

DETERMINATION OF DYNAMIC SOIL PROPERTIES USING GEOPHYSICAL METHODS

Ronaldo Luna and Houda Jadi

Department of Civil Engineering, University of Missouri-Rolla,
Rolla MO, 65409; rluna@umr.edu and hjadi@umr.edu

OVERVIEW

The analysis of foundation vibrations and geotechnical earthquake engineering problems in civil engineering requires characterization of dynamic soil properties using geophysical methods. Dynamic structural analysis of the superstructures also requires knowledge of the dynamic response of the soil-structure, which, in turn relies on dynamics soil properties. Machine vibrations, blasting and seismic events are examples of the type of dynamic input that engineered systems may be subjected to. Geophysical methods are often used to characterize the dynamic soil properties of the subsurface. Field methods discussed in this section will focus on the low-strain tests that are not large enough to induce significant non-linear, non-elastic stress strain behavior, they include: seismic refraction and reflection, suspension logging, steady-state vibration, down-hole, seismic cross-hole, spectral analysis of surface waves, and seismic CPT. Some reference is made of other non-geophysical tests used in geotechnical earthquake engineering that focus on the large-strain response of soils.

INTRODUCTION

The response of soils to cyclic loading is controlled mostly by the mechanical properties of the soil. There are several types of geotechnical engineering problems associated with dynamic loading, some examples include: wave propagation, machine vibrations, seismic loading, liquefaction and cyclic transient loading, etc. The mechanical properties associated with dynamic loading are shear wave velocity (V_s), shear modulus (G), damping ratio (D), and Poisson's ratio (ν). The customary name for these properties is "dynamic soil properties"; even though they are also used in many non-dynamic type of problems. The engineering problems governed by wave propagation effects induce low levels of strain in the soil mass. On the other hand, when soils are subjected to dynamic loading that may cause a stability problem then; large strains are induced.

The selection of the appropriate testing method used for engineering problems needs careful consideration and understanding of the associated level of strain. There are a variety of laboratory and field methods that measure the low- and high-strain soil behavior. This paper addresses the methods that are based on geophysics that for the most part encompass the low-strain properties or wave propagation type problems.

FUNDAMENTAL CONCEPTS

All tests or test procedures that characterize soil behavior need to apply the initial stress conditions and anticipate cyclic loading as best as possible. Field or in-situ tests have the advantage that the state of stress is inherently included in the procedure. However, laboratory tests need to confine and consolidate the soil sample back to the state of stress to replicate field conditions. The geophysical field tests have the advantage of testing undisturbed soil in the actual field condition with the actual effective stress and drainage conditions. Additionally, what is being tested is a volume or average condition of the material between the source and receiver.

Dynamic soil properties also require an active source of energy to excite the soil mass and/or induce a measurable wave. Geophysical tests propagate seismic waves through soil at a very low strain level (less than 10^{-3} percent), making practically impossible the measurement of strain. This low level of strain allows the use of elastic theory to associate measurements with mechanical properties and for the most part the response is linear. At intermediate levels of strain ($\sim 10^{-2}$ percent) this response starts becoming non-linear. At large strains ($\sim 10^{-1}$ to 5 percent) the dynamic behavior of soils remains non-linear and will begin experiencing permanent deformation (plastic) and eventually reach an unstable condition. For intermediate and large strains geophysical properties are not applicable anymore and specialized

laboratory soil tests such as cyclic triaxial shear tests are used. In summary, dynamic soil properties are strain-dependant and one of the challenges is having compatibility in the results of the different methods when the strain level overlaps.

The hysteresis loop produced from the cyclic loading of a typical soil can be described by the path of the loop itself or by two parameters that describe its general shape. These parameters are the inclination and the breath of the hysteresis loop; shear modulus and damping, respectively. Figure 1 is a simplified schematic showing one loop of symmetric cyclic loading and its corresponding parameters.

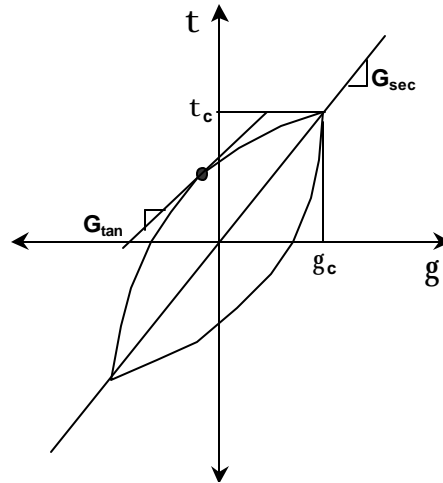


Figure 1 - Hysteresis Loop Showing Secant and Tangent Shear Modulus

As the strain amplitude is varied, different size loops will be developed and the locus of the points corresponding to the tips of these loops is called the backbone curve (or skeleton). As the strain increases the secant shear modulus will decrease. Therefore, the maximum shear modulus is developed at low shear strain where geophysical tests are used. Another way to represent this shear modulus degradation with cyclic strain is by means of the modulus reduction curve. The modulus reduction curve normalizes the shear modulus (G) with respect of the maximum shear modulus (G_{max}) and is commonly referred to as the modulus ratio. Figure 2 shows a schematic of the typical cyclic behavior of soils. As the soil element loses stiffness with the amplitude of strain, its ability to dampen dynamic forces increases. This is due to the energy dissipated in the soil by friction, heat or plastic yielding. The relationship of shear strain to damping is inversely proportional to the modulus reduction curve. Damping is often expressed as the damping ratio (D), which is defined as the damping coefficient divided by the critical damping coefficient. D can be obtained from the hysteresis loop by dividing the area of the loop by the triangle defined by the secant modulus and the maximum strain (energy dissipated in one cycle by the peak energy during a cycle) multiplying with a factor of $1/4\pi$. Values less than one are underdamped, equal to one are critically damped and greater than one are overdamped. Most problems in earthquake engineering are cases that are underdamped. Damping ratio represents the ability of a material to dissipate dynamic load or dampen the system. It should be noted that many factors contribute to the stiffness of soils during cyclic loading, such as, plasticity index, relative density, mean principal effective stress, overconsolidation ratio, number of loading cycles and void ratio. However, for low-strain dynamic behavior in geophysical tests, the shear modulus in that range remains constant as G_{max} and is commonly used as an elastic parameter.

