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Interpretation of Large-Strain Geophysical Crosshole Tests

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Westinghouse Hanford Company Richland, Washington

Management and Operations Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

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INTERPRETATION OF LARGE-STRAIN GEOPHYSICAL CROSSHOLE TESTS

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ABSTRACT

Stress-strain relationships of soils are notoriously non-linear. At sites in earthquake-prone areas, the nonlinear dynamic stress-strain behavior of soil with depth is essential for earthquake response analyses. Most currently used geophysical seismic tests only generate small-strain amplitude waves which are in the linear range, and the nonlinear behavior is inferred from laboratory tests. A seismic crosshole test has been developed where large dynamic forces are applied in a borehole. These forces generate shear strains in the surrounding soil that are well into the nonlinear range. The shear strain amplitudes decrease with distance from the source. Velocity sensors located in three additional holes at various distances from the source hole measure the particle velocity and the travel time of the shear wave from the source.

This paper provides an improved, systematic interpretation scheme for the data from these large-strain geophysical crosshole tests. Use is made of both the measured velocities at each sensor and the travel times. The measured velocity at each sensor location is shown to be a good measure of the soil particle velocity at that location. Travel times to specific features on the velocity time history, such as first crossover, are used to generate travel time curves for the waves which are nonlinear. At some distance the amplitudes reduce to where the stress-strain behavior is essentially linear and independent of strain amplitude. This fact is used together with the measurements at the three sensor locations in a rational approach for fitting curves of shear wave velocity versus distance from the source hole that allow the determination of the shear wave velocity and the shear strain amplitude at each of the sensor locations as well as the shear wave velocity associated with small-strain (linear) behavior. The method is automated using off-the-shelf PC-based software.

The method is applied to a case study where data were obtained at 5 ft (1.5 m) intervals at depths from 20 to 140 ft (6 to 43 m). Elastic shear wave velocities determined from this method compare well with those obtained from seismic cone penetration tests at the same site. Shear wave velocities were converted to shear moduli using densities from conventional bore hole logs. Curves of shear modulus reduction with shear strain amplitude were generated as part of the automated process. The curves varied with depth as would be expected and compared well with those from the published literature.

INTRODUCTION

Various analytical techniques of determining the earthquake response of a soil deposit or the seismic performance of a soil-structure system require the characterization of the modulus of the foundation soil as a function of shear strain induced by the earthquake. In most instances, the strain dependency of soil modulus has been determined by combining the results from different laboratory tests (typically cyclic triaxial and resonant column) performed at both low (10^{-4} percent) and at intermediate to high (10^{-2} to 1 percent) shear strains. Unfortunately the agreement between these different test results is not always good. More importantly, the accuracy of the laboratory tests is subject to the sample quality and reproduction of actual in-situ conditions. The real state at which the soil exists in the field, characterized by its void ratio, stress state, degree of cementation, and fabric, are often not easily duplicated in the laboratory.

To provide an in-situ method of determining the non-linear behavior of soil over a wide range of strains, Shannon & Wilson and Agbabian Associates (1976 and 1977) developed field equipment and testing procedures for a modified crosshole geophysical test in which shear wave velocities may be evaluated over the strain range of 10^{-4} to 10^{-1} percent. The equipment and the testing procedures were developed for the U.S. Nuclear Regulatory Commission as part of an overall research program to evaluate soil behavior under earthquake loading conditions.

TEST DESCRIPTION

The large-strain, in-situ crosshole test generates a shear wave in a borehole which propagates through a soil mass and is subsequently recorded by velocity transducers in nearby boreholes. A typical test set-up is shown schematically in Figure 1. The test set-up includes a wave-generating source with an attached velocity transducer, and three sensors (also velocity transducers) that are arranged in a horizontal plane at a given depth and at different radii from the source inside the boreholes.

For a given test, the time required for the shear wave to travel from the source hole to each of the sensors is measured. As the shear wave passes the sensor location, a time history of the particle velocity is recorded by the velocity transducer. The shear wave travel time and particle velocity amplitude are determined from the recorded particle velocity-time history at the sensor. The horizontal distances from the source hole to the sensors are determined from precise surveys of the verticality of each borehole.

Considerable thought was put into an interpretation procedure that would permit accurately inferring the modulus degradation curve fully from the test results. The interpretation of the method is discussed in a later section.

