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ANALYSIS OF IMPACT AND TRAFFIC-INDUCED VIBRATIONS FOR THE CHARACTERIZATION OF A CLAYEY SOIL

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ABSTRACT

The evaluation of the dynamic parameters of soils and particularly of the initial value of the shear modulus G_0 represent an important step in order to understand soil behaviour in the field of little deformation and to formulate proper constitutive laws able to model such behaviour.

This paper describes an experimental application of the Spectral Analysis of Surface Waves method to determine the initial value of the shear modulus at different depths for a clayey soil.

Traffic and impact generated Rayleigh waves have been recorded using several accelerometers placed on the soil suface at various distances from the vibration source. The random nature of the source was not relevant to the analysis performed so the wave arrival at the first accelerometer, the nearest to the source, has been considered as the excitation input. The recorded data have been processed to obtain shear wave velocities and G_0 profiles.

The characteristics of the soil were previously investigated and results of cross-hole and down-hole tests performed in the same site were available. So it has been possible to compare the results obtained in the present research employing the SASW method with those obtained using different techniques. The comparison showed a reasonable agreement in the value of G_0 for both impact and traffic induced vibrations though a certain scatter in results was observed.

KEYWORDS

Vibration; Rayleigh wave; field test; inverse analysis; shear wave velocity; shear modulus

INTRODUCTION

Shear wave velocity is an important parameter for the evaluation of the dynamic behaviour of soils as well as the static deformation of the ground. Most of field tests currently conducted for determining wave velocity profiles require boreholes, and thus are costly and may not conveniently be used in all cases.

The determination of wave velocity profiles from Rayleigh wave methods is promising and attractive since the field measurements can be performed just by placing sensors on the ground surface and without any boreholes. Besides, the method has a potential capability to detect a relatively soft layer sandwiched by stiffer layers, which capability cannot be offered by any other investigation made on the ground surface (Tokimatsu, 1991). It may also be desiderable for preliminary field investigation to be conducted prior to more detailed site investigation, and for quality control of ground improvement.

As a nondestructive test method, the spectral analysis of surface waves (SASW) method (Nazarian and Stokoe, 1986, 1987) has been used to determine the shear wave velocity or shear modulus profiles of soil sites. The SASW method is based upon the dispersive characteristic of seismic surface Rayleigh waves in layered media.

The in situ test consists of generating and detecting surface waves by impacting the surface of soil profile and monitoring and capturing the motion at the surface at several points. The captured signals are manipulated utilizing the Fourier and spectral analysis to determine the dependence of phase velocity on frequency or wavelength. The curve resulting from this procedure is called dispersion curve.

To determine the shear wave velocity profile or elastic modulus profile, the Rayleigh wave method, requires the inverse analysis on the measured curve.

In this study the vibration response of a clayey soil subjected to impact and traffic induced vibration is analyzed and described. and the result provided by the analysis in terms of initial shear modulus G_0 profiles are compared with available data obtained at the same site by conventional down-hole and cross-hole methods.

PREVIOUS STUDIES

The early developments of surface-wave method for use in the civil engineering field are summarized by Nazarian (1984). The major work for SASW method was laid in the last 10 years. Nazarian and Stokoe (1986, 1987) developed the experimental and theoretical aspects of the SAWS method as applied to geotechnical and pavement engineering fields. They also developed a computer algorithm named INVERT (Nazarian 1984) for determining the stiffness profile from a dispersion curve.

Drnevich et al. (1985) successfully utilized a vibrator connected to a random function generator as a source. Sanchez-Salinero et al. (1987) analytically studied the most feasible source-receiver configuration; they indicated that a desiderable distance between the source and the first receiver is equal to the distance between the adjacent receivers. Sheu et al. (1987) recommended that, for the set-up suggested by Sanchez-Salinero et al. wavelengths greater than three times the distance between the receivers should not be considered. Hiltenum (1988) experimentally confirmed this recommendation. Rix (1988), based upon an experimental investigation, concluded that most of the surface-wave energy is typically associated with the fundamental mode of vibration. Hossain and Drnevich (1989) presented an algorithm for determination of stiffness profile. Gucunski and Woods (1991) conducted an analytical study to quantify some of the problems associated with the alternative soft and hard layers. In addition, they studied the possibility of developing an impact-type low frequency source. Barker and Stevens (1991) reported some of the precautions that should be considered during the processing of the SAWS field date. Satoh et al. (1991) described an approximate method for the collection and reduction of data that has application in uniform and simple soil profiles. Nazarian et al. (1993) and Yuan et al. (1993) proposed a different automated surface wave method. Finally a comprehensive state of the art on geotechnical site characterization using surface waves has been recently provided by Tokimatsu (1995).

