A New Interpretation Method of Surface Wave Measurements to Obtain Representative Shear Wave Velocity Profiles of Soils

by

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ABSTRACT

Recently, the importance of obtaining a representative average shear wave velocity (SWV) profile has significantly increased with new methods proposed for the evaluation of site amplification. The new methods may require engineers to obtain cost-effective measurements of SWV profiles reaching significant depths. Non-invasive SWV profiling of soil deposits has long been recognized as a cost-effective approach to obtain such SWV data. The controlled-source measurement of surface wave dispersion (CXW) is a relatively new non-invasive method that is used for site characterization in the USA and abroad. The CXW method uses harmonic controlled sources to produce steady state Rayleigh waves in order to measure the dispersion characteristics of soil and rock. It may be regarded as a combination of the traditional spectral analysis of surface waves and steady-state Rayleigh waves methods. Several interpretation techniques may be used to obtain SWV structure from Rayleigh waves dispersion data (in a process that is referred to as the Vf-Vs method). CXW measurement data from more than 200 soil and rock sites were analyzed. These results were used to formulate a new interpretation procedure for the Vf-Vs method based on the concept of reference profiles that describes the average dispersion curve and SWV structure. The reference profiles functional form was formulated by taking into account the SWV dependency on confining pressure (depth) in soils. Simple equations for a direct inversion of the reference profile were developed. This paper presents the reference profile concept and shows that it fits well with measured CXW data. Reference SWV profiles may be obtained in the field almost immediately following the measurements and may be used as representative profiles for site amplification evaluations eliminating the need for computationally intensive inversion solutions used with other Vf-Vs methods.

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INTRODUCTION

Shear wave velocities of soil and rock deposits are essential data for the analysis of soil behavior under earthquake and other dynamic loading. Shear wave velocity (SWV) can also be used to define low strain elastic moduli for soil characterization and analysis of static problems. Dobry (1991) and others introduced the impedance ratio concept for the evaluation of site amplification. It is possible that this approach will affect design procedures and building codes in the near future. In this approach it is important to obtain representative SWV data to considerable depths. It appears that for this application layered data details are less important and since it is the average SWV structure of the deposit that is used in the computation of impedance ratio and resulting site amplification. This lends itself to application of non-invasive cost-effective surface wave methods.

Several seismic methods have been developed for situ SWV evaluation These methods are based on the propagation of elastic waves generated at one point (source) and monitored at other locations (receivers). Among them there is one group of methods that is based on non-invasive Rayleigh wave measurements at the ground surface. Because it is a non-invasive method it provides an attractive alternative to more costly intrusive methods such as down-hole and cross-hole SWV measurements. Other advantages of this group of non-invasive methods include its simple measurement procedures and the accuracy of measured data. Its disadvantages include difficult data interpretation and inherent resolution limitations.

The propagation velocity of surface waves depends on the SWV (**Vs**) structure of the soil. If the properties of the soil profile are constant with depth, surface waves of different wavelengths (or frequencies) travel at the same velocity. However, if soil properties vary, surface waves of different wave lengths travel at different phase velocities. This variation of the phase velocity (**Vf**) with wave length is referred-to as dispersion. In this paper, the process of obtaining **Vs** structure from measured **Vf** data is referred to as the Vf-Vs method. The Vf-Vs principle is used in several different methods such as the spectral analysis of surface waves (SASW), the controlled source spectral analysis of surface waves (CXW), and other techniques based on the use of background vibrations or earthquake data to define the surface wave dispersion.

The objective of the Vf-Vs method is to obtain a SWV profile for a site by using the measured dispersion curve. This is an inverse problem in which the properties of the system are computed from the response to an excitation of stress waves. The main tool available for the solution of this inverse problem is the forward modeling of elastic wave propagation. Using these models the dispersion curves can be computed for a known soil profile. Nonlinear optimization formulations are used with the forward modeling to compute a soil profile with a dispersion curve that is compatible with the measured.

Inversion procedures for Vf-Vs methods available to date have serious limitations. Even if the intent is to produce a "smooth" SWV profile, they require extensive computations, their results are not unique, and there are no appropriate means to evaluate the resolution and accuracy of the results. These procedures also require highly specialized and experienced analysts. These drawbacks have limited the general use of Vf-Vs methods. This paper presents a new reference profile concept that extends the application areas of these methods.

THE CXW METHOD

General

The CXW method may be regarded as a combination of the steady-state Raleigh waves and the spectral-analysis of surface waves, offering the advantages of both methods (Rodriguez-Ordonez 1994, Poran et al. 1992 and 93, Arbelaez-Hoyos 1992, and Satoh 1989 and 91).

In the CXW method, a powerful electromagnetic exciter (the controlled-source) generates operator-selected, repeated surface vibrations that are recorded by two vertically oriented receivers placed near the controlled source as shown in Figure 1. Various modes of repeated source excitation may be used for accurate data averaging. The control unit (CU) of the system is used both as signal generator and as a advanced signal analyzer.

Typically, the on-site time required for a complete CXW measurement and data interpretation (to generate a SWV profile) may range between 10 minutes for profiling depths of 10 m with a small exciter (70 kg maximum dynamic force) to 50 minutes for profiling depths of 35 m with a larger exciter (250 kg maximum dynamic force).

Computation of the Dispersion Curve by Spectral Methods in CXW Measurements

In a CXW test the receivers are located colinearly with the source at known distances. The acceleration or velocity response is measured at the receiver locations and the cross power spectrum is computed. The phase of the cross power spectrum of the recorded signals contains the information on the propagation velocity as a function of the frequency that is the basis of the spectral analysis of Rayleigh waves.

