revere Beach are all of the same magnitude so far as ratios are concerned

even though the actual velocities varied greatly from winter to spring.

It is, in general, impossible to check these velocities against work done by someone else, but in the "Handbook of Physical Constants" a few values of compressional velocity are listed. It should be realized, however, that these velocities were all determined with much larger spreads than used here. They are, therefore, average velocities which refer to relatively great depths and much more compacted materials. Thus, comparisons with these values are not especially relevant, but they are of some interest in that they show how the range of velocities should be increased.

For sand, the handbook gives 0.2 - 2 km/sec or 650 - 6500 ft/sec as compared with 775 - 1190 ft/sec from the present work. For clay, Birch gives values from 3280 to 9190 ft/sec as against 1550 ft/sec and for diluvium (glacial till) from 2300 to 5900 ft/sec compared to 910 ft/sec. Thus, excluding the sand, the values from this paper are much lower than those found by other workers in the field, as was expected. But, as velocities normally increase with depth, these results seem fairly reasonable. Added indication of their reasonableness comes from personal communication with members of an experimental seismic crew of the Texas Company who have been finding that the top layer of sands are giving what appear to be extremely low values of velocities for compressional waves, in the order of 400 ft/sec.

Dobrin, Simon and Lawrence (1951) give a plot of veloci-

ties against depth for a location in Texas. While they do not give any discription of the material being tested, the results are of the same order of magnitude as those found here. For compressional velocities from the surface to a depth of about ten feet, they get from 1200 to 1500 ft/sec and for corresponding shear velocities 200 to 700 ft/sec.

The most comparable values for shear velocities are with those of Iida's work on sand. From a comparison with photographs of his samples, the sand at Lexington seems to match his sand No. 2 for which he found v_s = 407 ft/sec, which compares favorably with 440 ft/sec. His coarser sands, which might roughly be compared to those at Revere Beach, has a v_s = 358 ft/sec as against 370 ft/sec.

In both cases (v_c and v_s) Iida's laboratory methods give lower values than do the field methods used for this paper. This is also true with his v_c/v_s ratios. How much these variations depend on experimental error and how much they depend on differences in material studied is not known. In the single case where both a wet and dry test was possible in the field, v_s increases slightly with moisture content and v_c decreases. Iida found that v_c first decreased and then increased as moisture content was increased, but that v_s continually decreased. Unfortunately, the lack of control over the moisture content in field work prevents the getting of any significant results on this subject.

Table II shows some approximate computations of rigidity

based on isotropic elastic theory, i.e. $v_s^2 = \mu/\rho$, and comparisons with the rigidity of other materials. This table

TABLE II

	ρ gm /cm^3	v_s^2 cm^2/sec^2	μ dynes /cm^2
gravel	1.7	1.2 x 10^8	2.1 x 10^8
sand	1.8	1.8 x 10^8	3.3 x 10^8
clay	1.9	6.4 x 10^8	12.2 x 10^8
granite			1.9 x 10^{11}
slate			2.2 x 10^{11}
copper			4.6 x 10^{11}
soda glass			3.0 x 10^{11}
steel piano wire			8.4 x 10^{11}

shows that gravel and sand are less rigid than clay, which is self evident, but that granite is ten times as rigid as clay, while steel piano wire has only about four times the rigidity of granite. Remembering that rigidity is a measure of a material's resistance to a torsional force, the rigidity of unconsolidated material seems to be a function of the boundary conditions as a handful of sand would not appear to have anything like the computed rigidity. Nonetheless, the values

computed, for materials in the form in which they were tested, seem to be of the correct order of magnitude when compared to known values of other materials. This, in turn, implies that the isotropic theory of elasticity is a fair approximation for these materials.

From Plate I, it can be seen that both the v_1, and v_2 of Gassmann's theory give unreasonable values as compared to the measured v_s. (Assuming that quartz spheres will give results of the same order of magnitude as sand.) The sand at Lexington had a measured shear velocity of 440 ft/sec. With horizontal direction of propagation, v_2 is about 550 ft/sec at a depth of 0.03 ft. and v_1 is 440 ft/sec at about 0.5 ft. With wave lengths of the order used in this test, it is not conceivable that any appreciable fraction of the energy could be confined to such shallow depths. When the direction of propagation is 45° from the horizontal, v_1 becomes much larger, by a factor of 12, and v_2 becomes smaller by a factor of 4. Thus, it would appear that v_1 is always larger than v_s while v_2 may be less.

While Gassmann's v_3 is zero for horizontal propagation, it is a maximum for vertical propagation. It will, therefore, also pass through the measured value for v_s as the direction of propagation is about 18° below the horizontal, $v_3 = v_s$ at a depth of five feet. This is very reasonable in that the plank may will propagate waves 18° downward instead of actually

horizontal. In the case of the sand at Lexington, the maximum depth of the wave would be about 7 feet, assuming a smoothly curved path. But this raises the interesting point of how v_3 can be recorded at the surface, for when it becomes horizontal at the bottom of the wave path, it equals zero. However, an SH wave is recorded at the surface, so it would seem that Gassmann's model is too over-idealized to be applied to an actual sand.

Unfortunately, while v_3 may be v_s, the rest of Gassmann's results are not so easily explainable. V_1 and v_2 are usually complicated combinations of SV and P waves, the measured quantaties, so that curves for v_1 and v_2 give little information about the SV and P waves. In addition, the crossover of the v_1 and v_2 curves as the system goes from dry to wet (see Plate I) requires more study to explain its significance. Thus, while it is impossible to apply Gassmann's theory completely at present, it seems probable that further work may show more satisfactory correlation between theory and experiment. The absence of legible records from the gravel pile at O'Toole's Gravel Pit strongly suggests that when conditions approach Gassmann's model of closed-packed spheres, no simple SH wave motion exists. This agrees with his theory.

SUGGESTIONS FOR FURTHER WORK

As this is only a preliminary study of the elastic properties of unconsolidated materials, there are many problems unanswered. Some of them could possibly be solved by concentrated work on a single area where the geologic properties of the material are known in detail.

The addition of filter circuits to the equipment would permit a study of the relationship between frequencies and velocities. This would give some interesting information about the dispersion and attenuation characteristics of the material.

It is possible that further study could find the depth of penetration of elastic waves and the mathematical relationship between depth and velocity. This, in turn, might lead to the development of an applicable elastic theory.

A study, which would have much interest for the author, would be one of Revere Beach to determine the causes of the velocity changes which were found. This would entail concomitant studies of the weather, the tides, and variations in density and composition of the beach.

ACKNOWLEDGMENT

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