TECHNIQUES FOR FIELD MEASUREMENT OF SHEAR WAVE VELOCITY IN SOILS

by
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Synopsis

Modern methods of earthquake resistive design of foundations and earth structures require a knowledge of the shear modulus of elasticity of earth materials, which is closely related to the velocity of propagation of shear waves.

An investigation was made of the state of the art of determining shear-wave velocity in soil and foundation materials by impulsive and sustained source seismic field methods. The impulsive source methods utilize body waves, surface waves and waves propagated along borings. The sustained source (vibration) methods utilize resonance techniques, surface-wave techniques, and a technique of cross correlation of varying-frequency vibrational inputs with detected responses.

Introduction

Major progress has been made in recent years in the development of theoretical approaches to the soil-related and site-conditions-related problems of earthquake engineering. Nearly all of these developments involve as a principal material property the dynamic shear modulus of elasticity of soils and rocks, which property is closely related to the velocity of propagation of shear waves. Applications of the theories can be made in a variety of ways if acceptable values of shear-wave velocity, and of damping, can be obtained for the earth materials comprising and supporting a structure.

The three simplified examples of Fig. 1 will suffice to illustrate the use of shear-wave velocity in earthquake engineering problems. The symbols are defined as follows:

ρ	mass density
c	shear wave velocity
ξ	coefficient of equivalent viscous damping
σ	Poisson's ratio
H	layer thickness
ω	circular frequency
r	footing radius
m	mass of footing and vibrator
U	amplitude of sinusoidally varying displacement
F	amplitude of sinusoidally varying force

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In Example (a), one may estimate roughly the maximum amplification, R, due to a shear wave of amplitude U arriving at the bottom of the layer, and the corresponding incoming resonant wave period, T, by the elastic formulas:[7,12]

$$R = 2\,\frac{\rho_2 c_2}{\rho_1 c_1} \qquad T = \frac{2\pi}{\omega} = \frac{4H}{c_1}$$

In Example (b), one may obtain an equation of the following form for the amplitude of footing motion:[39]

$$U = \frac{F}{f(\omega;\rho,c,\xi,\sigma;r,m)}$$

where the denominator is the compliance, analogous to a spring constant, needed in computations of soil-structure interaction. In Example (c), one may compute the stresses and deformations due to U, in an earth dam of given geometry, by a method such as the finite element method,[2] utilizing the indicated properties, notably c_1 and c_2.

Thus, acceptable values of shear-wave velocity are absolutely essential to the analysis and design of foundations and earth structures for earthquake loading and to the determination of the earthquake ground motion that will be imparted to structures of all types.

For a shear-wave velocity to be acceptable, it should be truly representative, within a satisfactory range of uncertainty, of the velocity with which earthquake shear waves will propagate in the materials of interest. Neither laboratory nor field techniques are entirely adequate in this sense. Frequently a combination of the two is advantageous.

Laboratory techniques[16-23] have certain advantages in that they can be adapted to measurements at the relatively higher stress, strain and damping levels corresponding with strong earthquakes, can incorporate measurement of pore water pressure, and can sometimes provide results in built-up areas or complex geology where field methods are difficult to apply. However, laboratory techniques suffer from the problems of representativeness and disturbance of samples, limited depth of exploration, and longer time required for drilling, sampling and testing.

Field techniques have the principal advantage that the wave velocities are measured in the same earth system that the earthquake waves will pass through, providing values that have been statistically smoothed by the natural irregularities of the soil and rock in situ. Other advantages are the speed with which results may be obtained, the absence of limits on geometric scope of the exploration, and the possibility of simultaneous obtaining of information on stratification. Perhaps the major disadvantage of field methods is that they normally employ stress, strain and damping levels substantially lower than the levels in strong earthquakes, so that errors will be introduced into the analyses. Furthermore, the conduct and interpretation of field measurements is an art requiring special training and experience.

Frequently, shear-wave velocity can be estimated from data on compressional wave velocity. For this purpose, use can be made of the following equation from the theory of elasticity:

$$\frac{c}{cp} = \left(\frac{1-2\sigma}{2(1-\sigma)}\right)^{1/2}$$

where c_p indicates compressional wave velocity. The relation is illustrated in Fig. 2.[9] Published data on Poisson's ratio, σ, for soils range approximately from 0.3 to 0.5. Some sources report the comparison directly in terms of the ratio c/c_p which is typically around 0.5 for deeper sediments but only 1/6 or 1/7 for many near-surface materials.[45] The latter ratios are to be associated with the relatively high c_p values in saturated porous materials.

Recent work is beginning to establish relationships between field or laboratory velocity measurements and such commonly known factors as void ratio and confining pressure.[18,22] In the future such relationships should become increasingly useful as more such work is done. However, even with a book of graphs or tables of this nature at hand, the engineer designing a major or novel structure will need to obtain measured values of shear-wave velocity for his particular situation.

Even though both field and laboratory techniques for shear-wave velocity measurement are being successfully used today, these techniques are still early in their developmental stages and are difficult to execute well, and very few persons have experience with them. Accelerated development and use are essential to progress in earthquake engineering.

Available field techniques for shear-wave velocity measurement may be classified as either impulsive seismic methods or sustained source methods, taking their names from the types of input signal. The impulsive seismic methods are adapted from exploration geophysics,[3-6,10,11,15] utilizing single-pulse type inputs and utilizing under appropriate circumstances body waves, surface waves, and waves traveling along a boring. The sustained source methods utilize constant or systematically varying sinusoidal inputs and measure outputs under appropriate circumstances adjacent to and/or remote from the vibrator.[40] Commercial equipment is available for both types of method, but normally requires modification for use with the relatively slow-velocity materials (200 to 2000 ft./sec.) and shallow depths (zero to 300 ft.) of interest in earthquake engineering.