During the tests, the phase shift, ϕ, between the two receivers is automatically computed by the CU. The computation of phase velocity is based on the consideration that the travel time for one wave length is the period **T**, that is the inverse of the frequency **f**. The travel time, **t**, equivalent to the phase shift is given by:

$$t = \frac{\phi}{360} f \tag{1}$$

During this time the wave traveled over the distance between the receivers, **X**, at a velocity Vf. This phase velocity ($\mathbf{V_f = X/t}$) is automatically computed as:

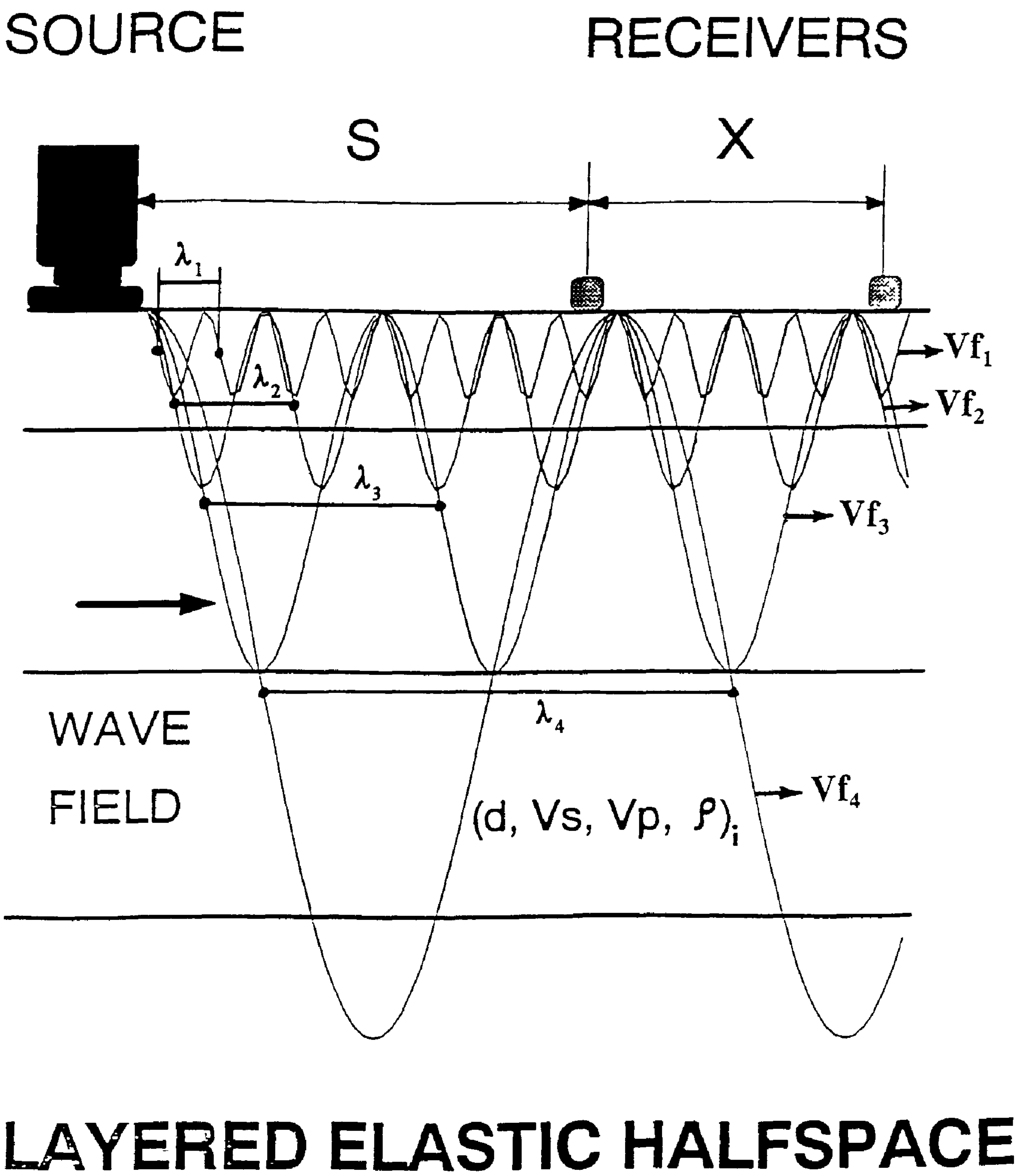


Figure 1. CXW Test Configuration

$$V_f = \frac{360 \, X \, f}{\Phi} \qquad (2)$$

The wavelength, λ, is computed as $\lambda = V_f/f$. The results from Equation 2 for the descritized frequency range used for the test define the experimental dispersion curve. These data are the basis for the interpretation of the SWV structure that is the purpose of the test as shown in Figure 2.

THE REFERENCE PROFILE CONCEPT

Phase and SWV Reference Profiles

Generally, CXW results show that the variation of phase velocity with wave length in soil profiles can be defined by a simple function of two parameters (Rodriguez-Ordonez 1994). This is based on data from more than 100 sites of different geological deposits and supported by SASW data from the literature. The function that best fit the experimental data is defined as the reference phase velocity profile. The reference profile in a uniform soil site is defined by two parameters, **Vof** and $\mathbf{m_f}$ which relate the phase velocity **Vf** with the wave length λ by the equation:

$$Vf = Vof \left(\frac{\lambda}{2} \right)^{m_f} \qquad (3)$$

The purpose of test data interpretation is to obtain a SWV profile with a dispersion curve that is close to the measured dispersion within a given tolerance. Experience has shown that there are different SWV profiles with a similar dispersion curve. The main difference between them is in their smoothness. This effect is illustrated in Figure 2 where a profile composed of a few layers like that shown in Figure 2.b have the same dispersion curve as the smoothly varying profile shown in Figure 2.c. Even in situations like the dotted line SWV profile, relatively thin layers with large SWV changes do not produce substantial change in the dispersion curve as shown in Figure 2.a.

Rodriguez-Ordonez (1994) concluded that a smoother profile is in a sense an average of the other rougher profiles that produce a similar dispersion curve. By increasing the smoothness it is possible to obtain a continuous **Vs** profile that matches the target data and resembles its dispersion curve.