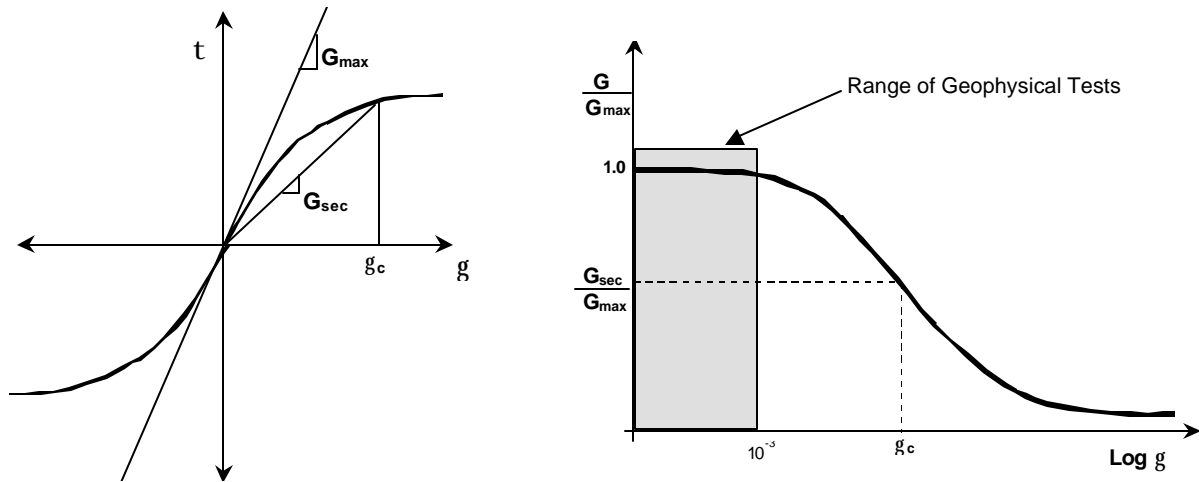


Figure 2 - Stress-strain curve with variation of shear modulus and modulus reduction curve.

The stress strain behavior of cyclically loaded soils is complex and geotechnical engineers are challenged by the need to characterize this behavior with accurate and simple models. The balance between accuracy and simplicity depends on many factors and several combinations have been proposed. For geophysical methods that induce low-strain ($<10^{-3}$ %) the soil models are based on *equivalent linear model*. These models are the simplest and most commonly used in dynamics, but they have a limited ability to represent many aspects of soil behavior under cyclic loading conditions.

Most seismic geophysical methods or tests induce shear strains lower than 10^{-4} % and the shear wave velocity (V_s) can be used to compute the G_{max} using the expression $G_{max} = \rho \cdot V_s^2$, where ρ is the mass density of the soil. The measured shear wave velocity is generally considered the most reliable means to obtain the G_{max} for a soil deposit. These methods involve the creation of a transient and/or steady-state stress waves (source) and the interpretation of the arrival time and spectral response at one or more locations (receivers). The generation of the impulse wave by the source can vary from a sledgehammer blow at ground surface, to a buried explosive charge or to an active varied frequency source vibrator. Figure 3 shows different methods for creation of impulse waves. These sources generate P-waves, S-waves and surface waves at different relative amplitudes depending of the dominant wave in the method used.

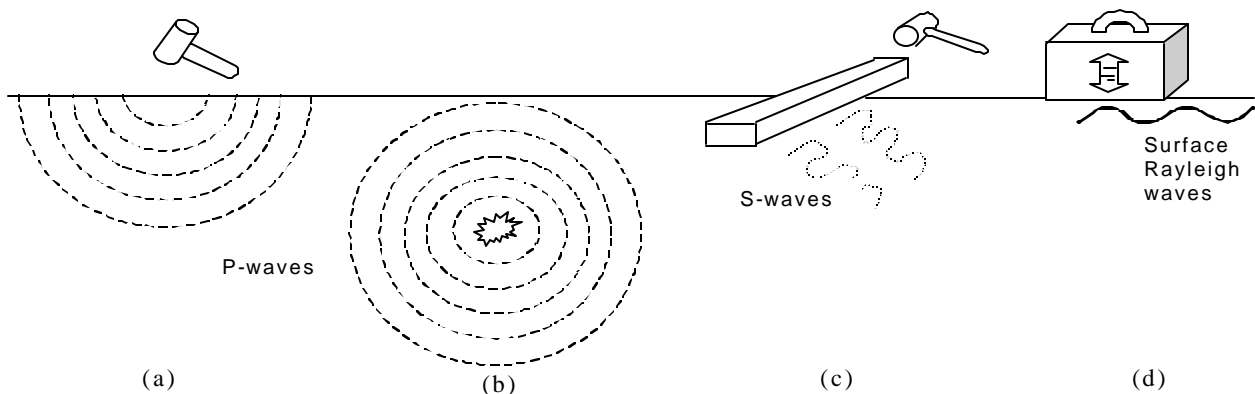


Figure 3 - Methods To Create Impulse Waves (a) Vertical Impact, (b) Shallow Explosive, (c) Horizontal Impact, And (d) Frequency-Controlled Surface Waves.
(Adapted from Kramer 1996).

