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LABORATORY EVALUATION OF DYNAMIC SOIL PROPERTIES BY ULTRASONIC TESTING METHODS

BY

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Approved by

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ABSTRACT

Measurement of ultrasonic compression and shear wave velocities through a soil material has been made with a pulse wave generator developed at the University of Missouri-Rolla. The variation of these velocities along with the behavior of the dynamic material parameters of the material (Young's modulus, shear modulus, Poisson's ratio) with void ratio and degree of saturation were determined. Compression wave velocity, shear wave velocity, Young's modulus and shear modulus were found to decrease with increasing void ratio; degree of saturation was of little influence. Wave attenuation could not be measured by the test procedure used.

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The designer and builder of the pulse-generator Mr. Daniel F. Thomure, deserves special recognition for his painstaking efforts.

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Lastly, the author wishes to acknowledge a friend, Judith L. Mueller, whose love and support in the past year has made the difficult times not so difficult. May the love and friendship presently shared, be lasting.

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I. INTRODUCTION

The deformation of soil under dynamic loading has become of increasing interest to the soil engineer. It has been recognized that values obtained from static strength tests tend to estimate moduli values lower than those encountered under small strain dynamic loading conditions. As a result, static test procedures are inadequate when designing for dynamic stresses which produce small strains. Static laboratory tests are also undesirable because they are destructive in nature in opposition to nondestructive repetitive field loading conditions.

A testing method is needed which permits the evaluation of dynamic material parameters from procedures which approximate the anticipated loads and loading conditions. It would also be desirable that the test be nondestructive so that a single sample may be tested many times under varying conditions of dynamic loadings.

As a result, in the past two decades there has been considerable effort made to replace the determination of dynamic soil properties as determined by static tests with some method of dynamic testing. The parameters of particular interest are Young's modulus (E), shear modulus (G), and Poisson's ratio (μ). The damping characteristics of a soil are also of interest in vibrational analysis.

Field tests such as geophysical tests, surface vibrator tests, and vibratory plate bearing tests produce low levels of strain and are of value in design use. There tests produce strains between 10^{-3} percent and 10^{-5} percent which are analogous in magnitude to machine vibrations, microtremors and vehicular traffic. While these tests are appropriate, they are extremely complicated and costly to perform.

Laboratory tests presently available to measure dynamic shear moduli are extremely complex. Tests include cyclic triaxial tests, cyclic simple shear tests, cyclic torsional shear tests, shake table tests, and resonant column tests. All but the last mentioned test, produce large magnitude strains ($>10^{-3}$ percent). The resonant column test is limited to strains greater than 10^{-4} percent.

It is evident that a simple, quick, nondestructive method of testing is needed. It is believed that the test technique used in the study of more homogeneous materials such as glass, metals, and plastics and in some cases, non-homogeneous materials such as concrete, can be adapted for the study of soils.

By measuring the propagation velocity of high frequency sound waves through a material, the dynamic material parameters can be determined. The advantages of this method are as follows: First, the test procedure is nondestructive, second; the test is dynamic, third; the test is easily and rapidly performed, and fourth; the strain levels are small.

While a sonic velocity test does have definite advantages, there are also some disadvantages which limit the use of this technique as a tool of the engineer. Most importantly the engineer must know the range of strains to be encountered in the field. This method yields moduli values that are too high when large strains ($>10^{-4}$ percent) are encountered. Another drawback is that the required electronic equipment is relatively expensive. In addition, the operator should possess a knowledge of acoustical theory as well as some knowledge of the expected behavior of the material being tested. Analyses of resulting wave patterns is, at times, complicated. It should also be realized that, as with other methods of dynamic testing, this method assumes that elastic theory is valid for the material under test.

Testing equipment for the pulse velocity method has been recently developed at the University of Missouri-Rolla and it was the partial intent of this investigation to determine if the generator could be used to obtain results indicative of several dynamic parameters of a material. Of equal interest in this study was the relationship between parameters derived from wave propagation velocity; (shear-modulus, Young's-modulus, and Poisson's ratio), void ratio and degree of saturation. Another area of interest was the effect of void ratio and degree of saturation on the damping characteristics of the soil.

II. LITERATURE REVIEW

The prediction of soil response to dynamic loading and evaluation of associated soil properties is a relatively new area of interest in engineering. The soil engineer must concern himself with dynamic engineering problems that lie in one of two groups. One of these groups associates itself with a single loading and unloading of the soil and a large peak stress value such as would occur with a nuclear blast or at the epicenter of an earthquake. The other group is concerned with small amplitude cyclic loadings, the type of stresses imposed by vibrating machine foundations, vehicular traffic, conventional blasts, and earthquakes (at some distance from the source the amplitudes of motion for blasts and earthquakes are small). Most emphasis has been placed on this second category.

The use of a reliable nondestructive dynamic test to replace static tests in the evaluation of materials which are subject to dynamic loadings has recently begun to be investigated extensively. As a result, the evaluation of soils by nondestructive methods has evolved from the realm of research to a meaningful test for the practicing soil engineer.

The ultimate objective of nondestructive tests is to predict the performance of soil systems under imposed dynamic loads. To predict the behavior of a soil system, it is necessary to evaluate primary elastic properties of the system and the behavior of those properties when subject to dynamic loadings. In particular, Young's modulus, (E), and shear modulus, (G), need to be evaluated.

The dynamic testing of soils has developed along two lines since the late 1930's. The first has been the study of soil systems in-situ and the second the study of materials in laboratory tests.

A. In-Situ Testing

Three field test methods that have been utilized to determine the in-situ dynamic shear modulus and its variation with depth are: 1) geophysical tests, 2) surface vibrator tests, and 3) static and vibratory plate bearing tests (see Table 1). Sketches depicting each test procedure are shown in Figure 1 (after Shannon & Wilson (47)).[1] Each method, except the static plate bearing test, require propagation of low energy waves through a soil deposit and measuring the shear-wave velocity directly, or deducing it indirectly from frequency and wave length measurements. These tests subject the soil to low levels of strain estimated to be between 10^{-3} and 10^{-5} percent (44).

In the static plate-bearing test, a repeated load procedure is employed on an exposed surface of soil, and the compressive load-deformation relationships are directly measured. The approximate strain level is 10^{-1} percent.

1. In-Hole Geophysical Tests

The most widely used of the three field tests described to evaluate the in-situ shear modulus is the in-hole geophysical test. In this procedure, a complex pattern of waves is generated by an explosive charge or a hammer blow and the time of first arrival of the generated shear wave traveling through the soil media from the

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[1] The numbers in parentheses correspond to the listing of the references in the Bibliography.

Table I. Field Tests to Evaluate Shear Modulus In Situ (from Shannon & Wilson (44))

Test Method	General Procedure*	Approx Strain Range %
1. In-Hole Geophysical Test	Direct shear-wave velocity measurement with depths	10^{-3}-10^{-5}
2. Surface Vibrator Test	Measurement of frequency and wave length of surface waves	10^{-3}-10^{-5}
3. Plate Bearing Tests		
a. Vibratory Test	Measure natural frequency of small vibrator	10^{-3}-10^{-5}
b. Static Test	Slow repeated load--settlement measurements	0.08-5

*Tests can be performed generally on all soil types

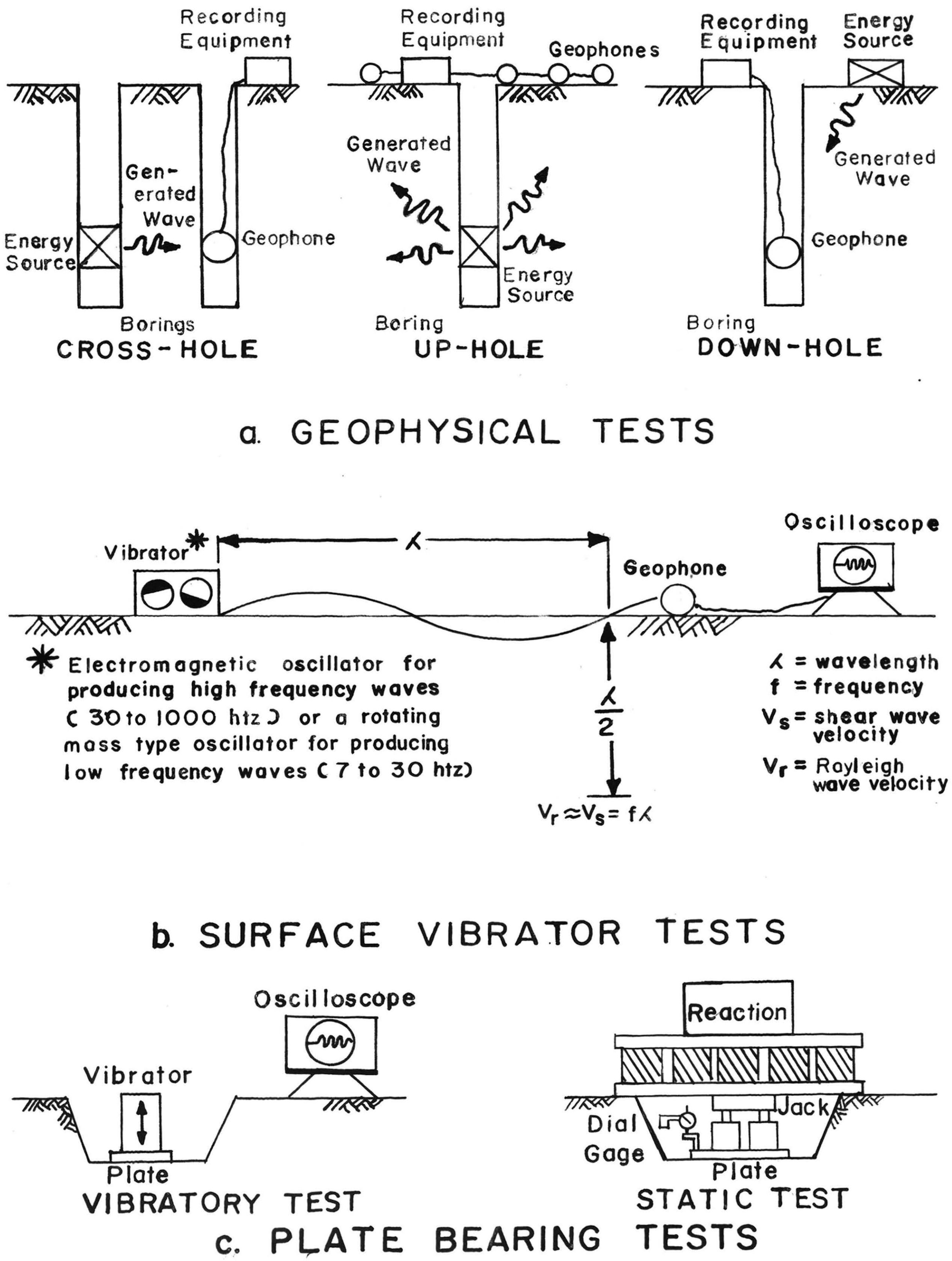

Figure 1. Field Tests to Evaluate Shear Modulus In-Situ

energy source to one or more geophones is measured. The measured shear or S-wave velocity, can be used directly in elastic wave theory to compute the shear modulus. However, faster traveling compression or P-waves, are also generated in addition to the shear waves, and must be filtered from the wave patterns to delineate the true shear wave velocity. Difficulties in clearly defining the first arrival of the S-wave from the faster P-wave records, pose difficulties in interpreting the results of geophysical procedures for evaluating the shear modulus.

One approach that may be considered, is measurement of the velocity of the easily distinguished P-wave, computation of the elastic E-modulus, and conversion of these values to shear modulus by the assumption of Poisson's ratio. For foundation design, this procedure is not usually accepted because the presence of water in soil (i.e., a water table) greatly influences the velocity of the P-wave measured. The presence of water does not, however, significantly influence the velocity of the shear wave. Thus, in most cases, it is usually preferable to measure the shear-wave velocity directly and compute shear modulus independent of Poisson's ratio.

As shown in Figure 1a, three basic techniques are employed in geophysical tests. The first technique (cross-hole technique) involves generating short bursts of energy at various depths in one bore hole and measuring the time of arrival of the induced waves at equal depths with geophones in other nearby bore holes. This procedure is commonly utilized and is very useful, especially in relatively homogeneous soil deposits.

The more homogeneous and less stratified the soil deposit, the easier it is to delineate shear waves from compression waves since each respective wave is traveling at a relatively uniform velocity. On the other hand, the delineation of waves in thinly bedded or stratified materials is very difficult and their interpretation should be viewed with caution. Not only is a complex pattern obtained from the waves traveling at various velocities, depending upon the density of each soil layer, but also the first arriving waves may be those traveling in the denser, higher velocity layers instead of an average value for the overall mass. The potential result may be higher computed shear modulus values than actually present.

The other two in-hole techniques (down-hole and up-hole tests) involve generating waves with an impulse source of energy at the surface or at depth in a boring, and measuring the average shear-wave velocity between the energy source and a geophone. In the up-hole technique, the waves are generated at various depths in a boring with geophones located along the ground surface. The down-hole technique utilizes waves generated at the ground surface with the geophones located within the boring. These techniques, which are both acceptable procedures, record average velocities for the soil between the energy source and the location of the geophone. Hence, velocities may be determined for different zones or layers in the soil deposit by locating the geophones or energy source at appropriate depths, in conjunction with boring information.

Although the up-hole and down-hole techniques allow wave types to be separated more rationally than the cross-hole technique, local bore hole effects can provide equally misleading results. Care must be taken so that these effects do not mask out the wave signals traveling through the soil. For instance, where casing is required in a hole to prevent caving, the velocity and strength of signals traveling through the casing may mask out the slower and weaker signals in the soil.

One shortcoming of all in-hole geophysical techniques is that present energy sources generate only a single short impulse of energy. This produces one massive radial pattern of waves which is difficult to duplicate, since the magnitude of the energy itself is difficult to couple to the bore hole wall, especially when explosive charges are used. In recent years, the Waterways Experiment Station (WES) has developed a vibropacker system for inducing steady-state polarized shear and compression waves at depth for cross-hole measurements (3). While the reported system has apparently been used only in feasibility studies, it shows promise for in-situ measurement of shear-wave velocity. One advantage, in addition to its ability to apply a controlled energy source over a period of time, is that this method provides constant coupling of the energy source to the bore hole wall.

A practical application of the cross-hole technique for determination of shear modulus by velocity measurement is reported by Stokoe and Woods (48).

2. Surface Vibrator Test

German researchers used nondestructive vibrational techniques to study the dynamic properties of roads and runways as early as 1928 (10)(21)(40). The vibratory characteristics of many different soils subject to vibration from an unbalanced rotary mass vibrator were studied.

Since 1948, much has been done by Van der Poel at the Amsterdam Koninklijke/Shell Laboratorium (22)(53). The vibrating source is a heavy unbalanced rotary mass type vibrator capable of producing vibrational forces of 2 ± 2 tons at frequencies of 5 to 60 htz (hertz) which is analogous to moving truck wheel loads. Nijboer developed a lighter electrodynamic vibrator designed to operate at higher frequencies but lower penetrating power (39).

Jones, at the English Road Research Laboratory describes a method for obtaining the dynamic shear modulus of the soil by means of an external vibrator vibrating perpendicular to the ground surface at resonant frequency (26).

In Australia, Kurzeme (31) has developed an electromagnetic vibrator for the generation of shear waves with frequencies of 30 to 300 htz to evaluate soil roadway properties. One, two, and three layer pavement systems were investigated and it was found that by observing the resulting velocity changes with frequency, the shear wave velocity could be determined. For a single layer system it was also possible to determine layer thickness.

Nair (38) has recently published a report of the work of various investigators in the area of pavement evaluation by vibratory methods. Methods of distinguishing soil layers through evaluation of E modulus are presented. Also methods to determine changes in the properties of individual layers with time are discussed.

Recently, in-situ procedures for measuring the shear modulus of all types of soil has been developed by the Waterways Experiment Station (2)(35). An electromagnetic oscillator is used at high frequencies of vibration (30 to 1,000 htz) and a rotating mass type oscillator is used for producing low frequencies (below 30 htz). Richart in 1960, discovered that these surface vibrators generate Rayleigh waves which, for all practical purposes at small strains, have a velocity very close to the shear-wave velocity (41). The velocity is computed from the wave length which is measured with geophones along the ground surface and the frequency of vibration at the source (Figure 1b).

