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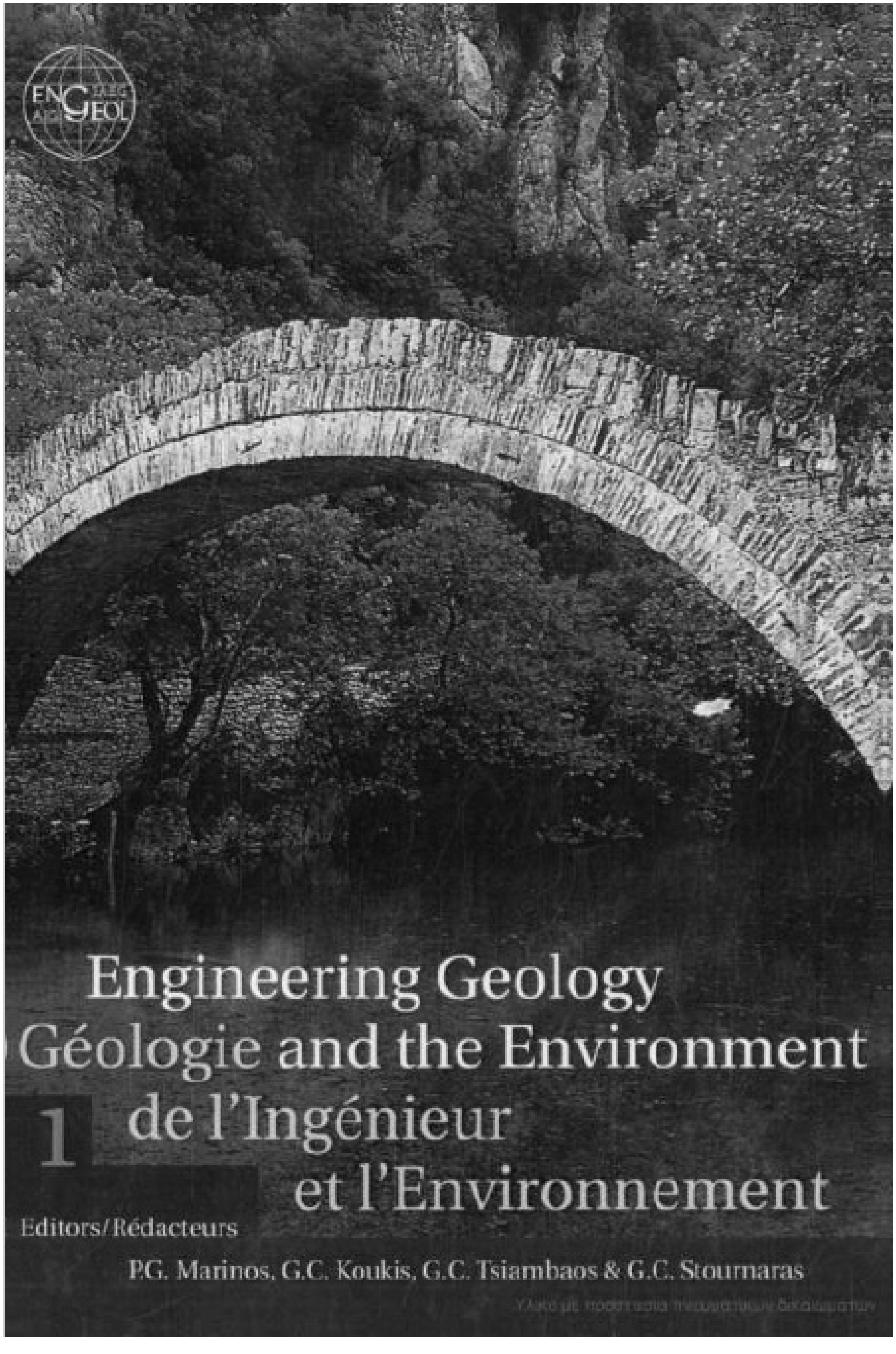

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Combined geophysical methods for subsurface characterization in the framework of microzoning studies

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ABSTRACT: The peak values of expected strong motion parameters on the ground surface is strongly dependent on the subsurface geology conditions and especially on what is characterized as the overburden layer. Shallow, complicated structures can be resolved by using the seismic refraction method, if an adequate seismic contrast between the bedrock and the overburden layer exists. In addition, conventional and modern geophysical methods contribute to the detailed delineation and evaluation of the subsurface structure, supplying the expert engineer with a valuable tool in order to transfer strong motion values from the bedrock to the ground surface within the framework of microzoning studies.

