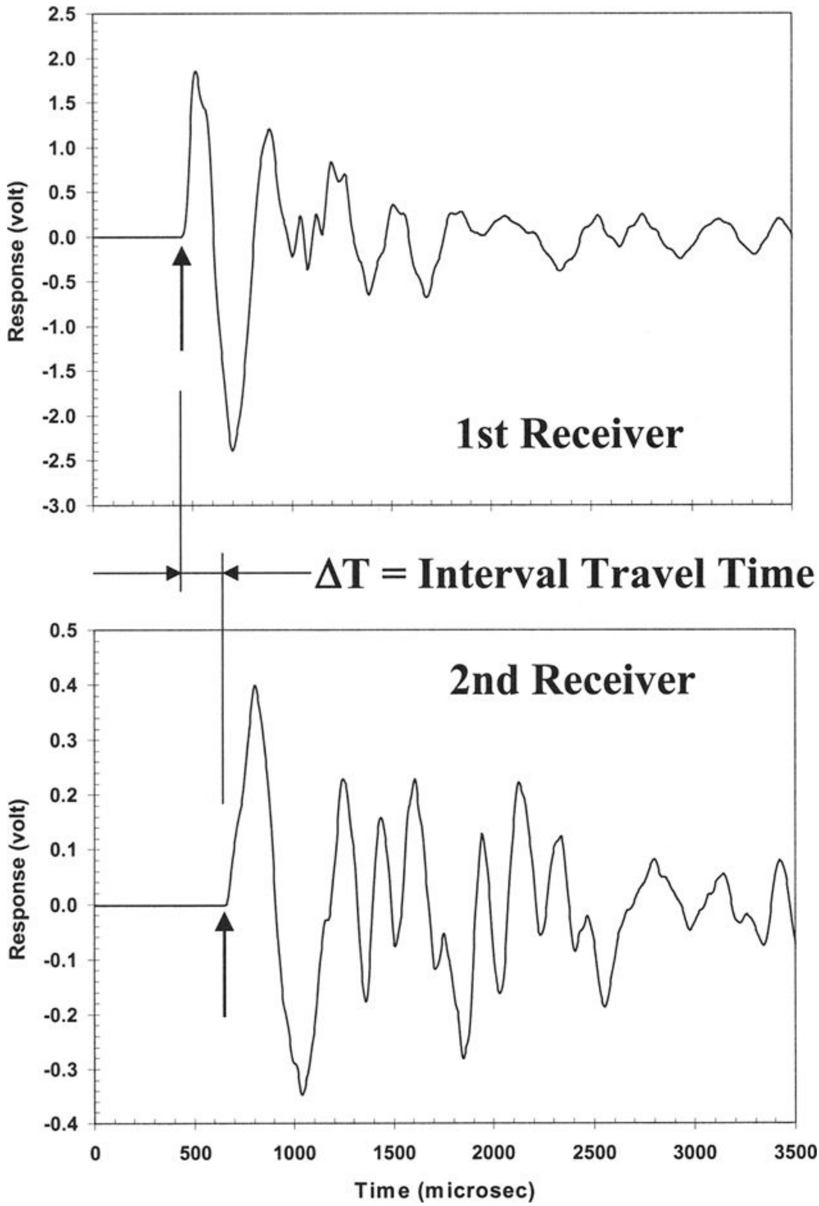

Figure 9. Typical Travel Time Record for Compression (P) Wave

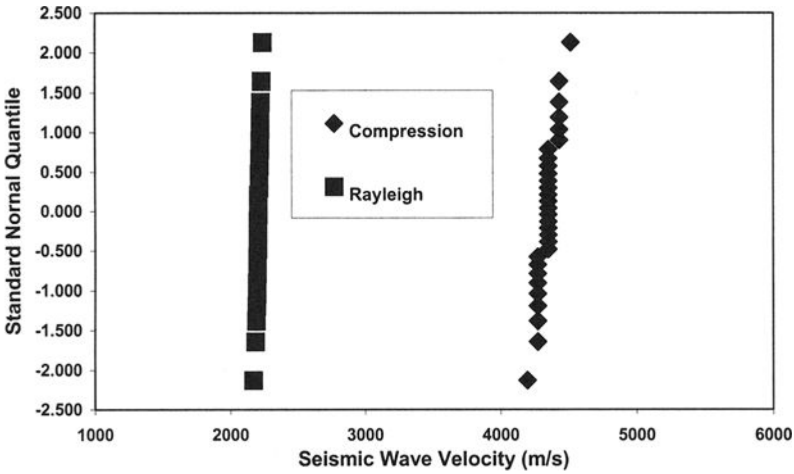

Figure 10. Normal Probability Plot for P-Wave and Rayleigh Wave Velocities

Rayleigh Wave SASW Testing

As suggested above, measurement of two different seismic waves must be obtained to characterize elastic properties of PCC. Compression wave velocities obtained from crosshole seismic surveying satisfy one of the required seismic waves. An attempt was made to produce and collect shear wave measurements in PCC using crosshole seismic surveying. However, no discernable shear waves could be obtained from crosshole testing. In fact, the majority of the energy from the source impact produced compression waves. Thus, shear waves could not be used as the second seismic wave. An alternative seismic approach was therefore sought. Using guidelines presented by Bay and Stokoe (1990, 1992), the spectral-analysis-of-surface-waves method (SASW) was used to obtain measurements of Rayleigh (surface) waves in PCC.

A number of publications in recent years have described in detail the SASW method (Nazarian [1984] and Hiltunen [1988]). Current practice calls for locating two vertical receivers on the surface a known distance apart; a wave containing a large range of frequencies is generated in the PCC by means of a hammer, vibrator, or other energy source. Surface waves are detected by receivers and are recorded using a Fourier spectrum analyzer. The analyzer is used to transform waveforms from the time to the frequency domain and then to perform necessary spectral analyses. Spectral analysis functions of interest are the phase of the cross power spectrum and the coherence function. Knowing the distance and relative phase shift between receivers for each frequency, the velocity of the Rayleigh wave (phase velocity) associated with that frequency is calculated.