The Rayleigh wave velocity, V_r, measured between adjacent points along the ground, has been assumed empirically to correspond to the velocity through the layer of soil located at an average depth equal to one-half of the wave length. By varying the frequency of the source, and hence changing the wave length, it is then possible to obtain the variation of shear wave velocity with depth. In reality, it is not known whether the velocity determined by this field procedure represents the average velocity of the layer or an average velocity between the ground surface and the computed depth. For relatively homogeneous materials, the half wave length criterion has been shown to give satisfactory modulus results, as a function of depth, when correlated with other field and laboratory procedures performed at equivalent low strain levels. For thick-layered materials, where waves are refracted several times, application of mathematical relationships appears to be an improved approach, although this method has only been verified in a few tests. For multilayer deposits, especially where data must be determined at significant depths, the assumed interpretation and validity of either approach will probably lead to quite different values of shear modulus. For such conditions, this test is as yet, of doubtful validity.

A recent paper by Cunny and Fry (6) reports data obtained in-situ by surface vibrators and corresponding resonant column laboratory tests. These tests were conducted at 14 sites around the world and were performed in conjunction with the Waterways Experiment Station. From the results of in-situ and laboratory tests it was concluded that shear and compression moduli can be expected to range within ± 50% of the in-situ moduli. This variation can be explained by small changes in confining pressure and material density.

3. Plate Bearing Tests

The modulus of soil can also be determined, under undrained conditions, by applying slow repeated loads to a small plate and measuring the slope of the load settlement curve; or by determining the resonant frequency of a small vibrator placed on the soil in-situ. Both procedures, shown schematically in Figure 1c, allow determination of modulus values for soil directly beneath the plate. The least desirable features of these test procedures are the sources of error introduced by seating irregularities, the lack of confinement, and the fact that the modulus determined is largely a function of the size of plate used. Also, these procedures are generally limited to determination of near-surface soil properties. Plate bearing tests are used primarily for footing design.

B. Laboratory Testing

Laboratory testing for the dynamic properties of soil has evolved into a sophisticated science. Today's laboratory equipment enables the scientist to approximate the state of the sample as it exists in the field and at the same time to be able to carefully control testing variables without outside interference.

Laboratory dynamic tests conducted on soil samples are usually of two types. One is a variation of dynamic triaxial testing and the other method is concerned with wave propagation. Other methods sometimes used are cyclic simple shear and shake table tests. Strain ranges of the various tests are given in Table II.

1. Modified Triaxial Tests

In this test, specimens are subjected to longitudinal compression and extension or torsional shear and the resulting load deformation relation measured directly. Calculation of Young's modulus in the former case, and shear modulus in the latter method, can be determined directly from the resulting hysteresis loop. The strain range of these tests is about 10^{-2} to 5 percent.

The effect of stress state on the dynamic modulus of elasticity for a dry sand was investigated by Shannon, Yamane, and Dietrich (45) by means of a modified triaxial apparatus in which the specimen was forced to vibrate at a small amplitude by an externally applied vibrator. The results of the dynamic tests as well as the results of a modified static test designed to simulate dynamic conditions indicate that modulus increases with increasing confining pressure. Also an increase in resonant frequency of the sample with increasing

Table II. Laboratory Tests for the Determination of Shear Modulus

Test Method	General Procedure	Approx Strain Range %
Modified Triaxial Test	Direct or indirect measurement of shear modulus by use of cyclic triaxial tests, or cyclic triaxial torsion tests.	$5-10^{-2}$
Wave Propogation Test		
Resonant Column Test	Computation of shear modulus from dimensions and resonant frequency of specimen.	$10^{-2}-10^{-4}$
Pulse Velocity Test	Computation of shear modulus from measurement of wave velocities.	$<10^{-4}$
Simple Shear Test	Direct determination of shear modulus from cyclic stresses and strains.	$10^{-2}-10^{-4}$
Shake Table Test	Measurement of vibration response of a large soil mass when the exciting force is removed.	.05-.005

confining pressure was noted.

A study by Wilson and Dietrich (56) of twelve cohesive soils gave similar results to those obtained by Shannon, Yamane, and Dietrich. Tests performed in a modified triaxial device, capable of longitudinal and torsional oscillation, indicated that the dynamic and static moduli of elasticity increase with increasing consolidation pressure and increasing compressive strength with the dynamic modulus being higher in value than the static modulus.

Free vibration torsion tests made by means of a modified triaxial apparatus, were performed by Zeevaert (58). Of primary interest in this study was the increase in shear modulus with increasing confining pressure.

2. Wave Test

Tests of this category are either resonant column tests or pulse velocity tests. Resonant column tests subject solid or hollow cylindrical specimens to longitudinal or torsional vibration. Knowing the length of the specimen and the resonant frequency of the soil column, the pulse velocity can be calculated (18)(42). Strains range between 10^{-2} and 10^{-4} percent for this method.

Pulse velocity tests use small strain producing piezoelectric crystals for generation and reception of high frequency sound waves. In this method, wave velocities are measured directly by use of an oscilloscope. Strains encountered are usually less than 10^{-4} percent. Yong, Dutertre, and Krizek (57) report that when using wave propagation techniques Young's modulus is frequency dependent for wave frequencies less than 200 htz.

a. Resonant Column Test

The effects of confining pressure, moisture content, void ratio, and grain characteristics of a material on wave velocities were made on sand samples by Hardin and Richart (17). Four resonant column devices were used in this experiment so that the mode of vibration and type of vibration could be varied. It was found that wave velocities for dry sand specimens varied with approximately the 0.25 power of the confining pressure and the effects of relative density, grain size and gradation entered only through their effects on void ratio. For a given confining pressure the most significant factor was void ratio; the wave velocity decreasing linearly with increasing void ratio.

The effect of high amplitude prestrain on the shear modulus of a sand was made by Drnevich, Hall, and Richart by means of a resonant column device (9). In general it was found that for a constant confining pressure, an increase in the number of cycles of high-amplitude prestrain increased the low-amplitude shear modulus at that confining pressure and at other confining pressures.

Humphries and Wahls (23) have reported on the effects of static stress history on two cohesive soils tested by a resonant column device. The shear modulus was found to increase with increasing confining pressure, decreasing void ratio, and decreasing amplitude of vibration.

Hardin and Mossbarger (20) investigated the different types of resonant column devices available and reported the following findings. For proper design and use of a resonant column apparatus the stiffness and coherence of the material to be tested must be taken into account. Consideration must be given to parameters such as stress and temperature which are important to material response and are to be controlled during testing. Finally, proper consideration must be given to the interpretation of test results.

Taylor and Hughes (49) investigated the effect of number of cycles of loading and strain amplitude on elastic modulus for three soil types. It was found that the modulus decreases with increasing cycles of loading and increasing amplitude.

Hardin and Black (27) list the variables which influences shear modulus for shear strain amplitudes less than 10^{-4} percent of a normally consolidated clay and report the effect of each variable. The variables found to be of most influence were void ratio and effective octohedral normal stress. The shear modulus increased with increasing confining pressure and decreasing void ratio. At a constant confining pressure an increase in shear modulus with time was noted. The shear modulus was also found to be independent of amplitude for shear strain amplitudes less than 10^{-4} percent. The effect of time on shear modulus was also noted by Afifi and Woods (1).

b. Pulse Velocity Test

One study involved the measurement of wave propogation and wave velocities for over 200 tests performed on samples of three basic soil types to study the effect of dry density, water content, and compactive effort on pulse velocity (46). It was found that wave velocity increased with increasing dry density for a given water content to a maximum value. Thereafter, an increase in dry density resulted in a rapid decrease of pulse velocity. For comparable water contents and densities, there was considerable variation between the velocities measured in specimens compacted in the Harvard mold and those compacted in the Proctor mold. The cause of this variation, in addition to possible differences due to the method of compaction, may be possibly explained by lateral inertial effects which may be more predominant in the smaller Harvard mold specimens, thus introducing a specimen size effect on the measured velocity. A similar effect was noted by Goto (12). Leslie (33) investigated the velocity-water content relationship for a silty clay and found that maximum velocity occurred at maximum density and optimum water content.

In a separate study by Manke and Galloway, it was found that wave velocity increased with increasing confining pressure and was unaffected by temperatures normally associated with subgrade materials except when temperatures were below freezing. Wave velocities increased drastically in frozen soils (34).

The influence of the structure of a kaolinite clay on elastic wave velocity was studied by Nacci and Taylor (37). Results are similar to resonant column tests mentioned in that the wave velocity increased with increasing confining pressure. There was found to be a definite relationship between void ratio, confining pressure, and wave velocity.

Lawrence (32) describes a study in which the ultrasonic shear wave velocity was measured in sand and clay. The use of the shear wave, rather than the longitudinal wave, offers the possibility of studying stress wave propagation through the skeleton of a soil independent of the pore fluid. The developed apparatus used ferroelectric ceramics to produce and receive a pulsed torsional shear wave in cylindrical soil samples subjected to various states of hydrostatic stress. Three soil materials were tested: a coarse rounded sand, and two types of saturated clay.

From the tests on sand it was found that the void ratio and level of effective hydrostatic stress determined the velocity of the shear wave; whereas, the level of shear stress and degree of saturation were found to have only a minor influence.

From the tests involving clay samples, it was found that the effective hydrostatic stress and the void ratio most heavily influenced the shear wave velocity, and the three quantities could be interrelated such that specifying any two would determine the third. Measurements taken during secondary consolidation indicated that the shear wave velocity is sensitive to small structural changes occurring during that period.

3. Other Tests

Simple shear tests were made by Theirs and Seed (51) by means of a simple shear device developed by the Norwegian Geotechnical Institute. The results obtained are similar to those obtained by Taylor and Hughes. The paper does give values of moduli for various cycles of loading and strain amplitudes. Strain dependence of shear modulus has also been studied by Donovan (8).

In Britain, at the Road Research Laboratory, a testing device developed specifically for measuring dynamic moduli of soil for pavement design has been developed (55). The apparatus is designed so that an axial load is imparted to the sample in form of a stress pulse by means of a spring and cam. The device also has the capability of stressing the sample in the lateral direction in phase with the axial stress.

C. Damping

As a wave travels through a media it loses energy due to different dissipation mechanisms. This dissipation of energy is called damping or attentuation. The damping capacity of some granular soils has been treated by Weissmann and Hart (54) and Hall and Richart (13). It was found that the confining pressure had little influence on damping and was effected by the degree of saturation and the grain characteristics of the material.

Hardin (15) presented an analytical solution of two systems with damping characteristics by use of a Kelvin-Voigt model. Experimental results were obtained from steady state, free vibration and static torsion tests for shear strain amplitudes ranging from 10^{-6} to 10^{-4} percent, confining pressure between 500 pst to 3000 psf, and for frequencies less than 600 htz.

deGraft-Johnson (7) measured the damping of compacted cylindrical samples of kaolinite in axial free-vibration tests. It was found that damping increased with increasing water content and stress level. Taylor and Menzies (50) concluded that damping was frequency dependent.

Attenuation measurements in sedimented soils have been conducted by Hampton (14). Attenuation in flocculated soils (high void ratio) was higher than in dispersed structures (low void ratio).

Kovacs, Seed, and Chan (28) and Krizek and Franklin (30) determined the damping ratios for a soft clay by cyclic loading of a sample in a triaxial device and also by free vibration. It was concluded for both simple cyclic shear and free vibration that damping was dependent on strain amplitude.

The effect of strain amplitude on damping was also investigated by Hardin and Drnevich (18). Damping was found to increase with increasing strain amplitude but the increase was higher for lower effective mean principal stresses, higher void ratios, and lower numbers of cycles of loading.

The effects of various parameters, testing procedures and evaluation procedures has been considered in detail by Richart, Hall, and Woods (42).

III. THEORY AND METHOD OF ULTRASONIC MEASUREMENTS

A. Waves in Elastic Bodies

There can be three waves in an elastic body depending upon particle displacement relative to direction of propagation of the wave. The compression wave particle displacement is parallel to the propagation of the wave and is capable of being transmitted through any media with volume elasticity, i.e. all types of media. Figure 2 shows a longitudinal wave with compression and rarifaction (11). Shear or transverse waves are the second wave and are of such a nature that they can be transmitted only in media with shear elasticity, i.e. solids only (29)(47). For transverse waves, the direction of propagation is transverse to particle displacement as shown on Figure 3 (11).

When a solid medium is bound by a free surface, another type of wave with particle movement in both the longitudinal and transverse direction is generated, i.e. the Rayleigh wave. This wave is propagated along the free surface of the medium. The wave energy of a Rayleigh wave decreases rapidly in the direction perpendicular to the plane of the surface to a depth of 0.5 times the wavelength (λ) of the Rayleigh wave at which point the wave energy is almost equal to zero.

1. Velocity

The velocity of transmission of the various waves is a function of the density and elastic constants of the medium. In general it has been found that the compressional wave has the greatest velocity and is almost twice as fast as the transverse wave or the Rayleigh wave both of which travel at about the same velocity.

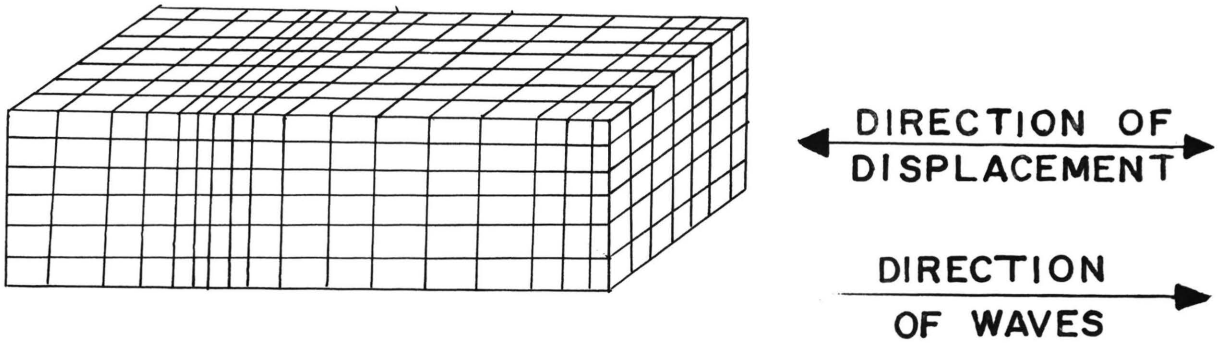

Figure 2. Particle Displacement of Longitudinal Wave (Compressional Wave)

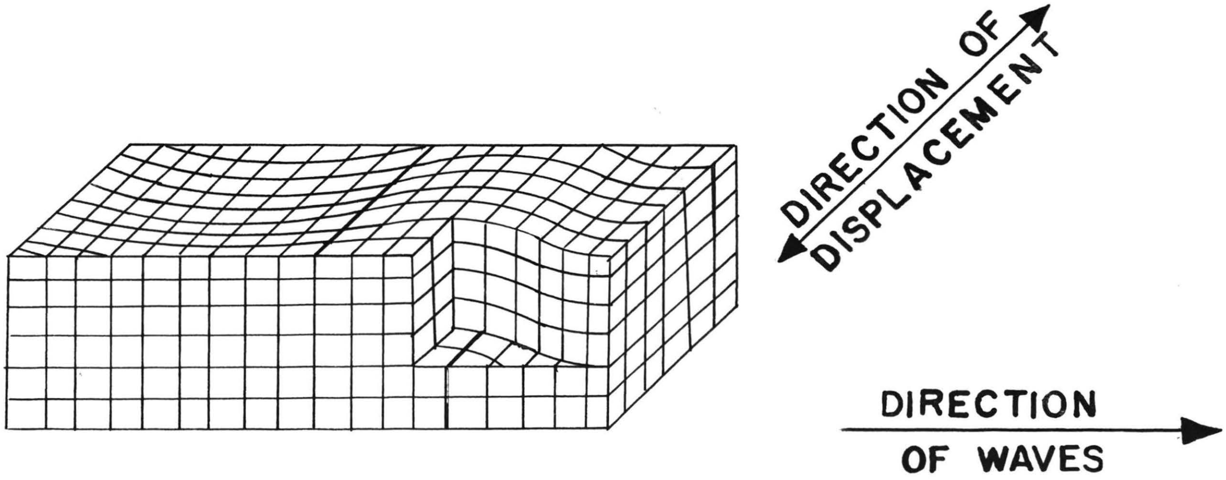

Figure 3. Particle Displacement of Transverse Wave (Shear Wave)

From elastic theory, it can be shown that:

$$V_c = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{1}$$

and

$$V_s = \sqrt{\frac{E}{2\rho(1+\mu)}} = \sqrt{\frac{G}{\rho}} \tag{2}$$

where

V_c = velocity of the compressional wave

V_s = velocity of the shear wave

μ = Poisson's ratio

E = Young's modulus

G = shear modulus

ρ = mass density = γ/g

γ = bulk density

g = acceleration due to gravity

From Equations (1) and (2), Poisson's ratio can be expressed as:

$$\mu = \frac{1 - 1/2(V_c/V_s)^2}{1 + (V_c/V_s)^2} \tag{3}$$

It can be seen that measuring the velocity of the compression wave and the shear wave independently in a specimen will provide a means for computing shear modulus, Young's modulus, and Poisson's ratio for the material.

