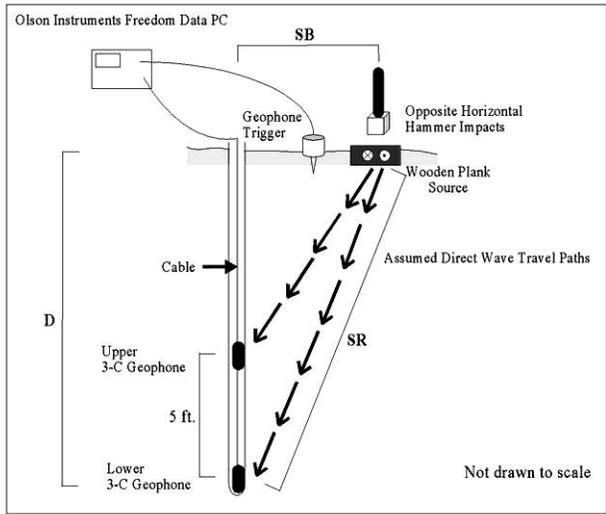
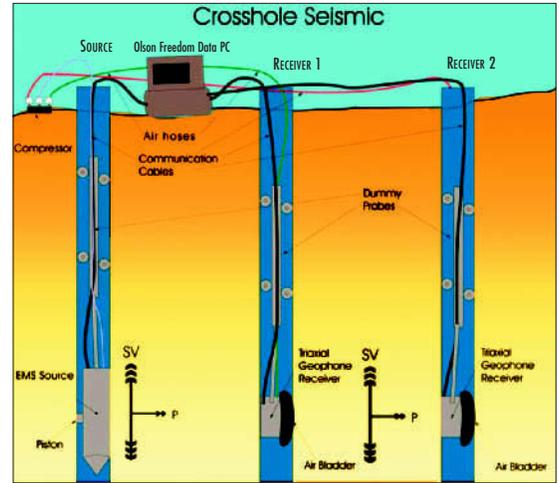


APPLICATION



CROSSHOLE SEISMIC (CS) investigations are performed to provide information on dynamic soil and rock properties for earthquake design analyses for structures, liquefaction potential studies, site development, and dynamic machine foundation design. The investigation determines shear and compressional wave depth versus velocity profiles. Other parameters, such as Poisson's ratios and moduli, can be easily determined from the measured shear and compressional wave velocities. In addition, the material damping can be determined from CS tests. The CS method is a downhole method for the determination of material properties of soil and rock. A source capable of generating shear and compressional waves is lowered in one of the boreholes, and a pair of matching three component geophone receivers are lowered to the same depth in two additional boreholes set at evenly spaced increments (typically 10 and 20 feet from the source borehole) in a line, as shown in the figure above. The receivers are positioned on the side of the borehole casing to allow detection of the passage of shear and compressional waves.



DOWNHOLE SEISMIC (DS) investigations are similar to the CS method, but require only one borehole to provide shear and compressional velocity wave profiles. The DS method uses a plank source at the surface to generate shear and compressional waves. A pair of matching three component geophone receivers are lowered downhole spaced 5 to 10 feet apart to sense the P- and S- wave energy.

STANDARDS

This method is performed in accordance with ASTM D4428-D4428M-00 Standard Test Methods for Crosshole Seismic Testing. CS is an acceptable investigation method for obtaining soil classification ratings as required by IBC/UBC. An example of this requirement can be found at www.ci.las-vegas.nv.us/Files/IBC_Amendments_2003.pdf, which outlines the City of Las Vegas amendments to the 2003 IBC Chapter 18 Section 1802. The particular section describing necessary investigations is 1802.4.2 Investigation.

■ See end of document for full references.

FIELD INVESTIGATION

ACCESS

The CS investigation requires drilling of two or more (typically three) boreholes. The boreholes are typically 3-4 inches in diameter cased with PVC or slope inclinometer casing, and grouted in accordance with ASTM Standards to ensure good transmission of the wave energy. The testing is simplified if inclinometer casing is used rather than normal PVC pipe. Typical distances between adjacent boreholes are on the order of 10 feet. A field setup for CS measure-

ments is shown on the previous page. The receiver boreholes are drilled to the total investigation depth. For tests using the split spoon as a source, the source borehole is advanced during testing at intervals equal to the measurement intervals required (2-5 feet). If a source containing an impactor that can be clamped to the borehole wall is used, then the source borehole can be drilled to the total investigation depth prior to testing.