Wave Characteristics

Of interest in the field measurement of shear-wave velocity are several types of waves usually present in the earth after any dynamic disturbance. They consist of the body waves P, SH and SV which propagate below the surface of the earth and the surface waves R and L which propagate in the near-surface region.[1,4,8,9,14] These wave types will be briefly described in terms of elastic theory as a foundation for subsequent discussion.

P wave designates the faster of the two body waves, a pure compression-rarefaction wave characterized by particle oscillation parallel to the direction of wave propagation. Its velocity is

$$c_p = \left(\frac{\lambda + 2G}{\rho}\right)^{1/2}$$

where the new symbols signify

λ Lame's constant

G shear modulus of elasticity

S wave designates the slower of the two body waves, a simple shear wave characterized by particle oscillation perpendicular to the direction of wave propagation, Its velocity, the subject of this paper, is expressed as

$$c = \left(\frac{G}{\rho}\right)^{1/2}$$

The particle motion in an S wave propagating in any direction can usefully be described in terms of the components in a horizontal plane and those in a vertical plane. The resulting polarized waves, which together constitute the S wave, are called SH waves and SV waves, respectively.

Fig. 3 illustrates the directions of particle oscillation in the three types of body waves.

R wave designates a surface wave, called the Rayleigh wave, characterized by particle oscillation of a retrograde elliptical pattern in a vertical plane parallel to the direction of wave propagation in a uniform half space. The amplitude diminishes rapidly with depth, reaching very small values at approximately 1/3 wave length below the surface. Rayleigh wave velocity, c_R, depends on c_p and c and is of the order of 5% less than shear wave velocity as shown in Fig. 2. Under the assumption of a homogeneous isotropic half space, the velocity is independent of wave length, but in nature the velocity of Rayleigh type waves generally increases with wave length. This is because c and c_p generally increase with depth, and the longer wave length surface waves penetrate more deeply.

L wave designates another surface wave, called the Love wave. This wave occurs in the presence of a low-velocity surface layer and is characterized by particle oscillation in the horizontal plane, transversely to the direction of wave propagation. The amplitude diminishes rapidly with depth below the bottom of the layer. Love waves are dispersive. Their phase velocity depends on the shear wave velocities in the layer and the underlying half space, taking the former value for short wave lengths and the latter value for long wave lengths. Their group velocity, corresponding with the propagation of a guided horizontal wave through the layer, takes the same limit values. The relationships are illustrated in Fig. 4, in which the new symbols are

ℓ	wave length
c_L	Love wave phase velocity
c_G	Love wave group velocity

Overlapping and interfering arrivals of these wave types and others, and the multiple reflections and refractions they produce in actual sites, tax the ingenuity of the designer of field measurement programs and of the interpreter of the records.

Although field measurements have repeatedly shown the usefulness of these idealized wave types, the underlying assumptions of elastic theory, a uniform half space, and a uniform layer certainly do not duplicate nature. Elastic theory usually gives good results for rocks but is only a rough approximation for soils except at small strains. Equivalent viscous or other damping should be incorporated, along with nonlinear stress-strain relationships. The uniform half space concept should be modified by considerations of decreasing void ratio and increasing confining pressure with depth, complex stratification, presence of the water table, and differences between vertical and horizontal velocities. These refinements are becoming more feasible as research in the subject proceeds, but first-approximation idealizations will always be needed in the planning and interpretation of field measurements.

Experimental Parameters

In designing a field procedure for shear-wave velocity determination, it is necessary to make a set of decisions which fall under the main headings of energy source and wave detection. These decisions are conditioned by considerations related to the character of the site and the existing knowledge of its details, the necessary geometric extent of the exploration, the accuracy required, and the availability of instrumentation and skilled personnel. Fig. 5 illustrates various approaches presently in use.

Suitable energy sources are impulsive sources such as explosions or moving masses, and sustained sources such as constant or varying vibrations. The energy may be applied at the ground surface or at some depth and may be directed so as to emphasize the propagation of a particular type of wave motion. Complex energy sources may be sued, which involve a system of synchronized explosions or vibratory inputs at more than one point, but such sources will not be treated here.

Simple near-surface explosions, falling-weight impacts, and vertical vibrations can be used effectively in many situations, particularly where it is desired to generate and measure SV or Rayleigh waves. However, shear-wave velocity measurements with surface detection are improved through impulses or vibrations directed horizontally and transversely to the direction of wave propagation measurement. Such directional sources, which accentuate SH waves and sometimes Love waves, may be achieved by horizontal firing of a special type of gun or charge, horizontal swinging of a weight, or horizontal or torsional motion of a vibrator. A vertical pipe set into the ground can be effectively used to transmit some of these inputs into the soil.

The detection of wave motion is normally done with transducers designed to measure one or more components of particle acceleration, velocity or displacement at selected points on or below the surface. The frequency range generally of interest is from 5 to 200 cps approximately. Horizontal and vertical geophones of the type normally used in exploration geophysics are suitable in most applications. Such geophones have natural frequencies ranging upward from about 3 cps and give a response proportional to particle velocity at a range of frequencies above the natural. Effective use can also be made of strain-gage type accelerometers and of displacement seismometers.

As with energy sources, the nature of shear waves points toward the desirability of detection of horizontal surface motion transverse to the direction of wave propagation for clearer Sh-wave detection. However, vertical and longitudinal measurements are often used successfully in connection with SV and Rayleigh waves.

The number and type of detectors required and their geometric configuration are determined by the site characteristics and the detailed information available thereon, the availability of open borings, and the type and directional characteristics of the enrgy source. With an impulse and the detectors located on the surface (Fig. 5a), a radial line from the source with at least 12 geophones is frequently used, the line length and number of geophones increasing with the required depth of exploration and with the complexity of the geologic formations. When the problem is adaptable to the use of steady-state vibrations on the surface (Fig. 5c), a smaller number of measurement points will suffice. Where open borings are available (Fig. 5b) it is often advantageous to have energy sources in one boring and detectors in an adjacent one, or to apply the energy at various depths in a boring with measurements made on or slightly below the surface. Sometimes the detectors are placed in the boring and the energy is applied at the surface. It may become feasible to make a continuous shear-wave velocity log of a boring, by lowering down the hole a unit containing appropriate detectors and an intermittent energy source.

