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지표층의 탄성계수 측정을 위한 새로운 탄성파 방법

CHARACTERIZATION OF GEOTECHNICAL SITES BY MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MCASW)

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대부분의 토목 건축공사에서 지표가까이의 땅속 (표토층 및 지반암) 에 대한 탄성계수들을 측정하는것은 여러측면에서 매우 중요하다. 지표에서 망치등을 이용하여 약한 지진파를 발생시키고 지표부근을 수평으로 진행하는 지표파 (Surface Waves) 를 다중기록 (Multi-channel Recording) 방식으로 측정하면 땅속의 탄성계수들을 깊이에 따라 계산해낼 수 있다. 이방법은 현재 Kansas 주 지질연구소에서 상업적 응용을 위해 연구가 활발히 진행중에있다.

ABSTRACT

Evaluating stiffness of near-surface materials has been one of the critically important tasks in many civil engineering works. It is the main goal of geotechnical characterization. The so-called deflection-response method evaluates the stiffness by measuring stress-strain behavior of the materials caused by static or dynamic load. This method, however, evaluates the overall stiffness and the stiffness variation with depth cannot be obtained. Furthermore, evaluation of a large-area geotechnical site by this method can be time-consuming, expensive, and damaging to many surface points of the site.

Wave-propagation method, on the other hand, measures seismic velocities at different depths and stiffness profile (stiffness change with depth) can be obtained from the measured velocity data. The stiffness profile is often expressed by shear-wave (S-wave) velocity change with depth because S-wave velocity is proportional to the shear modulus that is a direct indicator of stiffness. The crosshole and downhole method measures the seismic velocity by placing sources and receivers (geophones) at different depths in a borehole. Requirement of borehole installation makes this method also time-consuming, expensive, and damaging to the sites. Spectral-Analysis-of-Surface-Waves (SASW) method places both source and receivers at the surface, and records horizontally-propagating surface waves. Based upon the theory of surface-wave dispersion, the seismic velocities at different depths are calculated by analyzing the recorded surface-wave data. This method can be nondestructive to the sites. However, because only two receivers are used, the method requires multiple measurements with different field setups and, therefore, the method often becomes time-consuming and labor-intensive. Furthermore, the inclusion of noise wavefields cannot be handled properly, and this may cause the results by this method inaccurate.

When multi-channel recording method is employed during the measurement of surface-waves, there are several benefits. First, usually single measurement is enough because multiple number (twelve or more) of receivers are used. Second, noise inclusion can be detected by coherency checking on the multi-channel data and handled properly so that it does not decrease the accuracy of the result. Third, various kinds of multi-channel processing techniques can be applied to filter unwanted noise wavefields and also to analyze the surface-wavefields more accurately and efficiently. In this way, the accuracy of the result by the method can be significantly improved. Fourth, the entire system of source, receivers, and recording-processing device can be tied into one unit, and the unit can be pulled by a small vehicle, making the survey speed very fast. In all these senses, multi-channel recording of surface waves is best suited for a routine method for geotechnical characterization in most of civil engineering works.

INTRODUCTION

In most of civil engineering works, it is critically important to characterize the mechanical behavior of geotechnical materials under various types of loading. This characterization has normally been expressed in terms of elastic moduli, of which shear modulus is most important because it is directly related to the stiffness of material skeleton. For example, evaluation of pavement system (such as estimation of pavement life as well as appropriate remedial measures, checking the potential for deterioration and tensile cracking in the surface layer, etc.) is usually based upon the stress-strain behavior of the pavement system and this behavior is usually indicated by shear modulus. Low-amplitude shear moduli are used in designing facilities such as vibrating machine foundations as reference levels for evaluating dynamic soil performance and liquefaction potential during ground shaking, and also for insitu evaluation of hard-to-sample deposits like gravels and cobbles (National Research Council, 1985).

In general, there are two methods to characterize mechanical behavior of geotechnical sites under various types of loading (Heisey et al., 1982). One is the deflection-response method that measures stress-strain behavior of the sites caused by static or dynamic load. The major drawbacks of this method are that the overall stiffness is measured and, therefore, it is not possible to measure the stiffness at different depths, and the method can be destructive to the sites. The other method of characterization is the wave-propagation method that estimates the shear moduli at different depths by measuring seismic velocities. This method offers the most direct and nondestructive approach to determining stiffness at different depths of geotechnical sites.