2. Attenuation

If the tested specimen is an ideal elastic material the wave passing through the material would attenuate (lose energy) only by virtue of the spreading of the wave. If this is true, a plane wave will show no attenuation along its path and a spherical wave will decrease inversely with increasing distance from a specified point, the distance beyond which is called the far field. Since most materials do not behave ideally elastically, waves are weakened by scattering and absorption the combined effect of which is called attenuation.

Scattering results from the fact that some specimens are not homogeneous but contain boundaries on which the acoustic impedance changes abruptly because two materials of different density or sound velocity meet at these boundaries.

The acoustic impedance (W) of a material is defined as the product of the material density and the velocity of sound in that medium ($W = \rho c$). Sound wave pressure (P), intensity (I), and acoustic impedance are related through the following relationships:

$$P = W\omega A \tag{4}$$

$$I = \frac{P^2}{2W} \tag{5}$$

where

ω = angular frequency of sound wave

A = amplitude of particle motion

On an oblique boundary, a wave is split into various reflected and refracted wave types. This process repeats itself for each wave at the next boundary. As the process continues the path becomes exceedingly complex and lengthy and the waves are gradually converted into heat. This transformation of a wave from one type of wave to another is known as mode conversion.

As mentioned previously, when longitudinal or transverse waves are incident at an oblique angle to the boundary of two materials with dissimilar impedance, waves will in general be reflected and refracted as shown in Figure 4. The directions and velocities of these waves are related to one another as follows:

$$\frac{\sin\alpha_1}{V_{A_1}} = \frac{\sin\alpha_2}{V_{A_2}} = \frac{\sin\beta_2}{V_{A_3}} = \frac{\sin\alpha_3}{V_{A_4}} = \frac{\sin\beta_3}{V_{A_5}} \qquad (6)$$

where

V_{A_1} = incident compression or transverse wave velocity in material 1

V_{A_2} = reflected compression or transverse wave velocity in material 1 ($V_{A_1} = V_{A_2}$)

V_{A_3} = reflected transverse or compression wave velocity in material 1

V_{A_4} = refracted compression or transverse wave velocity in material 2

V_{A_5} = refracted transverse or compression wave velocity in material 2

As one can see on Figure 4, four separate waves are generated: shear and compressional waves are reflected and shear and compressional waves are refracted.

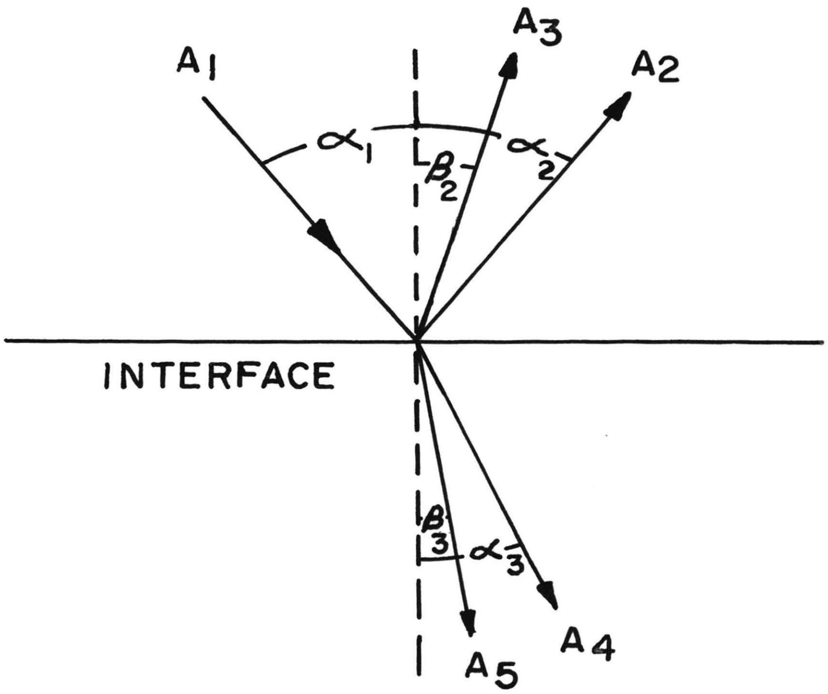

Figure 4. Reflection and Refraction of an Incident Wave at a Boundary of Materials with Dissimilar Impedance

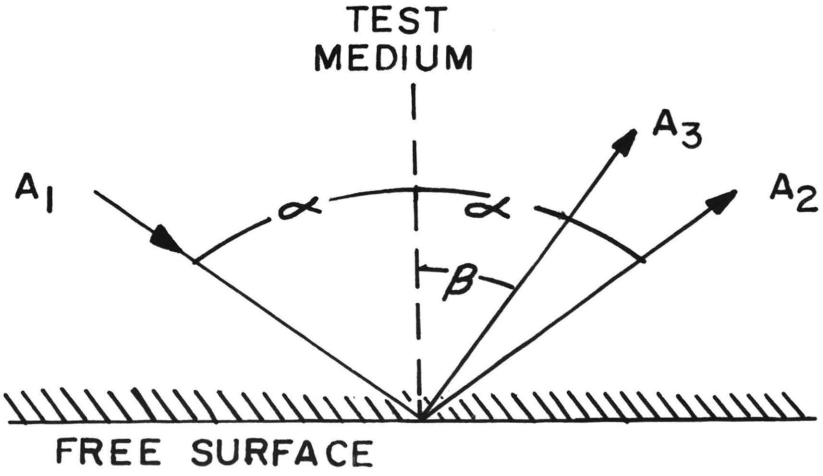

Figure 5. Reflection of an Incident Wave at a Free Boundary

A somewhat different phenomena occurs for longitudinal and transverse waves at a free boundary. Two reflected waves are generated as shown in Figure 5. Wave A_2 is of the same type as A_1 and the angle of reflection is equal to the angle of incidence and is called angle α. Wave A_3 is a wave of the other type and has a direction of travel at angle β. The two angles are related by the equation

$$\frac{\sin\alpha}{\sin\beta} = \frac{V_{A_1}}{V_{A_3}} \qquad (7)$$

The frequencies used in ultrasonic testing usually generate wavelengths larger than grain sizes. This is important since it has been found that as wavelength decreases from ten times the grain size to the grain size, scattering increases very rapidly.

Conversion of direct sound energy into heat, (adsorption) is a second cause of attenuation. The mechanisms responsible for this process are beyond the scope of this investigation. Rapidly oscillating waves tend to lose more energy than slowly oscillating waves; as a result, absorption usually causes an increase in attenuation with increase of frequency but is minor when compared to the attenuation due to scattering.

Both absorption and scattering set limitations on the testing of materials. Pure absorption weakens the transmitted energy. This can be overcome by increasing the input energy of the wave or exploiting lower absorption tendencies at lower frequencies. In addition to reducing energy levels, scattering tends to produce numerous new waves in which the original signal can be lost.

Attenuation can be measured for a given specimen by instruments designed for velocity measurements. The testing procedure is not unique but the quantity being measured is quite different. The quantity measured is the amplitude of a wave and can be defined several ways. Attenuation can be expressed as attenuation per sample or as a more meaningful quantity, attenuation per length of specimen.

A way in which to determine the amount of attenuation in a specimen is to measure the rate of decay of oscillation. This is conveniently expressed by a term called logarithmic decrement. The logarithmic decrement is defined as the natural logarithm of the ratio of any two successive amplitudes.

$$\delta = \ln \frac{z_1}{z_2} \qquad (8)$$

where

δ = logarithmic decrement

z_1 and z_2 = amplitudes of motion for two successive wave peaks

In the pulse echo technique, attenuation is calculated by comparing the amplitudes of successively related multiple echos in the test material. The coefficient of attenuation is obtained from the formula

$$\alpha = \frac{1}{2L} \ln \frac{1}{s_1 + s_n} \qquad (9)$$

where

α = coefficient of attenuation

L = thickness of specimen

s_1 = the ratio of the amplitude of the second pulse to the first pulse

s_n = the ratio of the amplitude of the n+1 pulse to the n^{th} pulse.

The transmission method defines attenuation by comparing the amplitudes of a pulse traveling through different thicknesses of a test material or through the test material and a standard material. The attenuation coefficient is then calculated from the equation:

$$\alpha = \alpha_0 + \frac{1}{L_2-L_1} \ln \frac{A_1}{A_2} \qquad (10)$$

where

α = coefficient of attenuation

α_0 = coefficient of attenuation for liquid in which the specimen is immersed

A_1 = pulse amplitude after passing through specimen thickness L_1

A_2 = pulse amplitude after passing through specimen thickness L_2

B. Generation and Reception of Ultrasonic Waves

Ultrasonic waves are soundwaves with frequencies greater than 15 to 20 kilohertz. These waves are imparted to a material by placing the material in contact with a vibrator having the desired frequency and waveform. The generated waves are detected in a similar manner by placing the material in contact with a receiver which is capable of measuring the sound pressure of an incident wave.

1. Piezoelectricity

Generation and reception of ultrasonic waves can be accomplished by means of energy transducers capable of transforming electrical energy to mechanical energy and vice versa. At present, the two main types of transducers used are quartz and ceramic oscillators. These oscillators are capable of energy transformation because of a phenomenon known as piezoelectricity. When a piezoelectric material is deformed by external mechanical pressure, electrical charges are produced on its surface. A reverse process occurs when such a material is placed between two electrodes causing the material to vibrate. This reverse mechanism is known as the inverse piezoelectric effect. The former is used for reception of ultrasonic waves and the latter for generation of waves.

Quartz and other minerals are capable of the piezoelectric phenomenon if the mineral is oriented such that the crystal structure is asymmetric and several polar axes result (25). By using different polar axes of quartz, one can generate transverse or longitudinal waves depending upon which polar axes is chosen to be asymmetric.

Ceramic transducers are commercially manufactured and are composed of a multitude of crystals with random orientation (24). The properties of the ceramic are the sum of all these crystallines. Ceramic transducers work much on the same principal as natural piezoelectric crystals.

Deflections in response to a driving signal of a ceramic transducer are small due to great stiffness of the transducers, strong signals are produced however, and signals are not easily blocked at the surface of a test specimen.

2. Acoustic Coupling

Many of the limitations of ultrasonic testing arise from the method of contact between the transducer and the surface of the tested object, i.e. the degree of acoustic coupling. This quantity depends on the amount of surface roughness of the test material and the nature of the coupling media. In general, the smoother the surface, the better the conditions for the penetration of ultrasonic waves into the examined material. As the surface roughness increases, it is more difficult to introduce ultrasonic waves into the specimen. This problem is circumvented by using lower frequencies.

The choice of a coupling media is a choice of impedance matching. The impedance of the coupling media must be at an optimum for the transducer-coupling media interface and coupling media-specimen interface in order to obtain good results. A bad impedance match results in an increase in attenuation due to scattering.

The most commonly used couplant is oil of a medium viscosity (SAE 30). On smooth surfaces, oil of low viscosity is preferable, and on rough surfaces, oil of higher viscosity. Of all suitable liquids, glycerine has the highest acoustic impedance. Highly viscous materials, such as mixtures of wax and oil and vegetable resins can be used for coupling normal probes for transverse waves. On smooth, flat surfaces it is sometimes advantageous to press the dry transducer against the specimen by a clamping device or weight.

3. Frequency

The sonic velocity of any material is constant, and since sonic velocity (v), frequency (f), and wave length (λ) are related by the equation: $v = f\lambda$, it is easy to see that in a given medium the frequency is proportional to the inverse of the wavelength. Increasing the frequency decreases the wavelength of the ultrasonic beam which in turn causes a higher wave intensity. This higher wave intensity results in a higher sensitivity but increased absorption. The problem therefore is to find the highest frequency permissable for a tolerable absorption level.

4. Pulse Width

When an electrical signal is applied to the electrodes of a transducer, the transducer vibrates with an amplitude which gradually increases until a steady state value is reached. When the signal is removed the oscillations of the transducer do not cease immediately but decrease to zero amplitude in an exponential manner. When the frequency of the applied electrical signal is equal to the resonant frequency of the transducer, the latter oscillates with maximum amplitude. As the electric signal is varied, the crystal not only oscillates at the resonant frequency but also at its harmonics.

The proper pulse width must be obtained to produce the optimum signal. If the pulse is too narrow, the crystal does not reach resonance and detectability is sacrificed. If the pulse width is too wide, secondary waves occur during transient decay which result in loss of detectability and resolvability at the receiver.

5. Surface Area of the Transducer

The intensity of the wave arriving at the receiving transducer is a function of the wavelength and of the size of the transducer. Divergence of wave energy occurs when the distance between the source and receiver is greater than

$$a^2/\lambda \tag{11}$$

where

a = radius of source transducer

λ = wavelength

This limiting distance is called the near field. Distance greater than the near field are considered to be in the far field and are subject to divergence as shown in Figure 6. This angle of divergence can be expressed as

$$\sin 2\alpha = 0.5\ \lambda/a \tag{12}$$

The smaller the divergence, the greater the wave energy at the receiver. It is desirable to keep the specimen of a length in which a far field will not develop; otherwise a beam hitting the sidewall at low angles of incidence will be reflected in such a way as to return to the receiving transducer after a number of reflections causing difficulties in defining first wave arrivals.

C. Principals of Ultrasonic Measurement

The propagation of sound waves in a medium is a function of the elastic properties of the specimen and its homogeneity. Ultrasonic testing has been used to detect and locate material flaws for some time but was first used for velocity determinations.