The recording, processing and interpretation of detected wave motions are intimately related. Common recording paper speeds for near-surface exploration are of the order of 12 or more inches per second. Selected frequencies including some ground noise can be filtered out in the recording system or, provided the records are on magnetic tape, filtering can be done afterward to improve signal-to-noise ratio or to accentuate certain wave types. Cross correlation between input and recorded signals, and other processing techniques, based on tape recording, can be of major assistance in the interpretation of data. However, most earthquake engineering studies utilize records on photographic or direct-writing paper, with filtering, if used, incorporated into the recording system.

A variety of portable recording systems are available from manufacturers of geophysical equipment, some of which are particularly adapted to earthquake engineering type studies. Most engineering research laboratories possess amplifying and recording equipment which can be adapted for field use for this purpose.

Accuracies in field determination of shear-wave velocity in soils and near-surface rocks can be better than ±5% under the best conditions. A reasonably achievable accuracy under average conditions is about ±5% to ±10%. Accuracies within about ±25% often can be obtained by estimation based on correlation between standard soil laboratory test data and published velocity data on similar materials, which places a practical limit on the minimum acceptable accuracy of field measurements.

Serious difficulties are often encountered in field experiments. Clearly the idealized geometric arrangements will seldom be encountered. In nature one must deal with varying ground water levels, sloping interfaces, faults, continuous increase of velocity with depth, non-isotropic velocity properties, paved surfaces, undergound pipes, and rough topography. Traffic noise may interfere with the obtaining of clear records. Various techniques have been used to cope with these difficulties, which provide many challenges to the investigator.

Impulsive Seismic Methods

In the impulsive seismic approach to the measurement of shear-wave velocities in near-surface materials, use is made of the techniques diagrammed in Fig. 5a and 5b.[24-38] The impulse is provided by detonation of explosives, or by a hammer or other mechanical means, applied at or below the surface, with the impulse arrival recorded as a function of time at one or more points along a radial line from the source. One procedure is based on measuring the arrival times of direct or reflected body waves of the SH or SV type. A second procedure measures the arrival times of the surface waves, R or L, including the determination of phase velocity as a function of wave length. Another procedure (right-hand sketch of Fig. 5b) involves simultaneous measurement of the local velocities of the "tube wave" in the fluid in a boring and of the body waves in the adjacent soil or rock.

By use of the refraction method (lower sketch of Fig. 5a) one may obtain, in addition to the wave velocities, the thicknesses of layers in the zone of investigation.

Impulsive seismic methods have been extensively developed and exploited by applied geophysicists in connection with mineral exploration. A wide range of amplifying and recording equipment is available from a number of manufacturers. Most of the emphasis in the past, however, has been on the use of P-waves and surface waves, and S-wave velocity has been of only secondary interest. Also, many new problems of measurement and interpretation are involved in applying the existing technology to exploration in soil as contrasted with rock.

The body wave procedure as applied to SH waves uses an impulse directed horizontally and transverse to the line of measurement by means of a swinging weight, a directed dynamite charge, or a special type of gun. Detection is by means of geophones oriented in the same direction as the impulse. As applied to SV waves, the impulse and geophone directions are vertical; a buried vertical pipe impacted vertically at its top is an additional good type of SV source.[29] For impulses on or near the surface, the refraction method[3] is commonly used. For measurements in borings, it is normally feasible to work with direct wave arrivals.[24,28,30]

Fig. 6 shows the record obtained by the body wave procedure at a location in Hemet, California on deep, uniform relatively dry silty sand. A horizontal transverse impact was applied with a 25-pound hammer on the side of a shallow trench at a distance of 125 feet from the nearest geophones. 4.5 cps vertical geophones and 7.5 or 4.5 cps horizontal transverse geophones were placed together at points spaced 25 feet apart. The recording system filtered out frequencies above 92 cps. The record shows the time of impact and the vertical and horizontal geophone responses, respectively, as the upper six and lower six traces. Note that P-waves and SV-waves are generated even with a horizontal impact. By scaling of arrival times from the two groups of traces, one computes:

$$c_p = 700 \text{ ft./sec.}$$

$$c_{SV} = 430 \text{ ft./sec.} \qquad c_{SH} = 440 \text{ ft./sec.}$$

In this example, the recorded first arrivals of the body waves were propagated directly from source to receiver, without reflection from the lower boundary. This can be seen from the fact that there were no changes in slope from arrival to arrival of a given wave type.

The surface wave procedure utilizes a vertical surface impulse, as with SV waves, to generate Rayleigh waves in a uniform half space or a horizontal transverse impulse, as with SH waves, to generate Love waves in a low velocity surface layer. Again, geophone orientation is made to correspond with the impulse direction. For analysis, one obtains from the records the direct arrival times of the identifiable phases of the surface waves and, where dispersion is apparent, prepares graphs of phase velocity versus frequency. The S-wave velocity is then determined from the R-wave or L-wave data by means of Fig. 2 or through computations involving dispersion curves like Fig. 4.

Figs. 7 and 8 show, respectively, Rayleigh-wave and Love-wave records obtained by the surface wave procedure at a location near Lakeview, Riverside County, California on a 12-foot layer of poorly sorted relatively dry arkosic silty sand overlying 32 feet of firmer material underlain by very hard unfractured granite. The impact was applied with a 25-pound hammer at a distance of 200 feet from the nearest geophone. Geophones were spaced 8 feet apart. Their characteristics were the same as for the body wave example. The recording system filtered out frequencies above 72 cps. Amplification was set at a low value to subdue the body waves.

