In situ seismic testing with surface waves

Les essais sismiques in-situ avec des ondes de surface

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SYNOPSIS: Shear wave velocities measured in situ can be used either directly or indirectly to evaluate material parameters and site characteristics. Traditional seismic methods of measuring shear wave velocities, such as the crosshole or downhole methods, can often be difficult or inappropriate to use because of the need to drill boreholes or advance probes. The Spectral-Analysis-of-Surface-Waves (SASW) method is well suited for these instances because testing is performed entirely from the surface. In the SASW method, field measurements of surface wave dispersion followed by inversion are used to estimate shear wave velocity profiles. The SASW method was used to assess the effectiveness of grouting in gravelly soils in Milan, Italy and to estimate qualitatively the in situ density of landslide debris in northern Italy. In both cases, the nonintrusive nature of the SASW method was instrumental in its selection and successful use.

INTRODUCTION

Shear modulus is an important parameter which can be used to characterize the behavior of geotechnical materials under both static and dynamic loads. Because the velocity of shear waves is directly related to the shear modulus of the material skeleton through which the waves propagate, it is possible to employ seismic methods to measure shear wave velocity in situ and then derive or infer material parameters or other site characteristics. For instance, in situ shear wave velocity can be used solely or in conjunction with other measurements to:
1. determine initial tangent shear moduli,
2. infer in situ density, 3. estimate in situ stress state, 4. infer the amount of natural cementation, or 5. evaluate sampling disturbance.

The seismic methods most often used to measure shear wave velocities at geotechnical sites are the crosshole and downhole methods. One characteristic of these methods is that they are intrusive; that is, either boreholes are drilled or probes are pushed into the ground to place seismic sources and/or receivers. This characteristic can preclude the use of these methods at sites where drilling or penetration testing cannot or should not be performed. A new seismic method, called the Spectral-Analysis-of-Surface-Waves or SASW method, is presented herein. Field testing is performed with both the source and receivers placed on the ground surface, and is, therefore, nonintrusive. Because no boreholes are required, the method is especially well-suited for those cases where intrusive tests cannot be performed. This strength of the method is illustrated with two case histories; the first involving testing of natural and grouted gravels in Milan, Italy and the second involving testing of landslide debris in northern Italy.

SPECTRAL-ANALYSIS-OF-SURFACE-WAVES METHOD

The dispersive nature of surface wave propagation in a layered, elastic half space forms the basis of the SASW method. Dispersion means that surface waves with different wavelengths propagate with different velocities because they sample different parts of the layered medium. Short wavelengths (i.e. high frequencies) sample near the surface while longer wavelengths (i.e. lower frequencies) sample the near-surface material and deeper layers. Therefore, all layers in the profile can be sampled simply by generating surface waves over a wide range in wavelengths (i.e. a wide range in frequencies).

Field measurements are performed for the purpose of measuring surface wave dispersion at a site. This dispersion is expressed in terms of a dispersion curve which is a plot of propagation velocity versus wavelength. Once the field dispersion curve has been determined, it is used to calculate the stiffness profile at the site using an inversion algorithm. Inversion allows detailed profiles of shear wave velocity to be determined at sites with very simple to very complex stiffness profiles. Descriptions of the test configuration, field procedure, and inversion methodology are presented in the following paragraphs.

Equipment and Field Testing

The general configuration of the source, receivers, and recording equipment is shown in Fig. 1. Surface waves are generated by applying a dynamic vertical load to the ground surface. The propagation of these waves along the surface is monitored with two receivers placed at distances of d_1 and d_2 from the source. Additionally, distance d_2 is usually equal to two times d_1. In principle it should be possible to use a single source/receiver spacing for the entire test. However, practical considerations such as attenuation and near-field effects dictate that several different source/receiver spacings must be used. Typically, distances between receivers of 1.2, 2.5, 5, 10, 20, and 40 m are used if the soil profile is to be evaluated to a depth of about 20 m. In addition, the location of the source is reversed at each source/receiver spacing so that both forward and reverse profiles are measured.

