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Soil Profiling by Spectral Analysis of Surface Waves

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SYNOPSIS: Methods for in-situ surface measurement and spectral analysis of Rayleigh waves for subsurface soil investigation have been tried by several researchers in recent years. The two most common methods, steady-state Rayleigh-wave and spectral-analysis-of-surface-waves (SASW) have certain disadvantages and are not used for routine soil investigation. The paper presents a system which uses a controlled vibration source with amplitude modulation and variable frequency capabilities. The electromagnetic vibrator, may be varied in size and weight according to the depth of the soil strata investigated. The Rayleigh wave phase velocity dispersion curves are used to compute apparent velocity distribution in depth. An approximate conversion method is then used to estimate Rayleigh wave velocity profiles of the layered soil from the apparent velocities distributions. Shear wave velocities, computed by using established theoretical relationship, may then be used to obtain design parameters for the soil strata. The system has been used routinely in Japan and South East Asia for several years now and results show good correlations with SPT and shear wave velocity measurements conducted as verification tests in a variety of sites.

INTRODUCTION

Accurate shear wave velocity profiles have been long recognized as essential data to evaluate the dynamic response of soil deposits, vibrations of machine foundations, and soil-structure interaction under earthquake and other forms of dynamic loading, as recently reported by Hiltunen and Woods (1988), Stokoe et al. (1988) and many others.

Direct measurement of body wave velocities using downhole or crosshole measurement have been used for many years. The problem with these widely used methods is that they are difficult and costly to conduct. Seismic refraction methods by surface measurements of reflected P-waves have also been developed and used for soil profiling. However, measurements from these seismic methods are generally difficult to interpret, especially in irregular and inclined soil deposits. Therefore, the advantage of obtaining shear wave velocity profiles by in situ surface wave measurements, especially in hard-to-sample soils, has been recognized since the 1960's when Jones (1962) and Ballard (1964) developed the first measurement systems. Since then several researchers have developed and improved the techniques for surface wave measurement. Using these methods, shear moduli may be determined for strains less than 0.001 percent where the elastic parameters of geotechnical materials are essentially independent of strain amplitude. These parameters may then be employed in designing facilities subject to dynamic loading, and other evaluations such as site response and liquefaction risk assessment. Shear wave velocity is directly related to the stiffness of the geotechnical material skeleton through which it propagates. Therefore it is possible to correlate material properties to the measured shear wave velocity. Correlations are available for in situ density from which other parameters, such as in situ static shear strength, may be estimated.

These surface-waves measurement methods include steady-state Rayleigh-wave, spectral analysis of surface waves (SASW), and the controlled-source SASW (CSSASW). The CSSASW is a combination of the steady-state Rayleigh wave and the SASW method. Stokoe et al. (1988) has described the evolution of the steady-state and the SASW methods. Although it is well understood, the steady-state method has a major disadvantage since the field procedure is very time consuming. The SASW method, where surface waves are generated by a single impact, is, generally, limited to near-surface profiling and results from deeper strata are difficult to interpret. The CSSASW may be regarded as a combination of the steady-state and the SASW methods. It offers the advantages of both methods without their disadvantages. The field procedure is simple and rapid and the system has been used for depth reaching 100 m (with a large vibrator). The CSSASW method is described in the following sections.

THE CSSASW TECHNIQUE

The propagation of surface (Rayleigh) waves is well understood and explained in the literature. The velocity of propagation of a Rayleigh wave in layered media depends on its frequency (or wavelength). The variation of wave velocity with frequency is called dispersion. The dispersion occurs because waves of different wavelengths affect different parts of the layered media. For example, low frequency waves (long wave lengths) propagate deep into the strata through both near-surface and deeper layers, whereas high frequency waves (short wavelengths) propagate only through near-surface layers. Therefore, all

