CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

Acquisition of an Engineering Seismograph

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16. Abstract The engineering seismograph will be used to collect reflection, refraction, cross-borehole and seismic tomography and SASW data in support of externally-funded research. These data will be acquired mostly in support of geotechnical and structural characterization studies.		
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SEISTONIX ENGINEERING SEISMOGRAPH AND LOW-FREQUENCY GEOPHONES

Rationale for purchase: The seistronix engineering seismograph and low-frequency geophones are specifically designed to acquire multi-channel surface (Rayleigh) wave seismic data. Acquired surface (Rayleigh) wave seismic data are processed (through spectral inversion); the output is a 1-D or 2-D MASW shear-wave velocity profile consisting of multiple stations (shear-wave velocity curves) spaced at 40 ft station intervals. The MASW tool is often a cost-effective alternative to standard invasive techniques.

A brief overview of induced seismic waves: When an acoustic source (weight drop, dynamite charge, etc.) is discharged at or near the surface of the earth, two fundamental types of acoustic waves (strain energy) are produced: body waves and surface waves. Two types of body waves can propagate through an elastic solid (compressional waves and shear waves). Similarly, two types of surface waves can propagate along the earth's surface (Rayleigh waves and Love waves).

Compressional waves (or P-waves) propagate by compressional and dilatational strains in the direction of wave travel (Figure 1). Particle motion involves oscillation, about a fixed point, in the direction of wave propagation. Shear waves (or S-waves) propagate by a pure strain in a direction perpendicular to the direction of wave travel (Figure 1). Body waves are essentially non-dispersive over the range of frequencies employed for earthquake studies and seismic exploration (i.e., all component frequencies propagate at the same velocity). The propagation velocities of body waves are a function of the engineering properties of the medium through which they are traveling (Figure 1).

Love waves propagate along the surface of a layered solid (earth's surface) if the shear-wave velocity of the uppermost layer is lower than that of the underlying layer (e.g., unconsolidated strata overlying bedrock). Love waves are polarized shear waves with an oscillatory particle motion parallel to the free surface and perpendicular to the direction of wave motion (Figure 2). Love waves are dispersive, and are characterized by velocities between the shear-wave velocity of the shallowest layer and that of deeper layers. The amplitude of a Love wave decreases exponentially with depth. The lower component frequencies of Love waves involve particle motion at greater depth and therefore generally exhibit higher velocities.

Rayleigh waves propagate along the earth's surface (free surface). The associated particle motion is elliptical in a plane perpendicular to the surface and containing the direction of propagation (Figure 2). The orbital motion is in the opposite sense to the circular motion associated with a water wave, and is often described as retrograde elliptical. The amplitude of a Rayleigh wave decreases exponentially with depth (Figure 2). Progressively lower frequency components of Rayleigh waves involve particle motion over progressively greater depth ranges (relative to free surface). Rayleigh waves in a heterogeneous medium (with respect to velocity) are therefore dispersive. The velocities with which the highest component frequencies travel are a function of the engineering properties of the shallowest sediment. The velocities with which progressively lower frequencies travel are functions of the varying engineering properties over a progressively greater range of sediment depths. In the "multi-channel analysis of surface wave" (MASW) technique, the phase velocities of the component frequencies are calculated. These data are then inverted and used to generate a vertical shear-wave velocity profile.

Rayleigh waves (overview of MASW technique): Rayleigh waves propagate along the free surface of the earth, with particle motions that decay exponentially with depth (Figure 2). The lower component frequencies of Rayleigh waves involve particle motion at greater depths. In a homogeneous (non-dispersive) medium, Rayleigh wave phase velocities are constant can be determined using the following equation:

$$\mathbf{V_R^6 - 8\beta^2 V_R^4 + (24 - 16\beta^2/\alpha^2)\beta^4 V_R^2 + 16(\beta^2/\alpha^2 - 1)\beta^6 = 0} \qquad \text{Equation 1}$$

where:

$\mathbf{V_R}$ is the Rayleigh wave velocity within the uniform medium
$\boldsymbol{\beta}$ is the shear-wave velocity within the uniform medium (also denoted Vs)
$\boldsymbol{\alpha}$ is the compressional wave velocity within the uniform medium (also denoted Vp)

Rayleigh wave velocities, as noted in Equation 1, are a function of both the shear-wave velocity and compressional wave velocity of the subsurface.