COLLECTION OF DATA

In a CS investigation, the source is lowered to the measurement depth and is incrementally advanced to the bottom of the borehole. One or two triaxial geophone receivers are incrementally lowered to the same depth in the other boreholes. Dummy inclinometer probes are used to maintain correct receiver orientation throughout the investigation as shown in the schematic above; if PVC casing is used, orientation rods must be attached to the source and receiver. The source is triggered from the surface to generate shear and compressional wave energy at depth. In some instances where a split spoon is used as the source, an instrumented hammer strikes the rod to generate shear and compressional

wave energy. The source borehole is incrementally advanced for the split spoon source. The vertical component of the receiver is used to capture the vertically polarized shear waves (SV). Both upward and downward polarized energy is generated for duplicity of data and to measure shear arrival effectively. The radial component senses the propagating compressional waves (P) and the tangential component senses the horizontally propagating shear waves (SH). An [Olson Instruments Freedom Data PC](#) with the [Crosshole or Downhole Seismic System \(DS/CS-1 and CS/CS-2\)](#) is used to record the P-SV source input as well as the receiver outputs. (see below).

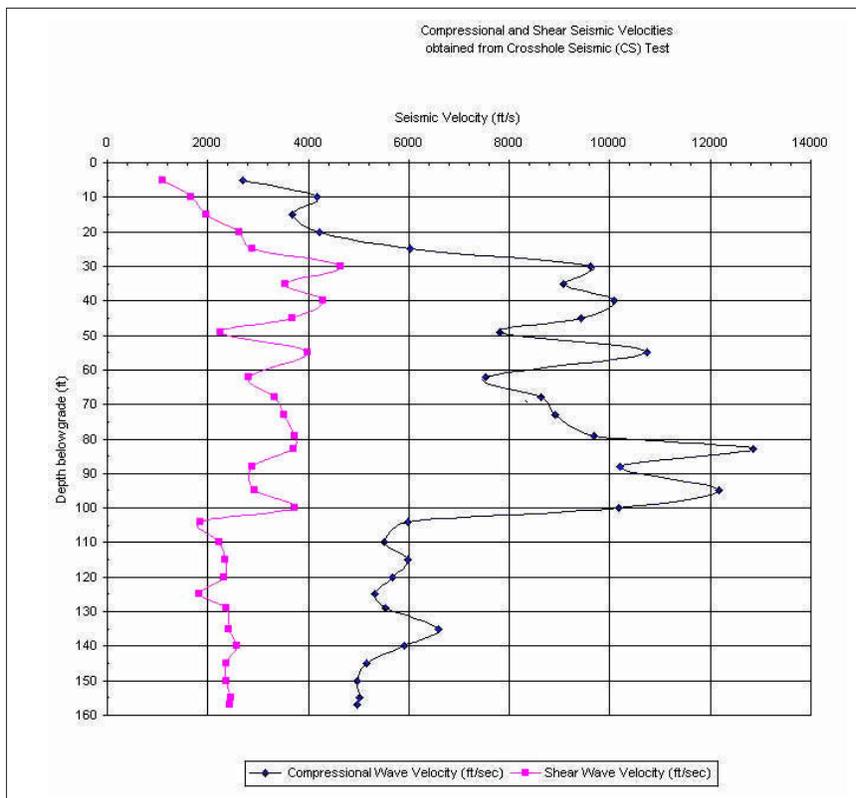
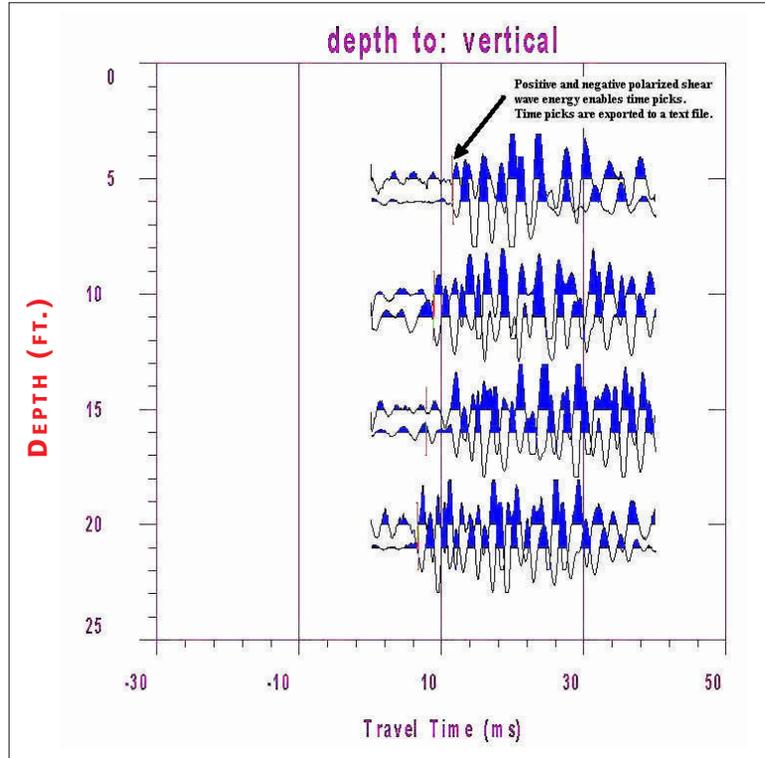
In a DS investigation, the source is typically a hammer hitting a plank at the surface and requires only one borehole. The three component geophones are separated 10 feet and lowered together downhole. The hammer source generates both shear and compressional wave energy and which are recorded by the geophones. The vertical component of the receiver is used to capture the vertically propagating compressional waves (P) and the radial transverse component senses the horizontally polarized shear wave (SH).