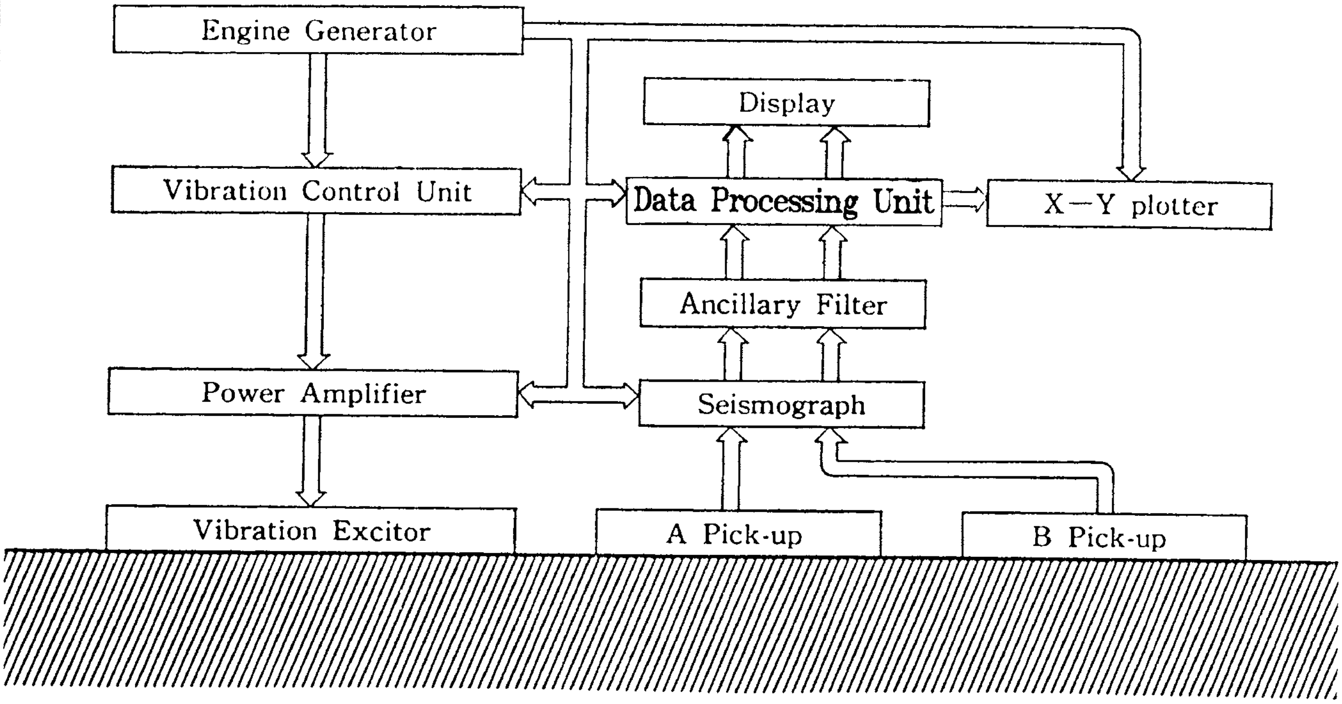


Figure 1 - Schematic Layout of the CSSASW System.

surface wave measurement methods use a wide range of surface wave frequencies, in order to sample the different parts and depths of the soil strata. In the steady-state method, the frequency is changed manually for each measurement, whereas the SASW is performed by using the frequency domain from a Fast Fourier Transform of an impact pulse.

The CSSASW concept is based upon the generation of a series of amplitude modulated (AM) vibration pulses at varied frequencies using a controlled electromagnetic vibrator which generates surface waves. Rayleigh waves are measured by two vertically oriented acceleration sensors positioned at a known distance near the excitor. Once positioned, the sensors are not moved until the profiling process is completed for that location.