MODE RESOLUTION IN RAYLEIGH WAVE METHOD

The principle of the Rayleigh wave methods lies in the fact that the Rayleigh wave is dispersive. Its phase velocity varies depending on wavelength or frequencies, i.e., waves with short wavelengths or high frequencies reflect soil properties at small depths, whereas waves with long wavelengths or low frequencies reflect soil properties down to a larger depth.The Rayleigh wave method generally consists of three steps:

a) Observation of Rayleigh waves;
b) determination of dispersion characteristics from the observed data;
c) estimation of shear wave velocity profiles through inverse analysis of the dispersion data.

Most of the methods currently used consider Rayleigh wave vertical motions. According to the type of observed waves, the method is classified into two categories: active and passive method. Table 1 summarizes the procedures of field observation and in-house analyses, the period range and applicable depths of these methods (Tokimatsu, 1995).

The active method includes the spectral analysis of suface waves (SASW).

This method measures Rayleigh waves in vertical ground vibrations induced either by an impulsive source (Nazarian and Stokoe, 1984; Gabriels et al., 1987; Stokoe et al. 1988; Barker and Stevens, 1991) or an exciter oscillating with a vertical harmonic motion (Jones, 1958; Tokimatsu et al., 1991) or a random traffic trucks (Taniguchi et al., 1979). In the active method, sensors are placed on the ground surface in a line with the source, and the phase velocity is computed based on spectrum analysis. The method is suited to explore surface soils to a depth smaller than 10 to 20 meters. Its application to deep soils appears restricted because it is difficult, without a heavy weight, to generate long wavelengths required to determine V_s profiles of deep soil. However a case history using as source a vibrodyne of two tons is reported by Maugeri et al. (1996).

The passive method observes either vertical or three component motions of microtremors using a two-dimensional array of sensors distributed over the ground surface, without actively generating any vibrations. The wave motions of microtremors is not restricted either to a single mode or to a single direction of propagation. This calls for a large number of sensors to introduce redundancy of information. Based on frequency-wavenumber (F-k) spectrum analysis on the vertical motions or spatial auto-correlation analysis dispersion characteristics of Rayleigh waves may be determined (Liaw and McEvilly, 1979; Horike, 1985).

TESTS AND ANALYSIS

For the experimental tests it was chosen a site in the town of Augusta (Sicily), called Saline. Fig. 1 shows

Table 1 Classification of Rayleigh-Wave Methods
(after Tokimatsu, 1995)

Method	Source	Period Range	Array Dimension	Applicable Depth	References
Active	Steady State Point Loading	less than about 0.2-0.5 s	Linear	less than 10 - 20 m	Jones
	Random Point Loading				Nazarian and Stokoe
Passive	Short-Period Microtremors	less than 1 s	Two-dimensional	less than 50 - 100 m	Tokimatsu et al.
	Long-Period Microtremors	1-5 s		up to several km	Horike, and Okada et al.

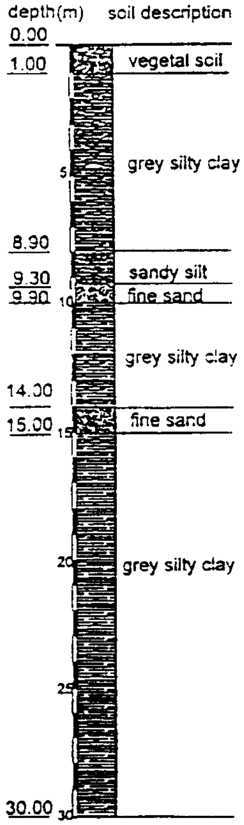

Fig.1 - Geological profile of the site
(after Maugeri et al., 1994)

the soil profile at the site where the surface wave tests were performed. Alternating layers of silty clay and sandy silt were found and lenses of silty fine sand are present at the depth of 10 and 15 meters. For the chosen site initial shear modulus profiles were available from cross-hole and down-hole tests (Maugeri et al., 1994).