To study Rayleigh waves, a vertical impact was used with vertical geophones. The record in Fig. 7 clearly shows related phases on the successive traces, including the high-amplitude "Airy phase." Because there is a low-velocity surface layer, the Rayleigh waves are seen to be dispersive. The measurable phase velocities and frequencies range from approximately 1150 ft./sec. and 8 cps at the beginning of the record to approximately 280 ft./sec. and 20 cps at the end, the latter velocity corresponding with R-wave velocity on the upper layer. Then from Fig. 2, assuming $\sigma = 0.4$, the value of S-wave velocity in the silty sand becomes $c = 300$ ft./sec.

To study Love waves, a horizontal transverse impact was used with horizontal transverse geophones. The record in Fig. 8 shows the expected dispersive characteristics due to the layer. The measurable phase velocities and frequencies range from approximately 550 ft./sec. and 7 cps at the beginning of the record to approximately 270 ft./sec. and 18 cps at the end. The latter velocity, according to Fig. 4, approximates the S-wave velocity, which may be compared with the 300 ft./sec. value obtained from the Rayleigh wave study.

The tube wave procedure[37] is still in an early stage of development, but it seems to hold promise for earthquake engineering applications. In this method, an energy source and a receiver are located along a boring filled with water or drilling fluid. See Fig. 5b. Measurement of velocity parallel to the boring, both through the rock or soil and through the fluid, enables computation of shear-wave velocity. Wave velocity in the fluid is affected by lateral expansion of the boring hole as the wave propagates along the boring. With an appropriately designed logging device, it should be possible to obtain continuous S-wave velocity logs of borings by this method, as is commonly done in oil well surveys for P waves.

Sustained Source Methods

The sustained source approach to measuring shear wave velocities utilizes a mechanical or an electromagnetic vibrator placed on or below the ground surface, with signals recorded at the vibrator base and at various points on or below the surface.[39-57] See Fig. 5c. One procedure is based on the determination of resonant frequencies of the vibrator-ground system. Another procedure is based on measurement of the wave length of surface waves at various frequencies, using two or more seismometers on a radial line through the vibrator. A third procedure utilizes cross correlation between the detected record and the input signal, the latter being swept through a range of frequencies.

The resonant frequency and surface wave methods are geometrically limited, theoretically, by the elastic half space assumption. The former should yield shear wave velocities reflecting the soil characteristics to a depth of perhaps three times the vibrator footing diameter. Larger vibrators will tend to emit waves that penetrate deeper, reflecting in their resonant frequency the usually higher velocities of deeper strata. In the surface wave method, the nature of surface waves limits the effective penetration depth to perhaps 1/3 the wave length with Rayleigh waves and to the thickness of the layer with Love waves. Sometimes these limitations can be eased by working in large open excavations, or using large wave lengths or large vibrators. Nonetheless these methods provide valuable information for many earthquake engineering applications, for often it is the near surface materials that present the greatest dynamic problems.

The resonant frequency procedure is based on theories and experiments in the field of soil-structure interaction, in which a considerable amount of work has been done in the past few years.[39,42,48,51,52,54-57] While in principle the best results could be obtained with torsional or horizontal vibrations, most of the relevant experimental and theoretical work to date has been done with vertical vibrations, so that the latter will be used in the present discussion.

In conducting a measurement, a vertical-motion vibrator is mounted securely on a circular base which is firmly seated on the soil surface. An accelerometer, a geophone or a displacement transducer is attached to the base so as to sense its vertical vibration. The test is subject to an acceleration limitation of approximately ± 0.5 gravity, to prevent separation or excessive stress between the oscillating system and the soil. The vibrator is actuated through a range of frequencies and the fundamental (lowest resonant) frequency and corresponding amplitude are determined from the response transducer. If feasible, the test should be repeated at various peak levels of the exciting force.

Computation of shear wave velocity in the assumed uniform half space under the vibrator may be made with the aid of Fig. 9 using the appropriate curves for either the constant force electromagnetic or the rotating mass mechanical vibrator, and assuming a rigid base.[52] Other soil pressure distributions on the base may be used where justified. The symbols not previously defined are as follows:

$a = \frac{\omega r}{c}$ frequency factor

$b = \frac{m}{\rho r^3}$ mass ratio

$A_m = \frac{\omega^2 \rho r^3}{F} U$ amplitude factor for mechanical oscillator

$A_e = \frac{c^2 \rho r}{F} U$ amplitude factor for electromagnetic oscillator

ω = resonant circular frequency

F resonant amplitude of vibrator force

U resonant amplitude of base displacement

One may enter the upper graph of Fig. 9 with b and an estimated σ and determine a, from which c may be computed. The lower graph may be entered to obtain A_m or A_e, from which U may be computed. Comparison of the measured and computed values of U provides a check on the measurements and on the assumption of σ.

As an example, consider the results of a test made with a mechanical vibrator at a site near Saugus, California, consisting of a 19-foot layer of relatively dry sandy soil overlying a slightly more firm alluvium. The data were as follows:

$mg = 3280$ lb.

$r = 2.00$ ft.

$\rho g = 110$ lb./cu. ft.

$F = 592$ lb.

$\sigma = 0.42$ (estimated)

$\frac{\omega}{2\pi} = 35$ cps

From Fig. 9, one obtains a = 1.43 (with a slight extrapolation) and $A_m = 0.24$, whence the computed results are:

$c = 310$ ft./sec. $U = 0.00045$ ft.

The footing displacement amplitude was measured only qualitatively, to establish the resonant frequency, and thus a check against the computed U was not possible. The velocity value is low compared with other measurements at the site, possibly due to the relatively higher strain level in this as compared with the other measurements.

The surface wave procedure is based on the generation and observation of Rayleigh waves due to vertical vibrator action or of Love waves due to horizontal vibrational input transversely to the line of measurement.[42,48-50] While some work has been done with horizontal vibration, the present paper will consider only the more extensively utilized vertical vibration.