One instance of this wave-propagation method is the crosshole and downhole methods that involve body-wave measurements and thus require the installation of one or more boreholes. Borehole installation is time consuming, costly, and destructive to the sites. Survey of a large area by this method is thus prohibitive. Another instance of this method is the Spectral-Analysis-of-Surface-Waves (SASW) by Dr. Stokoe and his coworkers at The University of Texas at Austin (Heisey et al., 1982; Nazarian et al., 1983; Stokoe et al., 1994). This method is nondestructive, but is known to be time consuming and labor intensive. Furthermore, credibility of the results by this method is often under question because of limited capability in appropriate handling of useful signals and harmful noise wavefields.

I develop a new instance of wave-propagation method and call it "Multi-Channel Analysis of Surface Waves (MCASW)." This method is still under intensive development at Kansas Geological Survey for a routine commercial usage. The method is based upon the multi-channel recording (Dobrin and Savit, 1988, p. 79) of surface waves using the seismic equipment commonly used in engineering seismic surveys (Steeples and Miller, 1990). It is much quicker and more accurate method than SASW method and, therefore, best suited for routine surveys over various kinds of civil engineering sites. The main purpose of this paper is to introduce the overall framework of this method without discussing the details.

(a)

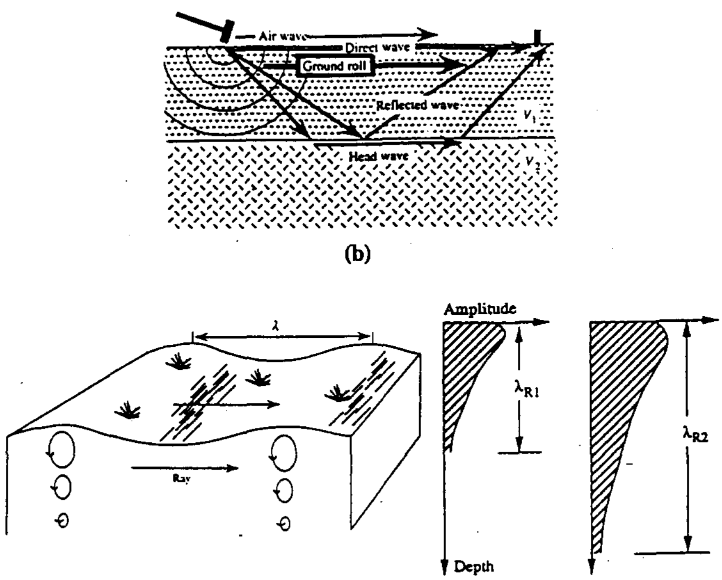


Figure 1. (a) When an impact source like sledge hammer strikes ground, various kinds of seismic waves are generated. Among them, surface waves (commonly called ground roll) are generated with most energy and propagate horiznotally along the surface (so called surface waves). (b) Ground roll has dispersion property that long wavelength (λ_{R2}) has deeper penetration depth than short wavelength (λ_{R1}), and, therefore, has faster velocity because the average seismic velocity generally increases with depth. (From Burger, 1992)

SURFACE-WAVE PROPAGATION METHODS

General

In general, there are two types of surface waves; Rayleigh and Love waves (Dobrin and Savit, 1988, p. 35). Both represent the plane-wave solutions to the following coupled elastic wave equation (Haskell, 1953):

$$\frac{\partial^2\Phi}{\partial t^2} = V_p^{\,2}\nabla^2\Phi \quad \text{and} \quad \frac{\partial^2\psi}{\partial t^2} = V_s^{\,2}\nabla^2\psi,$$

where Φ and ψ represent displacement potentials, and V_p and V_s represent P- and S-wave velocities. Rayleigh waves have particles motion in vertical direction, whereas Love waves have particles motion in horizontal direction. Rayleigh waves are more easily generated and recorded than Love waves. Propagation characteristics of surface waves under a specific circumstance can be predicted form the solutions to the above wave equation by putting proper initial and boundary conditions.