1. INTRODUCTION

In microzoning studies the knowledge of the subsurface structure, as well as the range of the dynamic elastic moduli of the substratum, is of great importance. Structural studies become available by utilizing surface geological mapping, borehole investigations and surface geophysical research. The combination of all the above mentioned methods gives a clear picture of the subsurface structure but fails to give reliable results concerning the determination of the dynamic elastic moduli. Surface high resolution techniques have been used recently (Zhang Shihong, 1990, Goforth T. and Hayward C., 1992, Alvarez J. et al., 1995) to obtain reliable shallow structures by elaborating Vp and Vs seismic waves. Besides, it is possible to determine the elastic moduli of these shallow formations by based on a density value from laboratory or borehole logging measurements. Surface, high resolution techniques have the disadvantage of depending greatly on the upper soil conditions and on the output of seismic source characteristics. Many types of seismic sources have been used and their efficiency for high resolution studies is commented in a recent paper of Miller R. et.al., 1992. Geophysical borehole logging represents another tool for obtaining information about the physical properties of the subsurface strata i.e. porosity, resistivity etc, but it is not an appropriate method for the elastic moduli determination. On the contrary, cross-hole and down hole techniques have been used mainly for the elastic moduli determination of surface (up to 30 m) layers. In cross-hole investigations the borehole pair is set 5 to 6 m apart. The energy source for seismic waves is usually the standard Terzaghi split sampler (SPT). Penetration of this sampler in soil produces mainly vertically polarized shear waves. The sampler's penetration creates also low amplitude P waves due to the compression of soil. Thus, the determination of P and S-wave arrival times permits the calculation of Vp and Vs velocities and the estimation of the elastic parameters Young's modulus, Ed, Rigidity modulus, Gd and Poisson's ratio, σ. This method has the disadvantage that is time consuming and that sometimes the first arrivals of the P waves produced cannot be easily distinguished.

Alternatively, a spring driven hammer striking an anvil can be used to produce signals for Vp and Vs waves for cross-hole investigations. A converter fixed at the lower part of the hammer is transforming the axial movement of the anvil-rod assembly into hydraulic shock. The fluid between the converter plates is pushed into the borehole walls. Due to the radially directed stress, the device outputs both compressional and shear waves. The delivered energy of this version is about 5-8 J/blow and the blows may be repeated within 2-3 seconds interval. The frequency range is within 200-1500 Hz. (Vibrometric OY, 1995). The hammer is easily handled and during field measurements presented in this paper it was

[7]

proven to be an appropriate device for conducting cross-hole tomographic investigations.

In this paper, the results of combined geophysical methods are presented in order to demonstrate their usefulness in delineating the subsurface structure and providing the elastic moduli determination in areas where microzoning studies are carried out. Seismic refraction surveys, geoelectrical soundings, conventional cross-hole measurements and modern cross-hole tomography images have been correlated in an effort to obtain a clear picture about their advantages and limitations, and in order to evaluate their usefulness in microzoning studies.

2. SURFACE SEISMIC METHODS

The most widely used geophysical method for geotechnical purposes is that of seismic refraction which can delineate the morphology and provide the seismic velocity of the bedrock and the overlain formations. The characterization of the basement as hard rock depends mainly on the Vs estimation (usually greater than 600 m/s) which, can be be determined for shallow depths only, by using surface seismic refraction methods. The determination of the seismic velocity Vp for the bedrock presents also difficulties in areas where the overburden layer is composed of a mixture of different materials i.e. clays, sands, marls and a water table might be present. In this case, there is no clear velocity contrast between the formations and their delineation and characterization is not possible. In addition, the water table shadows the subsurface structure, giving a pseudo-bedrock relief and the velocity (1500 m/s) of the water bearing formations. In order to overcome this problem an average velocity of the overburden mixture is assigned and the bedrock velocity can be determined by using the GRM method (Palmer, 1980). It is obvious that this method can be applied if an adequate velocity contrast exists between the overburden mixture and the bedrock. An example is given in figure 1. In this case, the surface layer shows relatively high velocity values (720-800 m/s), compared to the usual range of 360-540 m/s, which represents an average velocity of the overburden mixture.