DATA REDUCTION

PROCESSING TECHNIQUES

Data processing is performed using seismic analysis software such as IX Foundation to pick arrival times of the source and separate receiver components. The figure below shows a screen shot of the upper 25 feet of a profile. The split in polarization, as indicated, allows shear wave arrival times to be picked (red hash). IX Foundation exports pick times into a standard spreadsheet to calculate velocities, moduli, and Poisson's ratios.



Once shear velocity is calculated, a graph can be assembled to show a velocity profile. This chart shows the sensitivity of CS method in identifying layers of particular strata.

DATA REDUCTION *cont.*

INTERPRETATION OF DATA

If one receiver borehole is used, the travel time from source to receiver is measured. This is referred to as direct travel time measurements. If two receiver boreholes are used, the travel time between the receivers is measured. This is referred to as interval travel time measurements. The wave velocities at the measurement depth are simply calculated by dividing the travel distances by the measured travel time. The travel distances are determined after the verticality of the boreholes is evaluated (inclinometers are typically used). Note that interval travel times are normally more accurate than direct travel times, and thus the three hole test configuration is preferred.

The Poisson's ratio, as well as shear and constrained moduli can be determined from the shear and compressional wave velocities using the following equations:

$$G = \rho V_S^2$$

$$M = \rho V_P^2$$

$$\rho = [0.5 \rho (V_P/V_S)^2 - 1] / [V_P/V_S)^2 - 1]$$

where G is the shear modulus, ρ is the mass density, V_S is the shear wave velocity, M is the constrained modulus, V_P is the compressional wave velocity, ρ is the mass density, and V is Poisson's ratio.

EFFECTIVENESS

As compared to surface methods, the CS method is the most accurate method for determining material properties of rock and soil sites. Thin low-velocity layers lying between high-velocity layers can be detected with the method, like-wise, thin high-velocity layers between low-velocity layers can be detected, which may not be possible with surface methods such as Spectral Analysis of Surface Waves (SASW) or Refraction Survey tests. Often, when boring logs indicate particular strata of rock and soil of interest, such as a shallow, high-velocity layer, the CS equipment can be set to that depth easily and the overall stiffness of a particular site can be improved. In addition, the accuracy and resolution of the CS method is constant for all test depths, whereas the

accuracy and resolution of the surface methods decreases with depth. Olson Engineering has performed the CS and/or DS method in conjunction with SASW for comparison purposes and for repeatability of results. For CS investigations, two or preferably three boreholes are required to perform

the test. In circumstances where two or three boreholes are not economical or perhaps limited space is available the DS method can be utilized with only one borehole.

In rock site investigations, the boreholes may be uncased, but for most of the soil site investigations, the borehole should be cased (preferably with inclinometer casing) and grouted.