Ground roll is Rayleigh-type surface waves generated most effectively in all kinds of surface seismic surveys. It is generated when an impact source (like sledge hammer) strikes the ground (Figure 1a). Ground roll has an important property, called dispersion property, that is indicative of elastic moduli of near-surface earth materials (Bath, 1973, p. 77). This dispersion property is that different wavelengths have different propagation velocities and penetration depths (Figure 1b). Short wavelengths have shallow penetration depths and longer ones have deeper penetration depths. The propagation velocity for each wavelength, called phase velocity (Bath, 1973, p. 79), is determined mainly by the average shear (S)-wave velocity of the medium over the penetration depth. The phase velocities for different wavelengths can be found from the solutions to the above wave equation by treating the near-surface materials as layered earth medium (Haskell, 1953). Therefore, by analyzing the dispersion feature of ground roll represented in recorded seismic data, the near-surface S-wave velocity (V_s) profiles can be constructed and the corresponding shear moduli (μ) are calculated from the relation between the two parameters:

$$V_s = \sqrt{\frac{\mu}{\rho}},$$

where ρ represents density of material. Density of near-surface materials changes little with depth and, therefore, is generally assumed constant. Because the phase velocity is function of not only S-wave velocity but also P-wave velocity, although its contribution is minor, P-wave velocity profile can also be obtained from the analysis. With both P- and S-wave velocities available, profiles of all the elastic moduli can be obtained.

The wavefields of horizontally traveling ground roll are recorded by receivers (geophones) laid at the surface with certain separation (called offset) dx. Recorded wavefields are then analyzed at different frequencies (f) for the phase velocities (C_f) based upon the difference (Δt_f) in the arrival times of ground roll at two receivers as

$$C_f = \frac{dx}{\Delta t_f}.$$

This analysis produces a set of data (C_f vs. f), called dispersion data, that are, in turn, passed into next step of analysis, which is the inversion process. The inversion process backcalculates S-wave velocity (V_s) profile from the measured dispersion data by solving a matrix equation (Sanchez-Salinero et al., 1987; Rix and Leipski, 1991).

Because ground roll is always generated most effectively, the acquisition step by itself does not warrant a highly special technique. Instead, determination of dispersion data requires the most special care because accuracy of final result, V_s profile, is directly related to the accuracy of the dispersion data. Because recorded wavefields usually include noise, the technique to determine the dispersion data should be able to handle the noise properly.

Spectral-Analysis-of-Surface-Waves (SASW) method

SASW method uses only two receivers for one survey to record propagated surface waves (Dobrin and Savit, 1988, p. 35) that are usually generated by impact source like sledge hammer, and, therefore, the test needs to be repeated with many different field setups (different source and receiver spacings) to cover different depths of investigation (Figure 2a). Consequently, the method is time consuming and labor intensive. Furthermore, possible contamination of recorded data by the inclusion of body waves (such as direct, refracted, and reflected P-waves) and also by the inclusion of higher modes of surface waves (Bath, 1973, p. 85) cannot be detected and handled properly. Because of this, accuracy of the results by this method is often under question.

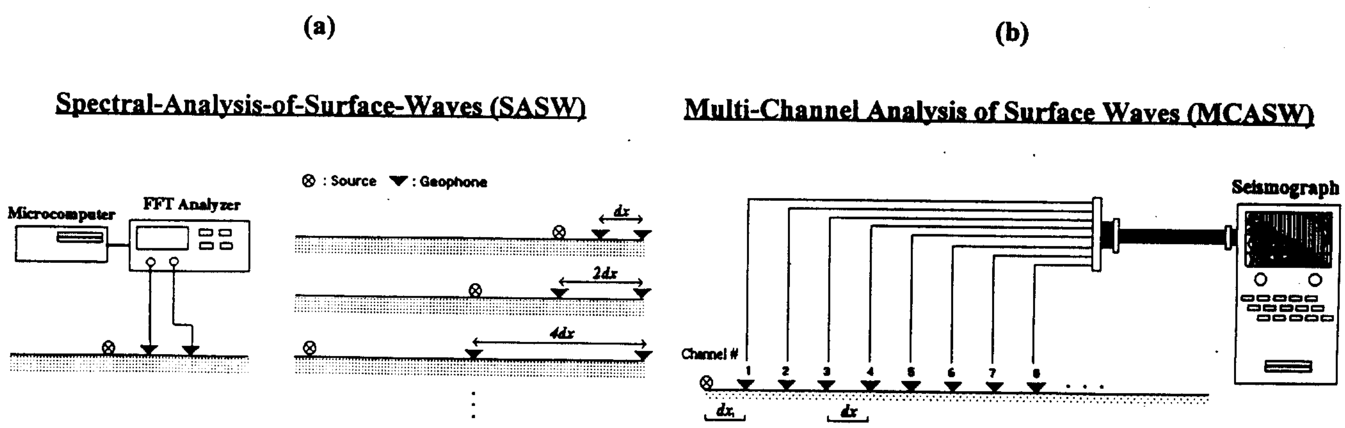


Figure 2. Basic configurations for Spectral-Analysis-of-Surface-Waves (SASW) method (a) and multi-channel analysis of surface waves (MCASW) method (b) presented on this paper. In SASW method, only two receivers are used, whereas more than two (usually twelve or more) receivers are used in MCASW method.