The experimental set-up utilized for the Rayleigh wave recording consisted in a linear array of five accelerometer connected to an amplifier and, through an analogic-digital converter, to a personal computer in which the recorded data were stored and successively processed.

Two kinds of vibration sources were adopted: random traffic-induced vibrations and impact-induced vibrations generated by heavy hammer. Since both kinds of sources were not controlled, the wave arrival at the first accelerometer, the nearest to the source, was considered as the excitation imput in the analysis of the recorded data. Traffic vibrations were induced by heavy trucks passing by at a very short distance from the first accelerometer, while impact vibrations were generated by strongly beating with a hammer on a concrete block.

Fourier spectra of the recorded accelerograms were derived and the phase lags between harmonic modes having the same frequency were computed. Typical accelerograms and spectra are shown in Fig. 2a for the case of vertical impact and 2b for the case of horizontal impact.

Once the phase lag $\Delta\phi$ of vertical partical motions between two sensors at a frequency f is given, the apparent wave velocity can be readily computed using the expression

$$V_r = 2\pi f D/\Delta\phi$$

where D is the distance from the source sensor to the receiver sensor. By noting

$$V_r = \lambda f$$

the corresponding wavelenght λ can be determined.

Fig. 3a and 3b show the dispersion curves obtained using the experimental data recorded during the field tests. A significant scatter can be observed in the range of frequencies between 30 and 40 Hz which may be partially due to the background noise on the accelerometric data relative to traffic vibration.

As a simple method of phase velocity inversion in the present analysis it is assumed that the shear wave velocity is approximately equal to about 110 percent of the Rayleigh wave velocity and the effective sampling depth of soil for each wavelength is equal to 1/2 of that wavelength. Thus the initial shear modulus is readily calculated through the relation

$$G_0 = \rho V_s^2$$

that allowed to determine the shear modulus profile in relation to the depth of the soil deposit.

The comparison between the results obtained by the application of SASW method and those provided by cross-hole and down-hole tests is shown in figure 4. A reasonable agreement is found for a depth of about 10 m as it was expected since an active method has been used.

CONCLUDING REMARKS

In the present paper a simple application of the SASW method for the analysis of field data concerning traffic and impact induced vibration of a clayey soil is described. The experimental data collected during the tests allowed to determine the dispersion curves and the initial shear modulus profile relative to the investigated deposit.

The comparison between the values of G_0 obtained using surface wave analysis and those determined by means of conventional cross-hole and down-hole tests showed that for a depth of about 10 m the method herein employed can be used with some confidence although an extremely simple inversion procedure was followed.

Since conventional dynamic in situ testing is costly and time-consuming, the use of surface wave tests and