Implementation of the SASW testing configuration on the surface of the PCC footing is shown in figures 7 and 8. The source consisted of a small ball peen hammer, and accelerometers were used as vertical receivers. Rayleigh wave measurements were collected at two receiver spacings, 76.5 and 153 mm. The recorder used in this study was a Hewlett Packard Dynamic Signal Analyzer, which is capable of recording wave arrival in the frequency domain. The essential measurement of the SASW method is the cross power spectrum, and a typical record for Rayleigh waves obtained from the SASW test on PCC is shown in figure 11. As mentioned previously, the cross power spectrum is used to calculate Rayleigh surface wave velocity, the average of which is shown in table 3 for the PSU test site.

The primary objective of seismic testing in this study was to determine uncertainty of wave velocities, including Rayleigh wave velocity. This determination required collection of replicate measurements. Specifically, thirty replicate measurements were collected at both the 76.5-mm and 153-mm receiver spacings. From replicate measurements, thirty Rayleigh wave velocities were calculated following standard SASW data processing procedures (Nazarian [1984] and Hiltunen [1988]). Descriptive statistics of these velocities were then computed and are shown in table 3. It is observed that there is low uncertainty in Rayleigh wave velocities collected from replicate tests on PCC using standard SASW test methods.

Figure 11. Typical Cross Power Spectrum for Rayleigh Waves in PCC

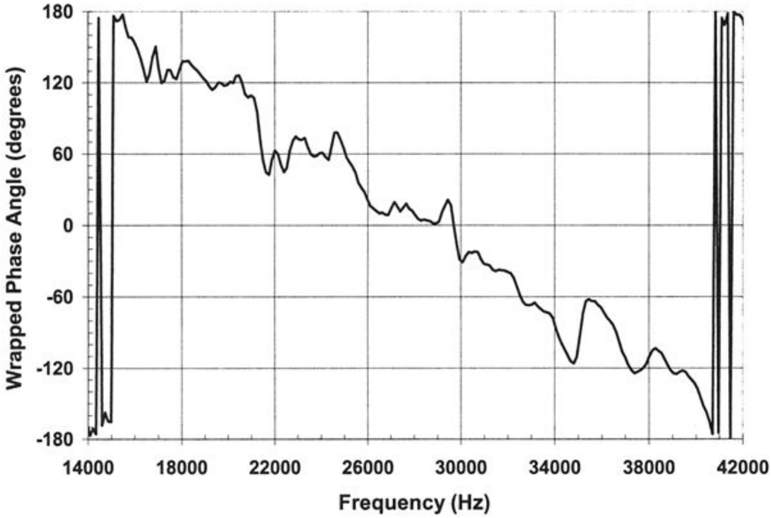

Table 3. Descriptive Statistics of Rayleigh Wave Velocity for PSU Test Site

	Average	Standard Deviation	Coefficient of Variation

Test Site	(m/s)	(m/s)	(%)
PSU	2208	13.7	0.6

The statistical distribution of Rayleigh wave velocities was also investigated by plotting a normal probability plot (figure 10). The data suggest that the normal distribution is the likely parent distribution of Rayleigh wave velocities. Thus, an assumption of normal distribution for Rayleigh wave velocity can be used for future error propagation techniques.