In areas where a clear velocity contrast exists the subsurface structure provided by the surface seismic refraction method is more reliable. In figure 2, a cross-section of a seismic refraction profile passing through the borehole pair H-2/H-1, which is in good accordance with the borehole results, is presented. In this section the surface layer is characterized by a low velocity range (360-540 m/s) and the intermediate layer by a velocity range 1400-1800 m/s and locally 2400 m/s. The deeper layer displays a clear velocity contrast with the overburden layers and a high velocity value along the whole length of the profile (3100-3270 m/s).

In order to check the reliability of the seismic refraction results obtained in such structurally complicated areas (interbedded clays, sands, presence of water table e.t.c) conventional cross-hole investigations and modern cross-hole techniques were used.

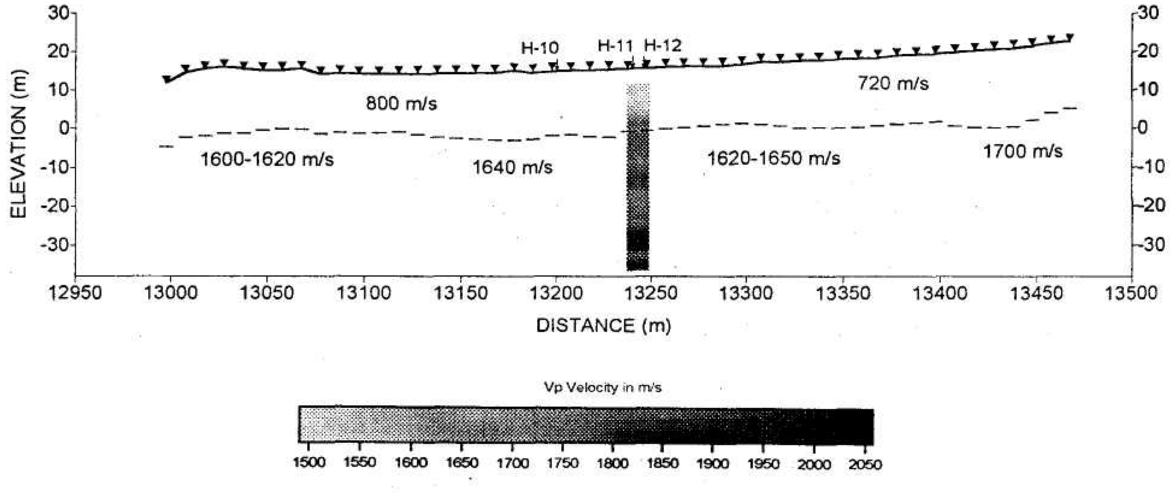

Figure 1. A seismic cross-section profile (T-H11H12) passing through the borehole pair H-11/ H-12, showing an average upper layer velocity. A gray-scale presentation of the corresponding cross-hole results is also shown.

3. CONVENTIONAL CROSS-HOLE TESTS

Cross-hole testing comprised two boreholes, for the source and the receiver, spaced 6 meters apart. After drilling a PVC pipe was installed in borehole pair (10 atm strength) with a 75 mm inside diameter and a closed bottom. The annular space between the casing and the borehole sidewall was grouted. The borehole was filled with water which is a strict requirement for the hammer use. Then, the hammer described earlier was lowered inside the source borehole and held at a given depth. A receiver chain of 8 triaxial geophones was lowered so that the 8th geophone was at the same depth as the hammer in the source borehole. The measurements were taken at 2 meters spacing and the whole procedure started from the bottom of the borehole and moved upwards. The results for borehole pairs H-1/H-2 and H-11/H-12, which are drilled close to the seismic refraction traverses T-H1H2 and T-H11H12 respectively, are shown in figures 1 & 2. It is clear that there is a good correlation between the seismic velocities determined by these different methods. That is, for borehole pair H-1/H-2 (fig.2) an average velocity of 2000 m/s is determined for depths 6 to 22 meters where the second seismic discontinuity appears in traverse T-H1H2. The velocity ranges from 1508 to 2528 m/s in the borehole pair while in the cross-section ranges from 1400 to 2420 m/s. For the deeper layer an average velocity of 3000 m/s for the borehole pair is obtained which is very close to that showing in the cross-section (3270 m/s).