For a typical flaw detection investigation, one looks for discontinuities which either reflect the waves or provide a shadow for them. The testing techniques fall primarily into three categories

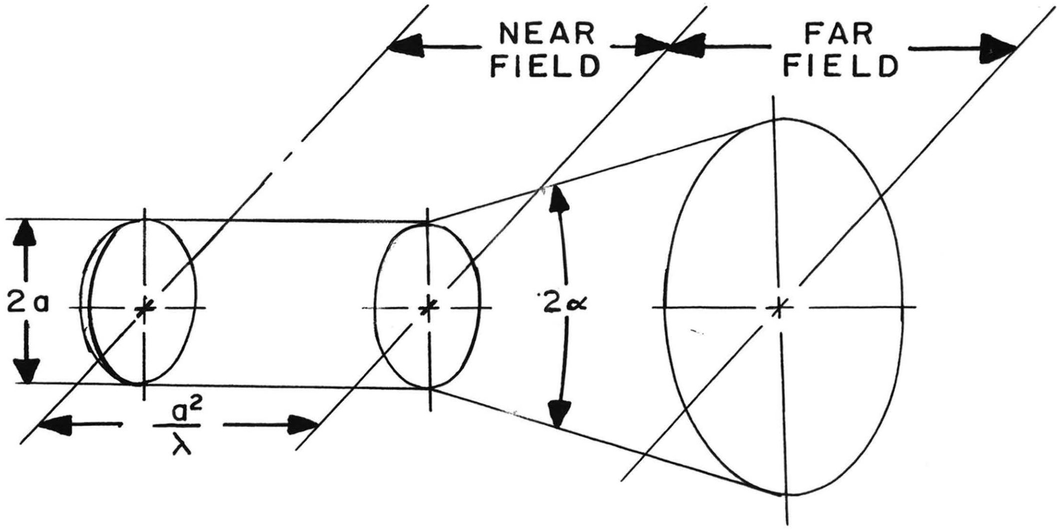

Figure 6. Approximate Shape of Ultrasonic Beam for Large Values of $2a/\lambda$

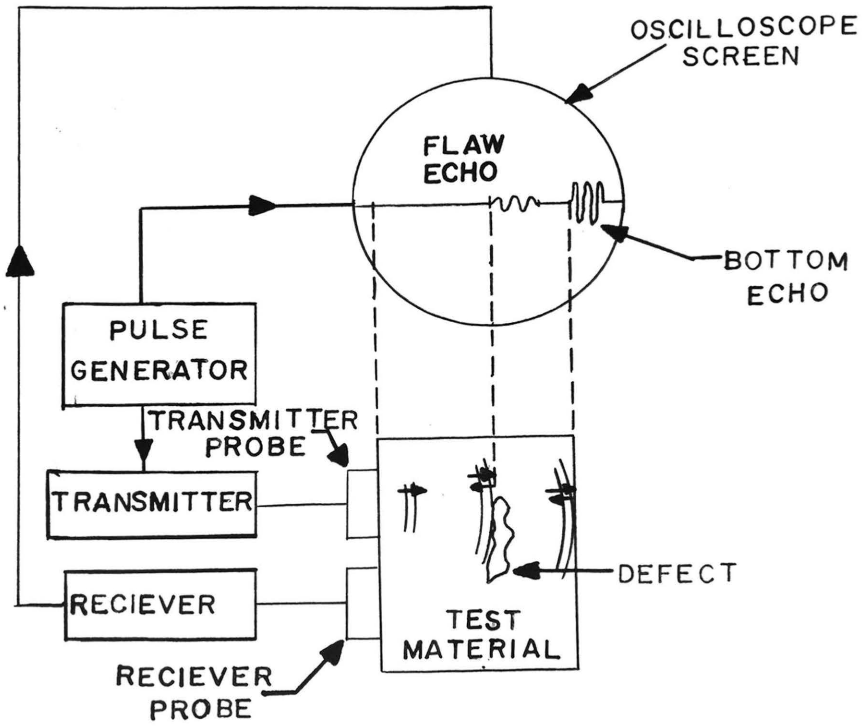

Figure 7. Diagram of Pulse Echo Technique

based upon the test apparatus. The different methods are the echo, transmission, and resonance method.

1. Pulse Echo Method

Apparatus for the echo method and a test specimen are shown in Figure 7. The apparatus consists of a transmitter which generates an electrical pulse and in turn excites a transducer. Ultrasonic vibrations are then propagated into the test material. At the instant the pulse leaves the transducer, a timebase generator is excited so as to cause a spot of light to move from left to right horizontally with a constant velocity across the screen of the cathode ray tube.

The presence of a defect will cause some of the waves to be reflected and return to a transducer fitted to a receiving probe. The waves are then transformed to electrical pulses which are relayed to the receiver. The pulses are amplified and then applied to the other plates of the cathode ray tube causing the light spot to move vertically, independent of the horizontal motion. Consequently an image of the reflected pulse appears on the screen; this is called the flaw echo.

Waves which do not intercept the defect reflect from the back wall of the specimen and produce an image on the screen to the right of the flaw echo known as the bottom echo.

The position of the flaw is calculated by knowing the speed of sound in the medium and the time of travel of the flaw echo from the transmitting to the receiving probe.

2. Transmission Method

For this method, ultrasonic waves enter the test object on one side and are picked up by a receiving transducer after emerging from the other side. Discontinuities in the path of the beam give rise to reflection resulting in a decrease in the intensity of the transmitted wave. The apparatus is shown in Figure 8.

Considerable difficulty arises with intensity methods when continuous ultrasonic waves of a given frequency are used: interference from standing waves result. The formation of standing waves can be avoided by using frequency modulation in which the frequency is varied periodically. It is much easier to use pulsed waves.

The most important advantage to the transmission technique is that it allows specimens with large grain sizes and uneven surfaces to be examined. Another important advantage is that there is no lower limit of thickness of specimen in direction of the propagated wave test specimen.

3. Resonance Method

The resonance method is much like the echo method in that it depends on reflections of ultrasonic waves from discontinuities in the form of defects. The difference is however, that the generated and reflected waves are not separate but are superimposed, such that the maxima coincide and resonance occurs. Pulse or continuous excitations can be used for this method.

Small flaws do not produce an appreciable effect on the resonance and as a result this method is not used often for flaw detection, but primarily for thickness measurements.

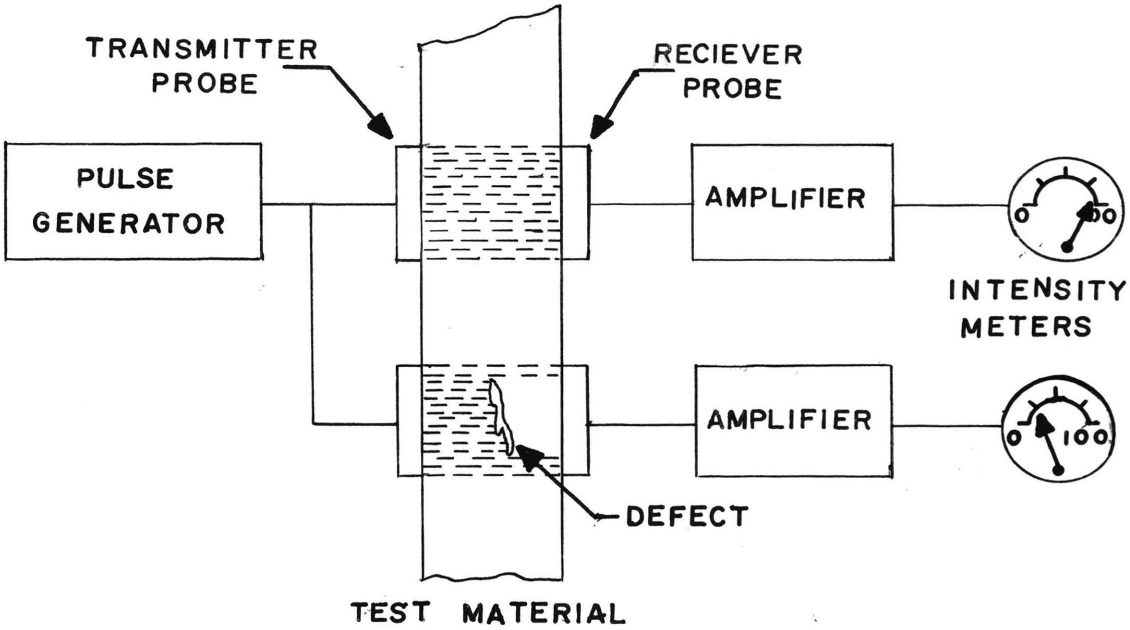

Figure 8. Shadow Method (Transmission) Using Continuous Waves

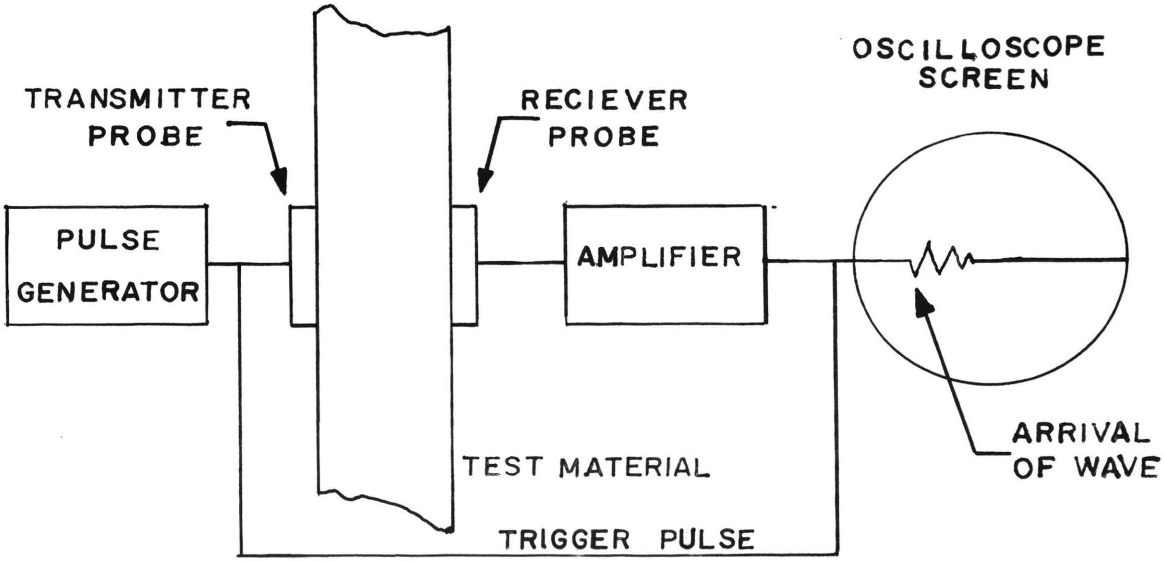

Figure 9. Transmission Method for Velocity Determination

D. Velocity Measurements

The same methods and equipment used in ultrasonic testing for flaw detection can be used to investigate the properties and material structure which influence the propagation velocity of ultrasonic waves.

The relationship between wave velocities and the elastic properties of materials have been presented earlier in this chapter. The elastic properties determined from wave velocity measurements, i.e. ultrasonic elastometry, are called dynamic constants.

The equipment used for velocity determinations is much the same as that used in flaw detection methods and will not be discussed here. A typical setup is shown in Figure 9. The velocity of wave propagation is obtained from measuring the length of the specimen and the travel time of the wave.

A method not previously discussed which can be used for velocity determination, is the interference method. This method is preferrable to pulse delay methods in testing thin specimens. Several testing techniques using this method exist. The basic method is shown in Figure 10. A pulse is introduced into the specimen and the pulse reflects between a generating and a receiving transducer. After a proper delay time, a second pulse is imparted to the specimen. The delay time is adjusted so that the first pulse is detected at the receiving crystal one echo transit time interval ahead of the second pulse pattern. These two pulses can be made to interfere in such a manner as to cancel each other. The velocity can then be calculated from the equation:

$$V = 2l\Delta f \tag{13}$$

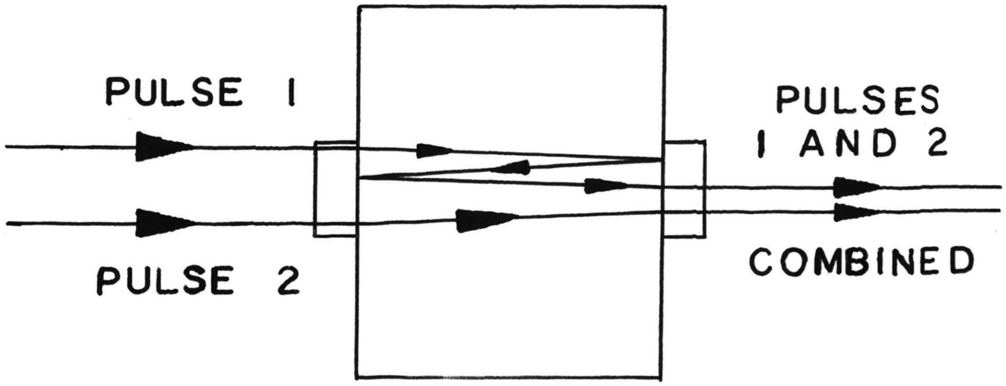

Figure 10. Interference Method

where

V = wave velocity

l = sample length

Δf = frequency change between two successive in-phase transmissions (resonance)

IV. TESTING DETAILS

A. Electronic Equipment

The electronic equipment used in this investigation to generate and detect the ultrasonic waves consisted of a pulse generator, source and receiver piezoelectric ceramic transducers, and an oscilloscope. This equipment is shown in Figure 11. The wire mesh screening device also shown in Figure 11, was used to minimize 60 htz noise from the surrounding lighting fixtures. This filtering device consisted of regular mesh aluminum housing screen wire grounded to the pulse generator.

The pulse generator was capable of delivering a variable voltage, (100-1100 volt) direct current pulse at a variable interval of 1 ms (millisecond) to 99 ms. A photograph of the source pulse is shown in Figure 12. The generator was also capable of a variable pulse duration ranging from 1 μs (microsecond) to 100 μs. However, due to internal switching delays, the pulse was 6 μs longer than specified by the selector. Thus, at a specified pulse width of 1 μs, the actual pulse duration was 7 μs (52).

The pulse generator also provided a trigger pulse of 7 volts DC to the horizontal time base of the oscilloscope. This pulse occurred simultaneously with the main voltage pulse. The generator was developed and constructed by Mr. Daniel F. Thomure according to specifications outlined by Dr. Richard W. Stephenson both of the University of Missouri-Rolla. The pulse generator is not commercially available.

Ceramic transducers used in this investigation were radial expanders (shear wave transducers) manufactured by Clevite Corporation.

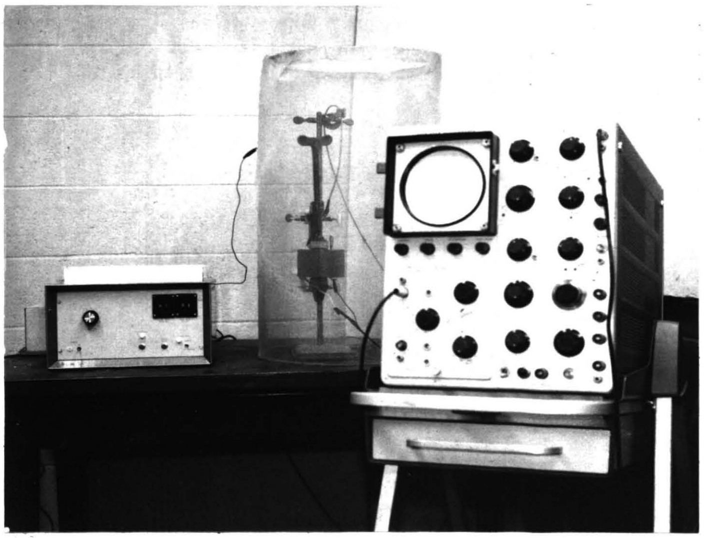

Figure 11. Testing Apparatus

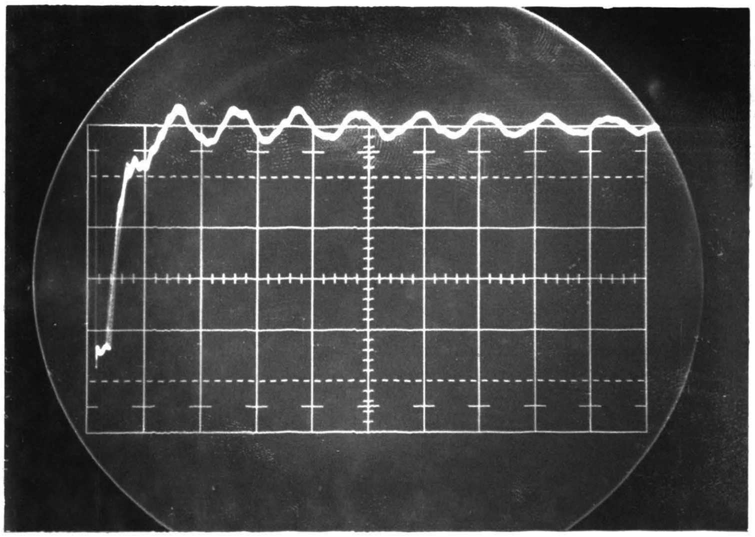

Figure 12. Oscilloscope Trace of Source Pulse at 100 Volts

The ceramic material from which the transducers were manufactured is a composition of lead ziroconate titanate (PZT) and is identified by Clevite as PZT-4. A summary of the specifications for this material is given in Table III.

Transducers of two different frequencies were used in this investigation. These transducers were poled to be radial expanders and, upon excitation, expanded in such a manner that a shearing action was imparted to the test material. The resonant frequency of a radially expanding crystal increases as the thickness decreases. Upon expansion and contraction, the crystal also changed in thickness resulting in the input of a compression wave into the test specimen. Transducers of both frequencies had a diameter of 1.0 inch.

Several of the crystals used were 0.015 in. thick and had a resonant frequency in the radial mode of about 250 khtz and 6000 htz in the thickness mode. Other crystals used in this investigation were 0.125 in. thick and had a resonant frequency of 90 khtz in the radial mode and 640 khtz in the thickness mode (4).