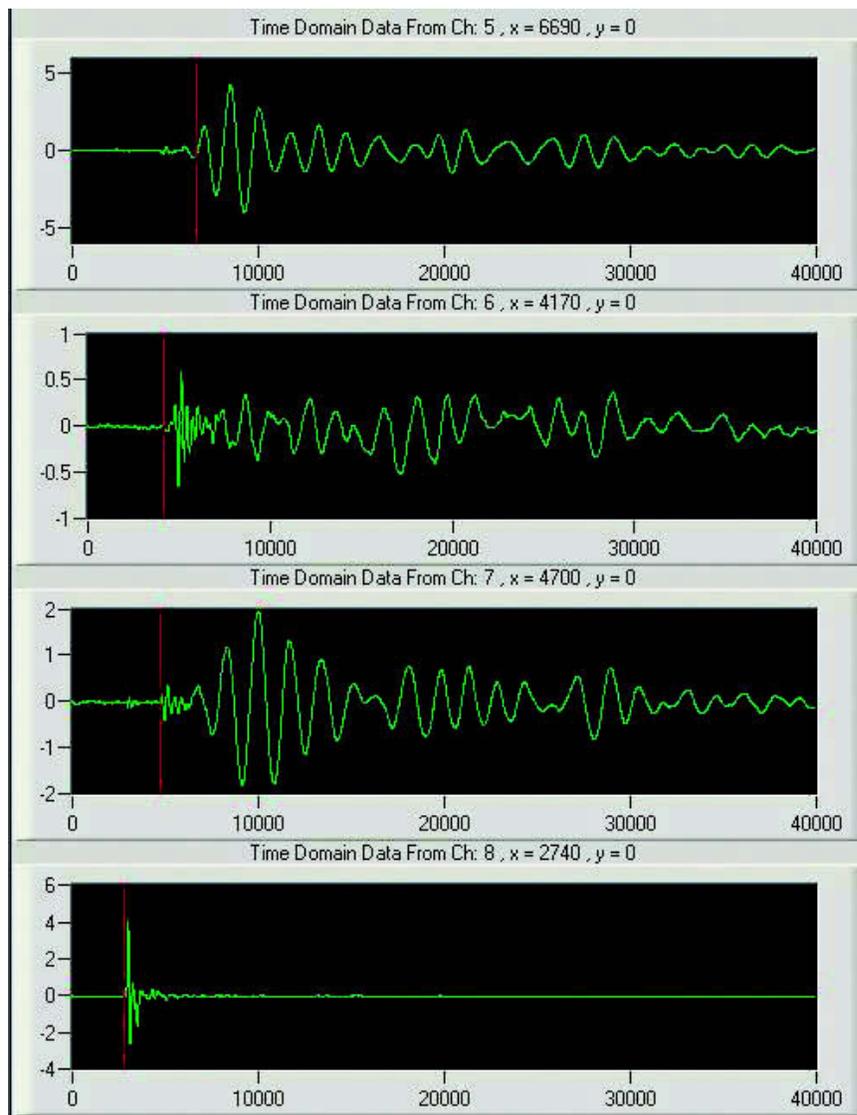
[Triaxial Geophone]

[P-SV Source for CS Tests]