Another example showing the relationship among the different methods of approach for seismic velocity determination, is drawn from the borehole pair H-11/H-12 (fig. 1) which was drilled in an area where no clear velocity contrasts appear. In this case, a discrepancy in seismic velocity assignment for the first layer is obvious. The average Vp velocity obtained from cross-hole measurements for depths 6 to 15 meters is 1536 m/s, showing the presence of water saturated formations. On the contrary, the corresponding surface seismic refraction cross-section (fig. 1) shows an average Vp velocity of 720-800 m/s from the surface up to a depth of about 16 meters where a discontinuity appears. This is due to the fact that the upper surface layers present very low Vp velocities (360-540 m/s) which in the average with the lower water saturated ones of higher velocities give intermediate velocities (720-800 m/s).

4. GEOELECTRICAL SOUNDINGS

A further investigation was conducted by carrying out a number of geoelectrical soundings parallel to the seismic profile T-H11H12. The purpose of this investigation was first to delineate the structure of the upper surface layers and second to check the reliability of the assumptions made for these layers by trying to interpret the seismic refraction results of surface layers. That is, the dry surface layer assumed in seismic refraction interpretation shows up (15-30 Ohm.m) in the geoelectrical profile GS-1 of figure

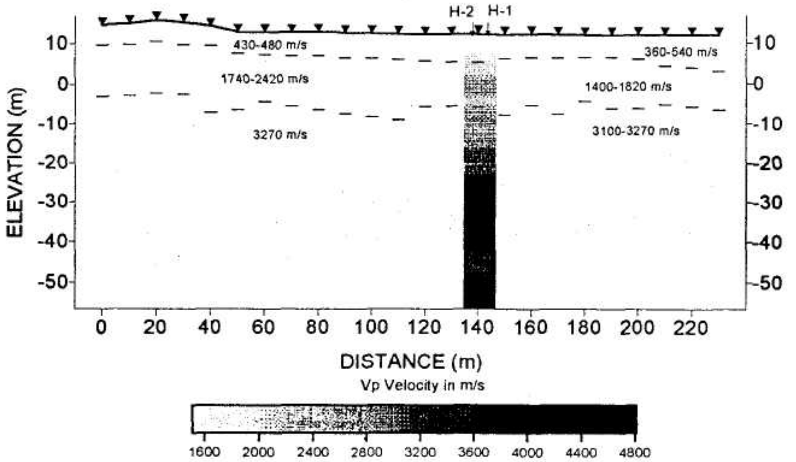

Figure 2. A seismic cross-section profile (T-H1H2), which passes through the borehole pair H-1/ H-2, showing discrete interval velocities with small lateral variations A gray-scale presentation of the cross-hole results is also shown.

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3. The intermediate layer of low resistivity (8-10 Ohm.m) corresponds to the water saturated formations and the layer below with higher resistivity (>15 Ohm.m) is attributed to coarser material (silty clay). All these observations are in good agreement with the results taken from the research borehole pair H-11/H-12.

5. CROSS-HOLE TOMOGRAPHY TESTS

The execution of surface seismic refraction investigations in populated areas imposes many difficulties, mainly due to the inability to use high energy-effective seismic sources. The use of conventional cross-hole tests for obtaining the appropriate knowledge of soil parameters is limited in narrow zones (6 meters apart) and it is not cost-effective. On the contrary, the use of cross-hole tomography can solve such problems by extending the area of investigation over longer distances. Of course there are limitations imposed mainly by the geometrical setting of the borehole array but in any case, the method can provide reliable results concerning the distribution of Vp and Vs velocities as well as the distribution of the dynamic elastic moduli between a pair of boreholes. Examples of tomographic images representing distributions of the above mentioned parameters are shown in figure 4.. The elaboration of a cross-hole tomography image requires a good geometrical coverage of seismic rays and an extensive wave field analysis that makes the method time consuming and expensive.