The crystals were electroded on their two largest surfaces by a thin plating of a silver-alloy affixed by the manufacturers. Leads of brass shemstock were attached to the electroded surfaces by soldering.

The cathode-ray oscilloscope was a Tectronix Type 545B with a Type B wide-band, high gain preamplifier plug-in unit. The instrument had two time-base generators (A and B) with delayed sweep operation ability. Time measurements were made using the delayed sweep operation. By operating the horizontal display in the 'A delayed by B' mode, time

Table III. Specifications of PZT-4 Transducers

Coupling Coefficients	
k_{33}	0.70
k_{31}	0.33
k_{15}	0.71
k_p	0.58
Piezoelectric Charge Coefficient	
d_{33}	285×10^{-12} meters/volt
d_{31}	-122×10^{-12} meters/volt
d_{15}	495×10^{-12} meters/volt
Piezoelectric Voltage Coefficient	
g_{33}	24.9×10^{-3} volts-meters/Newton
g_{31}	-10.6×10^{-3} volts-meters/Newton
g_{15}	38×10^{-3} volts-meters/Newton
Free Dielectric Constants	
k_1	1475
k_3	1300
Elastic Constants	
Y^E_{11}	8.2×10^{10} Newton/meter^2
Y^E_{33}	6.6×10^{10} Newton/meter^2
Y^E_{44}	2.6×10^{10} Newton/meter^2
Density	7600 kg/meter^3
Mechanical Q	500
Curie Point	>325°C

base A is displayed at the end of each delay period. Time base B is triggered by the pulse generator. Using the B Time/cm or Delay Time switch in conjunction with the Delay-Time Multiplier, the length of the delay period can be measured. This technique allowed time measurements to be made to an error of ± 2 minor divisions of the Delay-Time Multiplier dial on the oscilloscope. The preamplifier had a vertical deflection sensitivity of 0.005 to 20 volts per centimeter and a horizontal time base sweep rate of 2 microseconds per centimeter to 1 second per centimeter with an accuracy of ± 3%. The rise time of the preamplifier unit was 18 nanoseconds (10^{-12}).

B. Materials

The soil used in this investigation was a processed silty clay of low plasticity. The material has a liquid limit of 25%, a plastic limit of 15%, a shrinkage limit of 13%, and a specific gravity of 2.67. Hydrometer analyses (Figure 13) indicate 80% finer than .05 millimeters and 35% finer than .005 millimeters. The origin of this soil is unknown but was available in large quantities in the University of Missouri-Rolla soil mechanics laboratory.

C. Sample Preparation

Samples were prepared to predetermined void ratios and degrees of saturation. The amount of material needed to produce a given void ratio in a standard 4-inch compaction mold was determined. The required amount of water was added to the soil to produce the desired degree of saturation for that void ratio. The material and water was then mixed by hand until a uniform state was reached. After mixing, the sample material was cured for approximately 8 hours, and then

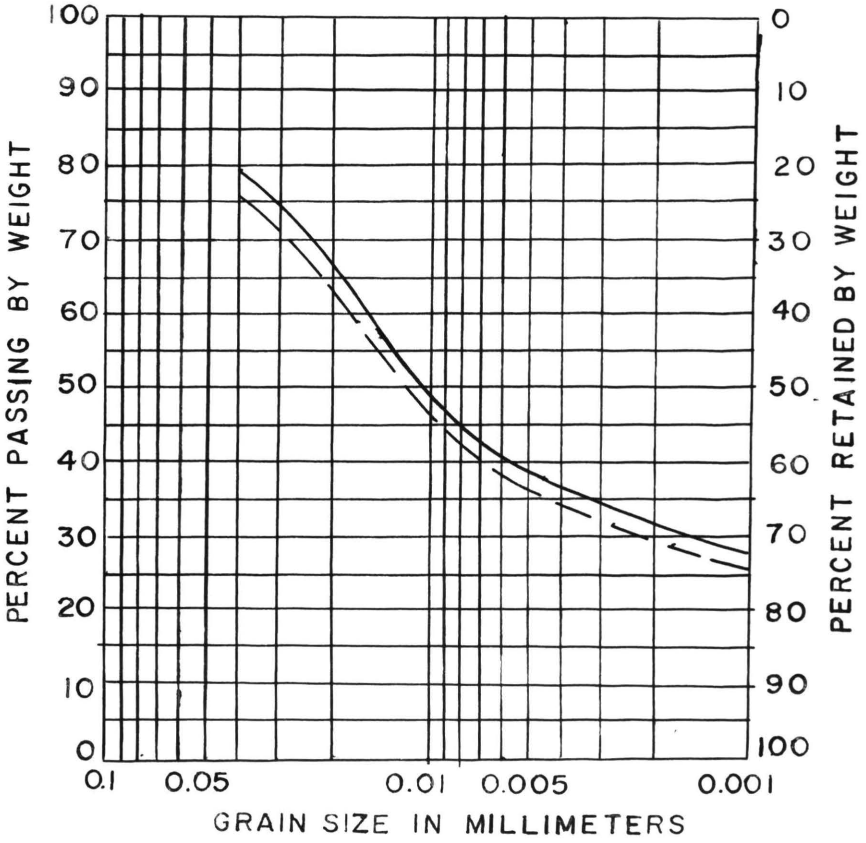

Figure 13. Hydrometer Analyses of Sample Material

compacted. Compaction to a uniform void ratio was accomplished by compacting the specimen in 5 layers. Each layer was of the same weight (the sum total was the original amount of soil plus water) and was compacted in layers with equal compacted thicknesses (the total height was the height of the lower section of a compaction mold). Compaction was accomplished by use of a 5.5 lb or 10 lb compaction hammer dropped various times and heights to obtain the specified height of layer. The sample was then wrapped in cellophane, waxed, and stored for later use.

Void ratios were varied from 0.30 to 0.60 in 0.05 increments and the degrees of saturation were varied from 30% to 100% in 10% increments. It was found that samples with water contents less than about 6% could not be adequately compacted; samples with water contents less than this amount cracked and broke at interfaces between layers. Therefore, samples with lower degrees of saturation could not be made for soil specimens with void ratios lower than 0.45.

D. Testing Procedure

The advantages of the use of ultrasonic waves in the examination of soils has already been discussed in this paper. As previously noted, Sheeran, Baker, and Krizek (46) used pulse velocity techniques for moisture content and density relationships. Similar results were found by Leslie (33). Manke and Galloway (34) made use of the pulse technique to generate longitudinal waves through soil. Lawrence (32) used pulse techniques in the investigation of various parameters on the effect of shear wave velocity.

Since little information on pulse testing could be found, and also since the performance of the apparatus developed at the University of Missouri-Rolla was unknown, it was necessary to investigate the effect of sample size, pulse width, rate of repetition of the pulse, pulse amplitude, and pulse frequency on the transmitted pulse.

The generating and receiving crystal were placed on test specimens and then mounted on a holding device as shown in Figure 14. To prevent waves from being generated into the metal holding device, it was necessary to find a backing material for the ceramic transducers. Several different materials were examined to determine the most suitable backing for the crystals. Optimum results were obtained using a combination 1/8 in. polyurethane rubber backing adjacent to the crystal which in turn was backed by a 1/2-in. thick wood block.

Pressure coupling of the transducer to the sample proved inadequate for shear wave transmission, an intermediate coupling media was needed. A stiff, highly viscous silicone compound was found to be an excellent transmission media. It is commercially known as Transistor Z-5 Silicone Compound and is manufactured by GC Electronics. A normal force was then applied by a C-clamp to obtain coupling.

More sophisticated methods of holding the sample in place were tried but failed to produce better results. Most devices were heavier than the holding mechanism and as a result, it was impossible to eliminate noise vibrations; the lighter frame structure, when grounded, eliminated all noise distortions. The disadvantage of the method used was that the coupling pressure was unknown and therefore could not be held constant.

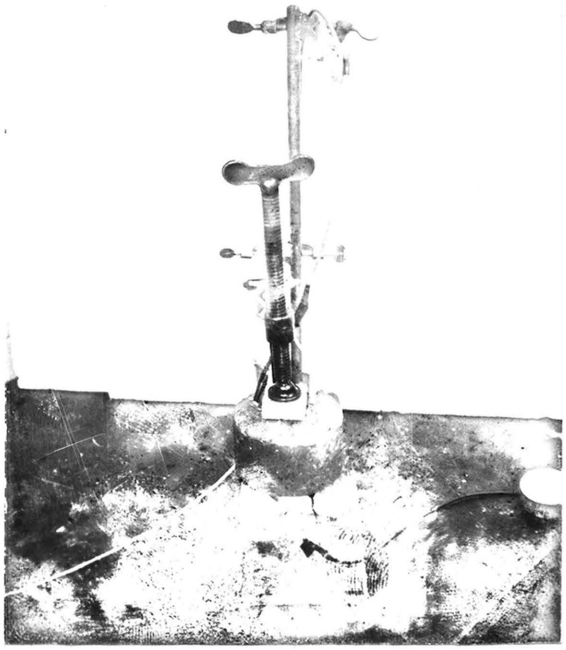

Figure 14. Holding Device with Sample in Place

The receiver transducer was found to be susceptible to noise and was highly affected by 60 htz noise emitted by lighting fixtures (52). A screening device consisting of a regular mesh aluminum housing screen was constructed in which the sample and holding device were enclosed. Grounding of the screen to the pulse generator eliminated noise from the lights.

1. Specimen Size

Tests were conducted on samples with void ratios of 0.45 and 0.50 and degrees of saturation of 85% and 77% respectively. Samples 4 in. and 2 in. in diameter with lengths varying from 1/2 to 3-in., in 1/2-in. increments were studied. It was generally found that samples 4 in. in diameter provided more clearly defined wave forms at all pulse widths than those 2 in. in diameter. From these tests it was also concluded that a length of 2 1/2-in. provided optimum transmission results.

Typical results are shown in Figures 15 and 16. These photographs are from a specimen with a void ratio of 0.50 and a degree of saturation of 77%. The oscilloscope trace shown in Figure 15 is a trace of a 4-in. diameter sample 2 1/2 in. in length; Figure 16 is a trace of a 2-in. diameter sample 2 1/2 in. in length.

Point A on the oscilloscope traces shown in Figures 15 and 16 represents the arrival of the compression wave. Defining the arrival of the P-wave is usually not a problem as can be seen in the figures; the wave arrival is quite sharp.

In Figure 16 one can see a distortion of the trace before point A. This condition was found to be a problem only with smaller

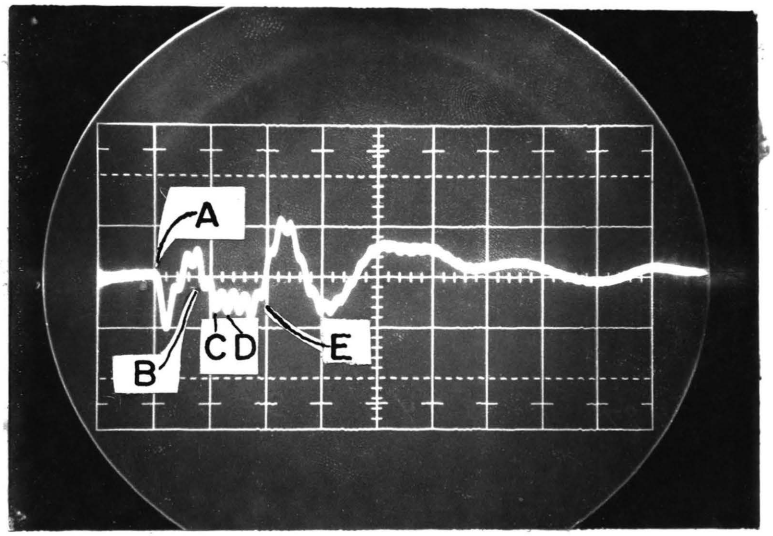

Figure 15. Oscilloscope Trace of a 4-in. Diameter Sample

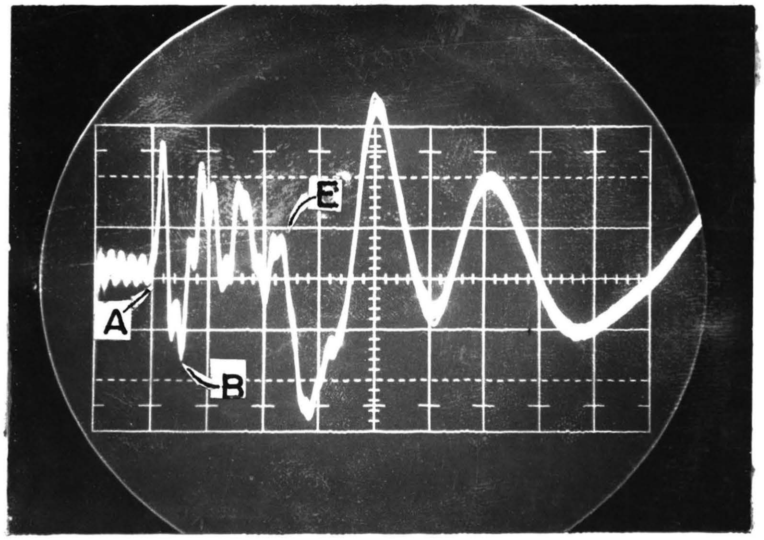

Figure 16. Oscilloscope Trace of a 2-in. Diameter Sample

diameter samples, examination of Figure 15 does not disclose a similar occurrence in the 4-in. diameter sample. It was discovered that shielding of the leads with aluminum foil and grounding of the foil to the pulse generator eliminated distortion in oscilloscope traces of smaller diameter samples. The explanation for this phenomenon is that the air between the two sets of leads was acting as a dielectric material and as a result, a capacitance was present which discharged a small amount of voltage to the leads of the receiving transducer.

Point B is the arrival of the shear wave. The arrival of the shear wave as shown in Figure 15 and most of the other 4-in. samples was defined as being the point where a strong change of pulse direction was noted, after which there occurred numerous smaller peaks representing the resonant frequency of the crystal in the shearing mode. Point C and D in Figure 15 represent one cycle of a wave at the resonant frequency. The computed frequency of these waves is about 96 khtz which corresponds closely to the manufacturers specification of 90 khtz. Point B is not easily defined in Figure 16 because the distortions at the beginning of the oscilloscope trace are present throughout the trace. The arrival of the shear wave in this case is defined as the point where a large reversal of slope occurs. This method of analysis gives inconsistent results.

Point E represents the arrival of the Rayleigh wave. The Rayleigh wave is usually characterized by a long period and large amplitude.

2. Pulse Width and Interval

Once sample length and diameter were determined, optimum pulse width and pulse interval needed to be investigated. Tests conducted on a sample with a void ratio of 0.54 and degree of saturation of 70% determined that a pulse width of 5 to 7 μs and a pulse interval of 2 ms obtained optimum wave forms. Interference from previous waves was nonexistant.

3. Pulse Amplitude

The amplitude of generated and received pulses is a function of the voltage applied to the generating crystal. It is desirable to use a combination of voltage from the pulse generator and oscilloscope magnification factor to obtain an oscilloscope trace that uses the full height of the oscilloscope scale but yet keeps noise levels low and maintains as narrow of a trace as possible. An amplitude of 600 volts was usually adequate for wave transmission but occasionally voltages up to 1100 volts combined with large magnification factors had to be used.

4. Pulse Frequency

Limitations on frequency as well as the frequencies of the crystals used in this investigation have been discussed previously. The 0.015 inch crystal was not used when testing soils; a combination of the pressure required for coupling, the roughness of the surface and the delicacy of the crystal prohibited its use.

The 0.125 inch crystal was used in this investigation and had a frequency such that the crystal in both the radial and thickness mode had wavelengths larger than most of the grain sizes. However, since attenuation does increase as wavelength approaches grain size some scattering could be attributed to the frequency of the crystals. Also dependent upon wavelength is the length of the near field which has an effect on mode conversion. The 2 1/2 inch length samples are within the near field.

5. Velocity and Damping Measurements

As previously stated, measurements of longitudinal wave velocity allows the calculation of several important dynamic material parameters that are descriptive of the dynamic nature of the test material. In addition, measurement of different arrival times of a given wave could possibly be made and a measure of the wave attenuation properties of the media ascertained.

Because soil does attenuate waves rapidly, it is desirable to use a testing technique that will allow detection of the waves before the waves are damped. Therefore, the direct transmission method as shown in Figure 9 is most appropriate. In this method the source and receiver crystal are placed directly opposite each other resulting in a minimum travel length.