The main problem in data interpretation is how to select the most representative profile. The Vf-Vs method by itself cannot provide a good answer to this question, since the data consist of the dispersion curve that can be equally well fitted by several different profiles.

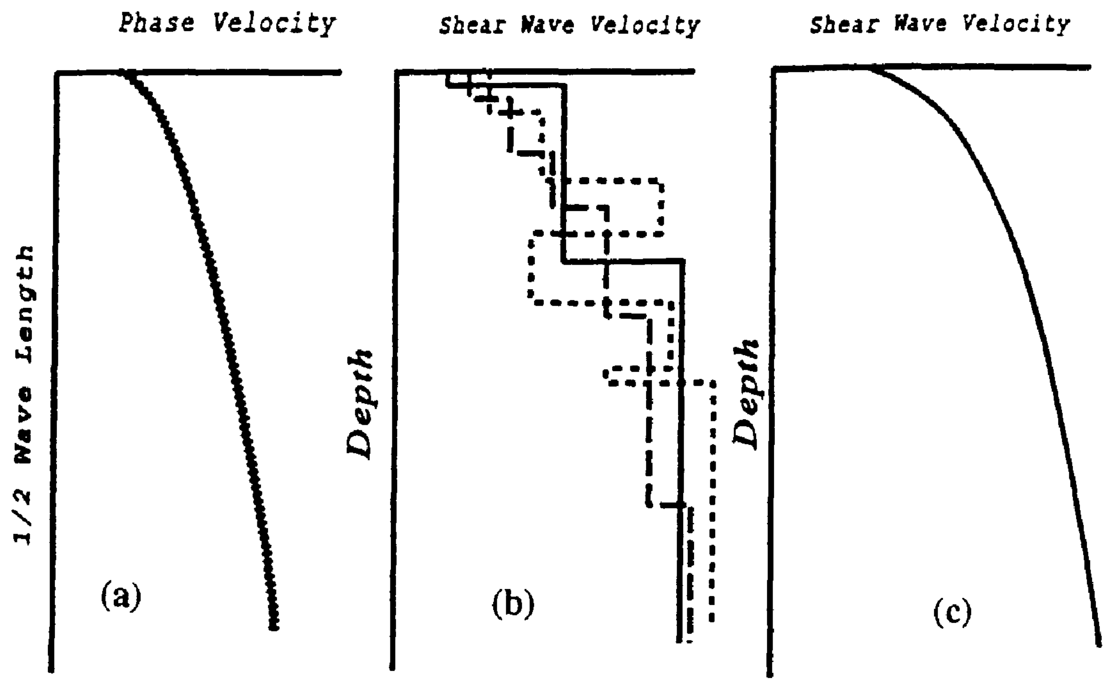


Figure 2. Illustration of: a) Dispersion Curves; b) Corresponding SWV Profiles; and, c) The Corresponding Reference SWV Profile

One can consider different criteria to constraint the solution (the smoothing criteria for the interpreted profile). The criteria may be the mathematical formulation of the optimization, or physical considerations. All the interpretation formulations used to date have used standard minimization formulations, some of them including smoothing constraints. The new interpretation procedure smoothing criteria is based on the reference profile concept that is based on physical, experimental and theoretical considerations.

The main assumption of the new method is that the form of the reference profile described by Equation 3 is a direct consequence of the actual variation of the SWV with depth in soil profiles. Since most available data show that SWV profile and the dispersion curve correlate in a similar way, the reference SWV profile may be described by an equation that is similar to Equation 3. The SWV reference profile in a uniform soil site is defined by two parameters **Vos** and $\mathbf{m_s}$ (Rodriguez-Ordonez 1994), which relate the SWV (**Vs**) to depth **Z** by the equation:

$$Vs = Vos\, Z^{m_s} \tag{4}$$

This assumption is based on the typical results illustrated in Figure 2, where the smooth SWV profile is also similar to the measured dispersion curve.

Physical Basis of the Reference Profile

SWV of soils depend on several parameters. According to Mitchell (1993), the most important are:

- The type of soil, defined by compositional and environmental factors such as mineralogy, internal structure, cementation, overconsolidation, and geologic age.
- The cyclic strain, strain rate and number of loading cycles.
- The effective confining stress.

The basic form of the relationship between these parameters was determined by Seed et al. (1984) and others from laboratory tests. For non cohesive materials the form is given by:

$$G = 4572\ K_2 \sqrt{\sigma_m} \tag{5}$$

The equation units are in kPa, where **G** is the shear modulus, σ_m is the mean effective stress and $\mathbf{K_2}$ is a coefficient that depends primarily on grain size, relative density, and shear strain. The shear modulus or shear stiffness is defined as the ratio of the shear stress and the shear strain.

For cohesive soils, the following equation was reported (Dobry and Vucetic 1987) to compute the shear modulus at low strains **Gmax**:

$$G_{max} = 625 \frac{OCR^k}{0.3 + 0.7 e^2} \sqrt{P_a \sigma_m} \qquad (6)$$

where **OCR** is the overconsolidation ratio, **e** is the void ratio, **Pa** is atmospheric pressure and **σm** is the mean effective stress, all in any consistent units. This equation was also developed based on laboratory tests data.

Equations 5 and 6 show that for all soils the shear modulus depends on a function of the soil type and strain level multiplied by the square root of the mean effective stress.

For the elastic waves used with the Vf-Vs method, the strain levels in the soil are very low. The shear modulus has its maximum value at low strains as given by Equation 6. In Equation 5 the value of K_2 is also a decreasing function of the strain level with the maximum at low strain level values. Therefore, for the Vf-Vs measurements the form of Equations 5 and 6 is in general:

$$G = F_1 \sqrt{\sigma_m} \qquad (7)$$

where F_1 is a function of the soil type.