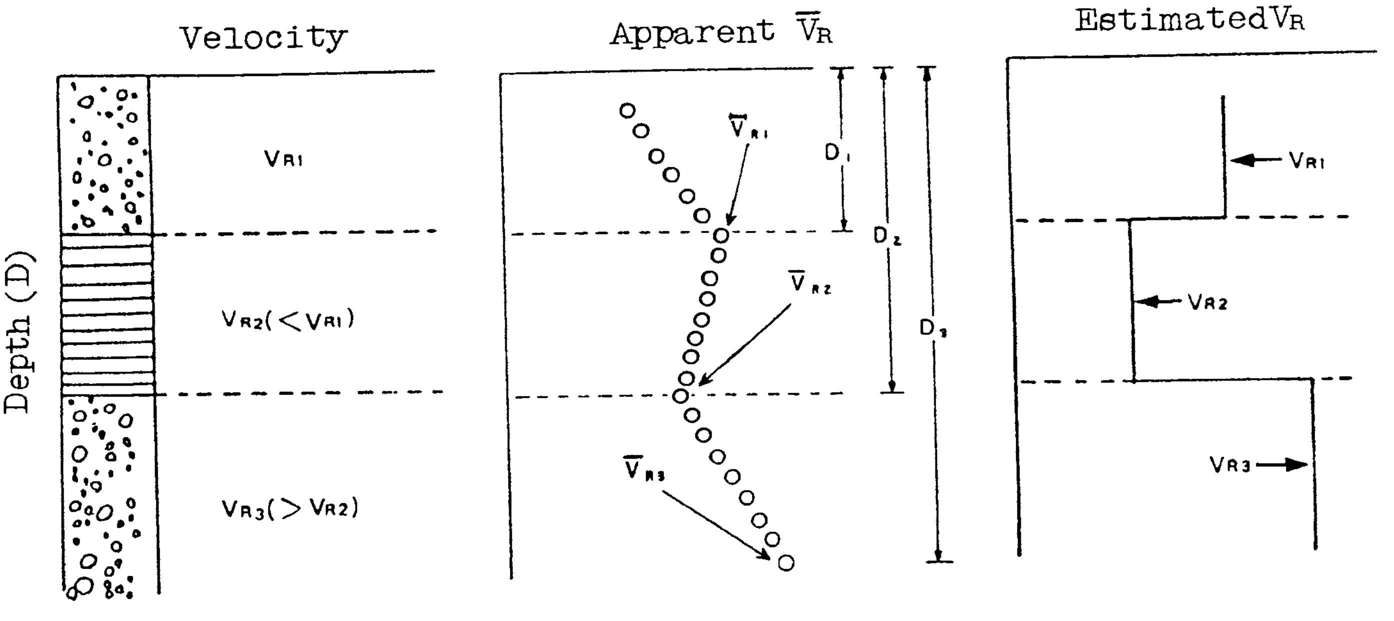
A layout of the system is shown in Figure 1. As previously indicated the vibrator is excited by a series of AM pulses at different frequencies. The vibration pulse generates primarily first-mode Rayleigh waves which are picked up by the two acceleration sensors connected to the data processing unit (DPU) via a seismograph and a signal conditioning ancillary filter. For a given pulse frequency, **f**, the signals are automatically processed by the DPU where the respective picks of the source pulse and the signals from the two pick-ups can be identified without difficulties due to the **AM** vibration pulse. The apparent Rayleigh wave velocity, $\bar{V}_R$, and the affected depth, D, are, respectively calculated, as:

$$\bar{V}_R = \frac{S}{\Delta T} \qquad (1)$$

where S is the distance between the two pick-up sensors and ΔT is the Rayleigh wave propagation time between the pick-ups determined by the DPU.

Equation 1 is similar to the steady-state method with the difference being that the distance S remains constant throughout the CSSASW testing. This automated process is very rapid, and when completed the data is stored in the microprocessor and the next AM pulse is generated by the vibrator at a different frequency to continue the profiling process. Generally, this discrete spectral analysis process starts at the higher frequency end (for surface layers) and the successive sampling frequencies are automatically lowered for deeper strata. The number of sampling pulses and frequency range may be adjusted according to the characteristics and depth of the strata.