Poisson's Ratio

Design codes often ignore Poisson's ratio. However, two- or three-dimensional analyses typically require an estimate for Poisson's ratio. Specifically, it is a salient design parameter in analysis of flat-plate floors, shell roofs, arch dams, and mat foundations. A typical value for Poisson's ratio of portland cement concrete (PCC) is 0.20 (Kosmatka and Panarese [1988]). However, Poisson's ratio can range from 0.15 to 0.25 depending on aggregate, moisture content, concrete age, and compressive strength.

It is common practice to obtain Poisson's ratio of PCC by testing cylindrical or cubed samples that are considered representative of the parent material. However, in situ measurement of Poisson's ratio would likely be more indicative of the parent material. In fact, Poisson's ratio can be related to wave propagation velocities determined from seismic testing. As shown by Bay and Stokoe (1990, 1992), a relationship can be developed between compressive wave velocity (V_P), Rayleigh wave velocity (V_R), and Poisson's ratio (ν):

$$\frac{V_P}{V_R} = \sqrt{\frac{2(1-\nu)}{1-2\nu}}\,\frac{1+\nu}{0.862+1.14\nu}$$

Thus, Poisson's ratio can be determined from wave velocities of two seismic wave types: the compression wave velocity from crosshole measurements, and the Rayleigh wave velocity from the SASW test method. It is observed from this equation that it is difficult to directly solve for Poisson's ratio. However, the implicit equation can be easily solved using an iterative process.

Because any two- or three- dimensional analyses require an estimate for Poisson's ratio, it is important to assess uncertainty in Poisson's ratio as a function of uncertainty in compression and Rayleigh wave velocities. Harr (1987) suggests three types of analytical methodologies for conducting reliability assessments: first-order, second-moment methods; point estimate method (PEM); and so-called exact methods, such as Monte Carlo simulation and numerical integration techniques. In this case, Monte Carlo simulation was chosen.

In a direct simulation, random values from parent distributions of random variables are generated and used to calculate a sample of the desired output. This process is repeated for a large number of cycles to generate a sample set that will adequately approximate the probability distribution of the output. Monte Carlo simulation requires that the entire probability distribution of each independent random variable be known. In the case of compression and Rayleigh wave data, the parent distribution is reasonably approximated by the normal distribution as previously discussed. Harr (1987) maintains that it is important to conduct an adequate number of Monte Carlo simulation cycles to produce an accurate approximation of the probability distribution of the output. This can be achieved by conducting simulation at varying numbers of repetitions until predicted uncertainty ceases to fluctuate.

For Monte Carlo simulation of uncertainty in Poisson's ratio, an EXCEL program was compiled. The program used a random number generator to create samples of a standard normal deviate with a mean of zero and a unit standard deviation. This standard normal deviate, z, was then used to create samples, x_1 and x_2, from parent distributions of the compression and Rayleigh wave velocities with mean, μ, and standard deviation, σ. Tables 2 and 3 present the mean and standard deviation of compression and Rayleigh wave velocities in PCC. Poisson's ratio was then calculated from an iterative subroutine using the ratio of sample seismic velocities. Table 4 presents the results of the Monte Carlo simulation. It is observed that there is low uncertainty in the inferred Poisson's ratio.

Table 4. Descriptive Statistics of Poisson's Ratio

Test Site	Average	Standard Deviation	Coefficient of Variation (%)
PSU	0.28	0.012	4.2

Monte Carlo simulation enables generation of a large data set for Poisson's ratio. This data set was then used to investigate the statistical distribution of Poisson's ratio by plotting a normal probability plot (figure 12). This figure suggests that variation in Poisson's ratio of PCC is normally distributed.