When a piezoelectric crystal is excited, all three types of waves forms are generated (compression, shear, and surface). A receiving transducer placed directly opposite a source transducer will receive the waves as shown in the schematic drawing of Figure 17. The first wave to arrive will be that with the greatest velocity, namely compression waves (L). Since shear wave velocity (S) and Rayleigh wave velocity (R) are approximately equal, the arrival times may be about the same and some difficulty distinguishing waves may result. Identification is usually not much trouble, however, because the Rayleigh wave has a much larger amplitude than the shear wave.

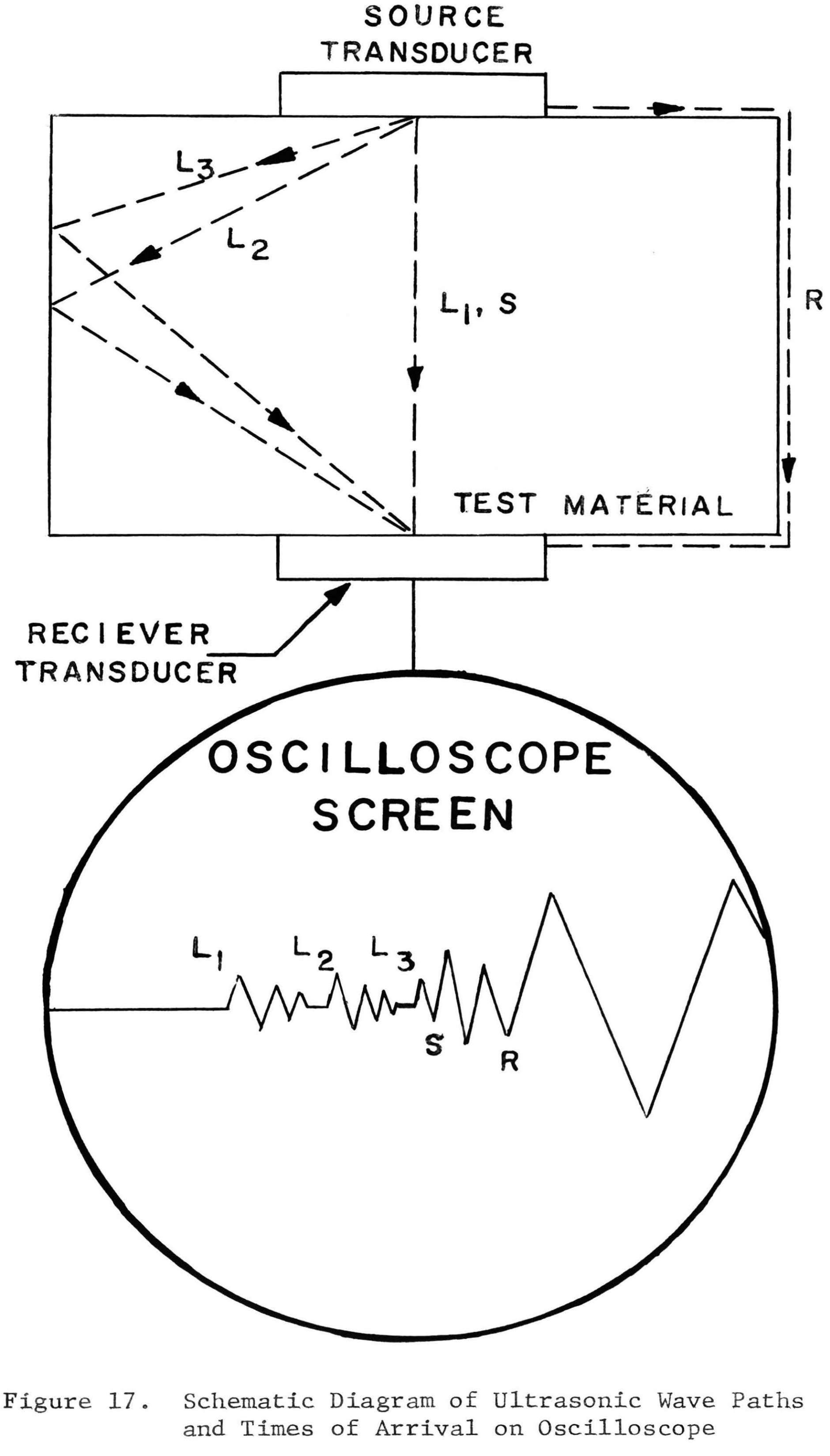

Figure 17. Schematic Diagram of Ultrasonic Wave Paths and Times of Arrival on Oscilloscope

These waves may be distorted by reflected and refracted longitudinal waves (L_2,L_3) due to longer path lengths.

A portion of the wave energy is lost at the specimen/receiver interface. As a result some of the energy is reflected back to the source crystal and back to the receiver crystal (Figure 18). The travel time of this wave is about 3 times the time required for the first wave to arrive. The arrival of this wave is important in attenuation measurements and may distort arrivals of other wave forms. Measurement of the difference in amplitude of the first and second arrival of the P-wave divided by the travel distance between first and second arrivals gives the amount of attenuation per unit length.

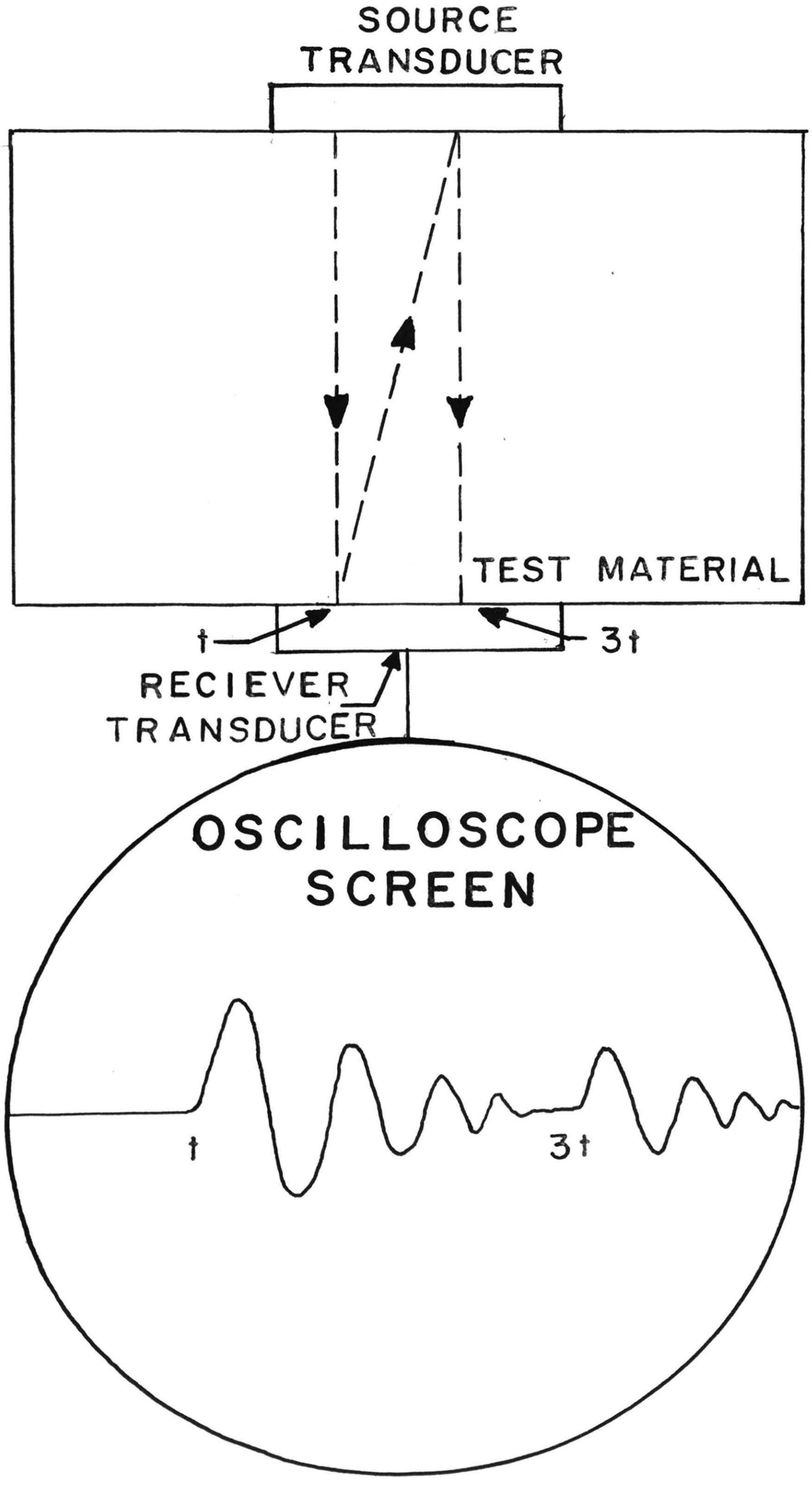

Figure 18. Schematic Diagram Showing Reflection of Waves in a Test Medium and Resulting Oscilloscope Trace

V. TEST RESULTS AND DISCUSSION

Any testing technique is of value if and only if results are indicative of the actual properties of the material being tested. It is believed that the results of the test method used in this investigation satisfy the above criteria, yield behavioral patterns as expected and are compatible with results obtained by other investigators using the same or similar technique. The test results reported here compare favorably with the results of other investigators who used different investigative methods. The influence of void ratio, and degree of saturation upon compression and shear wave velocity, and hence Young's modulus, shear modulus and Poisson's ratio were of primary concern in this study. Of equal significance in this study was the evaluation of a high voltage pulse generator for ultrasonic testing developed at the University of Missouri-Rolla. The results presented herein are to be considered indicative only of the material tested.

A. Apparatus

As was mentioned in the introduction of this chapter, it was the partial objective of this investigation to determine if a pulse generator developed at the University of Missouri-Rolla could be used as part of a pulse velocity testing method for the determination of certain dynamic material parameters of a soil. The results of this portion of the study have been discussed in a previous section and will not be repeated here.

B. Wave Velocity Tests

Forty-eight tests of compacted soil at seven void ratios and eight varying degrees of saturation were made in this study. Void ratios ranged from 0.3 to 0.6 and were generally increased in increments of 0.05. The degree of saturation was varied from 30% to 100% in about 10% increments. As stated previously, some samples with lower degrees of saturation were not tested for void ratios below 0.45.

1. Compression Wave Velocity

Figure 19 is a plot of compression wave velocity in feet per second (fps) versus void ratio for given ranges of degree of saturation. For clarity the actual data points have not been shown but it should be noted that a scatter of data points was present. The lines shown in Figure 19 represent equations obtained by linear regression analysis. Table IV gives the degree of saturation range, equation of the line obtained by linear regression analysis, and the sample correlation coefficient for lines shown in Figure 19.

The sample correlation coefficient is an indicator of how well data points fit the equation described by the data points. The coefficient normally ranges between 1 and -1 depending upon the slope of the line. A value of 1 or -1 is considered a perfect fit with 0 meaning no correlation.

The scatter of data is attributed mainly to the type of material being tested. Non-homogeneity in particle orientation, size, shape, surface roughness is probably the most obvious attributing factors. Operator and operation errors also influence the results.

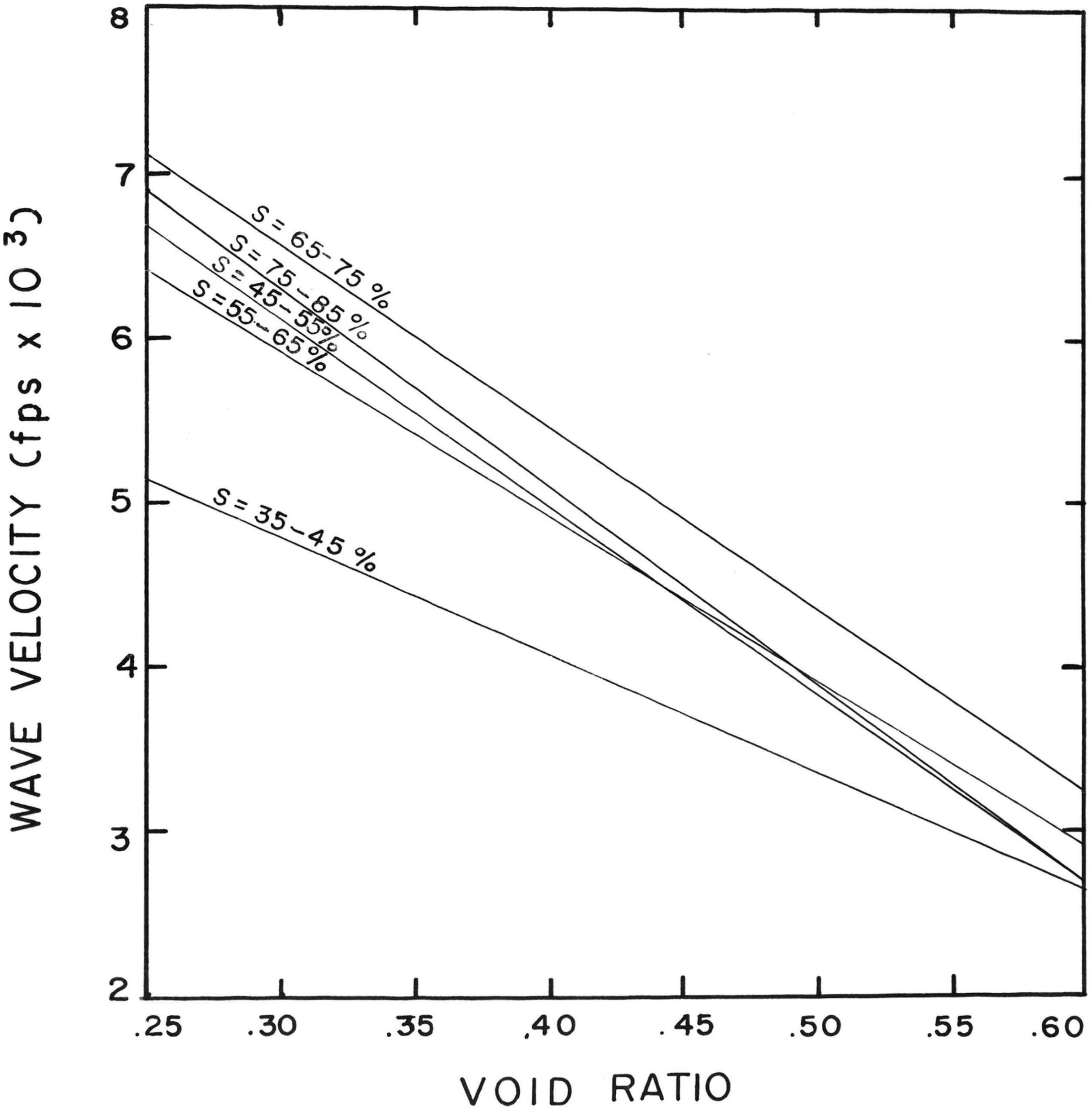

Figure 19. Graph of Compression Wave Velocity Versus Void Ratio for a Range of Degree of Saturation

Table IV. Linear Regression Analysis for Compression Wave Velocity Graph

Degree of Saturation %	Equation of Line y=mx+b	Sample Correlation Coefficient
35-45	-6882x+5081	-0.90
45-55	-11376x+9530	-0.97
55-65	-9919x+8925	-0.99
65-75	-11847x+9795	-0.92
75-85	-6604x+5857	-0.98

As can be seen in the table, the data has high correlation coefficients. It can also be noted on Figure 19, that lines representing degrees of saturation ranging from 30 to 35% and above 85% are not shown. A combination of lack of sample in this saturation range and difficulty in coupling sample and transducer in the first case and inability to define wave arrivals accurately in the latter case account for this lack of data.

One can see on Figure 19 that the compression wave velocity decreases with an increase of void ratio in any given range of degree of saturation. One can also see that saturation line slopes are approximately equal and that there is no absolute pattern when comparing wave velocities at a given void ratio against degrees of saturation. A general trend of higher wave velocities with increasing degree of saturation is evident however. It is believed that closer control of degree of saturation or the use of bands of narrower saturation range would have eliminated discrepencies and the resulting lines would have shown more pronounced trend of higher compression wave velocities with increase of degree of saturation at a constant void ratio.