The primary difference between this test and conventional crosshole tests is in the generation, magnitude, and control of the shear waves. This test utilizes a controlled in-hole energy source in which shear waves dominate. The resultant recorded velocity-time signatures, therefore, have a distinct controlled amplitude and shape as the shear pulse travels through the soil to successive sensor locations. A consistent shape enables the identification of characteristic points on each pulse, marking the time of passage of a wave through each sensor location. A consistent characteristic point, the crossover point after the first peak strain has been reached, is selected on each velocity-time history as the time of arrival for that sensor. The desired large amplitudes of the shear pulse are obtained by adjusting the spacing of the borings and changing the weight and height of drop of the impact hammer. Strains of 10^{-4} to 10^{-1} percent have generally been obtained by placing the sensors in three borings, spaced about 4, 8, and 16 feet (1.2, 2.4, and 4.8 m) from the energy source. These are considerably closer spacings than used in the conventional crosshole procedures and minimizes the inherent limitation in conventional crosshole procedures of having waves reflecting or traveling over paths greatly different from those assumed.

TEST EQUIPMENT

The testing equipment consists of four basic components:

- Hammer-and-anchor assembly
- Sensing equipment
- Recording equipment
- Surveying equipment

The hammer-and-anchor assembly is used to generate the shear waves. It consists of a hydraulic anchor and downhole hammer that are attached to the bottom of the drill stem and lowered to the desired test depth in the encased anchor hole. The anchor assembly is 4 ft (1.2 m)

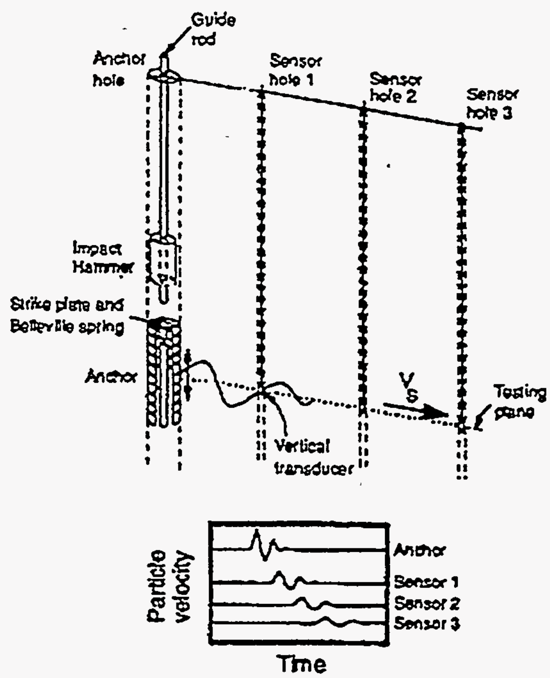

Figure 1. Schematic of large-strain in-situ crosshole test.

long, weighs approximately 200 pounds (90 kg), and can expand from 8 to 12 inches (0.2 to 0.3 m) in diameter. The anchor couples to the borehole wall via three aluminum curved face plates. The plates are expanded radially into the sides of the hole using a hydraulic ram controlled by a hand operated pump at the ground surface. When firmly coupled to the borehole, a 120-pound (53 kg) cylindrical downhole hammer is dropped onto the striker plate at the top of the anchor, creating a downward shear force at the anchor-soil interface. A Belleville spring between the hammer and striker plate controls the input characteristics of the shear wave (frequency and wave shape). This system produces a relatively clear impulse that can be traced as it passes from the anchor assembly to the geophones positioned at the same elevation in the three adjacent borings (Figure 1).

The sensing equipment consists of four velocity transducers (geophones). The transducer in the anchor hole is fixed to the anchor assembly to record the input motion characteristics, while the other three velocity transducers are placed in each of the three sensor borings. All of the geophones are orientated vertically, which is in the plane of maximum motion of the generated shear wave. Geophone coupling in the sensor borings is accomplished by inflating a rubber packer that forces the geophone against the wall of the boring. Ten-foot lengths of light-weight metal rods are used to lower the velocity transducers to the desired elevation and to orient the sensors in the front part of each hole, at a point closest to the energy source.

The recording equipment used when the testing procedure was developed in the 1970's consisted of a waveform recorder, an interface unit, an oscilloscope, and a digital seven track tape recorder. As electronic recording equipment has developed, more modern recording equipment has been used (e.g. Tektronix Test Lab[1] model TDS 540A four channel digital oscilloscope). The basic requirements of the recording equipment is that it must be able to simultaneously record 4 channels, simultaneously display the 4 recorded wave forms in real time, and provide a digital record for subsequent analyses of the wave forms. The recording equipment allows for simultaneous display of all wave forms for a given test so that the quality of the tests can be assessed in the field by checking anchor coupling, wave form clarity and shape, and geophone coupling. Testing at a particular depth may be repeated if the field assessment indicates poor quality of the data.

The survey equipment is used to accurately determine the shear wave travel distances at each test depth. The top of the boreholes are surveyed using standard surveying equipment and techniques. The verticality and drift of the boring is measured using a commercially available inclinometer.