FINDINGS

This study investigated uncertainty of parameters determined from seismic surveying. Through collection and analysis of a large sample of field data, this study documents the uncertainty and statistical distribution of three seismic wave velocities. In addition, descriptive statistics of Poisson's ratio assessed using error propagation techniques are reported. Based upon results of the testing and analyses conducted, key findings of this research are as follows:

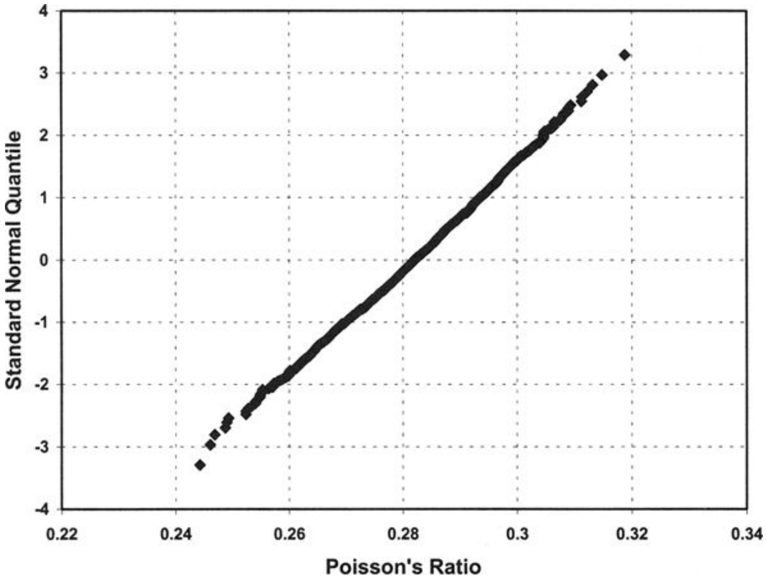

Figure 12. Normal Probability Plot for Poisson's Ratio

- Low uncertainty in vertical shear (SV) wave velocities collected from replicate tests on soil using standard crosshole seismic test methods. The coefficient of variation is typically less than 5%, and the distribution appears to be normal.

- Low uncertainty in compression wave (P) velocities collected from replicate tests on portland cement concrete (PCC) using standard crosshole seismic test methods. The coefficient of variation was found to be 1.5%, and the distribution appears to be normal.

- Low uncertainty in Rayleigh wave velocities collected from replicate tests on PCC using standard SASW test methods. The coefficient of variation was found to be less than 1%, and the distribution appears to be normal.

- Low uncertainty in inferred Poisson's ratio (ν). The coefficient of variation was found to be about 4%, and the distribution appears to be normal.

CONCLUSIONS

Based upon data presented herein, the following conclusions are appropriate:

- Small coefficients of variation of the SV, P, and Rayleigh wave velocities indicate a high degree of precision for these determined velocities.

- Small coefficient of variation for Poisson's ratio attests to the high precision of determining ν with seismic propagation techniques.

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SH-Wave Refraction/Reflection and Site Characterization

Zhenming Wang[1], Ron L. Street[2], Edward W. Woolery[3], Ian P. Madin[4]

Abstract

Traditionally, nonintrusive techniques used to characterize soils have been based on P-wave refraction/reflection methods. However, near-surface unconsolidated soils are oftentimes water-saturated, and when groundwater is present at a site, the velocity of the P-waves is more related to the compressibility of the pore water than to the matrix of the unconsolidated soils. Conversely, SH-waves are directly relatable to the soil matrix. This makes SH-wave refraction/reflection methods effective in site characterizations where groundwater is present. SH-wave methods have been used extensively in site characterization and subsurface imaging for earthquake hazard assessments in the central United States and western Oregon. Comparison of SH-wave investigations with geotechnical investigations shows that SH-wave refraction/reflection techniques are viable and cost-effective for engineering site characterization.

Introduction

Body waves propagate through soils or other materials by either inducing compression without a change in shape (P-waves), or by inducing a change in shape without changing the volume (S-waves). P-waves propagate through earth materials with a particle motion in the direction of propagation, whereas S-waves propagate with a particle motion perpendicular to the direction of propagation. The velocity of the P- and S-waves, V_p and V_s, can be expressed as