Vertical impact and shallow explosives are very effective in creating P-waves and will dominate the wave content. The horizontal sledgehammer used on a horizontal wood member in contact with the ground is good at generating s-waves, which have a particle motion perpendicular to the direction of wave propagation. The frequency-controlled vertical loading can generate different frequency content waves and with the aid of dispersion curves and the spectral analysis of surface waves (SASW) can characterize the subsurface using geophysics.

Groundwater conditions need to be taken into account for the proper interpretation of seismic geophysical tests. P-waves travel at approximately 5,000 ft/sec and in the presence of soft saturated soil deposits the wave will still travel at this speed even though the velocity is not indicative of the soil skeleton stiffness. Therefore, it is customary to use S-waves, which are propagated by the soil skeleton and not the fluid. Another aspect to take into consideration is the anisotropic stress conditions that may cause the measured shear wave velocities to vary with the direction of wave propagation and particle movement (Roesler, 1979; Stokoe, et al., 1985 and Yan and Byrne, 1991).

UTILITY OF MEASURED PARAMETER

Shear wave velocity (V_s) is the most commonly used measured parameter used in shallow soil geophysics for soil characterization. It is used to calculate the following parameters in the elastic range of soil behavior. The importance in its utility is that the particle of motion travels perpendicular to the direction of wave propagation being able to measure the shear properties of the soil skeleton and not the fluids that cannot take shear.

Shear Modulus (G) is a calculated parameter based on the V_s using the simple elastic relationship $G_{\max} = \rho \cdot V_s^2$. The mass density is often estimated or measured by a nearby subsurface sampling or using correlations. Advanced correlations to estimate the value of the dynamic shear modulus are available based on the standard penetration test, Atterberg Limits (plasticity index) and grain size distributions (Vucetic and Dobry, 1991, Idriss, et al., 1980). The shear modulus is used to perform more advanced soil modeling, and dynamic response of the soil-structure interactions. Shear modulus at low-strain levels as measured by geophysical techniques will provide the elastic parameter for machine foundation analysis or earthquake engineering. The important utility of this parameter is that it can be used as a varying parameter with respect to strain making the soil response represent the real modulus degradation in soil behavior. This parameter is used in defining the stiffness matrices for finite element analysis of earth structures and foundation soils.

Maximum Shear Modulus (G_{\max}) is used to normalize the shear modulus (G) versus shear strain relationships. These normalized relationships allow the engineer to use well-established degradation curves and scale them to the measured in-situ value of G_{\max} . For example, the classic relationships of the shear moduli for cohesionless and cohesive soils are provided in Seed, et al., (1984) and Sun, et al., (1988). In the absence of extensive dynamic soil testing at all ranges of shear strain these curves are used and G_{\max} is used as the scaling parameter.

Damping Ratio (D) is used in several dynamic analysis procedures to provide a realistic motion attenuation. This ratio is based on the material damping properties. The damping ratio vs. shear strain relationships for cohesionless and cohesive soils are provided in Seed, et al., (1984) and Sun, et al., (1988). Since damping ratio is also shear strain dependent, it is required to have several values with strain. Dynamic analysis results are also influenced by the damping ratio for single and multi degree modal systems. The effects of soil-structure interaction also influence the damping of the system making it an area where recent research has focused. The utility of this parameter is based on the ability of the system to absorb dynamic energy and how this will affect the duration and modes of vibration.

Poisson's Ratio (ν) is a fundamental parameter that is difficult to measure and it is usually estimated in engineering calculations. The ratio of horizontal to vertical strain is required to relate moduli and strains in a solid body. A suggested range of values for Poisson's ratio for soils is from 0.2 to 0.5, less common values may be as low as 0.1 for loess deposits and unsaturated clays. This ratio can be calculated $[\nu =$

(E/2G)-1] based on laboratory tests at low strains if G and E are obtained from torsional and longitudinal vibration, respectively. Poisson's ratio can also be directly calculated based on V_c and V_s , if measured by manipulating the above formulae: $[v = (2 - V_c^2 / V_s^2) / 2(1 - V_c^2 / V_s^2)]$.

SUMMARY OF GEOTECHNICAL APPROACHES TO DETERMINE DYNAMIC SOILS PROPERTIES

Geophysical methods have been used for many years by engineers in soils and foundation applications. Geophysics not only provides means to probe the properties of soils, sediments and rock outcrops, but are also used to determine dynamic properties of soils, particularly the soil's compression and shear wave velocities, as well as the soil's elastic and shear moduli. These properties are key parameters in predicting the response of soils and soil-structure systems to dynamic loading. The geophysical methods used in determining dynamic properties of soils are mainly field or in-situ tests based on measurement of velocities of waves propagating through the soil. The most common tests used for such purposes are presented subsequently.