INTERPRETATION OF LARGE-STRAIN CROSSHOLE TESTS

Travel Time Curves

For interpretation purposes it is convenient to assume that the soil at a certain depth does not vary significantly from the source hole to each of the three sensor holes. This is usually a realistic assumption. If it cannot be made, then it may be very difficult to interpret test results and it is questionable whether it is useful to do such testing at all.

The main objective of the interpretation procedure should be to arrive at the modulus degradation curves for the soil at a particular depth where measurements have been made for shear wave travel times and particle velocity at a finite number of sensors. This calls for (1) establishing a value of shear wave velocity at each position where the particle velocity is also known, (2) calculating a value of shear modulus corresponding to this particular value of shear wave velocity, and (3) calculating the shear strain corresponding to the values of shear wave velocity and particle velocity. What will result is a number of points in a shear modulus versus shear strain plot. A curve fit through these points will be the interpreted modulus degradation curve at the test depth.

In the cross-hole test developed by Shannon and Wilson in conjunction with Agbabian Associates the travel time curves must be generated from only four points for each test: anchor (source), and sensors S1, S2 and S3, as illustrated in Figure 2. By travel time curves we mean the plot of time taken for the shear wave to arrive at a location versus the horizontal distance from that location to the source hole. By definition, the travel time and distance for the anchor are both zero. As distance from the anchor increases, the travel time must also increase but its slope may change because of changes in wave propagation velocities in soil with shear strain. Because of large strain amplitudes near the anchor, the travel time curve must be curved downward. At some distance away from the anchor, the strain amplitudes become small and the wave propagation velocities become constant. This means that the travel time curve must become asymptotic to a straight line which has a slope equal to the inverse of the small-strain-amplitude shear wave velocity and an intercept greater

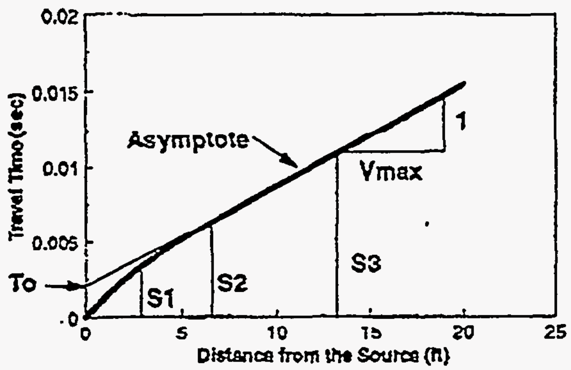

Figure 2. Travel time curve for large-strain crosshole test.

than zero. The equation of asymptote is

$$Traveltime = T_0 + \frac{1}{V_{max}} x \qquad (1)$$

where: T_0 = the intercept when x is zero,
V_{max} = is the inverse of the slope, and
x = the distance from the anchor.

Neither T_0 nor V_{max} can be determined directly except when only very small strain amplitudes exist throughout the region, when the travel time data should form a straight line through the origin. For large-strain crosshole tests, all data points must lie on or below this straight line, because velocities of propagation at larger strains are smaller than those for small strains.

The problem now reduces to finding a function that describes the position of the data below the small-strain asymptote. Numerous rational functions were examined and tried including various forms of hyperbolic and exponential functions. The best fitting was achieved by using a hyperbolic tangent function. The complete equation used to fit the travel time curve is

$$Traveltime = T_0 + \frac{x}{V_{max}} - T_0[1 - \tanh(bx)] \quad (2)$$

where b = regression constant

Spacing and travel time from a given test may be used to establish values of the three unknowns (T_0, V_{max}, and b) by a least squares fitting procedure. A software package such as MATHCAD[2] may be used for this.

Shear Wave Propagation Velocity, Shear Modulus, and Shear Strain Amplitude

The slope of the travel time is determined by differentiating (2):

$$Slope(x) = \frac{1}{V_{max}} + bT_0[1 - \tanh^2(bx)] \qquad (3)$$

The shear wave velocity V_s at a distance x from the source hole is the inverse of the slope *Slope(x)* of the travel time curve. The value of the shear modulus G at x can then be computed from

$$G = \rho V_s^2 \qquad (4)$$

Similarly, at a given depth, the small-strain shear modulus, G_{max}, may be determined from

$$G_{max} = \rho V_{max}^2 \qquad (5)$$

where ρ = mass density of the soil.

The shear strain corresponding to a given shear wave velocity and particle velocity is given by

$$\gamma = \frac{v_p}{V_s} \qquad (6)$$

where v_p = particle velocity of the soil at a given location.