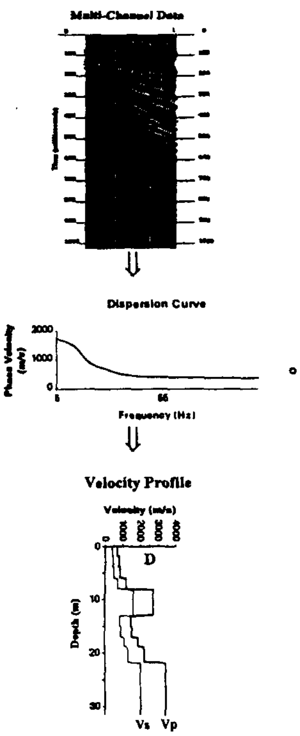


Figure 4. Processing of recorded multi-channel data in MCASW method consists of two steps. The first step prepares the dispersion data (commonly displayed as dispersion curve) and the second step uses these data as input to inversion process to produce the velocity profile.

the field. First, dispersion data are produced from the analysis. Various kinds of multi-channel processing techniques are available in this step (McMechan and Yedlin, 1981; Nazarian et al., 1983; Mokhtar et al., 1988). If a vibratory source is used as source, there is a new processing technique developed by Park (1995d) that produces dispersion data in fastest and most accurate manner in comparison to all others. Before the analysis begins, the data should be examined on the possible contamination by noise wavefields. This is not possible with all other kinds of wave-propagation method. The contamination if any will be obvious on the plot of multi-channel data by the unique occurrence pattern of noise wavefields (Figure 5). Multi-channel filtering techniques such as *f-k* filtering (Yilmaz, 1987, p. 69) can be used to eliminate any harmful effects by the contamination.

MCASW method can find various kinds of applications in civil engineering as a nondestructive method to characterize geotechnical sites. It can be used as a quick method to evaluate pavement system by surveying on top of the pavement in continuous (i.e., the receiver platform is moved after each survey by the same distance as the total receiver spread length) and fast manner. It can also be used to detect any underground anomaly zone such as voids or weak zones in a construction site (Figure 6). If the survey is performed in continuous manner, image of subsurface structure (e.g., structure of bedrock) can be extrapolated by displaying V_s profiles side by side (Figure 7). Then, the obtained image can find numerous utilization.

One example of MCASW method applied to a set of real data acquired in Weeks Island, Louisiana, is presented in Figure 8. 48-channel EG&G 2401X seismograph was used with 8 ft geophone spacing and 500 millisecond recording time. 8-gauge auger gun (Miller et al., 1986) was used as source. Noise contamination by body waves (refraction and reflection) is obvious (Figure 8a). Because ground roll is well separated from these body waves, no filtering process to eliminate the noise wavefields was necessary. Instead, the analysis was applied only to the wedge-shaped time window encompassing the ground roll. *P-w* method by McMechan and Yedlin (1981) was used to produce dispersion data. The final V_s profile (V_p profile was also obtained from the inversion process) indicates an abrupt velocity jump at depth of 14 ft. It is believed that this velocity jump was caused by the presence of highly consolidated rock (bedrock by definition) at that depth. The gradual increase of velocity with depth in the overlying unconsolidated zone (overburden by definition) indicates a gradual increase with depth in the degree of consolidation with no indication of anomaly zone. This real example illustrates an application of MCASW method to evaluate depth to bedrock and also to characterize overburden materials.

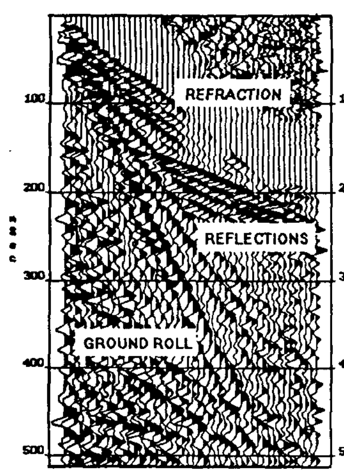


Figure 5. An example of multi-channel data in which nonsurface wavefields (refraction and reflection) are obvious. These wavefields should not be included in the surface-wave analysis.