Seismic Refraction

The seismic refraction method is well suited for general site investigations for soil dynamics and earthquake engineering purposes. This technique provides for the determination of elastic wave velocities of a layered soil profile. Wave velocities and thickness of each layer are determined as long as the wave velocities increase with each successively deeper layer. The test aims to accurately measure the arrival-times of the seismic body waves, which consists of Compression P and shear S waves, produced by a near-surface seismic source. The source travels through the soil to a linear array of detectors placed at the ground surface. Compression P-waves arrive at a receiver faster than shear S-waves, thus obscuring the arrival of the latter waves i.e. the S-waves. Therefore the P-waves have been widely used in seismic refraction tests (Woods, 1978; Whiteley, 1994). However, in most dynamic soils problems, the shear wave velocity and shear moduli are the most important properties of the soils. As such, direct measurement of the shear wave velocities, by using a rich source of shearing energy that is able to propagate over long distances, is in advantage for geotechnical earthquake engineering problems. In addition, P-wave velocities at or below the water table depend on the degree of saturation of the soil, whereas the S-wave velocities are independent (Woods, 1978).

One way to generate a rich source of shear energy was described by Kobayashi (1959). This method consists of spiking a plank to the ground and striking it with a hammer after weighing it. This will generate a pure surface traction, and a compression P-wave and shear waves of two polarities; vertical (SV-wave) and horizontal (SH-wave) are generated by this source. A nearly pure SH-wave propagates in a direction perpendicular to the axis of the source. Some other known SH-wave sources are the Explosive Recoil SH-wave device, which was developed by Jolly (1956), and the Hoar and Stokoe (1977) "Cast-in-place concrete block" and sledge hammer used to create an SH-wave source. The major drawbacks of the seismic refraction test from a geotechnical point of view are the inability to detect low velocity layers between high velocity layers and the fact that it samples only a portion of the material in a thick soil layer.

The dynamic soil parameters derived from data measured in a seismic refraction test and most geophysical tests used in geotechnical earthquake engineering are, assuming an elastic medium, the elastic modulus, E, and the shear modulus, G. These parameters are calculated from the velocity of compression (V_c) and shear (V_s) waves, using the following relationships (SW-AJA, 1972; Prakash, 1981):

$$E = \rho V_c^2 [(1+v) (1-2v) / (1-v)] \quad (1)$$

$$G = V_s^2 \rho \quad (2)$$

Where, ρ is the known total mass density of the soil and v is the soil's Poisson's ratio.

Cross-Hole Technique

The cross-hole technique is one of the best methods used for determining the variation with depth of low strain shear wave velocity. In this test, a source of seismic energy (mainly S-waves) is generated in or at the bottom of one borehole and the time for that energy to travel to another borehole through the soil layer is measured. From the borehole spacing and travel time, the velocity of the seismic wave is computed. Both body waves P-waves, and S-waves can be utilized in this test (Woods, 1978, 1994). At least two boreholes are required, one for the impulse and one or more for receivers as shown in Figure 4. The shear wave velocity is then used to compute the soil's shear modulus using equation (2).

For the success of a cross-hole test there are several requirements. (1) Although a minimum of two boreholes is sufficient to perform the test, three or more boreholes improve the capabilities of the cross-hole method. (2) The energy source should be rich in shearing energy (S-waves) and poor in compressional energy (P-waves) such that the arrival of S-waves can be detected easily. (3) Geophones in the receiver boreholes should have proper frequency response and be oriented in the direction of particle motion. The geophones should also be in contact with the soil, either directly in case of cohesive soils, or indirectly in case of granular soils. Finally, the coupling between geophone transducers and vertical wall should be accomplished with specially designed packers. (4) Travel time measurement of shear waves should be measured accurately using direct or indirect resolution techniques. Often a direct time measurement is made by dual channel oscilloscopes or by digital oscilloscopes. Indirect time resolution involves cross-correlation functions generated from wave trains recorded at two receiver boreholes, and automated frequency domain techniques, which calculate travel time based on the cross spectral density function of wave trains obtained at the receiver borehole(s) (Gazetas, 1991; Woods, 1978, 1994).

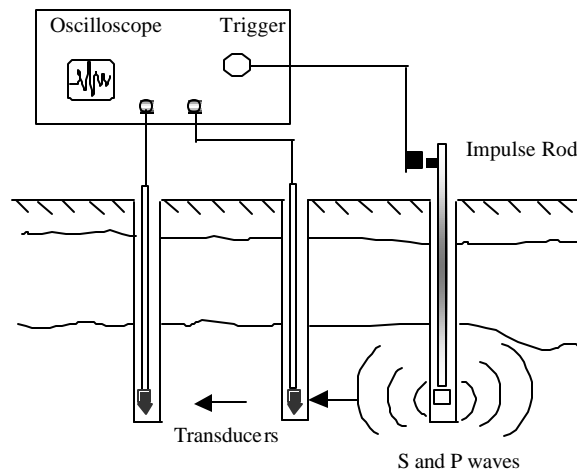


Figure 4 - Seismic Cross-Hole Test

Down-Hole And Up-Hole Techniques

The up-hole and down-hole techniques are a more economical alternative to the cross-hole technique; only one borehole is needed. In the down-hole technique, the impulse source of energy is generated at the ground surface near the top of the borehole, in which one or multiple geophones are lowered at predetermined depths, whereas in the up-hole test, waves are generated at various depths in the borehole and receivers are located along the ground surface. Figure 5, shows schematics of the up-hole and down-hole tests. Travel time of the body waves (S- and P-waves) between each geophone and the source are recorded. Recorded travel time is then plotted versus depth as in the seismic refraction test. These plots are then used to determine the maximum compression and shear wave velocities; $V_{C_{max}}$ and $V_{S_{max}}$ of all soil layers (SW-AJA, 1972; Woods, 1994; Gazetas, 1991).