The shear modulus is related to the SWV by the equation:

$$Vs = \sqrt{\frac{G}{\rho}} \qquad (8)$$

where ρ is the mass density ($\rho = \gamma/g$), γ is the total effective unit weight and **g** is the gravity acceleration. Also, the mean effective stress in geostatic conditions is:

$$\sigma_m = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3} = \frac{(1 + 2\,Ko)}{3} \sigma_v \qquad (9)$$

where **Ko** is the at-rest coefficient of earth pressure, which is a function of soil type and geologic history, and σ_v is the vertical effective stress which is given by:

$$\sigma_v = \gamma_{avg} Z \qquad (10)$$

where γ_{avg} is the average effective unit weight from the surface to the depth considered.

Substituting Equations 8 through 10 into Equation 7, we have:

$$Vs = \sqrt{\frac{g}{\gamma} F_1 \sqrt{\frac{1 + 2\,Ko}{3} \gamma_{avg} Z}} = F_2 Z^{0.25} \qquad (11)$$

Equation 11 shows that the SWV is a function of depth. For a uniform granular, recently deposited soil F_2 is approximately constant. However, F_1, **Ko** and γ are functions of **Z** and, therefore, lead to the more general expression of Equation 4. This finding was supported with a very large data base of CXW measurements (Rodriguez-Ordonez 1994, USC 1993). In Equation 4, the parameter **Vos** depend on the type of soil, while m_s reflects the combined effect of soil properties variation with depth and the SWV change with the confining stress.

The predicted range of **Vos** and m_s from Equation 4 was compared with the values obtained from the interpretation of CXW test data to verify consistency. Typical values of the parameters in Equations 5 through 11 are discussed in the following.

- Non dimensional parameter K_2: The values of this parameter for low strains depend on the type of soil as shown in Table 1 (Seed et al. 1984, Seed and Idriss 1970).

  The values of K_2 were obtained mostly from laboratory tests conducted on remolded soil samples. It is well recognized (Schmertmann 1991) that field values of K_2 are higher than laboratory results due to effects such as aging, cementation, densification due to earthquake shaking, water table variations and other causes that can not be reproduced in the laboratory. Over time, such effects have been found to cause an increase in the shear modulus up to 50 to 100% with respect to laboratory values. The shear modulus increase with time at a diminishing rate which is approximately linear with the logarithm of time. At any given site, measured properties may be significantly higher (up to two times or even more) than the values from laboratory tests.

- Unit weight: varies between 12 to 22 kN/m^3 depending on the soil type and particularly dependent on mineralogy and void ratio.

- Earth pressure coefficient **Ko**: depends on the mineralogy, fabric and the overconsolidation ratio. It varies typically between 0.4 and 0.6, although it may reach values of 1.0 or higher in some cases.

Table 1 - Range of Laboratory Values of K_2

Type of Soil	Relative Density	K_2
Loose sand	30-50%	34-45
Medium sand	60%	52
Dense sand	75-90%	59-70
Sandy gravel with some clay		90
Dense sand and gravel		122
Dense sand and sandy gravel		190

- Void ratio **e**: depends on the soil type and structure. For granular soils it varies between 0.4 and 0.9. It can be much higher in some cohesive soils.

Based on typical soil parameters form laboratory tests, the range of **Vos** values in Equation 4 is between 50 and 150 m/s. When field effects previously discussed are taken into account, this range can be extended to 300 m/s. This range compares well with the results from the CXW measurements.

Rodriguez-Ordonez (1994) showed that **Vos** values vary between 80 and 250 m/s depending on the soil type. He also showed that typical $\mathbf{m_s}$ values in soils range between 0.25 and 0.50. His results show that the reference profile is qualitatively and quantitatively consistent with published laboratory data of soil behavior under dynamic loads at low strain.

INVERSION OF THE REFERENCE PROFILE

Vf-Vs Relationship Approximation

The use of a reference profile that represents an average of the actual SWV variation in the soil deposit is also the basis of a new inversion procedure that was developed by Rodriguez-Ordonez (1994) for detailed layered SWV data. However, due to length limitations the new interpretation procedure will not be discussed in this paper.

Rodriguez-Ordonez (1994) showed that if the relationship between **Vf** and the corresponding **Vs** profile could be found, it is possible to establish a direct method for inversion of the reference profile. He performed a large scale, comprehensive parametric analysis to obtain **Vs** profiles over the range of values of **Vof** and $\mathbf{m_f}$ that occur in actual soil deposits and obtained an optimal correlation based on error minimization, as follows.

The dispersion curve for the fundamental mode of plane Rayleigh waves was computed for the assumed soil profile by using the transfer matrix method (Saito 1987). A nonlinear curve-fitting procedure was used to obtain the reference phase velocity profile parameters from the computed dispersion curve. This formulation minimizes the deviations between Equation 2 and the target dispersion curve to obtain the parameters **Vof** and $\mathbf{m_f}$ that produce the best fit by a least squares criteria. The NOLSOL computer routines based on the method by Dennis et al. (1981) were used for this computation.

The step to obtain the reference profile parameters used for the parametric analysis is similar to that which was used to compute those parameters from field test data. This is a very efficient optimization to obtain only two parameters from many phase velocity-wave length points. As expected, the curve-fitting of Equation 6.1 with the computed dispersion curve was very good for all cases, with average relative variations within ±1% for most cases.

Based on his results Rodriguez-Ordonez (1994) concluded that the variation of **Vf** may be described by the following equation:

$$Vof = \frac{0.94 - 0.36\, m_s^{1.19}}{1.04 - 0.04\, m_s}\, Vos \tag{12}$$

The corresponding equation obtained for $\mathbf{m_f}$ is as follows:

$$m_f = 0.09 \ \ln(1.48\, Vos)\, m_s \tag{13}$$

With Equations 12 and 13 the SWV reference profile may be obtained from the phase velocity reference profile very efficiently. The problem is reduced to solving this non linear system of equations for **Vos** and $\mathbf{m_s}$. This is accomplished without any difficulty by using the Newton method with analytical Jacobian.