DISCUSSIONS

Only the most fundamentals of a new surface-wave method of geotechnical characterization has been presented and details are missing. Considering the potential significance of the topic as a development of a new method, it is not surprising that there are many other issues stemming from the fundamentals. Readers are kindly referred to the relevant literature cited on this paper for the details of each issue. In addition to them, details of data-acquisition techniques as well as proper selection of recording parameters can be found in Park et al. (1995b). Details of data-processing techniques are listed in Park et al. (1995c) and Park and Black (1995). Research is also under progress at Kansas Geological Survey to come up with more efficient inversion technique than pre-existing ones.

CONCLUSIONS

Because of the multi-channel recording, there are several advantages in the presented method over the other pre-existing methods. First, many different depths are investigated simultaneously at one survey and, therefore, the method is quick and requires least labor. Second, because, after long period of oil exploration from which the multi-channel recording method originated, various kinds of data-processing techniques are available, there is a greater flexibility in handling acquired data. Therefore, results by the method can be more accurate and obtained in faster speed than by the other methods. This also means the possible contamination of the acquired data by non-surface and higher-modes surface waves can be minimized. Third, the entire system of source, receivers, and recording-processing equipment can be tied into one unit and moved into next survey sites by a small vehicle, making the survey speed very fast. In all these senses, the presented method provides a quick, economical, and effective technique to evaluate elastic moduli profile of various kinds of geotechnical sites. Geotechnical application of this method is almost endless. It can be used not only for the accurate and detailed characterization of a small area but also for the quick detection of underground anomaly zones from a reconnaissance survey over a large area.

Detection of Anomaly Zones by MCASW Method

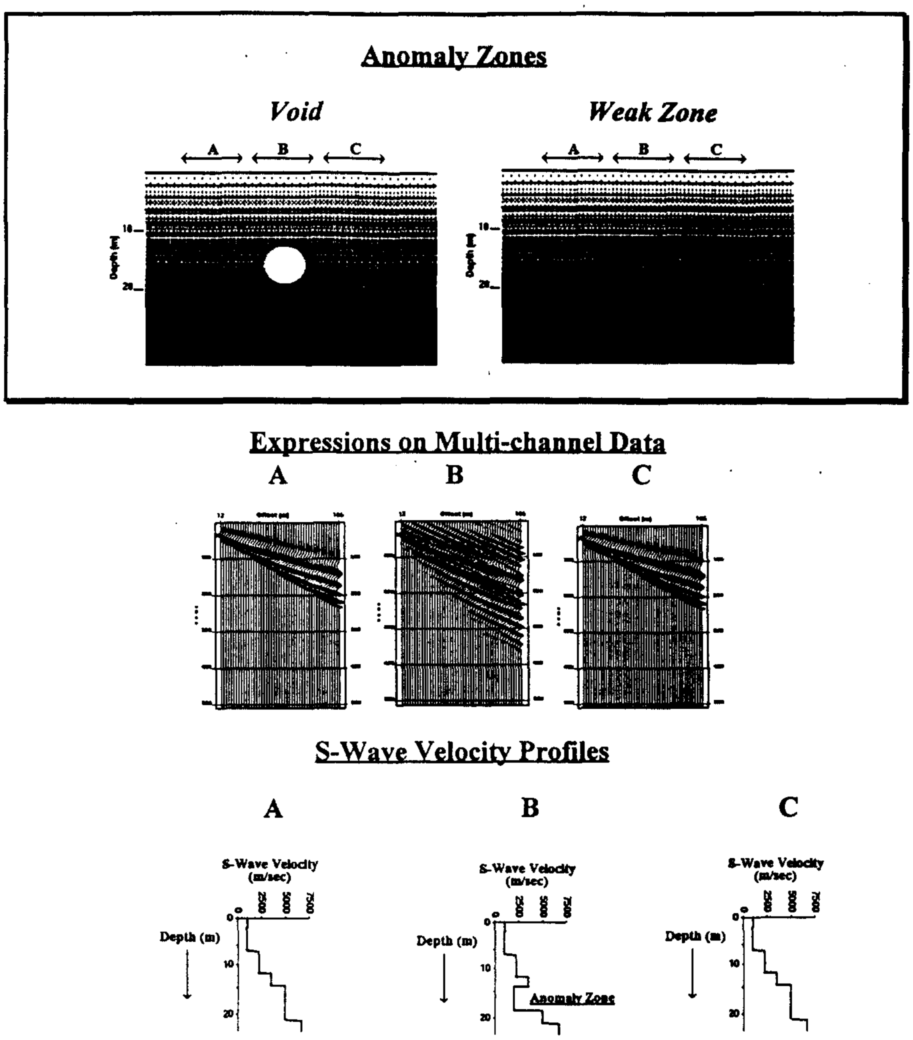
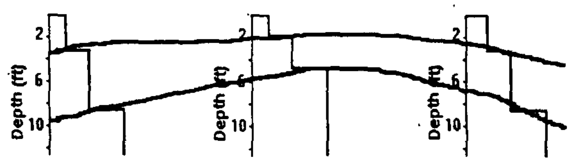