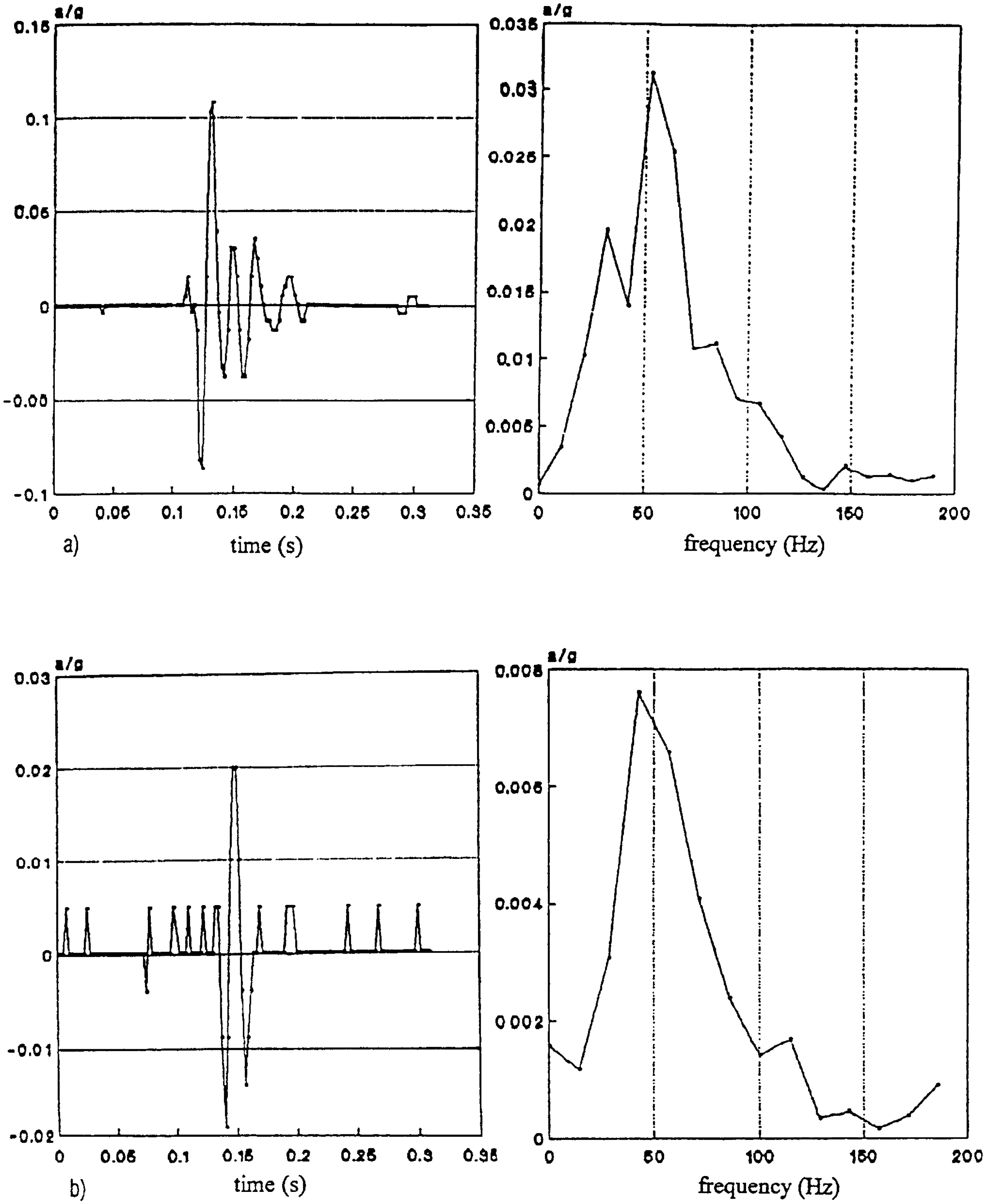

Fig.2 - Typical accelerograms and spectra for impact vibration.
a) vertical impact
b) horizontal impact