Equation 2 is based on an approximate approach, reported by Richart et al. (1970) and other researchers, where the depth is estimated as half of the appropriate wavelength. Using Equation 2, the simplified experimental dispersion curve for the first-mode phase velocity is then computed by the DPU and displayed versus depth (rather than wavelength).



a) Schematic Composition of sub-surface layers

b) D-$\bar{V}_R$ curve (Apparent Velocity)

c) Layer Velocity

Figure 2 - Simplified Conversion of Apparent Rayleigh Wave Velocities.

$$D = \frac{\bar{V}_R}{2f} \qquad (2)$$

As indicated by Stokoe et al. (1988), this approach provides an approximated dispersion curve since the parameters above and below a depth of one-half the wavelength have some effect on the propagation velocity at that frequency (or wave length). Nazarian (1984) has presented an "inversion" technique for converting an experimental "raw" dispersion curve ($\bar{V}_R$ vs. f) to idealized layered profile where the shear wave velocities and layer thickness are adjusted to produce a computed dispersion curve which correlates to the raw, measured profile. This inversion technique does indeed produce more accurate results when compared to the simplified approach used in earlier steady-state and SASW measurements. However, it is time consuming and, generally, effective only in sites with limited number of horizontal layers.

Satoh (1989) has developed a simplified conversion technique to estimate the Rayleigh wave velocity, V_R, for the layered strata, based on the approximate $\bar{V}_R$ vs. D profile previously discussed. Satoh's conversion takes into consideration the effect of the material above and below depth D by referring to the peak values and slope changes in the $\bar{V}_R$ vs. D curve, as shown in Figure 2. The conversion technique uses two typical relationships. The first relationship is for the case where $\bar{V}_R$ is increasing with depth. For example, this relationship is used to calculate the estimated layer velocity V_{R3} shown in Figure 2 as:

$$V_{R_3} = \frac{\bar{V}_{R_3}D_3 - \bar{V}_{R_2}D_2}{D_3 - D_2} \qquad (3)$$

where the generalized form of Equation 3 is

$$V_{R_n} = \frac{\bar{V}_{R_n}D_n - \bar{V}_{R_{n-1}}D_{n-1}}{D_n - D_{n-1}} \qquad (4)$$

The second relationship is used where $\bar{V}_R$ is decreasing with depth such as shown for layer 2 in Figure 2 where V_{R2} is computed as:

$$V_{R_2} = \frac{D_2 - D_1}{\dfrac{D_2}{\bar{V}_{R_2}} - \dfrac{D_1}{\bar{V}_{R_1}}} \qquad (5)$$

where the generalized form of Equation 5 is

$$V_{R_n} = \frac{D_n - D_{n-1}}{\dfrac{D_n}{\bar{V}_{R_n}} - \dfrac{D_{n-1}}{\bar{V}_{R_{n-1}}}} \qquad (6)$$

Satoh (1989) has shown that this simplified conversion technique is, generally, sufficient to correct the apparent $\bar{V}_R$ vs. D profile for the effects of the soil below and above any depth