The reference SWV profile provides a very good approximation to the actual average SWV structure of the soil. For many cases this is all the meaningful information that may be obtained from the Vf-Vs measurements. In those cases, the Vf-Vs inversion is reduced to an optimization to obtain **Vof** and $\mathbf{m_f}$ and the solution for **Vos** and $\mathbf{m_s}$. This process is accomplished in a few seconds with any personal computer (PC) currently used.

Other formulations are available to obtain comparable results. However, several soil layers are needed for these formulations in order to model the basic variation of SWV with depth. These formulations are iterative and require appropriate smoothing restraints for the optimization procedure. At each iteration the dispersion curve and the gradients of all the parameters in the model should be obtained. The computational effort of such formulations is several orders of magnitude higher.

Accuracy of the Approximation

Equations 12 and 13 are approximations to the actual variation of the **Vf** profile parameters. In order to use these equations for an interpretation procedure it is important to know their accuracy. Rodriguez-Ordonez (1994) showed that even for the cases where the relative errors may be large. the actual absolute errors of **Vof** are small. under 15 m/s over the entire range of **Vos** and m_s values. These absolute errors are less than the standard deviation that can be obtained from experimental data from CXW, SASW, or any other surface wave measurement.

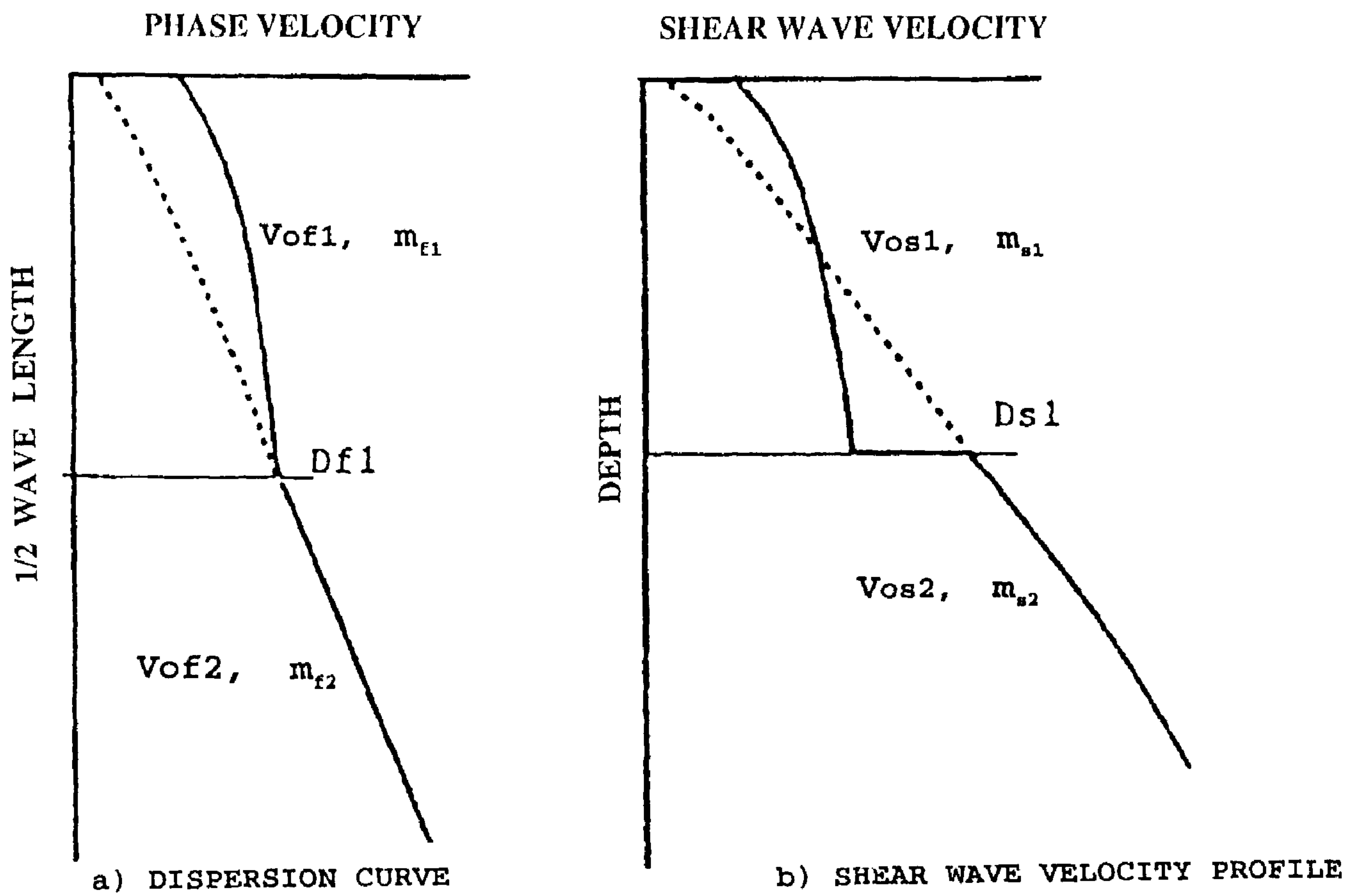
These results show that the reference profile inversion may be obtained with a degree of accuracy that is consistent with the resolution of the CXW method (and other surface wave measurement techniques), by means of a simple procedure. This procedure may be used for field evaluation of CXW data or as an excellent starting point for an additional optimization step, and in some cases it may be used as a final result.

Reference Profile for Multiple Soil Layers

The reference profiles considered so far assumed that the soil deposit is relatively uniform or that when there are some soil layers in the deposit, they may be determined from the deviations with respect to the reference profile. In other words, a profile described by Equation 3 provides a good approximation to the average of the measured dispersion data. There are cases where a sequence of soil layers with relatively similar properties overlay a stiffer material, such as bedrock. In other cases, the soil profile may be composed of two or more different soil layers with significant thicknesses. In these cases the considerations for the reference profile development apply for each distinct layer, and a single reference profile for the whole deposit is not appropriate.