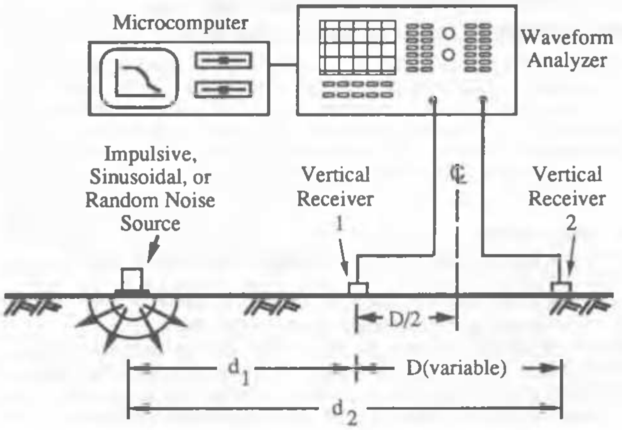

Fig.1 Source-Receiver Configuration

Surface wave frequencies used in SASW testing range from several Hertz to about 500 Hz for most soil sites. In this case, velocity transducers with natural frequencies between 1 and 4.5 Hz work well as receivers. When rock or some other stiff material such as concrete is at the surface, frequencies on the order of 10 to 50 kHz must be generated, and accelerometers are used as receivers (as noted in Case Study 1). In both instances, the most common types of sources are either simple hammers (small, hand-held hammers or sledge hammers) or dropped weights weighing from 200 to 1500 N. Electromagnetic vibrators in conjunction with sinusoidal or random input motion can also be used as sources. At soil sites where wavelengths longer than 10 to 20 m are desired, bulldozers have been effectively used as the source (as noted in Case Study 2).

Waveform analyzers are used to capture, store and process the receiver outputs. The waveform analyzer must be capable of calculating Fast Fourier Transforms on recorded data in real time. The ability to calculate transforms rapidly in the field is an essential part of the SASW method, allowing operators to immediately assess the quality of the data being collected and, if necessary, modify the arrangement of source and receivers or other test parameters accordingly.

Dispersion Calculations

For each source/receiver spacing, the time histories recorded by the two receivers, $x(t)$ and $y(t)$, are transformed to the frequency domain resulting in the linear spectra of the two signals, $X(f)$ and $Y(f)$. The cross power spectrum of the signals, $G_{yx}(f)$, is then calculated by multiplying $Y(f)$ by the complex conjugate of $X(f)$. In addition to the cross power spectrum, the coherence function and auto power spectrum of each signal are also calculated. It must be emphasized that all of these frequency domain quantities are calculated in real time by the waveform analyzer. The key data, consisting of the phase of the cross power spectrum and the coherence function, are shown in Fig. 2. The coherence function represents a signal-to-noise ratio and should be nearly one in the range of acceptable data (e.g. 27 to 100 Hz in Fig. 2).

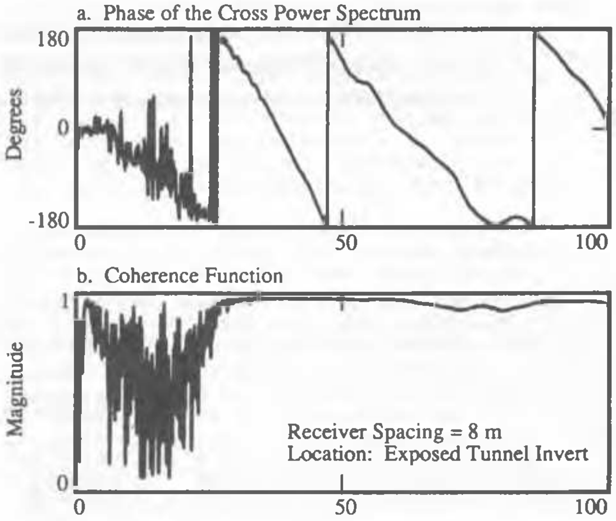

Fig.2 Key Records for One Receiver Spacing

The time delay between receivers as a function of frequency is calculated using the phase of the cross power spectrum, denoted as $\theta_{yx}(f)$ from:

$$t(f) = \theta_{yx}(f)/2\pi f \qquad (1)$$

where the phase angle is in radians and the frequency, f, is in Hertz. The surface wave phase velocity, V_R, is determined using:

$$V_R(f) = (d_2 - d_1)/t(f) \qquad (2)$$

and the corresponding wavelength of the surface wave is calculated from:

$$L_R = V_R/f. \qquad (3)$$

The result of these calculations is a dispersion curve (V_R versus L_R) for one receiver spacing. Individual dispersion curves from all receiver spacings are assembled together to form the composite dispersion curve for the site. An example of a composite dispersion curve is presented in Fig. 3. The portion of the curve determined from the phase record shown in Fig. 2a is outlined by the dashed box in Fig. 3. The calculations described by Eqs. 1 through 3 are performed on a microcomputer connected to the waveform analyzer (Fig. 1). If desired, these calculations can be performed on a portable microcomputer in the field to provide immediate feedback to the operators about the progress of the SASW test.

Inversion

Inversion is the process of calculating the stiffness profile using the field dispersion curve. In the inversion process, a theoretical dispersion curve is calculated for an assumed stiffness profile and is compared to the field dispersion curve. The theoretical curve is calculated using a modified Haskell-Thomson algorithm (Haskell, 1953; Thomson, 1950; and Nazarian, 1984). The shear wave velocities and thicknesses of the layers in the assumed profile are adjusted until a satisfactory match between the theoretical and field dispersion curves is obtained. The comparison of theoretical and field dispersion curves after the final adjustment of velocities and thicknesses is illustrated in Fig. 4. The final profile is assumed to represent the actual site conditions accurately. Application of inverse theory to surface wave testing has increased the accuracy of resulting wave velocity profiles and has significantly expanded the variety of sites at which the SASW method can be successfully used.