6. RIGIDITY MODULUS DETERMINATION

In microzoning studies a basic factor for the seismic response analysis of the ground is the dynamic rigidity modulus of the medium which is determined through the relationship

$$Gd = \rho V_s^2 \qquad (1)$$

where ρ is the density of the ground.

The velocity Vs depends on the number of strikes/30 cm (Nspt) of SPT method (Standard Penetration Test) and its relationship is given for different geological formations from empirical equations (Imai-Tonuchi 1982, Zervogiannis Ch. et.al. 1987). The velocity Vs is usually determined by using the standard Terzaghi split sampler which produces clear vertically polarized S waves. In this paper a spring driven hammer was used to produce radially directed stress which outputs compressional and shear waves. The velocity Vs determined in this way and for different formations, was correlated with the number of strikes Nspt obtained from the Terzaghi test (up to depth of 40 metres) and the results are shown in figures 5a and 5b.

7. DISCUSSION

Geophysical investigations can provide valuable information about the subsurface structure in areas where detailed microzonation studies carried out. In structurally complicated areas the delineation of the morphology of the deep seated bedrock is possible by using the seismic refraction method, if an adequate

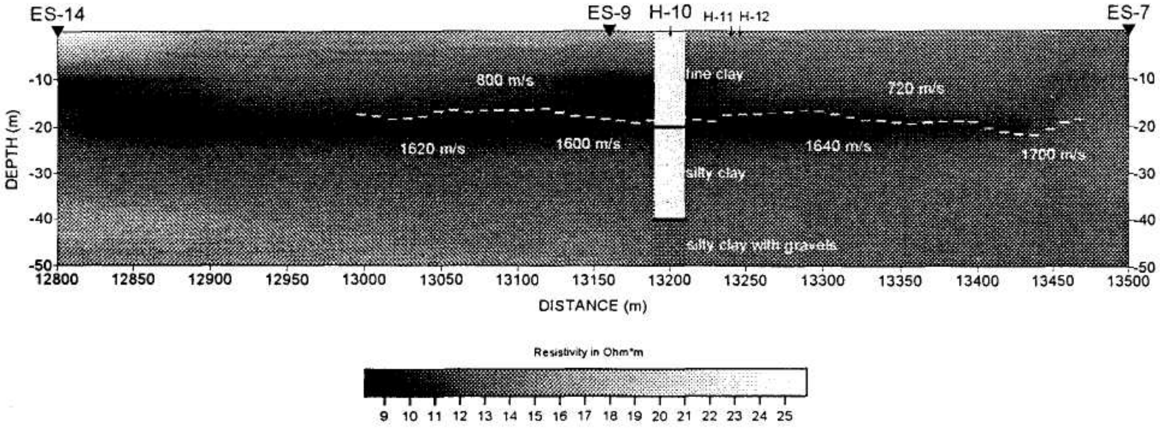

Figure 3. A geoelectrical cross-section (GS-1) showing the resistivity distribution, along a profile parallel to the seismic line of figure 1, in gray-scale. The stratigraphic column is also presented (H-10). The dotted line separates two layers with adequate seismic velocity contrast.

velocity contrast between the overburden and the bedrock exists. It should be emphasized that the estimation of the average velocity of the overburden layer is more helpful on ground response analysis than the discrete but laterally limited or hidden seismic layers. The high energy requirement of the seismic refraction method for deeper structure investigations limits its use in populated areas. Besides, geoelectrical soundings can provide with valuable information for the geometry of the deeper seated discontinuities as well as for the nature of the formations present.