The theory of the method is very simple, involving direct measurement of Rayleigh wave velocity on the surface and the computation therefrom of shear wave velocity by means of Fig. 2. A strong theoretical point favoring the method is the fact that approximately 2/3 of the vibrator power is radiated as a surface wave.[13] Thus, since the body waves produced by the vibrator are largely radiated into the half space, the vibrations detected on the surface are almost purely Rayleigh waves. On the other hand, real-earth deviations from the theoretical conditions cause the Rayleigh waves to increase in velocity with wave length. This makes it necessary to work with the shorter wave lengths which then yield the characteristic velocity of the near-surface material.

An example of an actual test, conducted at the Saugus, California, site, will illustrate the method. An electromagnetic vibrator weighing 46 pounds with its 0.5 square foot base and having a frequency-independent vertical force amplitude of approximately 5 pounds was seated on the ground surface. A vertical geophone was placed on the surface next to the vibrator, and a second 10 feet away, and the vibrator was actuated at a frequency of 50 cps. A third geophone was placed a few feet from the second on a radial line from the vibrator, and a record was made on the geophysical camera to ascertain the phase relationship of the second and third phones. The third phone was then moved out until the records written by the two were in phase, indicating that the geophones were one wave length apart, and the distance between them was measured to be 8.0 feet. As a check, a fourth geophone was placed 16 feet out from the third, and all three phones wrote in-phase records, as shown in Fig. 10. As a further check, the vibrator frequency was set at 25 and 100 cps, resulting in 180° out-of-phase and in-phase records, respectively. Apparently the Rayleigh waves were not dispersive within the range of test conditions. The computation is simply

$$c_R = \frac{\omega}{2\pi} \ell$$

whence, for the example, $c_R = 400$ ft./sec. Taking $\sigma = 0.42$, $c = 420$ ft./sec. from Fig. 2. This value may be compared with the 310 ft./sec. obtained from the resonance experiment and 415 ft./sec. obtained from refraction measurements with impulsive sources.

Some comments should be made on the example. Substantially greater accuracy can be had through recording of phase relationships at different distances with an "x-y" oscilloscope. Field procedures are accelerated by using fixed geophone distances and varying the frequency. Often it is desirable to continue the measurements out to a distance of several wave lengths. The double peaks on some of the curves in Fig. 10 could be due to improper seating of the geophones or the vibrator.

The cross correlation procedure is based on the use of a sinusoidal SH-wave signal of a few seconds duration with frequency varying continuously from a lower to an upper limit, as illustrated in Fig. 11a.[43-45,53] The signal is provided by a horizontally oscillating surface vibrator, and wide-band horizontal geophone responses are recorded at selected locations on magnetic tape. Cross correlations are obtained by analog computer between input signal and geophone responses, incorporating a range of delay times. The resultant record is a set of traces, Fig. 11b, called crosscorrelograms, which resemble refraction or reflection records from standard geophysical work but accentuate the events of the seismogram, particularly the SH-wave-related events.

This method was pioneered by the Continental Oil Co., which offers exploration services of this type with a system called Vibroseis. This system uses a very heavy truck-mounted horizontal servohydraulic vibrator, a large array of 8 cps horizontal geophones recording on magnetic tape, a frequency sweep of the order of 8 to 80 cps, and has been used successfully in explorations down to 10,000 feet.

While the method has not been applied so far as is known in earthquake engineering problems, it should prove useful for such problems because of the large force available and the predeominantly SH-wave input and response. Probably smaller scale equipment could be adapted to smaller scale problems. It would be interesting to experiment with this approach using both steady-state and pseudo-random vibration inputs.

Closure

It is vital to the progress of earthquake engineering that acceptable methods of determination of shear-wave velocity in near-surface materials be developed. The paper has presented the current state of the art of field methods for this purpose. The relative advantages of field and laboratory methods suggest that both should be used whenever feasible.

Substantial progress has been made with impulsive seismic field methods through transfer of the technology of seismic geophysical exploration. Further development is needed with special attention to shear waves and surface waves, relatively smaller geometrical dimensions, effects of water table, and the characteristics of soil as contrasted with rock. Some work has been done with sustained source seismic field methods, which show considerable promise for future development and application, particularly for measurements in the upper strata. Greater space herein has been given to the latter methods because of their relative novelty.

Subject to the limitations described in the paper, several variations of these two classes of field technique can be employed to obtain useful results. It is always necessary, however, to give attention to the fact that shear-wave velocity will probably be lower under earthquake strain levels than under the smaller strain levels usually involved in seismic exploration. A great deal of professional skill and ingenuity are required, even with the best of instrumentation, to obtain valid measurements under conditions involving traffic noise, complex geology, fluctuating ground water level, anisotropy of materials, or the presence of buildings, pavement and pipes. Such skill can be acquired through training and experience, but its acquisition is not easy.

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References

General and Theoretical

1. Cherry, J.T., "The Azimuthal and Polar Radiation Patterns Obtained from a Horizontal Stress Applied at the Surface of an Elastic Half Space," Bull. Seis. Soc. Am., v 52, no. 1, 1962.
2. Clough, R.W. and A.K. Chopra, "Earthquake Stress Analysis in Earth Dams," Jour. Engr. Mech. Div. ASCE, v 92, no. EM 2, Apr. 1966, pp 197-211.
3. Dobrin, Milton B., "Introduction to Geophysical Prospecting," McGraw-Hill, 1960.
4. Ewing, W.M., W.S. Jardetzky and F. Press, "Elastic Waves in Layered Media," McGraw-Hill, 1957.
5. Grant, F.S. and G.F. West, "Interpretation Theory in Applied Geophysics," McGraw-Hill, 1965.
6. Heiland, C.A., "Geophysical Exploration," Hafner Publishing Co., New York, 1963.
7. Kanai, K., "The Requisite Conditions for the Predominant Vibration of Ground," Bull. Earthq. Res. Inst., v 35, 1957, pp 457-472.
8. Kanai, K., "On the Group Velocity of Dispersive Surface Waves," Bull. Earthqu. Res. Inst., v 29, 1951, pp 49-60.
9. Knopoff, L., "On Rayleigh Wave Velocities," Bull. Seis. Soc. Amer., v 42, 1952, pp 307-308.
10. Kolsky, H., "Stress Waves in Solids," Dover, New York, 1963.
11. Leet, L. Don, "Earth Waves," Harvard University Press, 1950.
12. Matthiesen, R.B. and C.M. Duke, "Earthquake Amplification Spectra Obtained from Site Conditions," Bull. Seis. Soc. Amer. (submitted).
13. Miller, G.F. and H. Pursey, "On the Partition of Energy Between Elastic Waves in a Semi-infinite Solid," Proc. Royal Society, v 233, 1955, pp 55-69.
14. Stoneley, R., "The Continental Layers of Europe," Bull. Seis. Soc. Amer., v 38, 1948, pp 263-274.
15. White, J.E., "Seismic Waves," McGraw-Hill, 1965.