If both V_c and V_s are measured, the soil's Poisson's ratio (ν) can be determined using equations (1), (2), and the following relationship between E and G (SW-AJA, 1972):

$$G = E / 2(1+\nu) \quad (3)$$

By means of substitution, we obtain:

$$\nu = (2 - V_c^2 / V_s^2) / 2(1 - V_c^2 / V_s^2) \quad (4)$$

In the seismic down-hole test, low velocity layers can be detected even if they are between high velocity layers if geophone spacing is sufficiently close. Sources of S-wave used in seismic refraction can be used for the seismic up- and down-hole testing. Depending on the depth of the soil layers investigated, the source of seismic waves will vary from hand generated sources to the use of large mechanical equipment. In addition, in the seismic up-hole and down-hole tests, the difficulty of picking up the first arrival of shear waves from compression waves is resolved, by reversing the polarity of the source generating the wave pattern. The wave pattern is measured twice, using a horizontally directed sledge hammer blow on a firmly embedded post, which is struck in a direction parallel to the ground surface at first, then struck 180 degrees out of phase a second time (in the opposite direction). Reversing the direction of the energy blow, allows for the shear wave pattern to be recorded in the reverse direction while the compression wave pattern is essentially unchanged. In this manner, the shear wave patterns are distinguished from compression wave patterns. However, in the up-hole test, it is more difficult to generate selected shear waves. P-waves tend to be predominant within the source generated (SW-AJA, 1972; Woods, 1994; Gazetas, 1991).

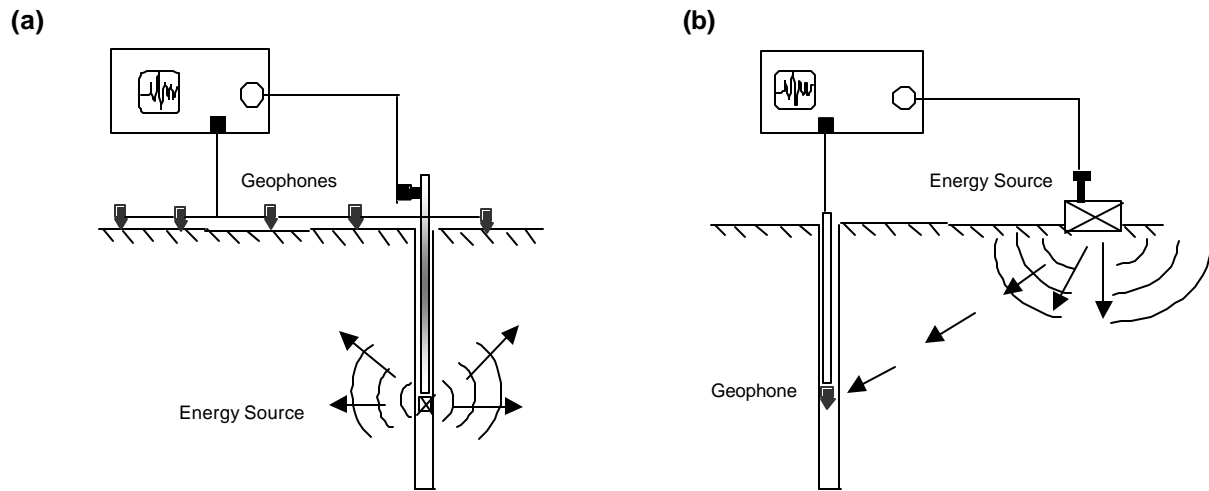


Figure 5 - Schematic of (a) Up-Hole Test and (b) Down Hole Test.

Steady-State Surface Wave Technique

The steady state surface wave technique does not require boreholes and is another in-situ method used to measure the shear modulus (G) of all types of soils. In this test, an electromagnetic oscillator at high frequency (30 to 1000 cycles/second, cps) or a rotating mass type oscillator to produce low frequency vibrations (less than 30 cps) are used. These surface vibrators generate Rayleigh R-waves, which at low strains have nearly the same velocity as the shear waves. The ground surface can be deformed as shown in Figure 6. The shear wave velocity is computed from the Rayleigh wave-length measured with receivers placed along the ground surface, and the frequency of vibration at the source using the following equation (SW-AJA, 1972; Gazetas, 1991):

$$V_s = V_R = f \lambda_R \quad (5)$$

Where,

f = Frequency of vibration
 λ_R = Rayleigh wave length

The effective depth of the Rwave has been empirically related to the soil layer at a depth equal to one-half the wave-length, λ_R (Heukelom and Foster, 1960, Fry, 1963 and 1965, Ballard 1964). The variation of shear wave velocity with depth is obtained by changing the frequency of the source and thus changing the wave-length λ_R . This technique requires however, large force-generating equipment that can operate at low frequencies (i.e., rotating mass oscillators) to explore deep soil profiles.

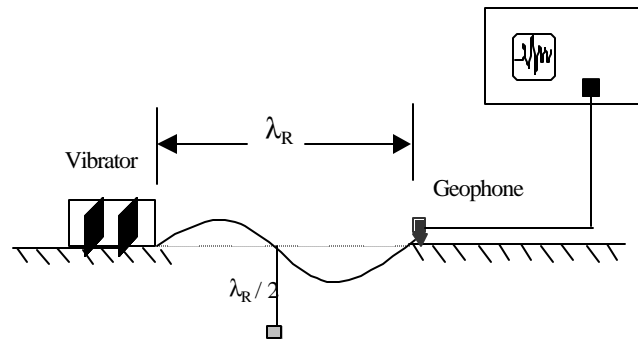


Figure 6 - Steady-State Surface Wave Test

Spectral Analysis of Surface Waves (SASW)