Rodriguez-Ordonez (1994) showed that two or more reference profiles with parameters pairs **(Vof, m_f)i** may be obtained to fit the measured data over different ranges of wave length as shown in Figure 3. The parameter sets of this reference model are obtained by using a procedure similar to the case where there is a single profile. A curve fitting procedure based on nonlinear least squares is used to minimize the difference between the reference model and the measured data. This model is described by pairs of **(Vof, m_f)i** applicable over certain ranges of wave length. The ranges are defined by the values of half wave length **(D_f)i** over which there is an optimal fit. The SWV reference profile is also obtained from two or more pairs of parameters **(Vos, m_s)i** that are valid over their corresponding depth ranges.

An optimization is used to obtain the parameters of the **Vs** profile. This optimization is similar to the formulation used for the refinement of the shear wave velocity reference profile of a uniform soil. The purpose of this optimization is to minimize the sum of squares of the differences between the phase velocity reference curve (Figure 3.a) and the dispersion curve obtained by using the shear wave velocity profile shown in Figure 3.b. The reference phase velocity profile is computed using the parameters shown in the left of the figure. The



igure 3. ‹am⁞ . ·f a Reference Profile with Two Materials

variables for the optimization are the parameters shown in the right. The dispersion curve is computed by using the transfer matrix formulation (Saito 1987).

The initial guess for the optimization is obtained by using Equations 12 and 13 with each **(V_{of}, m_f)i** pair under consideration. The initial value of **Ds1** may be selected as the same value obtained for **Df1**. Computations show that **Ds1** is generally very close to **Df1**, therefore, this parameter can usually be considered as known and not as one of the parameters subject to optimization. With this initial guess the computation of the shear wave velocity profile parameters is very efficient and takes only a few iterations.

If **Ds** is estimated directly, the number of parameters subject to optimization is twice the number of materials in the model. For two materials there are four parameters. The dispersion curve should be defined at a minimum number of frequencies that is larger than the number of parameters in the model. The number of points must be adequate to accurately compare the computed dispersion curve with the reference phase velocity profile. Numerical experiments showed that by using three or four points for each material, the model produces satisfactory results. Therefore, for each iteration of the optimization for a two-material model the dispersion curve should be computed at 6 to 8 frequencies. If needed, these computations can be performed at the site in a few seconds by using a typical notebook PC.

INTERPRETATION PROCEDURE

The complete interpretation procedure (Rodriguez-Ordonez 1994) also handles distinct layers with SWV that deviates from the reference profile. However, the focus of this paper is on obtaining only the reference SWV profile of the soil from the measured dispersion curve. It is assumed that the SWV reference profile has a typical form (as most soils do) and that it is composed of one or more relatively uniform materials.

Figure 4 shows the flow chart for the new interpretation procedure to obtain a SWV reference profile. It has three main components:

1- Definition of the target dispersion curve from the Vf-Vs measurement, $\mathbf{F(\lambda)}$: This component describes the phase velocity as a function of wavelength λ. $\mathbf{F(\lambda)}$ is compared with the dispersion curve of the SWV profile obtained from the interpretation. The new interpretation procedure is useful for cases where the dispersion curve is controlled by the fundamental mode of Rayleigh waves.

2- Computation of the phase velocity reference profile: The parameters describing the reference profile are obtained by minimizing the sum of squares of the difference between the target data and the reference profile, **Ro**, as follows:

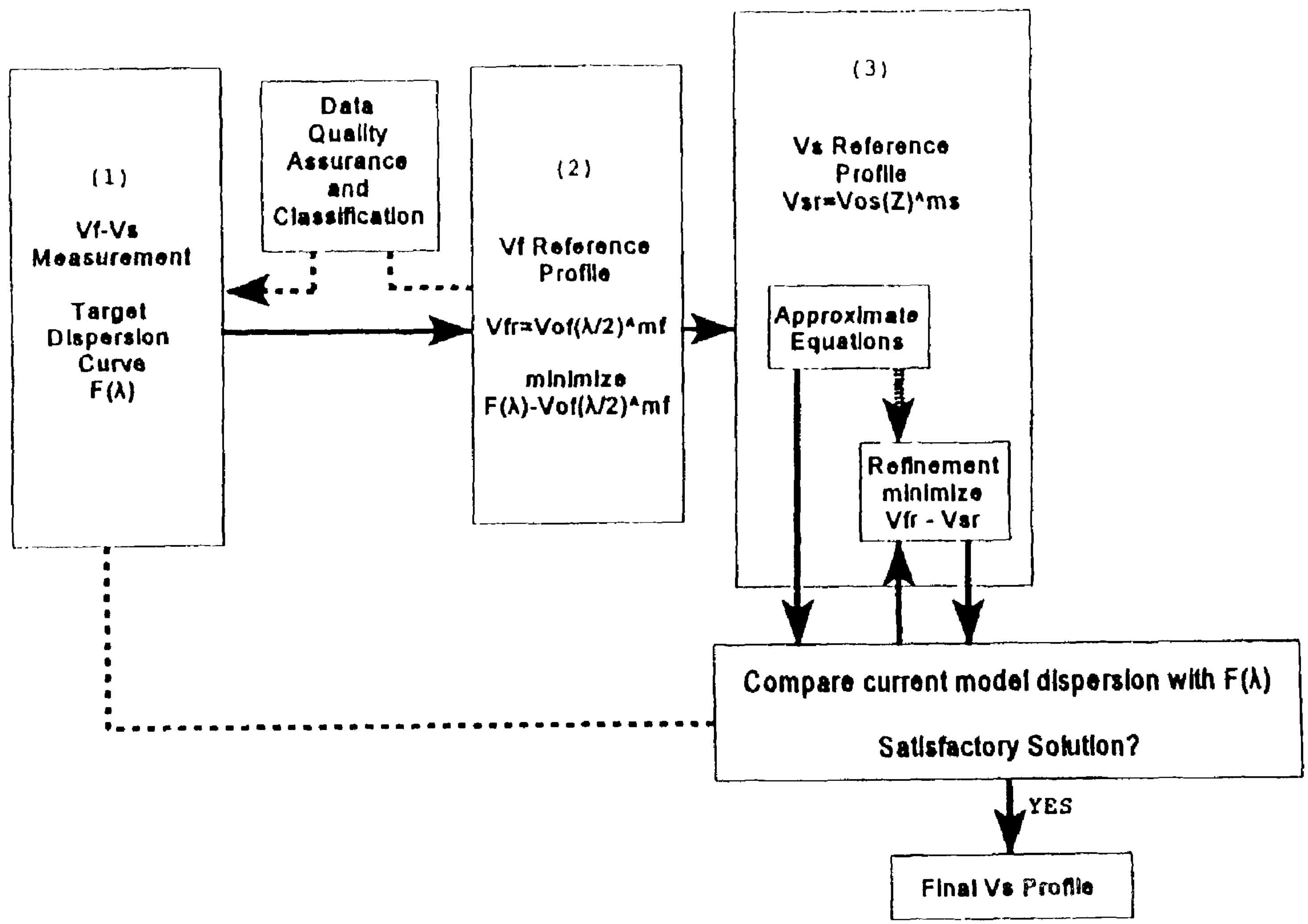


Figure 4. Flow-Chart of the New Vf-Vs Interpretation Procedure to Obtain a Reference SWV Profile

$$Ro = \sum_i \left(F(\lambda_i) - Vof\left(\frac{\lambda}{2}\right)_i^{m_f} \right)^2 \qquad (17)$$

3- <u>Computation of the SWV reference profile</u>: The dispersion curve of the SWV reference profile matches the phase velocity reference profile. It is assumed that both the SWV and the phase velocity reference profiles have the same functional form. Equations 12 and 13 may be used to compute the SWV reference profile parameters when only one material is considered. An optional optimization may be carried out to refine the parameters obtained from the equations, although usually this is not required for a single material model.

When there are several materials, Equations 12 and 13 can be used to compute a first estimate of the parameters for the SWV reference profiles associated with each material. A refinement is then obtained by minimizing **R1**, the sum of squares of the difference between the phase velocity reference profile and the dispersion curve obtained with the SWV reference profile parameters:

$$R1 = \sum_i \left(Vof\left(\frac{\lambda}{2}\right)_i^{m_f} - Vos\, Z_i^{m_s} \right)^2 \qquad (18)$$

The computation of this optimization phase is also efficient, and may be performed in a few seconds using a typical PC.

At this point, the dispersion curve obtained from the reference profile is compared with the target dispersion curve **F(λ)**. Often the approximation obtained from the reference profile is good enough for a final interpretation within the resolution limits of the Vf-Vs method. In the case of site amplification evaluation these data are adequate.

CASE STUDIES

Rodriguez-Ordonez (1994) applied the new interpretation procedure in several case studies where cross-hole SWV data were available. An example of these results is shown in Figure 5 with data from the Hollywood Storage Building Site located in the Piedmont of Santa Monica Mountains in California (USC 1993). At this site the reference profile was obtained based on measured CXW dispersion curve. Two distinct materials were used for the reference profile interpretation. Interpretation results show that the reference profile provides a good average to the SWV distribution obtained from the cross-hole results. Such a reference profile (that may be obtained about 5 minutes after the CXW measurement is completed) may be used for site amplification evaluation. This and other case studies (Rodriguez-Ordonez 1994) show that the new method may be applied successfully even in soil deposits were there are several distinct soil layers with large SWV differences.