In a heterogeneous earth, shear-wave and compressional-wave velocities vary with depth. Hence, the different component frequencies of Rayleigh waves (involving particle motion over different depth ranges) exhibit different phase velocities (Bullen, 1963). The phase velocity of each component frequency being a function of the variable body wave velocities over the vertical depth range associated with that specific wavelength. More specifically, in a layered earth, the Rayleigh wave phase velocity equation has the following form:

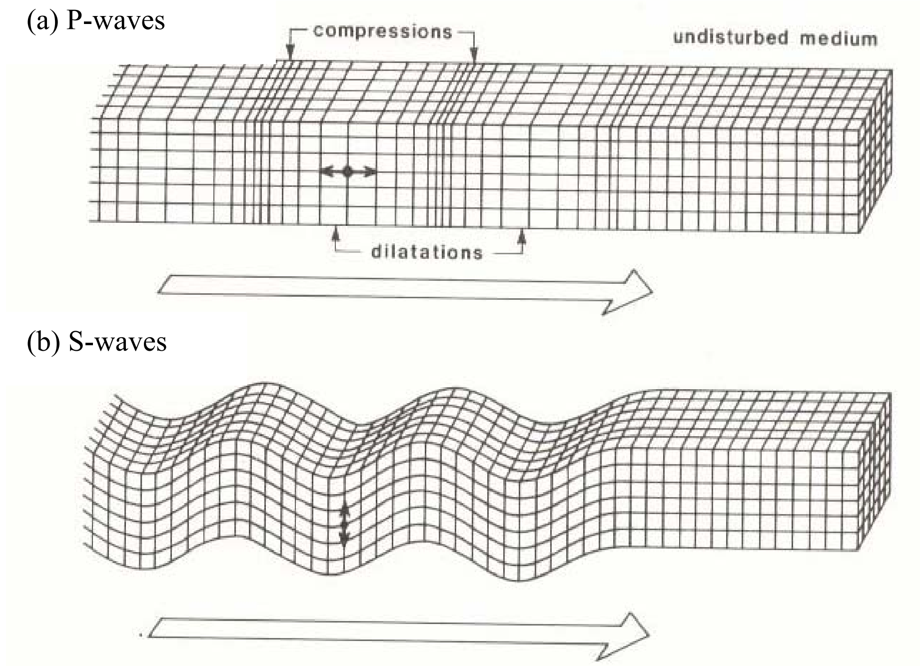
$$\mathbf{V_R(f_j, C_{Rj}, \beta, \alpha, \rho, h) = 0 \quad (j = 1, 2, \ldots, \mathit{m})} \qquad \text{Equation 2}$$

where:

$\mathbf{f_j}$ is the frequency in Hz
$\mathbf{V_{Rj}}$ is the Rayleigh-wave phase velocity at frequency $\mathbf{f_j}$
$\boldsymbol{\beta} = (\boldsymbol{\beta}_1, \boldsymbol{\beta}_2, \ldots, \boldsymbol{\beta}_n)^T$ is the s-wave velocity vector
$\boldsymbol{\beta}_i$ is the shear-wave velocity of the ***i***th layer
$\boldsymbol{\alpha} = (\boldsymbol{\alpha}_1, \boldsymbol{\alpha}_2, \ldots, \boldsymbol{\alpha}_n)^T$ is the compressional p-wave velocity vector
$\boldsymbol{\alpha}_i$ is the P-wave velocity of the ***i***th layer
$\rho = (\rho_1, \rho_2, \ldots, \rho_n)^T$ is the density vector
ρ_i is the density of the ***i***th layer
$\mathbf{h} = (\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{n-1})^T$ is the thickness vector
$\mathbf{h_i}$ the thickness of the ***i***th layer
n is the number of layers within the earth model

The spectral analysis of surface waves (MASW) technique is based on the relationship between Rayleigh wave phase velocities and the depth-range of associated particle motion. More specifically, in this technique, phase velocities are calculated for each component frequency of field-recorded Rayleigh waves (active monitoring). The resultant dispersion curve (phase velocity vs. frequency) is then inverted using a least–squares approach and a vertical shear-wave velocity profile is generated (Miller *et al*., 2000; Nazarian *et al*., 1983; Stokoe *et al*., 1994; Park *et. al.,* 2001; Xia *et al*., 1999).

MASW field technique: The acquisition of the "active" Rayleigh wave (surface wave) data is usually relatively straightforward (Figure 3). Essentially, multiple (typically 12) low-frequency (4.5 Hz) vertically-polarized geophones, placed at appropriate intervals, are centered about MASW station location #1. Acoustic energy is generated at an appropriate offset (distance to nearest geophone) using a sledge hammer and metal plate (or other appropriate acoustic source). The generated Rayleigh wave data are recorded. For "all intents and purposes", the entire 12-channel geophone array and source is then shifted (iteratively, and at an appropriate interval) along the entire test segment of interstate. At each "station" location, Rayleigh wave data are generated and recorded.



$\alpha = [(K + 4\mu/3)/\rho]^{1/2}$

$\beta = [\mu/\rho]^{1/2}$

where:

α = P-wave velocity (Vp)