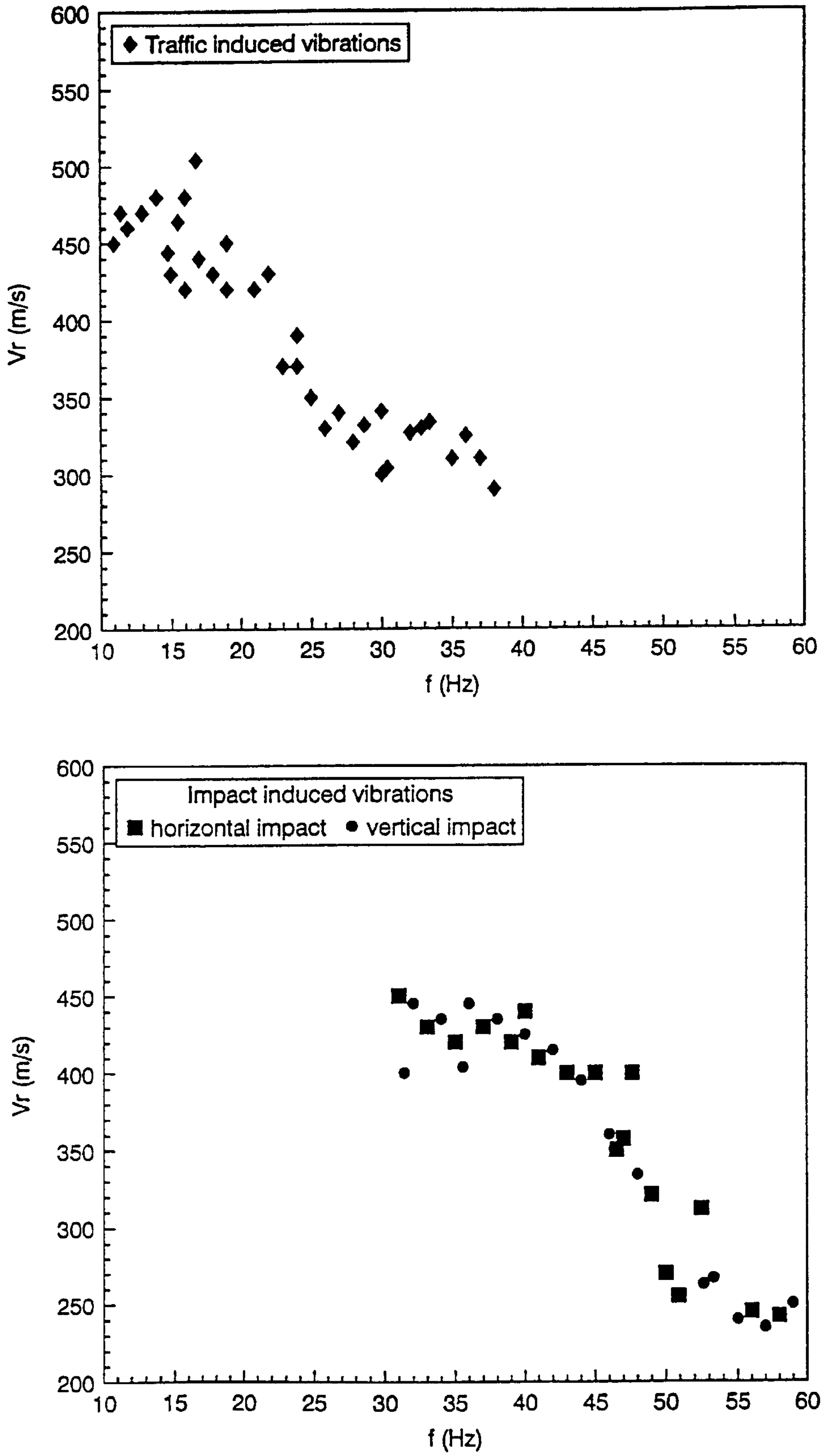

Fig.3 - Experimental dispersion curve.
a) traffic induced vibrations
b) impact induced vibrations