The elastic parameters can be determined by carrying out either conventional cross-hole tests for on site estimation or cross-hole tomography techniques for covering larger areas. The recognition of S waves is not always an easy task at longer distances and S arrival times may be

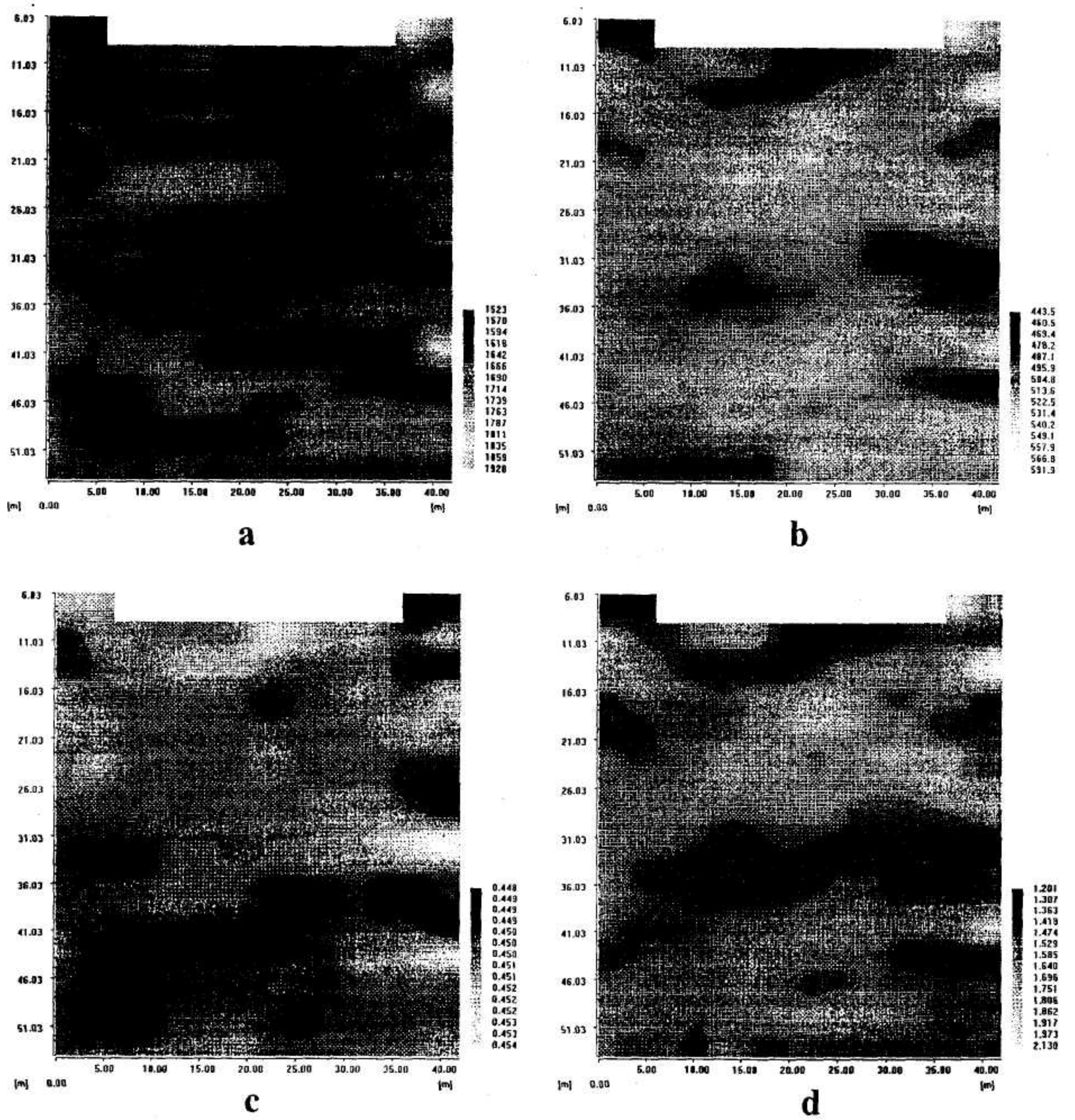

Figure 4. Tomographic images obtained between borehole pair H-10/H-11 showing the distribution of (a) Vp (m/s), (b) Vs (m/s), (c) Poisson ratio and (d) Young modulus (GPa).