Laboratory Measurements

16. Hardin, B.O. and W.L. Black, "Vibration Modulus of Normally Consolidated Clay," Jour. Soil Mech. and Fndns. Div. ASCE, v 94, no. SM2, Mar. 1968, pp 353-369.
17. Hardin, B.O., "Dynamic vs Static Shear Modulus for Dry Sand," Am. Soc. Test. Matls. Materials Research and Standards, May 1965.
18. Hardin, B.O. and F.E. Richart, Jr., "Elastic Wave Velocities in Granular Soils," Jour. Soil Mech. Fndn. Div. ASCE, v 89, no. SM1, Feb. 1963, pp 33-65.

19. Hardin, B.O. and W.L. Black, "Sand Stiffness under Various Triaxial Stresses," Jour. Soil Mech. Fndn. Div. ASCE, v 92, no. SM2, Mar. 1966, pp 27-42.

20. Humphries, W.K. and H.E. Wahls, "Stress History Effects on Dynamic Modulus of Clay," Jour. Soil Mech. Fndns. Div. ASCE, v 94, no. SM2, Mar. 1968, pp 371-389.

21. Ishimoto, M. and K. Iida, "Determination of Elastic Constants of Soils by Means of Vibration Methods," Bull. Earthq. Res. Inst., v 14 (1936), pp 632-657; v 15 (1937), pp 67-86; v 16 (1938), pp 131-144, 391-406; v 18 (1940); pp 675-691.

22. Lawrence, F.V. Jr., "Ultrasonic Shear Wave Velocities in Sand and Clay," Report R65-05, Dept. of C.E., Mass. Inst. of Tech., to Waterways Experiment Station. 1965.

23. Wilson, Stanley D. and Ernest A. Kaarsberg, "Vibration Apparatus for Determination of Elastic Properties of Soil," Rock Mechanics and Engineering Geology, Springer-Verlag, v IV/1, 1966, pp 14-24.

<u>Impulsive Source Methods</u>

24. Figueroa, A.J., "Determinación de las Velocidades de Propagación y Constantes Elásticas por Prospección Sísmica," Bol. Soc. Mex. de Ing. Sism., 1964.

25. Jolly, R.N., "Investigation of Shear Waves," Geophysics, v 21, no. 4, Oct. 1956, pp 905-938.

26. Kawasumi, H., E. Shima, Y. Ohta, M. Yanagisawa, A. Allam, K. Miyokawa, "S Wave Velocities of Subsoil Layers in Tokyo. 1," (In Japanese) Bull. Earthq. Res. Inst., v 44 (1966), pp 731-747.

27. Kisslinger, C., E.J. Mateker and T.V. McEvilly, "SH Motions from Explosions in Soil," Jour. Geophys. Res., v 66, 1961, pp 3487-3496.

28. Meinardus, H. and C. Valdenegro, "Velocidades de Ondas Sismicas y Constantes Elásticas en los Sedimentos del Subsuelo de Concepción," Department of Geophysics and Geodesy, Univ. of Chile, Dec. 1967.

29. Ohta, Yutaka and Etsuzo Shima, "Experimental Study on Generation and Propagation of S-waves: II. Preliminary Experiments on Generation of SV-waves," Bull. Earthq. Res. Inst., v 45 (1967), pp 33-42.

30. Poblete, Mauricio, "El Subsuelo del Centro de Concepcion en relación con el Diseño Antisísmico," Thesis for the Title of Civil Engineer, Univ. of Chile, 1967.

31. Shima, Etsuzo, "Vibration Problems of Subsoil Layers," Proc. Japan National Symp. on Earthq. Engr., 1966, Tokyo, pp 437-445. (In Japanese).

32. Shima, Etsuzo and Yutaka Ohta, "Experimental Study on Generation and Propagation of S-waves: I. Designing of SH-wave Generator and Its Field Tests," Bull. Earthq. Rest. Inst., v 45 (1967) pp 19-32.

33. Swain, R.J., "Recent Techniques for Determination of InSitu Elastic Properties and Measurement of Motion Amplification in Layered Media," Geophysics, v 28, 1962, pp 237-421.

34. "In Situ Determination of Elastic Parameters," United Electrodynamics Inc., ESD-049, Oct. 20, 1964.

35. Whitcomb, James H., "Shear-Wave Detection in Near-Surface Seismic Refraction Studies," Geophysics, v 31, Oct. 1966, pp 981-983.

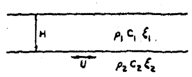
36. White, J.E., S.N. Heaps and P.L. Lawrence, "Seismic Waves from a Horizontal Source," Geophysics, v 21, 1956, pp 715-723.

37. White, J.E. and R.L. Sengbush, "Shear Waves from Explosive Sources," Geophysics, v 28, Dec. 1963, pp 1001-1019.

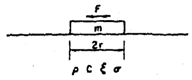
38. Wright, J.K. and E.W. Carpenter, "Generation of Horizontally Polarized Shear Waves by Underground Explosions," Jour. Geophys. Res., v 67, no. 5, May 1962, pp 1957-1963.