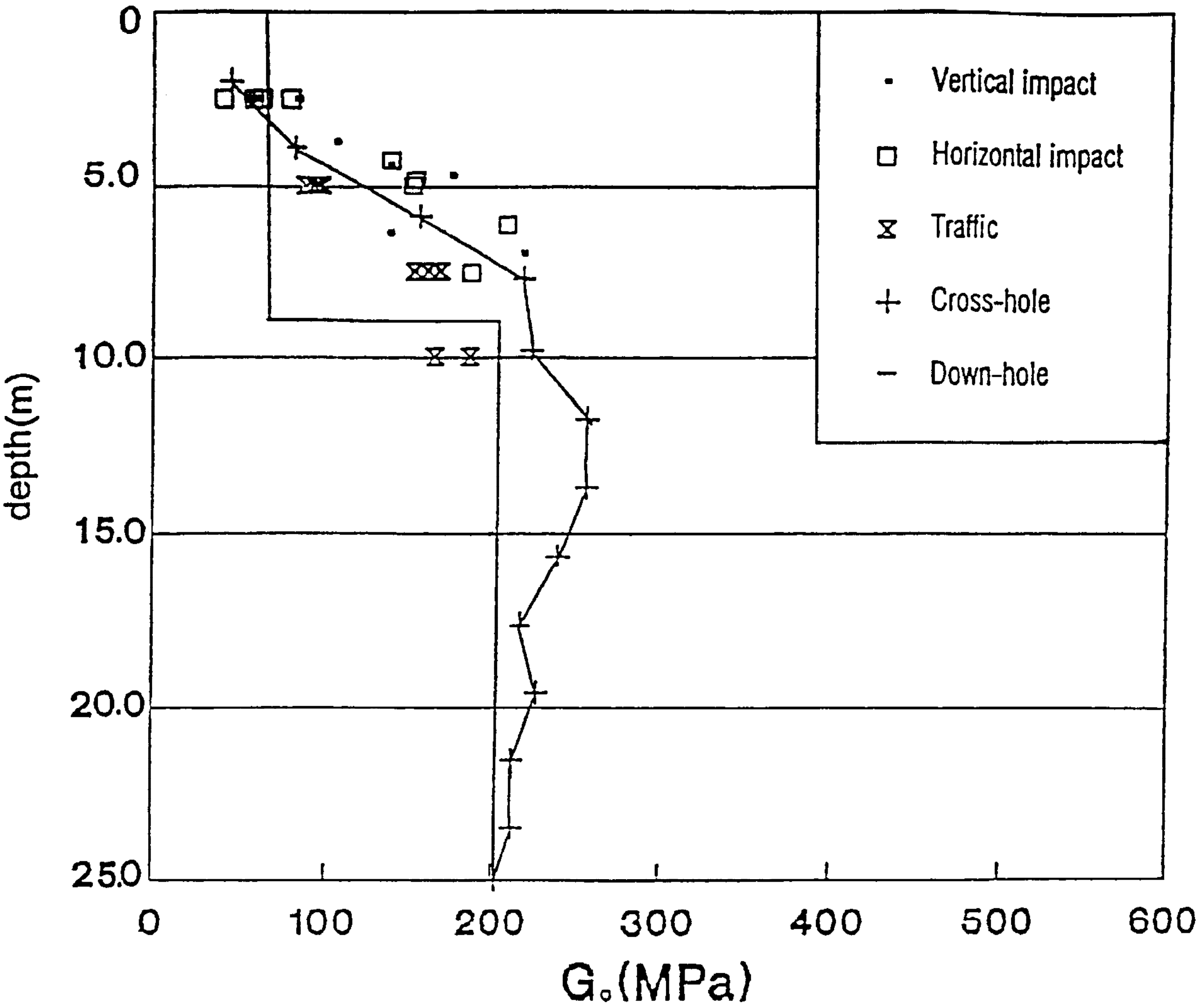

Fig.4 - G_0 profiles determined by different methods

analysis is recommended when data on shallow layers are required or when preliminary investigations on a site are needed.

REFERENCES

Barker, T. G. and Stevens, J. L. (1991). Array processing of Rayleigh waves for shear structure. *Proc., 2nd Int. Conf. on Recent Advances In Geotechnical Earthquake Engrg. and Soil Dynamics*, Univ. of Missouri-Rolla, Rolla, Mo., 1393-1397.

Drenvich, V. P., Kim, S. I., Alexander, D. R. and Kohn, S. (1985). Spectral analysis of surface waves in pavement systems with random noise excitation. *Expanded abstracts: 55th Annual Meeting*, Soc. of Exploration Geophysicists, Tulsa, Ok.

Gabriels, P., Snieder, R. and Nolet, G. (1987). In situ measurements of shear-wave velocity in sediments with higher-mode Rayleigh waves. Geophysical Prospecting, 35, 187-196.

Gucunski, N. and Woods, R. D. (1991). Use of Rayleigh modes in interpretation os SASW test. *Proc., 2nd Int. Conf. on Recent Advances In Geotechnical Earthquake Engrg. and Soil Dynamics*, 1399-1408.

Hiltenun, D. R. (1988).Experimental evaluation of variables affecting the testing of pavement by the spectral-analysis-of-surface-waves method. *PhD thesis*, The University of Michigan, Ann Arbor, Mich.

Horike, M. (1985). Inversion of phase velocity of long-period microtremors to the S-wave-velocity structure down to the basement in urbanized area. *J. Phys. Earth.*, 33, 59-96.

Jones, R. B. (1958). In-situ measurement of the dynamic properties of soil by vibration methods. *Geotechnique*, Vol. 8, N°. 1, pp. 1-21.

Liaw, A. L. and McEvilly, T. V. (1979). Microseisms in geothermal exploration - studies in Grass Valley, Nevada. *Geophysics*, Vol. 44, N°. 6, pp. 1097-1115.

Maugeri, M., Castelli, F. and Motta, E. (1994). Pile foundation performance of an earthquake damaged building. *Proceedings of the Italian-French Symposium on Strengthening and Repair of Structures in Seismic Areas.* Nice, France.