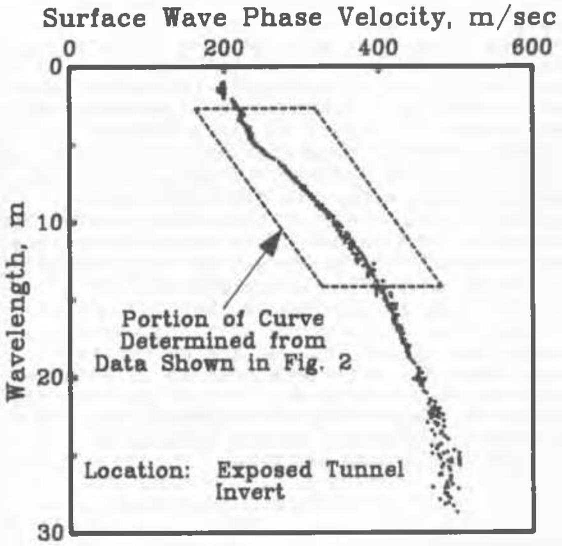

Fig.3 Field Dispersion Curve Developed from All Receiver Spacings (from Case Study 1)

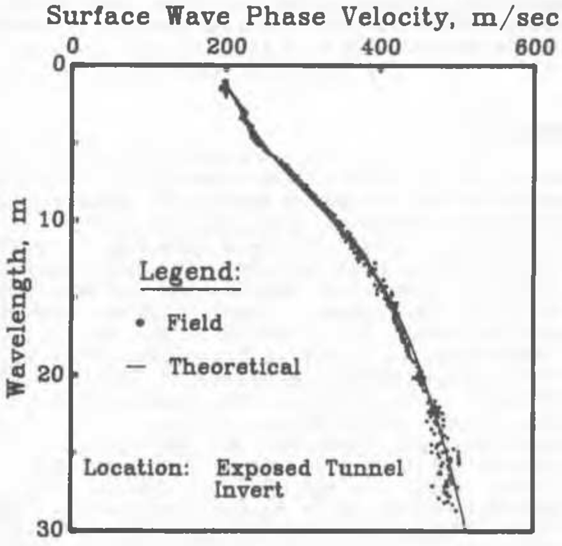

Fig.4 Comparison of Theoretical and Field Dispersion Curves (from Case Study 1)

CASE STUDY 1: EVALUATION OF GROUT AROUND TUNNEL

A routine procedure used to construct tunnels in gravelly materials around Milan, Italy is pre-excavation consolidation grouting. Depending on the circumstances, some type of grouted annulus or zone is often formed by injection from the ground surface. Questions can arise about the extent and quality of the grouted materials. To study the feasibility of addressing these questions with the SASW method, testing was performed in proximity to an active excavation.

SASW testing was conducted on the tunnel walls and invert. The gravelly materials beneath the invert were left ungrouted as shown in the insert in Fig. 5. A 15-cm thick layer of shotcrete covered the walls and crown. Shear wave velocity profiles at two locations (one on the wall and one on the invert) are shown in Fig. 5. Profile 1 shows that the gravelly soil beneath the invert is very stiff. Profile 2 shows: 15 cm of shotcrete, 2.5 m of mildly grouted soil (or grouted material which has possibly been disturbed), 2 m of heavily grouted soil, and soil with a stiffness decreasing until it becomes similar to the gravel beneath the invert. Delineation of the heavily grouted material is easily seen in Profile 2 and the competency of the material can be inferred from the high values of shear wave velocity.