EXAMPLE RESULTS

CS METHOD - SOIL SITE TEST

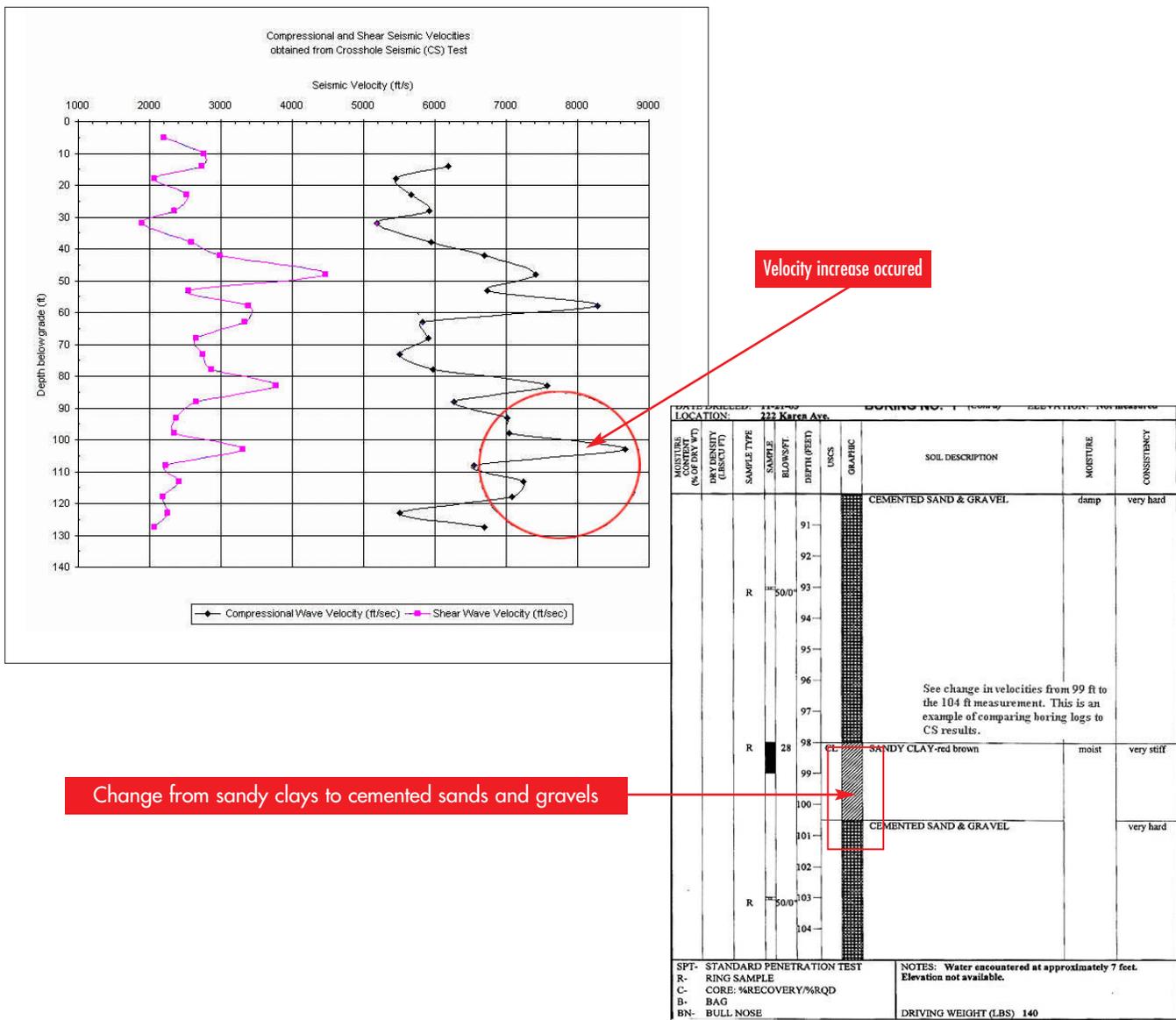
To illustrate the concepts of the CS method, example results from CS tests on a soil site are presented below. The records shown are from CS measurements at a depth of 116 feet. The figure below shows a screen shot from an Olson Instruments Freedom Data PC showing the aforementioned record. Channel 5 is the vertical component of the three component geophone, which is measuring the vertically polarized shear wave energy. Channels 6 and 7 are the radial and transverse components, respectively, and they measure the compressional wave energy. Typically, the radial component is aligned with the source and is thus used to measure the arrival of the compressional wave more accurately. Channel 8 is the trigger component from the P-SV source for timing.



EXAMPLE RESULTS cont.

CS METHOD - SOIL SITE VELOCITY PROFILE

In determining a velocity profile, comparison between boring logs and calculated shear wave velocities are routinely done to confirm data clarity and accurate representation of the subsurface material. The figures below correspond with each and show the CS chart as well as the boring log from a particular site. The example exemplifies the accuracy of the CS method in identifying a change in soil strata. The red circle on the chart shows the area where a velocity increase occurred; a similar change in soil strata is indicated at 100 ft. in the boring logs as a change from sandy clays to cemented sands and gravels.



REFERENCES

Standards and Governmental Reports

- ASTM D4428/D4428M-00, "Standard Test Methods for Crosshole Seismic Testing," ASTM International.
- City of Las Vegas: Amendments to 2003 International Building Code, Chapter 18 Section 1802 Soils and Foundations, 2003 International Building Code®.



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