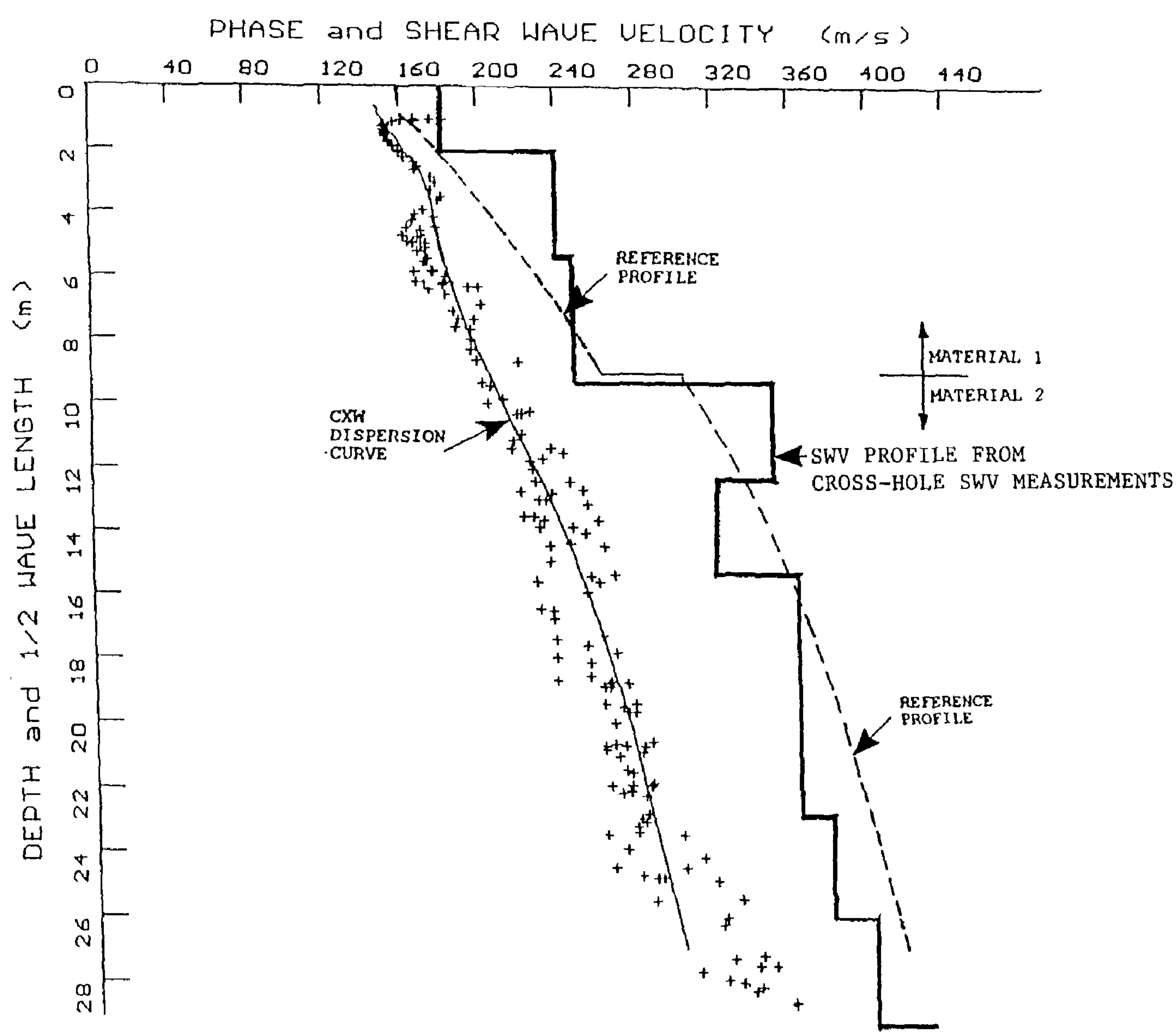


Figure 5. Measured Cross-Hole SWV Profile and CXW Data, and Computed SWV Reference Profile at the Hollywood Storage Building Site

SUMMARY AND CONCLUSIONS

The new approach to the interpretation of SWV structure from Rayleigh waves dispersion data (the Vf-Vs method) is based on the reference profile concept. A reference profile describes the average dispersion curve and corresponding SWV structure and is consistent with the fundamental dependency of SWV on confining pressure (depth) in soils. Simple equations were developed for direct inversion of the reference profile based on data from more than 100 sites.

The new reference profile concept is particularly useful for site amplification evaluations using the impedance ratio approach. Non-invasive, controlled-source surface wave measurements provide cost-effective dispersion data to great depth. These data are used to obtain reference profiles for most soil formations. The procedure is rapid and computationally efficient and its results are more representative of actual soil structure than results obtained from other non-invasive methods. This method was verified at several sites where accurate cross-hole SWV data was also available.

REFERENCES

- Arbelaez-Hoyos, M.C. (1992). "Soil profiling using controlled source spectral analysis of surface waves," MS Thesis in Civil Engineering, University of North Carolina at Charlotte.

- Dennis J., Gay D., and Welsch R., (1981). "An adaptive nonlinear least-squares algorithm," *ACM Trans. Math. Software,* Vol. 7, No.3, 348-367.

- Dobry, R. (1991). "Soil Properties and earthquake Ground Response," Key-Note Lecture, Proceedings of the IX Panamerican Conference on Soil Mechanics and Foundation Engineering, Vol. III, Vina del Mar, Chile, August.

- Dobry, R., and Vucetic, M. (1987). "State-of-the-art report: Dynamic properties and response of soft clay deposits," Proceedings of the International Symposium on Geotechnical Engineering of Soft Soils, Mexico City, Vol. 2, 51-87.

- Mitchell, J.K. (1993). Fundamentals of Soil Behavior 2nd Edition. John Wiley & Sons, Inc. New York.

- Poran, C.J., Rodriguez, J.A., and Satoh, T. (1993). "Controlled source surface waves measurements for shear wave velocity profiling of soils," Proceedings, National Science Foundation Workshop on Geophysical Techniques for Site and Material Characterization, Atlanta, Georgia, June, 231-242.

- Poran, C.J., Rodriguez, J.A., Arbelaez, M.C., Satoh, T., and Kavazanjian, E. Jr. (1992). "Non-invasive Rayleigh wave measurement system for soil profiling in ports," Proceedings of Ports '92, ASCE Specialty Conference, Seattle, July, Vol 1., 390-402.

- Rodriguez-Ordonez, J.A. (1994). "A New Method for Interpretation of Surface Wave Measurements in Soils," PhD Dissertation, North Carolina State University, Civil Engineering Department, August.

- Satoh, T. (1989). "On the controlled source spectral Rayleigh wave excitation," Research Report, Vibration Instruments Company Ltd., Tokyo.

- Satoh, T., Yamagata, K., Poran, C.J., and Rodriguez, J.A. (1991). "Soil profiling by spectral analysis of surface waves," Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, 2,1429-1434.

- Saito M., (1987). "Transfer Matrix Approach for Rayleigh Waves Analysis," Research Report to Vibration Instruments Company Ltd., Tokyo (translated from Japanese).

- Schmertmann, J. (1991). "The mechanical aging of soils," *Journal of Geotechnical Engineering ASCE*, Vol. 117, No.9, 1288-1330.

- Seed H.B. and Idriss I.M. (1970). "Moduli and damping factors for dynamic analyses," Earthquake Engineering Research Center Report No. UCB/EERC-70/10, University of California, Berkeley.

- Seed H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K. (1984). "Moduli and damping factors for dynamic analyses of cohesionless soils," Earthquake Engineering Research Center Report No. UCB/EERC-84/14, University of California, Berkeley.

- USC (1993). "Shear wave velocity profiling of instrumented sites in the greater los angeles area using Rayleigh waves measurements," Research Report for Subcontract Between the University of Southern California and Vibration Instrument Company, Ltd., CALTRANS Contract No. O7G297, May.