Results obtained were expected since previous investigators have reported similar data. Most previous works however, have been concerned with velocity as a function of confining pressure or shearing strain magnitude. Figure 20 shows the results obtained by the author and the results of another study (37). It can be seen that wave velocities from this study are of the same magnitude as the Nacci and Taylor data, but that the slope of the range of values is less. This

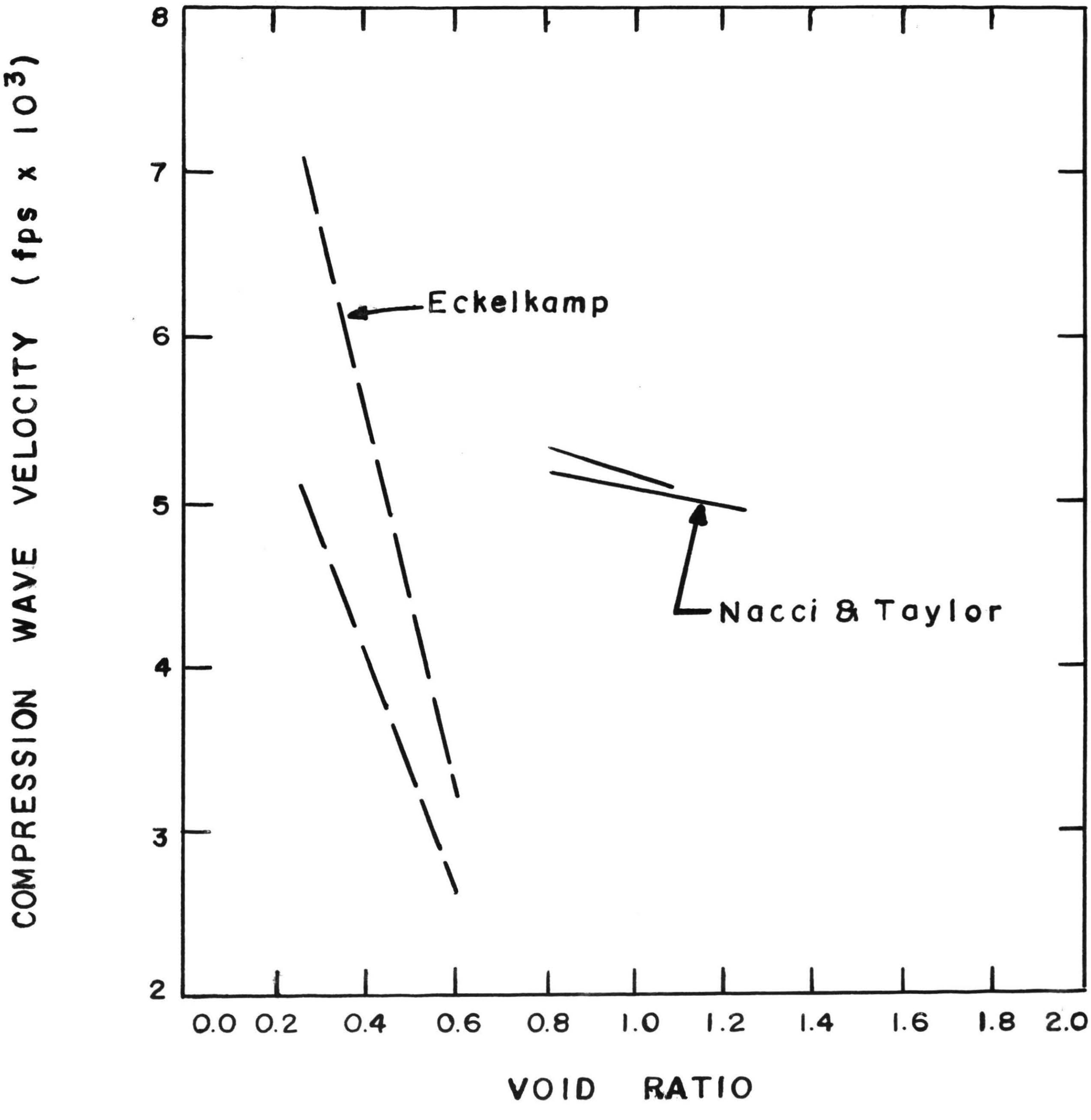

Figure 20. Graph of Compression Wave Velocity Versus Void Ratio for Various Investigations

difference can be attributed to the difference in materials and slightly different testing techniques. It should also be noted that the band given for the Nacci and Taylor report does not specify ranges of saturation but is a band for confining pressures of 3.5 to 55 pounds per square inch (psi).

2. Shear Wave Velocity

Figure 21 shows plots of shear wave velocity in feet per second versus void ratio for given degrees of saturation. As in the compression wave velocity plot, lines shown represent linear regression analysis on data within selected degree of saturation bands. A tabulation of lines shown in Figure 21 are given in Table V. The sample correlation coefficient, reasons for data scatter, and lack of data for lower and higher degrees of saturation other than those shown have been discussed previously and will not be repeated in the subsequent paragraphs.

It can be readily seen from Figure 21 that the shear wave velocity decreases with an increase in void ratio and at a given void ratio increases generally with an increase in degree of saturation. It can also be seen that all data lies within a relatively narrow band and that all lines are about of the same slope. This is to be expected since shear waves cannot be transmitted through water and should be relatively independent of degree of saturation.

The decrease in velocity with increasing void ratio was expected since various investigators have reported similar phenomenon as shown on Figure 22. It should be noted that both sets of data used in

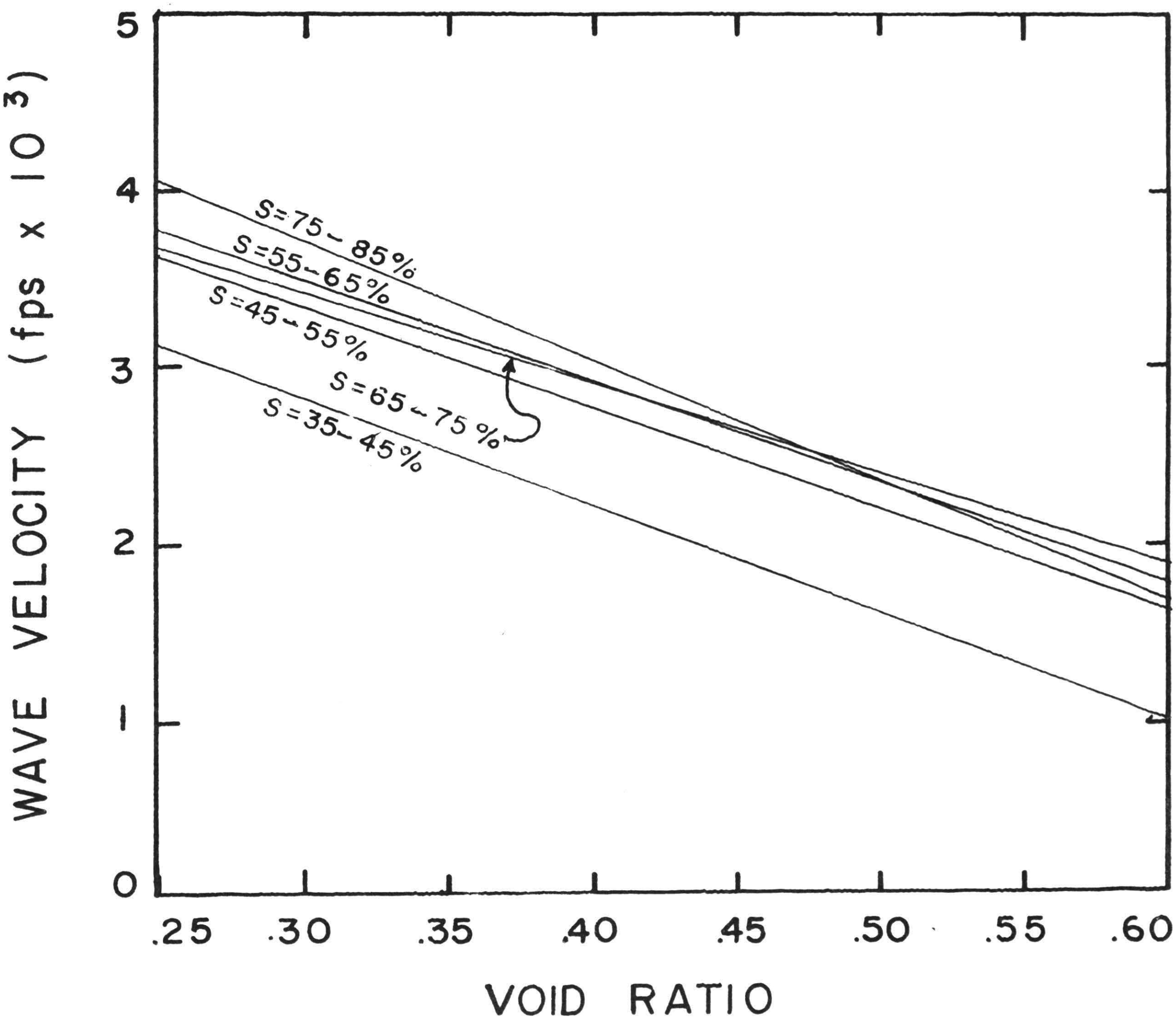

Figure 21. Graph of Shear Wave Velocity Versus Void Ratio for a Range of Degree of Saturation

Table V. Linear Regression Analysis for Shear Wave Velocity Graph

Degree of Saturation %	Equation of Line y=mx+b	Sample Correlation Coefficient
35-45	-4666x+4289	-0.91
45-55	-5782x+5078	-0.98
55-65	-5829x+5216	-0.99
65-75	-5094x+4922	-0.89
75-85	-6720x+5666	-0.99

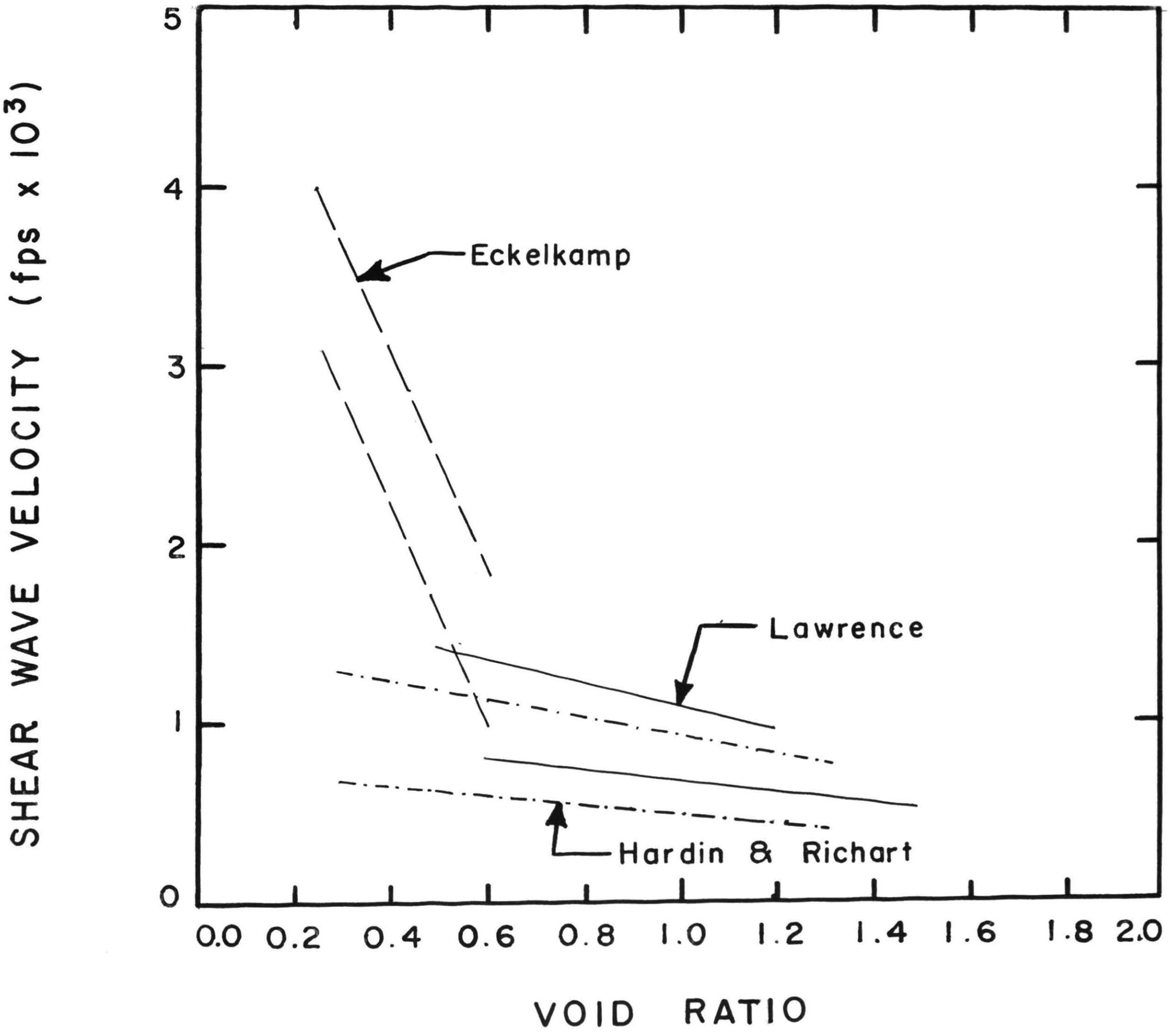

Figure 22. Graph of Shear Wave Velocity Versus Void Ratio for Various Investigations

comparison are functions of confining pressure and not degree of saturation which partially explains the difference of results. Other factors influencing the difference include a dissimilar range of void ratios, the use of the resonant column test in the Hardin and Richart data which utilizes higher strains, and also differences in material. Data obtained by Lawrence (32) was from a clay but that of Hardin and Richart (17) was for a dry quartz sand.

C. Dynamic Material Parameters

The dynamic material parameters studied in this investigation, and their relationship to void ratio and degree of saturation are presented and discussed in the following sections.

1. Young's Modulus

Figure 23 shows a plot of E-modulus in psf versus void ratio for given ranges of degree of saturation. Table VI gives correlation coefficients for given degrees of saturation as well as equations for the plots shown on Figure 23.

As expected, Young's modulus decreases with increasing void ratio for all degrees of saturation. Since moduli values are dependent on velocity, it should follow that the moduli of a soil would behave as the velocity with respect to void ratio. However, moduli values are also influenced by the density of a soil which will result in minor deviations of linear plots when compared against velocity data.