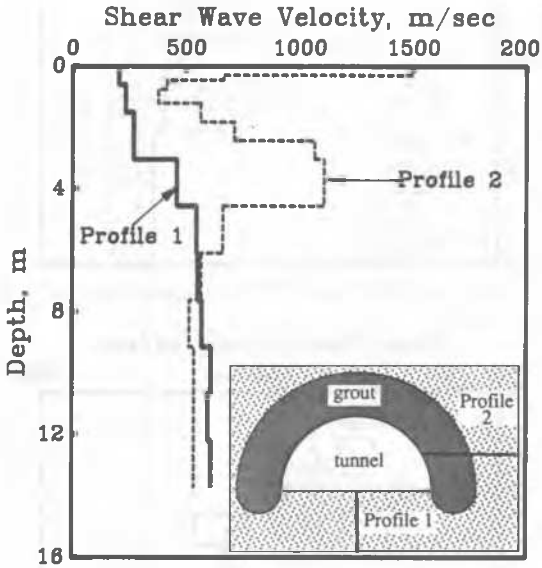

Fig.5 Velocity Profiles of Grouted and Ungrouted Materials Around Tunnel

CASE STUDY 2: EVALUATION OF LANDSLIDE DEBRIS

A massive landslide occurred in the Valtellina valley of Northern Italy in 1987. Following the landslide, it became necessary to make a qualitative estimate of the density of the landslide debris. The debris consisted of a heterogeneous mixture of silt, sand, cobbles, and boulders which could not be tested using standard geotechnical tests because of the difficulty of advancing boreholes or penetration devices. Therefore, the SASW method was used determine shear wave velocity profiles in order to infer the density of the debris.

SASW testing was performed at five locations. Measurements to depths on the order of 30 to 100 m were desired, and therefore a bulldozer was used as the source of low-frequency (less than 3 Hz) surface waves. The resulting shear wave velocity profiles for two of the five locations are shown in Fig. 6. Measurements were effectively performed in this difficult-to-sample material to depths of 50 m.

To estimate qualitatively the density of the debris, measured values of shear wave velocity were then compared with values calculated using empirical relationships developed by Seed et al (1986) following the procedure discussed by Stokoe et al (1988). Measured shear wave velocities presented in Fig. 6 are shown together with empirically determined values in Fig. 7 for three qualitative densities. Values of the coefficient K_2 equal to 40, 80 and 120 were taken as representative of loose, medium and dense gravelly materials. The result of this comparison indicates that the debris at these two locations is very dense. Similar results were also found at the other locations.

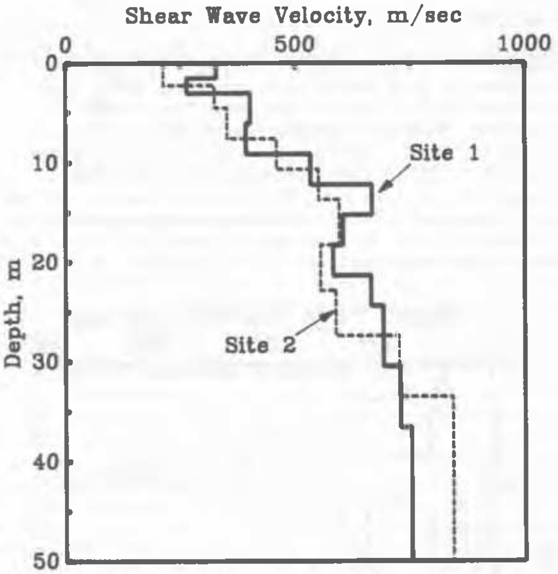

Fig.6 Velocity Profiles of Landslide Debris

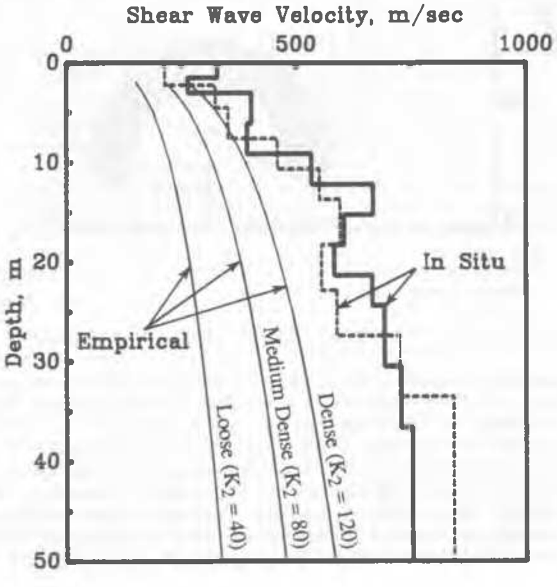

Fig.7 Qualitative Evaluation of In Situ Densities of Landslide Debris from Velocity Profiles

CONCLUSIONS

The Spectral-Analysis-of-Surface-Waves method is a new engineering seismic method which utilizes the dispersive nature of surface waves in a layered half space to determine shear wave velocity profiles of geotechnical sites. The method involves making field measurements of surface wave dispersion and then using an inversion process to calculate the shear wave velocity profile. Two important characteristics of the method are that: 1. field testing is performed entirely from the exposed surface, and 2. the shear wave velocity of softer materials beneath stiffer materials can be accurately measured. As a result of these characteristics, SASW testing can be performed where traditional seismic methods are difficult or inappropriate to use. Two case studies are presented to illustrate the advantages of the SASW method. In the first case study where drilling was not allowed, the extent and quality of grouted gravels behind a shotcrete coating in a tunnel excavation were evaluated. In the second case study which involved hard-to-sample soils, a qualitative evaluation of the density of landslide debris was performed.

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