Figure 6. Multi-channel data acquired over the anomaly zone will show different feature in the expression of ground-roll wavefields from the feature of the data acquired over a normal zone. This feature by itself can be used to tell the existence of anomaly zones, or the velocity profiles may be used as a better indicator.

2-D or 3-D Subsurface Structural Image by MCASW Method

(a)



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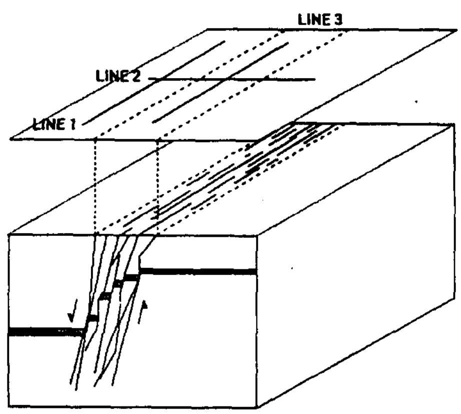
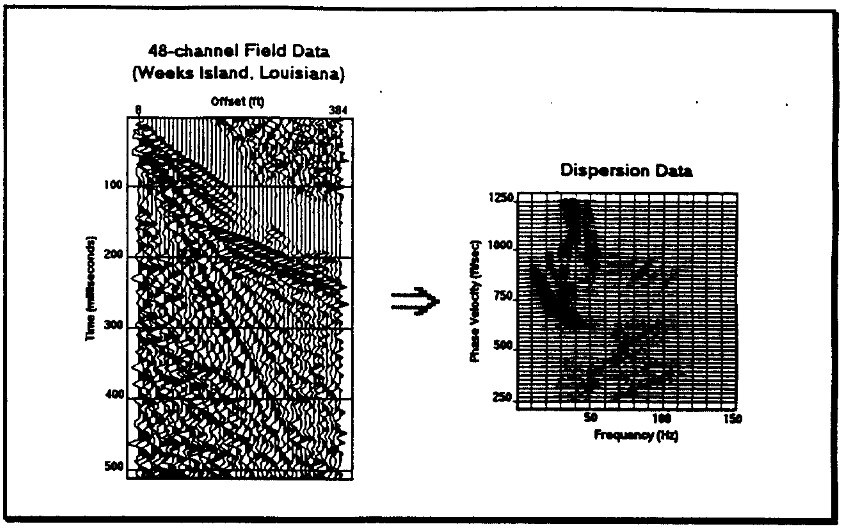


Figure 7. (a) Two dimensional (2-D) subsurface structural image can be constructed by displaying the velocity profiles obtained from MCASW method side by side. (b) Three dimensional (3-D) image of subsurface structure (for example, near-surface fault zone) can be obtained from MCASW method by properly designing survey lines in several different directions.

Field Data Example from Weeks Island, Louisiana

(a)



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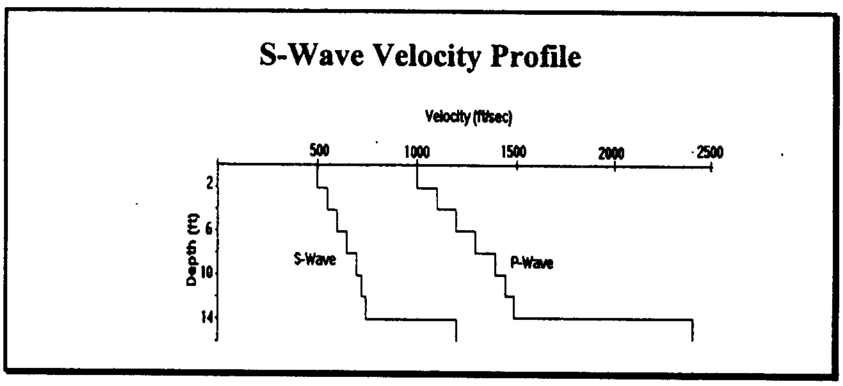