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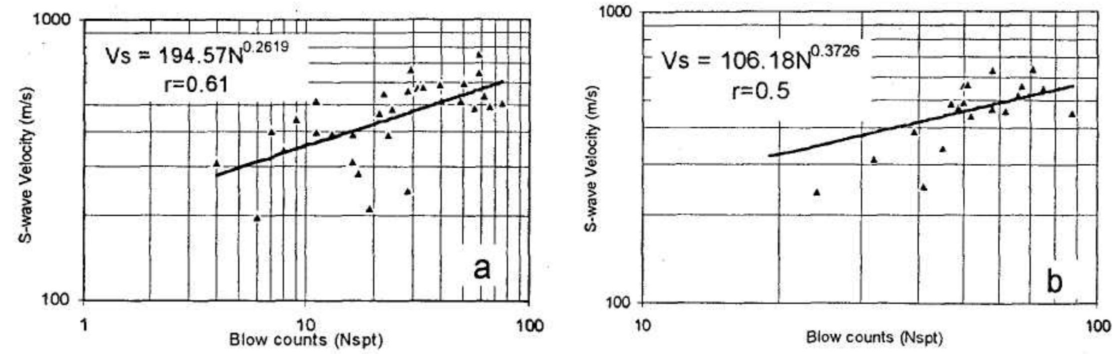

Figure 5. Correlation of Vs velocity values and number of strikes for clays (a) and sands (b).

wrongly picked because of the contemporary appearance of other later arrivals i.e. ground roll waves, resulting to erroneous calculations of the Vs velocity. If, however, the distribution of Vp and Vs velocities is known, the gross determination of the elastic parameters can be obtained by assigning a mean bulk density. The detailed knowledge of the bulk density i.e. determined from borehole logging, provides a better estimation of the elastic parameters inside and between the borehole pair. The correlation of the Vs velocity with the number of strikes/30 cm (Nspt) gives another tool for a gross estimation of the dynamic elastic moduli. The empirical equations shown in figures 5a and 5b for clays and sands respectively, give generally higher estimated values for Vs versus Nspt than those given by other authors (Imai & Tonuchi 1982, Zervogiannis et al. 1987).

In conclusion, both conventional and modern geophysical methods can be used in microzoning studies for local or large scale investigations, depending on the needs of the specific research project. It is emphasized here that there is always the need for a minimum package of geophysical works to be designed to fulfill the needs of an integrated microzoning study.

REFERENCES

Alvarez, J., Chavez, R.E. and Lomnitz, C. (1995). Shallow SH-refraction survey on Mexico City mud: amplification by wedge effects. *First Break*, Vol. 13, No 12, 471-479.

Goforth, T. and Hayward Ch. (1992). Seismic reflection investigations of a bedrock surface buried under alluvium. *Geophysics*, Vol. 57, No 9 1217-1227.

Imai, T. And Tonuchi, K. (1982). Correlation of N value with S-wave velocity and shear modulus. *Proc. Second European Symposium on Penetration Testing, Amsterdam, May, 24-27.*

Miller, R.D., Pullan, S.E., Steeples, D.W. and Hunter, J.A. (1992). Field Comparison of Shallow S-Wave Seismic Sources near Houston, Texas. *Kansas Geological Survey. Open-file Report #92-33.*

Palmer, D. (1980). The generalized reciprocal method of seismic refraction interpretation. *Soc. Of Explor. Geophys. Monograph, Tulsa, Oklahoma, 104.*

Zervogiannis, Ch., Boukovalas, G. and Christoulas, St. (1987). Correlations of mechanical characteristics and classification of soil formations. *Bulletin of Public Works Laboratory Center (CPWL)*, Vol. 4, 255-265.

Zhang S. H. (1990). Shallow SH-Wave Seismic Exploration for Subway Construction in Shanghai. In *S.H. Ward (Eds), Geotechnical and Environmental Geophysics*, 175-179.

Zohdy, A.A.R. (1989). A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics*, Vol. 54, No 2, 245-253.