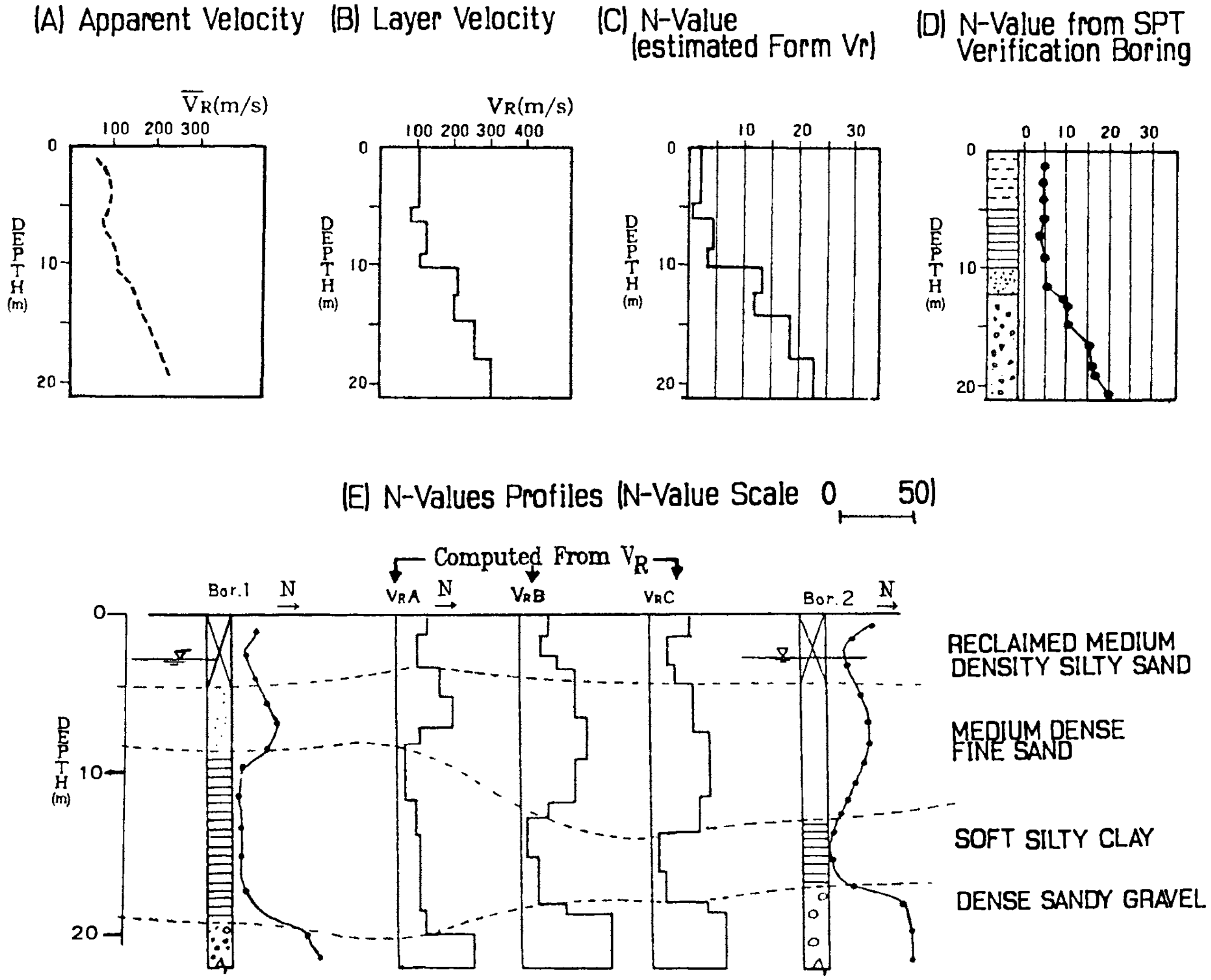


Figure 3 - Case Study at Housing Project Near Osaka (Satoh, 1989).

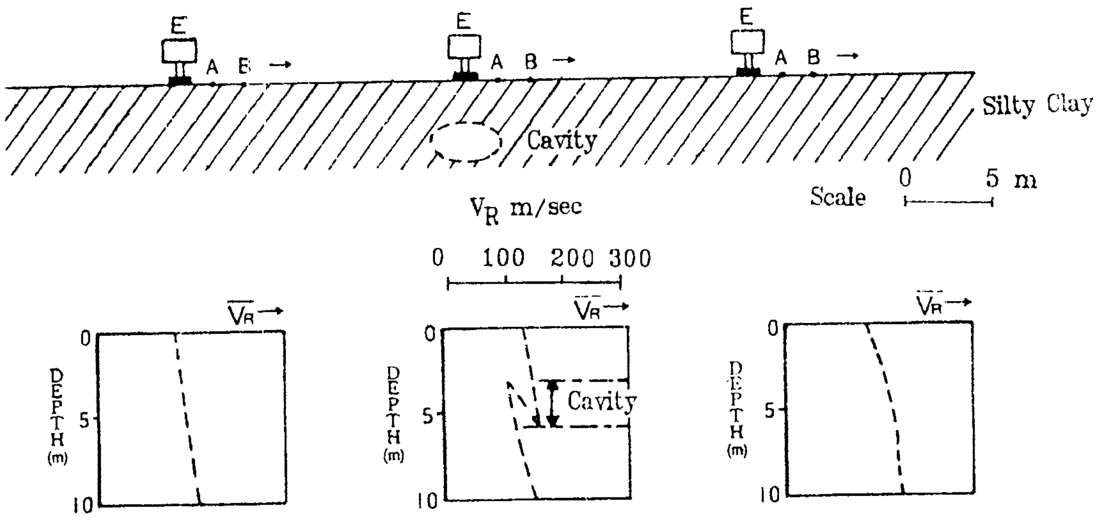
and obtain an accurate layered profile. His study indicate that theoretical dispersion curves computed according to a modified Haskell (1953) solution, may be correlated with apparent dispersion curve measured by the CSSASW method. An estimated layered profile may then be adjusted in an iterative computational process until the theoretical dispersion curve correlates well with the measured one. However, like the inversion method (Nazarian, 1984), this computation is complex and limited to ideally layered strata. Therefore, at present the simplified conversion proposed by Satoh (1989) provides a preferable alternative.