The SASW method evolved from the steady-state vibration test discussed in the previous section. The purpose of the SASW test is to determine a detailed shear wave velocity profile working entirely from the ground surface. The method involves using a series of successively longer source-receiver arrays to measure the propagation of Rayleigh waves over a wide range in wavelengths. A vertical impact is applied at the ground surface generating transient Rayleigh Rwaves. Two or more receivers placed at the surface, at known distances apart monitor the passage of these waves (Stokoe, et. al., 1994; Gazetas, 1991). Figure 7 shows a schematic of the field setup of this test. The receivers or vibration transducers produce signals that are digitized and recorded by a dynamic signal analyzer, and each recorded time signal is transformed to the frequency domain using a fast Fourier transform algorithm. The phase difference $\phi(f)$ between two signals is then determined for each frequency, and the travel time ($t(f)$) between receivers is obtained for each frequency as follows:

$$t(f) = \phi(f) / 2\pi f \quad (6)$$

where,

$\phi(f)$ = phase difference for a given frequency in radians
 f = frequency in cycles per seconds (cps)

The velocity of R-waves is determined as:

$$V_R = \Delta d / t(f) = \lambda_R f \quad (7)$$

With

Δd = distance between receivers.
 λ_R = surface wave-length

The calculations of V_R and λ_R are performed for each applied frequency, and the results plotted in the form of a dispersion curve. The dispersion curve is the characteristic or “signature” of a site. Using forward modeling or “inversion” analysis, the dispersion curves are used to determine the shear wave velocity profile of the site. Forward modeling is an iterative process involving assumption of a velocity profile and a theoretical dispersion curve for a given site using the two-dimensional solution for waves propagating along the surface of an elastic medium. The theoretical dispersion curve is then compared to the experimental curve measured at the site. The assumed profile is then modified and the process repeated until a match is achieved between theoretical and experimental dispersion curves. Shear moduli and shear wave velocity of the soil profile are then determined (Stokoe, et. al., 1994).

In a deep, homogeneous subsoil profile where the subsurface can be represented by a half-space, the signals of the transducers would have the same shape. However, in a layered soil profile, the various frequency components generated by the source propagate at different speeds, thus arriving at different times at the two receiver locations, and the signals would then have different shapes (Gazetas 1991).

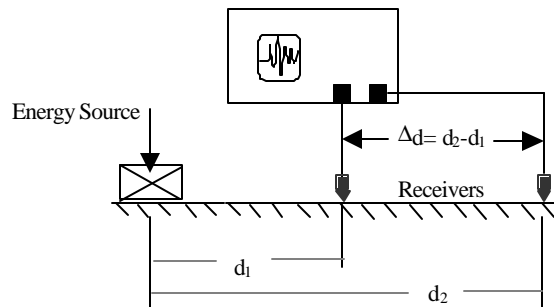


Figure 7 - Spectral Analysis of Surface Wave Test

Suspension PS Logging

The suspension PS logging is a recently developed tool for measurement of seismic wave velocity profiles. A seismic source and two receivers are built in a single borehole probe. Compression (P) and shear (S) waves are generated by a seismic source that involves the use of a solenoid hammer. The solenoid hammer produces a pressure wave in the borehole fluid. This pressure wave converts into seismic body waves (P and S) at the borehole wall. The waves travel in a radial direction from the borehole wall. Receivers contain two-component geophones, one vertical to record Pwaves, and one horizontal for recording of S-waves. The body waves are converted back to pressure waves in the borehole fluid and detected by the geophones. The source and the two receivers are connected with rubber-filter tubes to isolate vibration between them. The Spacing between two receivers is usually one (1) meter (Nigbor and Imai, 1994). Figure 8 shows a schematic of the test field setup.

Advantages of the suspension PS logging are that it is not necessary to clamp the probe against the borehole wall, and because the wavelength of excited shear waves is much greater than the borehole diameter, shear excitation is almost independent of the borehole fluid. As such, geophones in the probe can record the behavior of the borehole wall without clamping the probe. The other advantage of the suspension PS logging is accurate measurement of the shear wave velocity values and because the frequency of the shear wave generated by the source is generally higher than the other methods, wavelengths are shorter and propagation time measurements are more accurate. (Kaneko, Kanemori and Tonouchi, 1990).

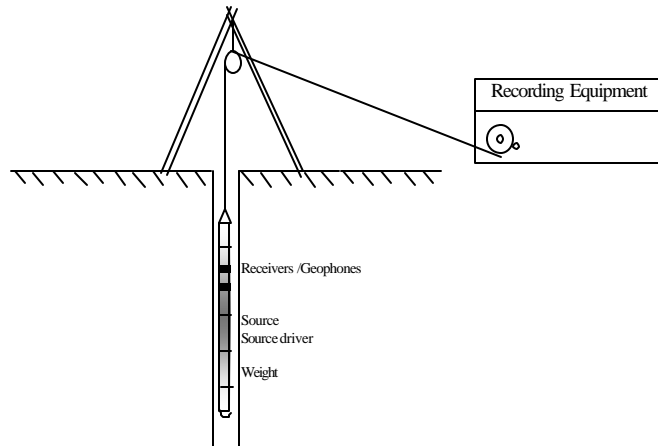


Figure 8 - Suspension PS Logging test

Seismic Cone Penetration Test (SCPT):

The SCPT has been more recently developed (Campanella and Robertson 1984). The test combines the seismic downhole technique with the standard Cone Penetration test. A seismic pick-up or receiver is added to the cone, then the similar procedure as the one followed with the seismic downhole test is used. At the surface, a shear force is induced while the penetration is paused momentarily. In order to compare the intensity of signals arriving at the receiver at various depths, a source that is capable of generating repeatable signals is used. This is insured by the use of a single hammer weight and height of fall (Campanella and Davies, 1994). Typical test set up of the SCPT is presented as Figure 6. The shear wave velocity, V_s , is calculated by dividing the difference in travel path between two depths by the time difference between the two signals recorded.