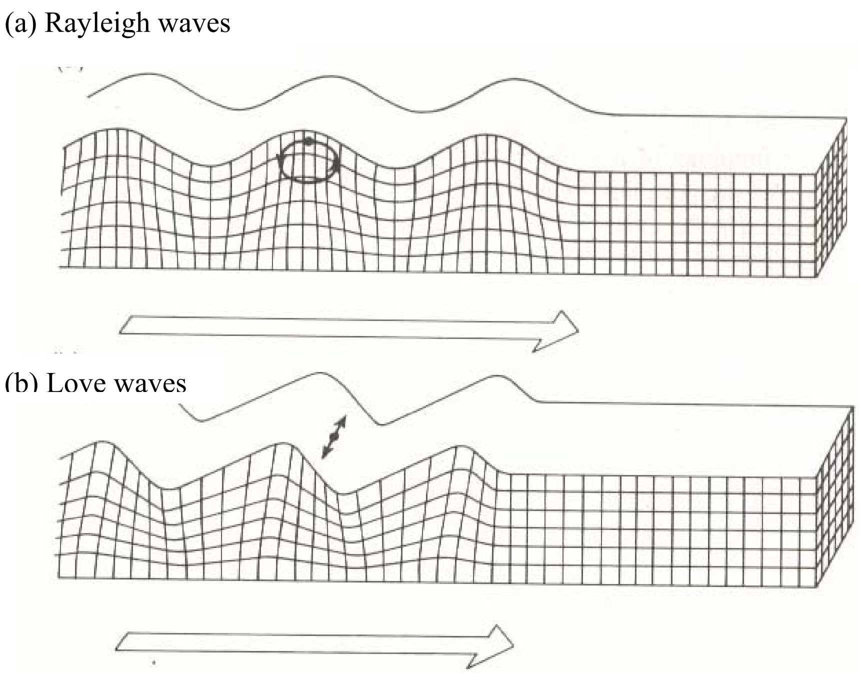
β = S-wave velocity (Vs)

K = bulk modulus

μ = shear modulus

ρ = density

Figure 1: Particle motions associated with compressional waves (P-waves; upper caption) and shear waves (S-waves; lower caption).



Rayleigh wave particle motion
- retrograde elliptical
- decreases exponentially with depth
- function of α and β

Love wave particle motion
- horizontal
- decreases exponentially with depth
- function of β

Figure 3: Particle motions associated with Rayleigh waves (upper caption) and Love waves (lower caption).

Processing of MASW data: The acquired Rayleigh wave data are processed using the software like KGS SURFSEIS (Figure 4). Using KGS software, each set of Rayleigh wave data (12 channel data set for each station location) is transformed from the time domain into the frequency domain using Fast Fourier Transform (FFT) techniques. These field-based data are used to generate site-specific dispersion curves (**V_R(f)** versus **λ_R(f)**) for each station location. The site-specific dispersion curves (**DCS**) generated from field-acquired Rayleigh wave data are then transformed into vertical shear-wave velocity profiles (**SASW** shear-wave velocity profile).

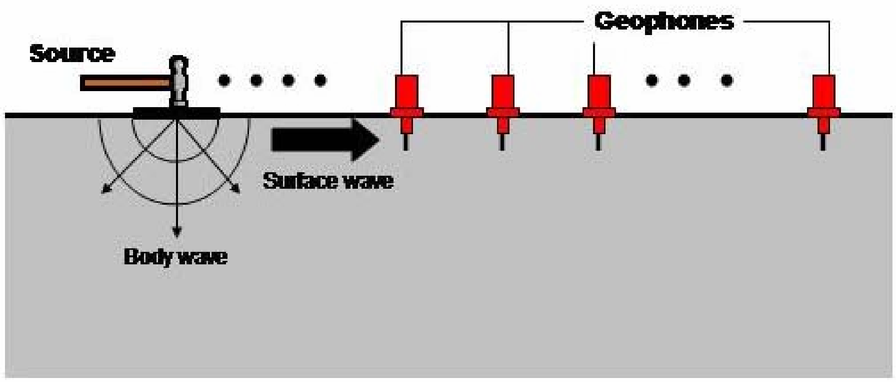


Figure 3: Field configuration. Each Rayleigh wave data set is recorded using an array consisting of multiple low-frequency geophones

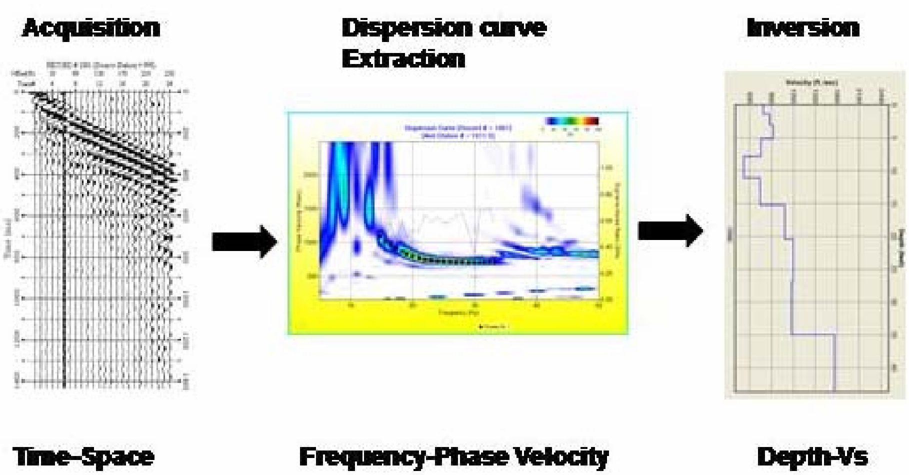


Figure 4: Dispersion curves are generated for each acquired Rayleigh wave data set.