FIELD PROCEDURE

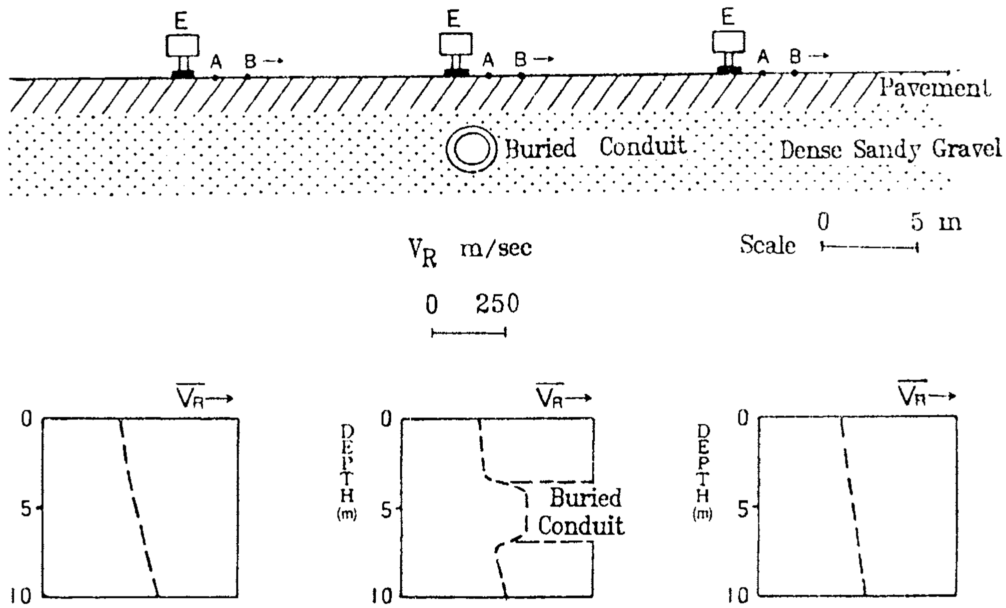
The field procedure, generally, includes the following steps:

i) The selection of the appropriate vibrator and its power amplifier is based on the required profiling depth. At present 6 vibrator sets are available for depths of 10, 20, 40, 50, 70, and 100 m, where deeper profiling requires larger excitor, respectively.

ii) The vibrator and the pick-up sensors A and B are placed at the profiling location, where A is located approximately 1 m from the vibrator, and B is located any where between 0.5 and 2 m from A, at any



(A) Cavity Detection



(B) Buried Conduit Detection

Figure 4 - Case Studies of Cavity and Buried Conduit Detection (Satoh, 1989).

convenient point on the straight line extending from the vibrator through sensor A.

iii) The sampling frequency range and decrements are set up based on the profiling requirements.

iv) The system is activated and the first AM pulse is applied by the vibrator at frequency f_1. The propagation time of respective AM Rayleigh wave peaks between sensor A and B (ΔT) is computed by the DPU. Then the DPU computes the apparent Rayleigh wave velocity V_R and its respective depth D and the data is stored and displayed as a dot on the apparent velocity profile. When this rapid computation is completed the next AM pulse is automatically applied at frequency f_2. This process is automatically repeated for the successive sampling frequencies until the profile is completed.

v) The $\overline{V}_R$ vs. D profile is displayed as discrete dots and may be plotted if desired. The simplified conversion computation is then rapidly conducted by the DPU and the layered V_R profile is stored and displayed, and may be plotted, as appropriate.

vi) The profiling is now completed at that location. The excitor may be loaded to the light equipment truck and moved to the next profiling location. Generally, the time required for this measurement process ranges between 5 to 30 minutes, for near-surface and very deep soil deposits, respectively.