Advantages of the SCPT in comparison with other conventional seismic in-situ tests, reside in its speed, the fact that it also provides static soil properties such as point bearing (q_c) and sleeve frictional resistance (f_s) as well as ground profiling and stratigraphy of the site. The strain induced immediately around the probe during penetration is a very large strain and thus, both large and small strain parameters can be obtained. In addition the SCPT can be considerably less expensive than other conventional seismic techniques.

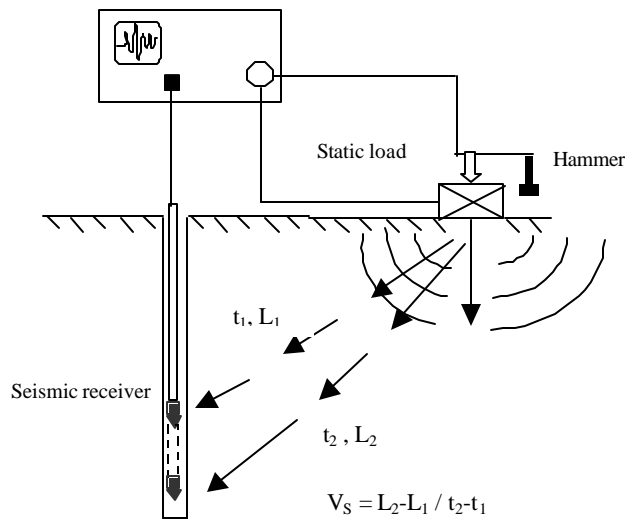


Figure 9 - Seismic Cone Penetration Test

SUMMARY

A collection of geophysical methods often used by engineers to determine dynamic properties of soils were presented. Recent developments of these methods in the past decade were also included. The geophysical tests were described within the context of how a geotechnical engineer would use the measured parameters. These methods provide crucial data that define only the low strain portion of the modulus and damping strain dependent relationships. The great utility of the geophysical methods reside in the measurement of the in-situ conditions including all the environmental factors at the time of testing.

REFERENCES

- Campanella, R.G., Davies, M.P., 1994, The Seismic Peizocone: A Practical Site Investigation Tool: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 49-55
- Idriss, I.M., Dobry, R., and Singh, R.D., 1978, Nonlinear behavior of soft clays during cyclic loading, Journal of the Geotechnical Engineering Division, ASCE, **104**(GT12), 1427-1227.
- Gazetas, G., 1991, Foundation Vibrations: Foundation Engineering Handbook, 2nd Edition, Hsai-Yang Fang, and Editor, 553-593.
- Jolly, R.N., 1956, Investigation of Shear Waves: Geophysics, **XX1**(4), October, 905-938.
- Kobayashi, N., 1959, A Method of Determining the Under-ground Structure by Means of SH Waves: Zisin, Ser. 2, **12** (1), 19-24.
- Kaneko, F., Kanemori, T., and Tonouchi, K., 1990, Low Frequency Shear Wave Logging in Unconsolidated Formations for Geotechnical Applications: Geophysical Applications for Geotechnical Investigations, Frederick L. Paillet and Wayne R. Saunders, Editors, 79-98.
- Kramer, S.L., 1996, Geotechnical Earthquake Engineering: Prentice Hall, 653p.
- Prakash, S., 1981, Soil Dynamics: Mc. Graw Hill Book Co., New York, NY, Reprint, 1991, S.P. Foundation, Rolla, MO.
- Seed, H.B., Wong, R.T., Idriss, E.M., and Tokimatsu, K., 1984, Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils, Report No. UCB/EERC-84/11, Earthquake Engineering Research Center, University of California, Berkeley.
- Stokoe, K.H., II and Hoar, R.J., 1978, Variable Affecting In-situ Seismic Measurements: Proceedings of the ASCE Conference on Earthquake Engineering and Soil Dynamics, Geotechnical Engineering Div., Pasadena, CA, June, 19-21.
- Stokoe, K.H., Lee, S.H.H., and Knowx, D.P., 1985, Shear Moduli Measurements under the True Triaxial Stress: Proceedings, Advances in the Aret of Testing Soils under Cyclic Conditions, ASCE, New York, 166-185.
- Stokoe, K.H. II, Wright, S.G., Bay, J.A., Roesset, J.M., 1994, Characterization of Geotechnical Sites By SASW Method: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 15-25.
- Sun, J.I., Golesorkhi, R., and Seed, H.B., 1988, Dynamic Moduli and Damping Ratio for Cohesive Soils, Report No. UCB/EERC-88/15, Earthquake Engineering Research Center, University of California, Berkeley.

SW-AJA, 1972, Soil Behavior Under Earthquake Loading Conditions, State of the Art Evaluation of Soil Characteristics for Seismic Response Analyses: Prepared Under Subcontract No. 3354, Union Carbide Corp., for U.S. Atomic Energy Commission, Contract No. W-7405-eng-26, January.

Vucetic, M. and Dobry, R., 1991, Effect of Soil Plasticity on Cyclic Response, *Journal of Geotechnical Engineering*, **117**(1), 89-107.

Whiteley, R.J., 1994, Seismic Refraction Testing-A Tutorial: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 45-47.

Woods, R.D., 1978, Measurement of Dynamic Soil Properties, State of the Art Report: Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference, Earthquake Engineering and Soil Dynamics, Pasadena, CA. **1**, 91-178.