Sustained Source Methods

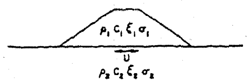
39. Arnold, R.N., G.N. Bycroft and G.B. Warburton, "Forced Vibration of a Body on an Infinite Elastic Solid," Jour. Appl. Mech., v 77, no. 3, Sept. 1955, pp 391-400.
40. Barkan, D.D., "Dynamics of Bases and Foundations," McGraw-Hill, 1962.
41. Bergstrom, S.G. and S. Linderholm, "A Dynamic Method for Determining Average Elastic Properties of Surface Soil Layers," Swedish Cement and Conc. Res. Inst., Royal Tech. Univ., Stockholm, 1946.
42. Bernhard, R.K., "On Determination of Dynamic Characteristics of Soil in Situ," Spec. Tech. Publ. 254, Am. Soc. Testing Matls., 1959, pp 327-339.
43. Cherry, J.T. and K.H. Waters, "Shear-Wave Recording Using Continuous Signal Methods, Part I - Early Development," Geophysics, v 33, no. 2 (April 1968) pp 229-239.
44. Crawford, John M., William E. Doty and Milford R. Lee, "Continuous Signal Seismograph," Geophysics, v 25, no. 1, Feb. 1960, pp 95-105.
45. Erickson, E.L., D.E. Miller and K.H. Waters, "Shear-Wave Recording Using Continuous Signal Methods. Part II - Later Experimentation," Geophysics, v 33, no. 2 (April 1968) pp 240-254.
46. Evison, F.F., "The Seismic Determination of Young's Modulus and Poisson's Ratio in Situ," Geotechnique, v VI, no. 3, Sept. 1956, pp 118-123.
47. Howell, L.G., C.H. Kean and R.R. Thompson, "Propagation of Elastic Waves in the Earth," Geophysics, v 5, no. 1, Jan. 1940, pp 1-14.
48. Jones, Ronald, "In Situ Measurements of the Dynamic Properties of Soil by Vibration Methods," Geotechnique, v VIII, no. 1, Mar. 1958, pp 1-21.
49. Kanai, K., "An Explanation for the Ground Vibration Caused by Periodically Exerted Force," Bull. Earthq. Res. Inst., v 33, Sept. 1955, pp 283-286.
50. Maxwell, A.A. and Z.B. Fry, "A Procedure for Determining Elastic Moduli of In Situ Soils by Dynamic Techniques," Symposium on Wave Propagation and Dynamic Properties of Earth Materials, Univ. of New Mexico, Albuquerque, N.M., June 1967.
51. Richart, F.E. Jr., and R.V. Whitman, "Comparison of Footing Vibration Tests with Theory," Jour. Soil Mech. Fndns, Div. ASCE, v 93, No. SM6, Nov. 1967, pp 143-168.
52. Richard, F.E. Jr., "Foundation Vibrations," Transactions ASCE, v 127, part I, 1962, pp 863-898.
53. "An Introduction to Vibroseis," Seismograph Service Corp., Tulsa, Oklahoma.
54. Sung, T.Y., "Vibrations in Semi-Infinite Solids Due to Periodic Surface Loading," Spec. Publ. 156, Am. Soc. Testing Matls., Symposium on Dynamic Testing of Soils, 1953, pp 35-64.
55. Thomson, W.T., "A Survey of the Coupled Ground-Building Vibrations," Proc. 2nd World Conf. Earthq. Engr., Tokyo, 1960, pp 833-847.
56. Warburton, G.B., "Forced Vibration of a Body upon an Elastic Stratum," Jour. Appl. Mech., v 24, 1957, pp 55-58.
57. Whitman, R.V. and F.E. Richart, Jr., "Design Procedures For Dynamically Loaded Foundations," Jour. Soil Mech. Fndns. Div. ASCE, v 93, no. SM6, Nov. 1967, pp 169-193.



(a) EARTHQUAKE RESPONSE OF A SOIL LAYER ON A HALF SPACE



(b) DYNAMIC COMPLIANCE OF A CIRCULAR FOOTING ON A HALF SPACE



(c) EARTHQUAKE RESPONSE OF AN EARTH DAM ON A HALF SPACE

FIGURE I. ILLUSTRATIONS OF THE USE OF SHEAR WAVE VELOCITY.

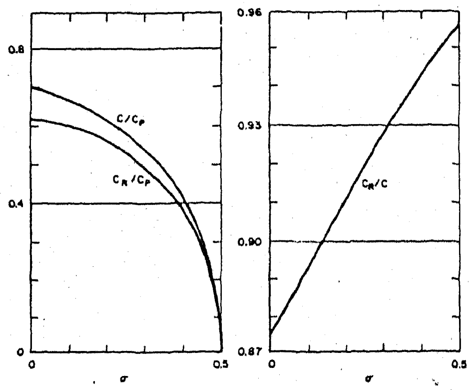


FIGURE 2. EFFECT OF POISSON'S RATIO ON THE RELATIONSHIPS AMONG COMPRESSIONAL, SHEAR AND RAYLEIGH WAVE VELOCITIES. (AFTER KNOPOFF 1952.)

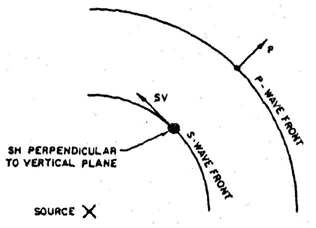


FIGURE 3. VERTICAL PLANE ILLUSTRATING DIRECTIONS OF PARTICLE VIBRATION IN BODY WAVES

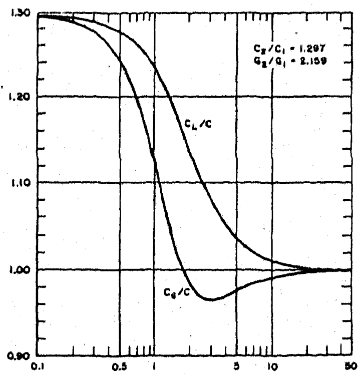
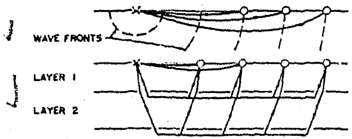
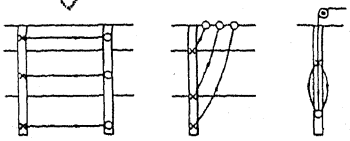


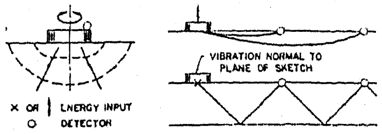
FIGURE 4. TYPICAL DISPERSION CURVES OF FIRST MODE LOVE WAVE PHASE AND GROUP VELOCITIES. (AFTER STONELEY 1948.)



a) IMPULSE ON OR NEAR SURFACE



b) IMPULSE OR VIBRATOR AT DEPTH



c) VIBRATOR ON SURFACE.