CORRELATIONS TO RAYLEIGH WAVE VELOCITY

Shear wave velocity are computed from V_R based on relationships established in the literature where the ratio of V_R to shear wave velocity, V_S, ranges between 0.874 to 0.955 for Poisson's ratio of 0.0 to 0.5, respectively. Based on his data from many Japanese sites, Satoh (1989) applies an empirical relationship to compute V_S, where:

$$V_R = 0.89\, V_s + 4 \qquad (7)$$

and the units are m/sec.

Satoh (1989) also presented many correlations from the literature between shear wave velocity and soil parameters such as elasticity and shear moduli, SPT N-value, unconfined compressive strength, internal friction angle, at-rest earth pressure coefficient, and others. The SPT N-value conversion is, generally, desired in many routine projects in Japan and is based on:

$$N = 10^{\frac{\mathrm{Log}\, V_s - 1.954}{0.337}} \qquad (8)$$

where V_S is in m/sec.

CASE STUDIES

Since the CSSASW method is being routinely used in Japan for several years now many case studies are available where verification tests were carried out together with the V_R profiling. A case study is presented in Figure 3, where N-value profiles calculated from V_R profiles show good correlation to verification SPT borings conducted on the site. The system has been also successfully used for specialized applications such as surface monitoring of tunnel construction, identification and location of sub-surface cavities and buried objects as shown in Figure 4, location of failure surface of unstable slopes, and quality control of the concrete and foundation rock in concrete gravity dam construction.

CONCLUSIONS

The CSSASW method may be used for near-surface and deep profiling of soil strata by surface measurements of Rayleigh waves generated by applying a series of AM pulses at varied frequencies with a controlled electromagnetic vibrator. Layered profiles obtained from the simplified conversion method of apparent Rayleigh wave velocity profiles show good correlation to results from verification borings and direct shear wave velocity measurements. Soil parameters are correlated to shear wave velocities computed from the Rayleigh wave profiles. These parameters are then used in evaluation and design for static and dynamic load conditions. In addition to soil profiling, the method may be used for a variety of applications including cavity and buried object detection.

REFERENCES

Ballard, R.F., Jr, "Determination of Soil Shear Moduli at Depth by In Situ Vibratory Techniques," Miscellaneous Paper No. 4-691, U.S. Army Engineer Waterways Experiment Station, Vicksburgh, Mississippi, 1964.

Haskell, N.A., "The Dispersion of Surface Waves in Multilayered Media," Bulletin of the Seismological Society of America, Vol.43, 17-34.

Hiltunen, D.R., and Woods, R.D., "SASW and Crosshole Test Results Compared,"ASCE Specialty Conference on Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, Park City, Utah, 1988, 279-287.

Jones, R., "Surface Wave Technique for Measuring the Elastic Properties and Thickness of Roads: Theoretical Development," British Journal of Applied Physics, 1962, Vol. 13, 21-29.

Nazarian, S., "In Situ Determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral-Analysis-of-Surface-Waves Method," Ph.D. Dissertation, The University of Texas at Austin, 1984.

Richart, F.E., Hall, J.R., and Woods, R.D., <u>Vibrations of Soils and Foundations</u>, Prentice-Hall Inc., New Jersey, 1970.

Satoh, T., "On the Controlled Source Spectral Rayleigh Wave Excitation and Measurement System," VIC, Tokyo, 1989.

Stokoe , H.S. et al, "In Situ Testing of Hard-to-Sample Soils by Surface Wave Method," ASCE Specialty Conference on Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, Park City, Utah, 1988, 264-278.