Work by Hardin and Drnevich (1972) showed that modulus reduction curves could be reasonably well described by the use of a modified hyperbolic function:

$$\frac{G}{G_{max}} = \frac{1}{1 + \frac{\gamma}{\gamma_r}\left[1 + a\exp\left(-b\frac{\gamma}{\gamma_r}\right)\right]} \qquad (7)$$

where γ_r is the reference strain (ratio of maximum shear strength to G_{max}), and a and b are constants. In this equation, there are three unknowns, γ_r, a and b. A least square fitting is now done with the G/G_{max} and data calculated above to determine these unknowns. Once they are established, curves for G/G_{max} as a function of γ/γ_r are plotted.

CASE HISTORY

Large-strain crosshole tests were performed as part of studies for the design and construction of the proposed Multi-Function Waste Tank Facility (MWTF) which is planned for the Hanford Site near Richland, Washington. Information given below on the site was obtained from a report by Shannon & Wilson (1994). The ground surface through out the area is slightly undulating (elevation range: 720-732 ft (220-223 m)) with a moderately thick cover of sage brush, cheatgrass, and other deciduous plants. Beneath the surface is a 2-5 ft (0.6-1.5 m) thick layer of windblown fine sand. These overlie the undulating surface of the Hanford formation, the uppermost part consists of a sandy gravel layer extending to a depth of approximately 20 ft (6 m). Below this is a stratum that consists of dense to very dense, brown, fine to medium sand that is slightly cemented. This stratum extends to depths in excess of 140 ft (43 m). Bedrock at the site is estimated to be at a depth of 470 ft (143 m) and the ground water at a depth of 300 ft (90 m).

To illustrate the application of the method to real test data, the values of T_D, V_{max}, and b were obtained using the proposed interpretation procedure from five crosshole tests between depths of 20 ft through 40 ft. The resulting fitted travel time curve through all data points for this depth range is shown in Figure 3. Figure 4 shows the

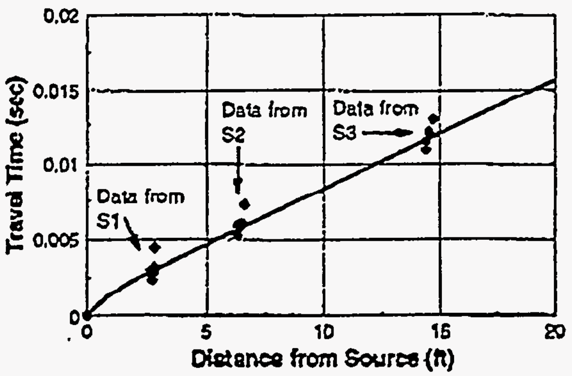

Figure 3. Fitted travel time curve.

interpreted modulus degradation curve for the 20-40 ft depth range compared with a corresponding Seed and Idriss (1967) curve.

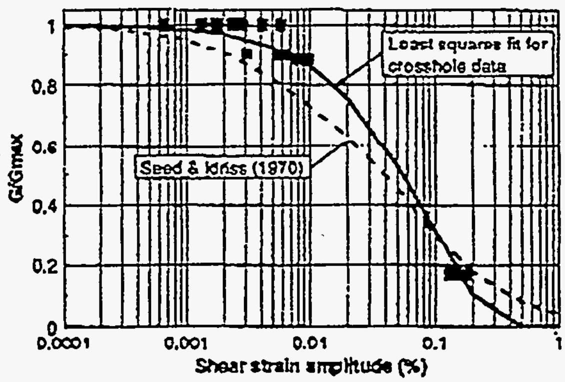

Figure 4. Modulus degradation curves for 20-40 ft (6-12 m) depth range.

The large-strain crosshole tests were conducted at this site at 5 ft (1.5 m) increments of depth for depths ranging from 20 to 140 ft (6 m to 43 m). Data were analyzed for each elevation tested and also for ranges of elevation where the variation in soil properties was relatively small. For example, the data presented herein are for the range in depths from 20 to 40 ft (6 to 12 m). In addition to a variety of conventional borehole tests done at the site, seismic cone penetration tests were done to depths of approximately 50 ft (15 m). These provided independent measurements of low-strain shear wave propagation velocities. The shear wave velocity from the seismic cone penetration test averaged approximately 1400 ft/sec (425 m/sec) for the depths from 20 to 40 ft (6 to 12 m) and the calculated low-strain value of shear wave velocity from the large-strain crosshole test is 1364 ft/sec (416 m/sec). When data from individual depths are compared, the agreement also is excellent.

CONCLUSION

The proposed method of fitting travel time curves from large-strain crosshole tests is rational and provides consistent values of V_{max} as well as modulus degradation curves with shearing strain amplitude. The large-strain cross-hole test combined with the interpretation procedure described in this paper provides a valuable way to develop soil properties not only for earthquake geotechnical engineering applications, but also for any geotechnical application for which it is important to have in-situ information on how soil stiffness varies with strain.

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1. Tektronix Test Lab is a trademark of Tektronix, Inc.

2. MATHCAD is a trademark of MathSoft.