FIGURE 5. VARIOUS APPROACHES TO SHEAR WAVE VELOCITY DETERMINATION

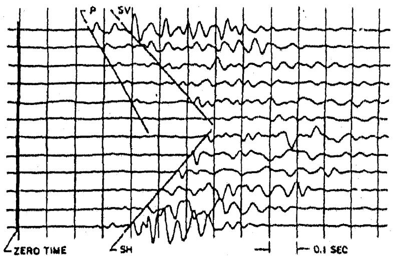


FIGURE 6. BODY WAVES DUE TO HORIZONTAL TRANSVERSE IMPULSE. (RECORDED BY JOHN D. FETT.)

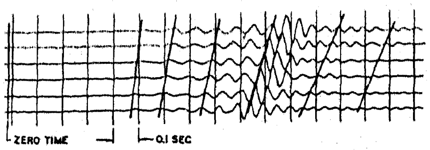


FIGURE 7. RAYLEIGH WAVES DUE TO VERTICAL IMPULSE. (RECORDED BY JOHN D. FETT.)

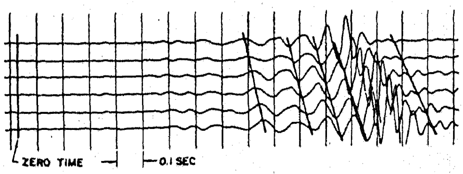


FIGURE 8. LOVE WAVES DUE TO HORIZONTAL TRANSVERSE IMPULSE. (RECORDED BY JOHN D. FETT.)

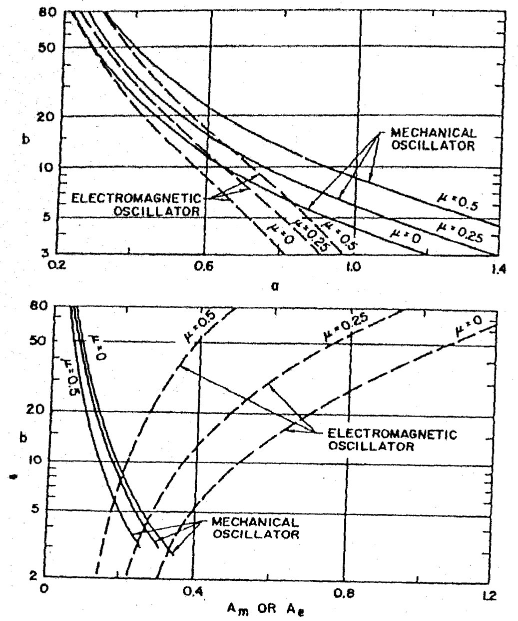


FIGURE 9. COMPUTATIONAL PARAMETERS FOR VERTICAL VIBRATOR ON RIGID BASE ON ELASTIC HALF SPACE. (AFTER RICHART 1962.)

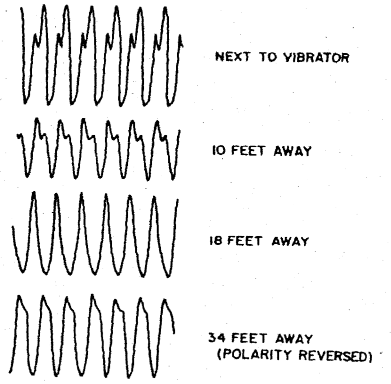
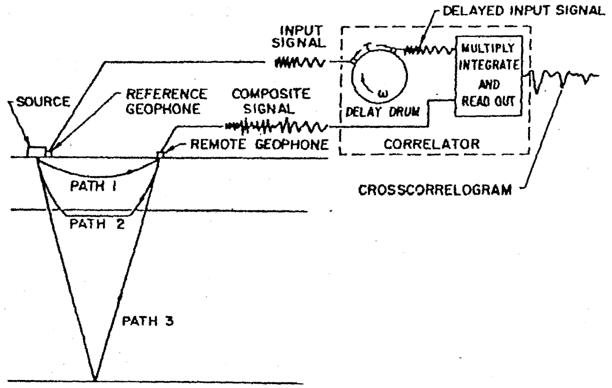
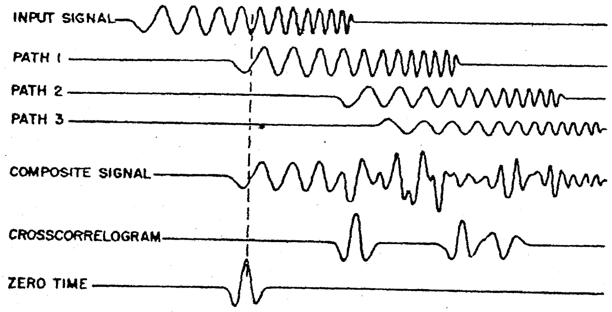


FIGURE 10. SAMPLE RECORD FOR SURFACE WAVE METHOD.



a) SYSTEM OF INSTRUMENTATION AND ANALYSIS



b) IDEALIZATION OF SIGNALS AND RECORDS

FIGURE 11. FEATURES OF THE CROSS CORRELATION METHOD. (AFTER CRAWFORD, DOTY AND LEE 1960.)