Woods, R.D., 1994, Borehole Methods in Shallow Seismic Exploration: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 91-100.

Yan, L. and Byrne, P.M., 1991, Stress State and Stress Ratio Effects in downhole and crosshole in shear wave velocities on sand, Proceedings: 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol 1, and pp. 299-306.

Selected Bibliography

Arango, I., Moriwaki, Y., and Brown, F., 1978, In-situ and Laboratory Shear Velocity and Modulus: Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference: Earthquake Engineering and Soil Dynamics, Pasadena, CA., **1**, 198-212.

Ballard, R.F., Jr., and McLean, F.G., 1975, Seismic Field Methods for In Situ Moduli: Proceedings of the Conference on In-Situ Measurements of Soil Properties, Geotechnical Engineering Division, ASCE Specialty Conference, Raleigh, N.C., **1**, 121-150.

Butler, D., and Pedersen, E. P., 1993, Shear Wave Investigations in Poorly Consolidated Materials: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, San Diego, **1**, 79-89.

Campanella, R.G., Davies, M.P., 1994, The Seismic Peizocone: A Practical Site Investigation Tool: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 49-55.

Campanella, R.G., Stewart, W.P., 1992, Seismic Cone Analysis Using Digital Signal Processing for Dynamic Site Characterization: *Canadian Geotechnical Journal*, **29**(3), June.

Davenport, G.C., Sena, J., and Rivera, J.A., 1989, Vibration Measurement and Control at the Pueblo Viejo Mine: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Golden, CO., 467-478.

Descour, J. M., and Miller, R.J., 1989, Microseismic Monitoring of Engineering Structures: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Golden, CO., 235-261.

Gazetas, G., 1991, Foundation Vibrations: *Foundation Engineering Handbook*, 2nd Edition, Hsai-Yang Fang, and Editor, 553-593.

- Harris, J.B., and Street, R.L., 1991, Integrated Seismic Site Characterization of the Paducah, Kentucky Area, Preliminary Results: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Knoxville, TN., 23-37.
- Kaneko, F., Kanemori, T., and Tonouchi, K., 1990, Low Frequency Shear Wave Logging in Unconsolidated Formations for Geotechnical Applications: Geophysical Applications for Geotechnical Investigations, Frederick L. Paillet and Wayne R. Saunders, Editors, 79-98.
- Nazarian, S., 1984, In-situ determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral Analysis of Surface Wave Method: Ph.D. Dissertation, University of Texas, Houston, TX 458p.
- Nazarian, S., and Diehl, J., (Eds.) 2000, Use of Geophysical Methods in Construction, ASCE Geotechnical Special Publication, No. 108, American Society of Civil Engineering, Reston, VA, 242p.
- Nigbor, R.L., and Imai, T., 1994, The Suspension PS Velocity Logging Method: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 57-61.
- Prakash, S., 1981, Soil Dynamics: Mc. Graw Hill Book Co., New York, NY, Reprint, 1991, S.P. Foundation, Rolla, MO.
- Redpath, B.B., and Lee, R.C., 1986, In-situ Measurements of Shear Wave Attenuation at a Strong Motion Recording Site: Report Prepared for USGS Contract No. 14-08-001-21823.
- Sawada, Y., 1992, Ashigara Valley Geotechnical Data: Proceedings of the International Symposium on the Effects of Surface Geology on Seismic motion, Odawara, Japan, 2, 29-42.
- Skokan, C.K., and Chi, D., 1990, Use of the Seismo-Electric Effect in Engineering Problems: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Golden, CO., 341-347.
- Stokoe, K.H. II, Wright, S.G., Bay, J.A., Roesset, J.M., 1994, Characterization of Geotechnical Sites By SASW Method: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 15-25
- Stokoe, K.H., 1980, Field Measurement of Dynamic Soil Properties: Civil Engineering and Nuclear Power, 2, 7-1-1 to 7-1-31.
- SW-AJA, 1972, Soil Behavior Under Earthquake Loading Conditions, State of the Art Evaluation of Soil Characteristics for Seismic Response Analyses: Prepared Under Subcontract No. 3354, Union Carbide Corp., for U.S. Atomic Energy Commission, Contract No. W-7405-eng-26, January.
- Whiteley, R.J., 1983, Recent Developments in the Application of Geophysics to Geotechnical Engineering: in Erwin, M C (ed) In-situ Testing for Geotechnical Applications, Balkema, Rotterdam, 87-110.
- Whiteley, R.J., 1994, Seismic Refraction Testing-A Tutorial: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 45-47.
- Woods, R.D., 1978, Measurement of Dynamic Soil Properties, State of the Art Report: Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference, Earthquake Engineering and Soil Dynamics, Pasadena, CA. 1, 91-178.

Woods, R.D., 1983, Measurement and Application of Shear Wave Velocity for Soil-Structure-Interaction, State of the Art Paper: Proceedings of the International Workshop on Soil Structure Interaction, Roorkee, India, **2**, 67-80.

Woods, R.D., 1994, Borehole Methods in Shallow Seismic Exploration: Geophysical Characterization of Sites, Volume prepared by ISSMFE, Technical Committee # 10, XIII ICSMFE, New Delhi, India, Richard Woods, Editor, 91-100.

Woods, R.D., and Stokoe, k. H., II, 1985, Shallow Seismic Exploration in Soil Dynamics, Richart Commemorative Lectures: Proceedings of a session sponsored by the Geotechnical Engineering Division, ASCE, Detroit, MI., 120-156.