Figure 8. An example of MCASW method applied to 48-channel real data acquired in Weeks Island, Louisiana. (a) The field data clearly show the dispersive ground roll as well as the inclusion of body wavefields. The analysis was applied only to the ground roll wavefields to generate the velocity profiles (b).

REFERENCES

Båth, M., 1973, Introduction to seismology: A Halsted Press Book, 395 pp.

Burger, H. R., 1992, Exploration geophysics of the shallow subsurface: Prentice Hall, Inc., Englewood, NJ, 489 pp.

Dobrin, M. B., and Savit, C. H., 1988, Introduction to geophysical prospecting, 4th ed.: McGraw-Hill, Inc., 867 pp.

Haskell, N. A., 1953, The dispersion of surface waves on multilayered media: ***SSA Bull.***, **43**, 17-34.

Heisey, J. S., Stokoe II, K. H., and Meyer, A. H., 1982, Moduli of pavement systems from spectral analysis of surface waves: ***Transportation Research Record No. 852,***
22-31.

McMechan, G. A., and Yedlin, M. J., 1981, Analysis of dispersive waves by wave field transformation: ***Geophysics***, **46**, 869-874.

Miller, R. D., Pullan, S. E., Waldner, J. S., and Haeni, F. P., 1986, Field comparison of shallow seismic sources: ***Geophysics***, **51**, 2067-2092.

Mokhtar, T. A., Herrmann, R. B., and Russel, D. R., 1988, Seismic velocity and *Q* model for the shallow structure of the Arabian shield from short-period Rayleigh waves: ***Geophysics***, **53**, 1379-1387.

National Research Council, 1985, Liquefaction of soils during earthquakes: ***Proceedings***, Workshop organized by R. Dobry and R. V. Whitman, National Academy Press, 240 pp.

Nazarian, S., Stokoe II, K. H., and Hudson, W. R., 1983, Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems, ***Transportation Research Record No. 930***, 38-45.

Park, C. B., and Black, R. A., 1995a, Simple time-variant band-pass filtering by operator scaling: ***Geophysics***, **60**, 1527-1535.

Park, C. B., Miller, R. D., Steeples, D. W., and Black, R. A., 1995b, Swept impact seismic technique (SIST): ***Geophysics***, accepted for publication on April.

Park, C. B., Miller, R. D., and Xia, J., 1995c, Surface-wave analysis of multi-channel Vibroseis data: Submitted for publication in ***Geophysics***.

Park, C. B., 1995d, Techniques to analyze phase velocities of surface waves on multi-channel data: Submitted for publication in ***Geophysics***.

Rix, G. J., and Leipski, E. A., 1991, Accuracy and resolution of surface wave inversion, *in **Geotechnical special publication no. 29***, Recent advances in instrumentation, data acquisition and testing in soil dynamics, edited by S. K. Bhatia, S. K. and G. W. Blaney, American Society of Civil Engineers, 17-32.

Sanchez-Salinero, I., Roesset, J. M., Shao, K. Y., Stokoe II, K. H., and Rix, G. J., 1987, Analytical evaluation of variables affecting surface wave testing of pavements, ***Transportation Research Record No. 1136***, 86-95.

Steeples, D. W., and Miller, R. D., 1990, Seismic reflection methods applied to engineering, environmental, and groundwater problems, *in **Geotechnical and environmental geophysics***, Investigations in geophysics, no. 5, edited by S. H. Ward, Soc. Expl. Geophys., 1-30.

Stokoe II, K. H., Wright, G. W., James, A. B., and Jose, M. R., 1994, Characterization of geotechnical sites by SASW method, *in **Geophysical characterization of sites***, ISSMFE Technical Committee #10, edited by R. D. Woods, Oxford Publishers, New Delhi.

Yilmaz, O., 1987, Seismic data processing: Doherty, S. M., Ed.: ***Investigations in Geophysics, no. 2***, Soc. of Expl. Geophys.