Examination of Figure 23 and Table VI show that correlation coefficients for the test data curves are high. It can also be seen that the data has approximately the same slope except for the 35% to

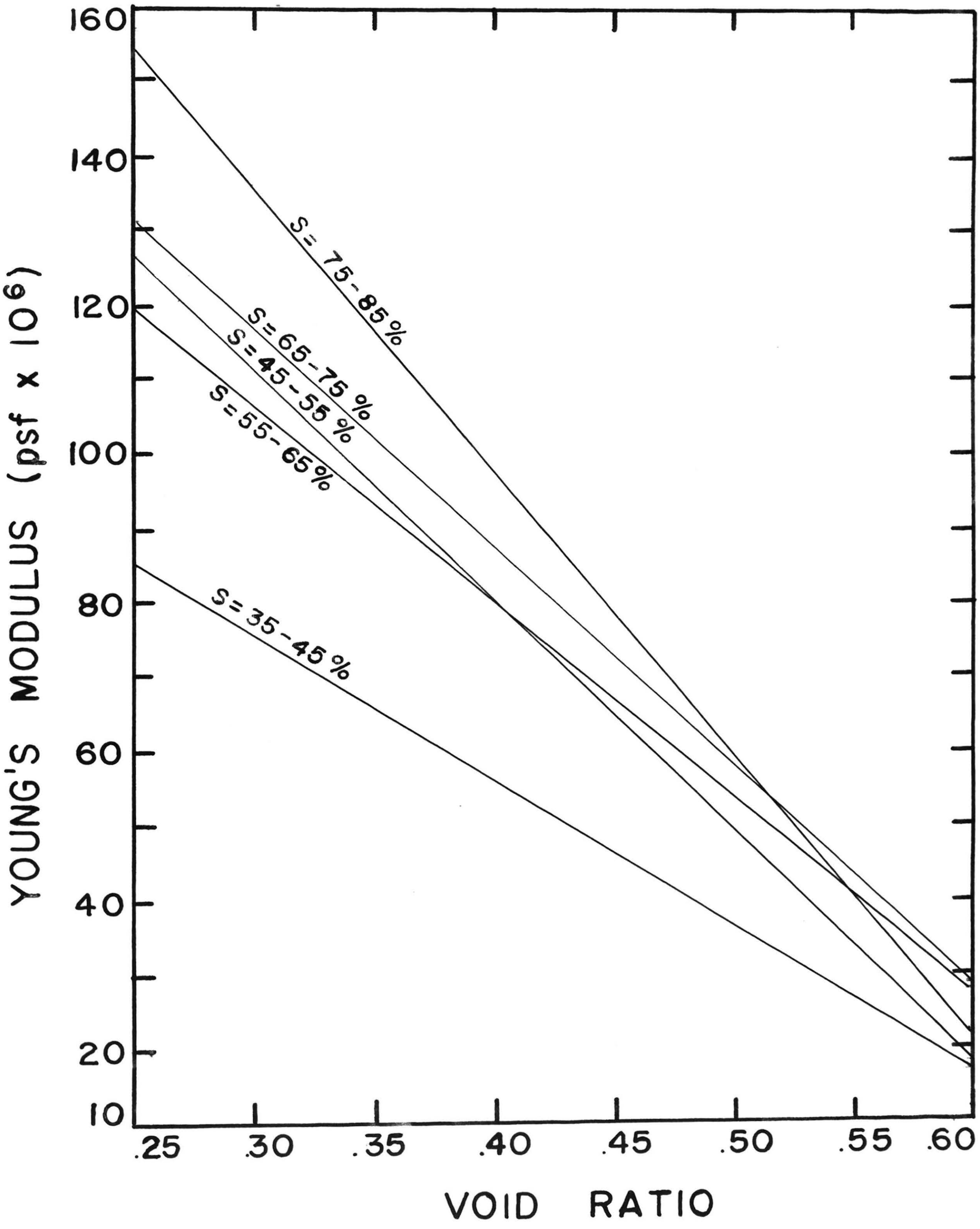

Figure 23. Graph of Young's Modulus Versus Void Ratio for a Range of Degree of Saturation

Table VI. Linear Regression Analysis for Young's Modulus Graph

Degree of Saturation %	Equation of Line y=mx+b	Sample Correlation Coefficient
35-45	-193x+133	-0.92
45-55	-311x+204	-0.98
55-65	-260x+184	-0.88
65-75	-290x+205	-0.94
75-85	-388x+251	-0.98

45% degree of saturation range line. This deviation is attributed to the difficulty in obtaining good coupling between sample and transducer for soil samples in this range. This coupling difficulty also explains lower compression wave velocities for the 35%-45% saturation range which are reflected in moduli values.

Increasing the degree of saturation at a given void ratio generally increases the moduli values. A slight discrepancy occurs between the degree of saturation range of 45 to 55% and 55 to 65%. However, the difference between the two curves is small and may be attributed to coupling or oscilloscope reading errors.

A comparison of results from other studies was not made because published values for the E-modulus of a soil could not be found.

2. Shear Modulus

A plot of shear modulus in psf versus void ratio is shown in Figure 24. Corresponding correlation coefficients are shown in Table VII.

Since shear wave velocities decreases as void ratio increase, it is not surprising that shear moduli exhibit a similar tendency. The decrease of moduli for increase in void ratio can be explained by the fact that as a rule, for the same material with an identical stress history, an increase in the amount of voids will decrease the shearing resistance for a given amount of strain and consequently reduce the shear modulus. A similar explanation can account for the decrease of Young's modulus with increase of void ratio.

For a given void ratio, shear moduli increase with degree of saturation. As was explained earlier, shear wave velocity for an

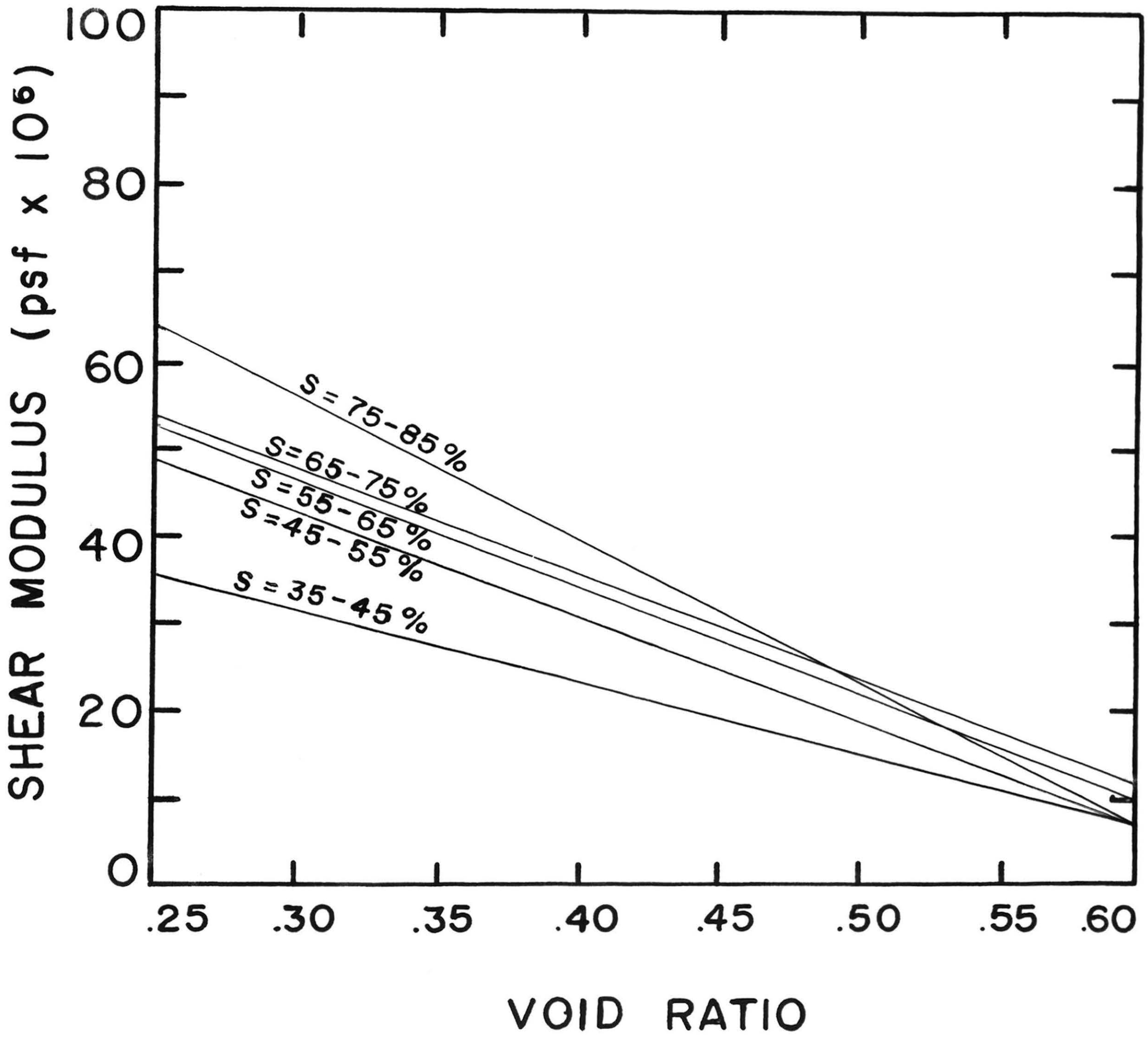

Figure 24. Graph of Shear Modulus Versus Void Ratio for a Range of Degree of Saturation

Table VII. Linear Regression Analysis for Shear Modulus Graph

Degree of Saturation %	Equation of Line y=mx+b	Sample Correlation Coefficient
35-45	-83x+56	-0.90
45-55	-120x+79	-0.97
55-65	-125x+84	-0.99
65-75	-116x+82	-0.92
75-85	-160x+103	-0.98

increase in degree of saturation at a given void ratio should remain constant. Because of the way in which shear modulus is defined in Equation 2, any variation in shear modulus should be due to an increase in unit weight which increases with degree of saturation. One would therefore expect shear modulus to increase at a given void ratio for an increase of degree of saturation. Additional increase of shear modulus can be attributed to variation of shear wave velocity.

Values of shear moduli obtained in this text and another investigation are shown on Figure 25. The data of Hardin and Black (27) was obtained from tests performed on a clay material by means of a modified triaxial apparatus for pressures of 20 to 100 psi. Differences of results are due to variation of material, parameters studies, and ranges of strain encountered.

3. Poisson's Ratio

Results of Poisson's ratio versus void ratio were too scattered to reveal any definite relationship. However, when several data points are deleted, a relationship of decreasing Poisson's ratio with increasing void ratio can be noted. At a given void ratio, an increase in degree of saturation gave a slight decrease in Poisson's ratio. The scatter of Poisson's ratio can be attributed to the fact that calculation of Poisson's ratio is highly sensitive to velocity changes. A 10% change in velocity may change Poisson's ratio by as much as 100%.

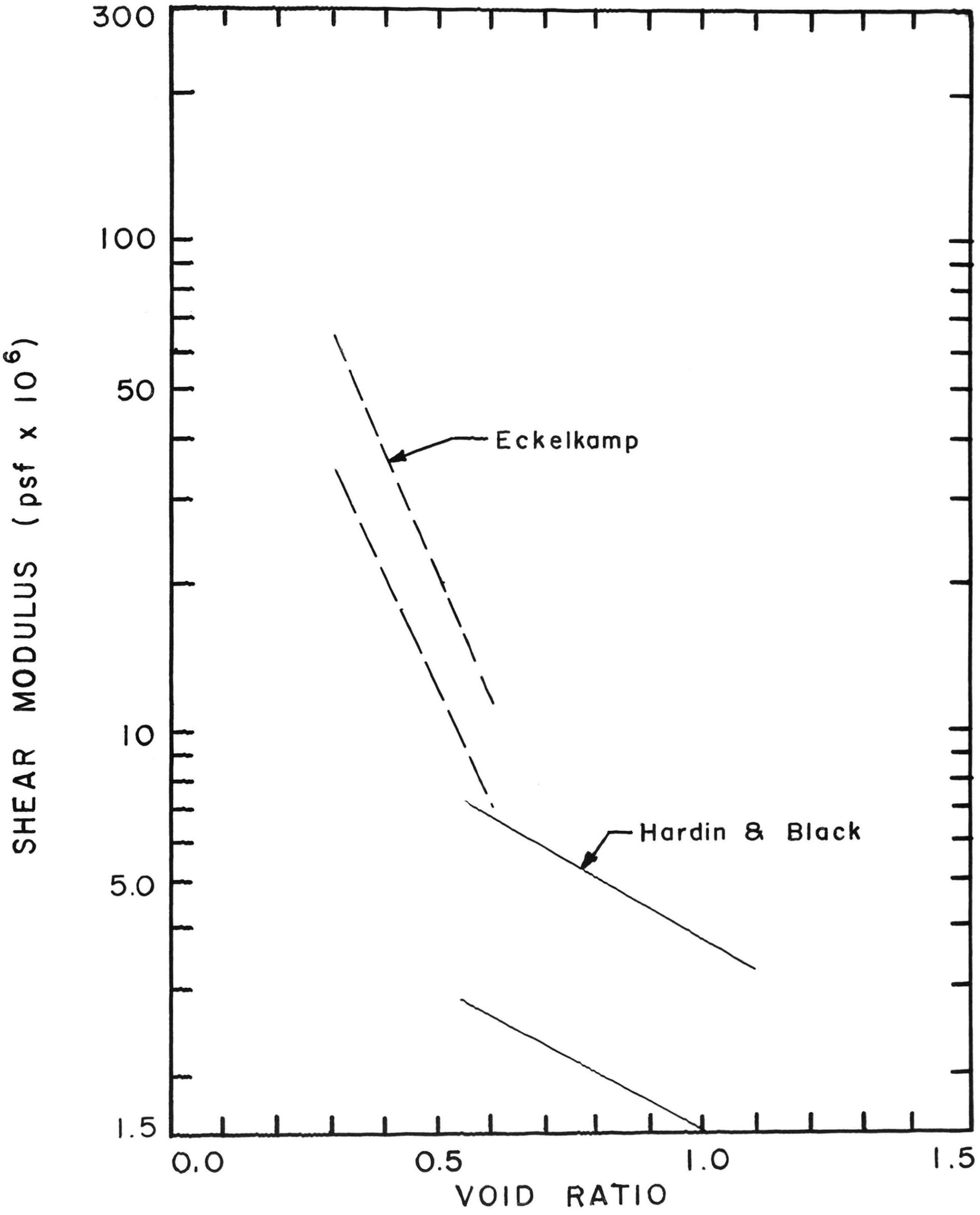

Figure 25. Graph of Shear Modulus Versus Void Ratio for Various Investigations

D. Damping

Measurements of material damping could not be made with the test setup used. In order for the damping of a wave to be measured, it is necessary to detect the first arrival of a wave form and also the wave that is reflected and arrives at a time 3 times the first arrival. This could not be done because of large surface waves which were encountered at 3 times the first arrival. These surface waves masked all other wave forms. Recommendations for damping measurements are made in a following chapter. References to investigations of damping by others are given in the Bibliography and also in Chapter II.

VI. CONCLUSIONS

Of primary importance in this study was the investigation of the possibility of evaluating Young's modulus, shear modulus, Poisson's ratio, and damping for a soil by use of a pulse velocity technique. This test would be of value because it would provide a quick, non-destructive method of determining soil parameters appropriate for dynamic analysis at strain ranges smaller than tests presently available.

From test data described herein, it can be said that it is possible to measure ultrasonic wave velocities through soil and the testing procedure employed for the determination of wave velocities can be used to define the dynamic properties of interest. The possibility also exists that parameters as determined by this testing technique can have some application in the design, control, and investigation of soils subject to small strain dynamic loadings such as machine vibrations, microtremors and vehicular traffic vibrations.

The following conclusions are based on the material and test procedure outlined in the preceding pages. Testing of a wider range of materials needs to be done before general conclusions can be made.

1. It is possible to generate the detect ultrasonic compression and shear waves in a soil material with equipment developed at the University of Missouri-Rolla.

2. Specimen size does effect velocity measurements; length effects the intensity of a wave at the receiver; and diameter directly influences the arrival of the large amplitude Rayleigh wave.

3. Optimum pulse duration, interval, amplitude, and frequency vary within a soil and it is suspected that these parameters will differ from soil to soil.

4. Compression and shear wave velocity tends to decrease with an increase of void ratio for a given band of degree of saturation. Shear wave velocities do not decrease as rapidly with increase of void ratio as compression wave velocities.

5. At a constant void ratio, wave velocity generally increase with degree of saturation.

6. Young's modulus and shear modulus have behaviors similar to that of the corresponding velocity. As with velocity measurements, G-modulus did not decrease as rapidly as Young's modulus.

7. Data points of Poisson's ratio versus void ratio were widely scattered but a general trend of a decreasing Poisson's ratio with increasing void ratio was noted.

8. Damping could not be determined with the test procedure used.

VII. RECOMMENDATIONS FOR FURTHER RESEARCH

This investigation has illuminated areas in which research is needed if ultrasonic testing for the determination of dynamic parameters of soil materials is to be of value. It is suggested that work be done in the following areas to enhance the usefulness of ultrasonic testing.

1. A method in which wave forms can be more easily distinguished needs to be developed. It is suggested that piezoelectric crystals of the appropriate type be used for individual determinations of compression and shear wave velocity of the same specimen.

2. The above suggestion would also facilitate damping measurements. Use of crystals with a primary wave form of a compression wave would improve the detectability of the second arrival. It is believed that damping could be measured most easily in this manner.

3. Larger diameter crystals should be used in conjunction with larger diameter samples to decrease the influence of coupling.

4. A holding device capable of controlling axial pressure should be constructed. It would also be desirable that this machine be capable of imparting an all around confining pressure to a specimen so that effects of confining pressure could be studied.

5. A laboratory study on soils of different types both in a natural and remolded state for a wide range of void ratios should be done.

6. Finally, it would greatly benefit this area of interest to have a study made of laboratory data and data obtained in-situ.

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