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[1]Earthquake Geotechnical Specialist, Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street #28, Suite 965, Portland, OR 97232
[2]Associate Professor, Department of Geological Sciences, University of Kentucky, Lexington, KY 40506
[3]Head, Engineering Seismology and Geological Hazards, Kentucky Geological Survey, University of Kentucky, Lexington, KY 40506
[4]Director, Geologic Mapping Program, Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street #28, Suite 965, Portland, OR 97232

$$V_p = \sqrt{\frac{3K+4\mu}{3\rho}} \quad (1)$$

and

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

where K is the bulk modulus, μ is the modulus of rigidity, and ρ is the density of the material through which the seismic waves are propagating. The bulk modulus and modulus of rigidity are elastic constants that define the way a material will respond to a small strains (typically less than 0.001%) of the materials configuration (Kramer, 1996). Other elastic constants commonly used in geotechnical engineering are:

$$Poisson's\ ratio:\ \sigma = \frac{1}{2}\left[\frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2}\right] \quad (3)$$

and

$$Young's\ modulus:\ E = 2\mu(1+\sigma) \quad (4)$$

Since any of the elastic constants can be expressed in terms of two others, the elastic characteristics of a material, such as soil or rock, can be determined by measuring the P- and S-wave velocities and knowing the density of the material.

P- and S-waves are refracted and reflected as they propagate through the soils and rocks in the earth because of stratification in the elastic properties of these materials. Fig. 1b shows the travel paths of the direct wave, reflected, and refracted waves for a two-layered medium with a horizontal interface. The travel times are a function of horizontal distance as shown in Fig. 1a. From the travel-times and distances, the velocities V_1 and V_2 for layers 1 and 2, respectively, as well as the thickness of layer 1, H, can be determined. The detailed derivation of these parameters is well known and can be found in many references, such as Lankston (1990) and Kramer (1996). Seismic data acquired from surface refraction and reflection studies have been widely used for determining the P- and S-wave velocities and thicknesses of soils in geotechnical engineering studies (Peck and others, 1974; Whitlow, 1990; Kramer, 1996; Merritt and others, 1996).

Surface P-wave refraction and reflection methods have been commonly used in site characterization studies, but they are limited at sites where P-wave velocities of soil matrices are less than the velocity of water and high ground water levels are present.

Water is incompressible and transmits P-waves with a constant velocity of about 1,433 to 1,463 m/s (Peck and others, 1974; Merritt and others, 1996). However, the velocity of P-waves in unconsolidated and unsaturated soils is generally much less than 1,433 m/s. Peck and others (1974) gave P-wave velocities for dry silt, sand, loose gravel, loam, and talus of 183 to 762 m/s and noted, that if the same materials were saturated, the P-wave velocities would equal or exceed 1,433 m/s. By contrast, the S-wave propagates only through the soil matrix, and can not be transmitted through water because the shear modulus of water is zero (equation 2).

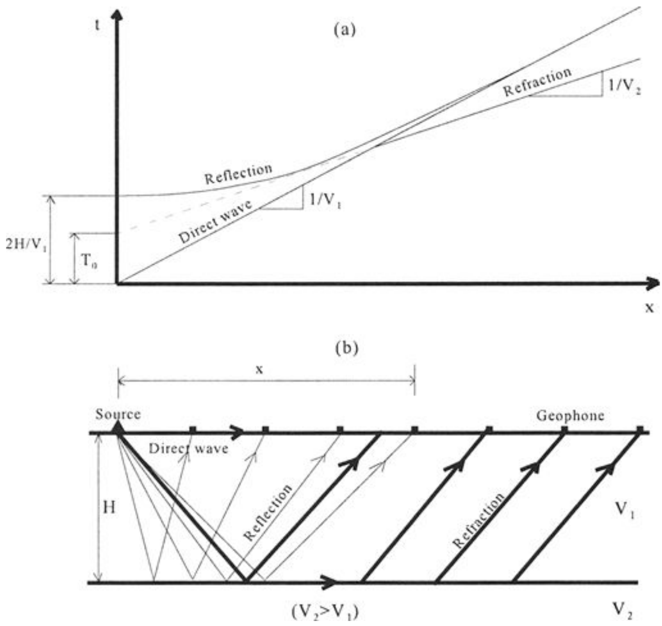

Figure 1. Refractions and reflections in a two-layer medium and their travel-time curves.

Refractions in a soil or rock occur because of contrasts in velocity, whereas reflections in a soil or rock occur because of contrasts in impedance at interfaces. The impedance of a soil or rock unit is defined as the product of density times the velocity of the soil or rock unit. The P-wave velocities of most dry soils, such as silt, sand, and loose gravel, are less than the P-wave velocity of water (Peck and others, 1974). Since the P-wave propagates with the velocity of the water in these soils when they are saturated, there are no contrasts in velocity between the soils if they are below the water table. The P-wave refraction method is ineffective, and the reflection method depends