Maugeri, M., Frenna, M. S. and Spatola, P. (1996). On Rayleigh waves propagation in layered soils. *Eleventh World Conference on Earthquake Engineering.* Acapulco, Mexico, 23-28 June, 1996.

Nazarian, S. (1984). In situ determination of elastic moduli of soil deposits and pavement systems by spectral-analysis-of-surface-waves method. *PhD thesis,* The University of Texas at Austin; Austin, Tex.

Nazarian, S. and Stokoe, K. H., II (1984). In situ shear wave velocity from spectral analysis of surface waves. *Proceedings, 8th World Conference on Earthquake Engineering,* 3, 31-38.

Nazarian, S. and Stokoe, K. H., II (1986).Use of surface waves in pavement evaluation. *Transportation Research Record,* 1070, 132-144.

Nazarian, S. and Stokoe, K. H., II (1987). In situ determination of elastic moduli of soil deposits and pavement systems by spectral-analysis-of-surface-waves method (theoretical aspects). *Research rep. 437-2, Ctr. for Transp. Res.*, The University of Texas at Austin ; Austin, Tex.

Nazarian, S. and Desai, M. R., (1993). Automated surface wave method: Field testing. *Journal of Geotechnical Engineering, ASCE,* Vol. 119, N°. 7, pp. 1094-1111.

Rix, G. R. (1988). Experimental study of factors affecting the spectral-analysis-of-surface-waves method. *PhD thesis,* The University of Texas at Austin ; Austin, Tex.

Sanchez-Salinero, I., Roesset, J. M., Shao, K. Y., Stokoe, K. H. II and Rix G. J. (1987). Analitical evaluation of variables affecting surface wave testing of pavements. *Transp. Res. Record 1136,* Washington, D. C., 86-95.

Satoh, T., Poran, C. J., Yamagata, K. and Rodriguez, J. A. (1991). Soil profiling by spectral analysis of suface waves. *Proc., 2nd Int. Conf. on Recent Advances In Geotechnical Earthquake Engrg. and Soil Dynamics,* 1429-1434.

Sheu, J. C., Stokoe, K. H. II and Roesset, J. M. (1987). Effect of reflected waves on SASW testing of pavements. *Transp. Res. Record 1196,* Washington, D. C., 51-61.

Stokoe, K. H. II and Nazarian, S. (1985). Use of Raileigh waves in liquefaction studies. *Proceedings, Measurement and Use of Shear Wave Velocity for Evaluating Dynamic Soil Properties, Geotechnical Engineering Division, ASCE,* 1-17.

Stokoe, K. H. II, Nazarian, S., Rix, G. J., Sanchez-Salinero, I., Sheu, J. C. and Mok, Y. J. (1988). In situ seismic testing of hard-to-sample soils by surface wave method. *Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground MOtion Evaluation, Geotechnical Special Publication N°. 20, ASCE,* pp. 264-278.

Taniguchi, E. and Kenkichi, S. (1979). Attenuation with distance of traffic-induced vibrations. *Soils and Foundations,* Vol. 19, N°. 2, pp. 15-28..

Tokimatsu, K., Kuwayama S., Tamura, S. and Miyadera, Y. (1991). V_s determination from steady state Rayleigh wave method. *Soils and Foundations,* Vol. 31, N°. 2, pp. 153-163.

Tokimatsu, K., Tamura, S. and Kojima, H. (1992a). Effects of multiple mode on Rayleigh wave dispersion. *Journal of Geotechnical Engineering, ASCE,* Vol. 118, N°. 10, pp. 1529-1543.

Tokimatsu, K., Shinzawa, K. and Kuwayama, S. (1992b). Use of short-period microtremors for V_s profiling. *Journal of Geotechnical Engineering, ASCE,* Vol. 118, N°. 10, pp. 1544-1558.

Tokimatsu, K. (1995). Geotechnical site characterization using surface waves. *First International Conference on Earthquake Geotechnical Engineering,* IS-Tokio.

Yuan, D., Nazarian, S. (1993). Automated surface wave method: Inversion technique. *Journal of Geotechnical Engineering, ASCE,* Vol. 119, N°. 7, pp. 1112-1126.