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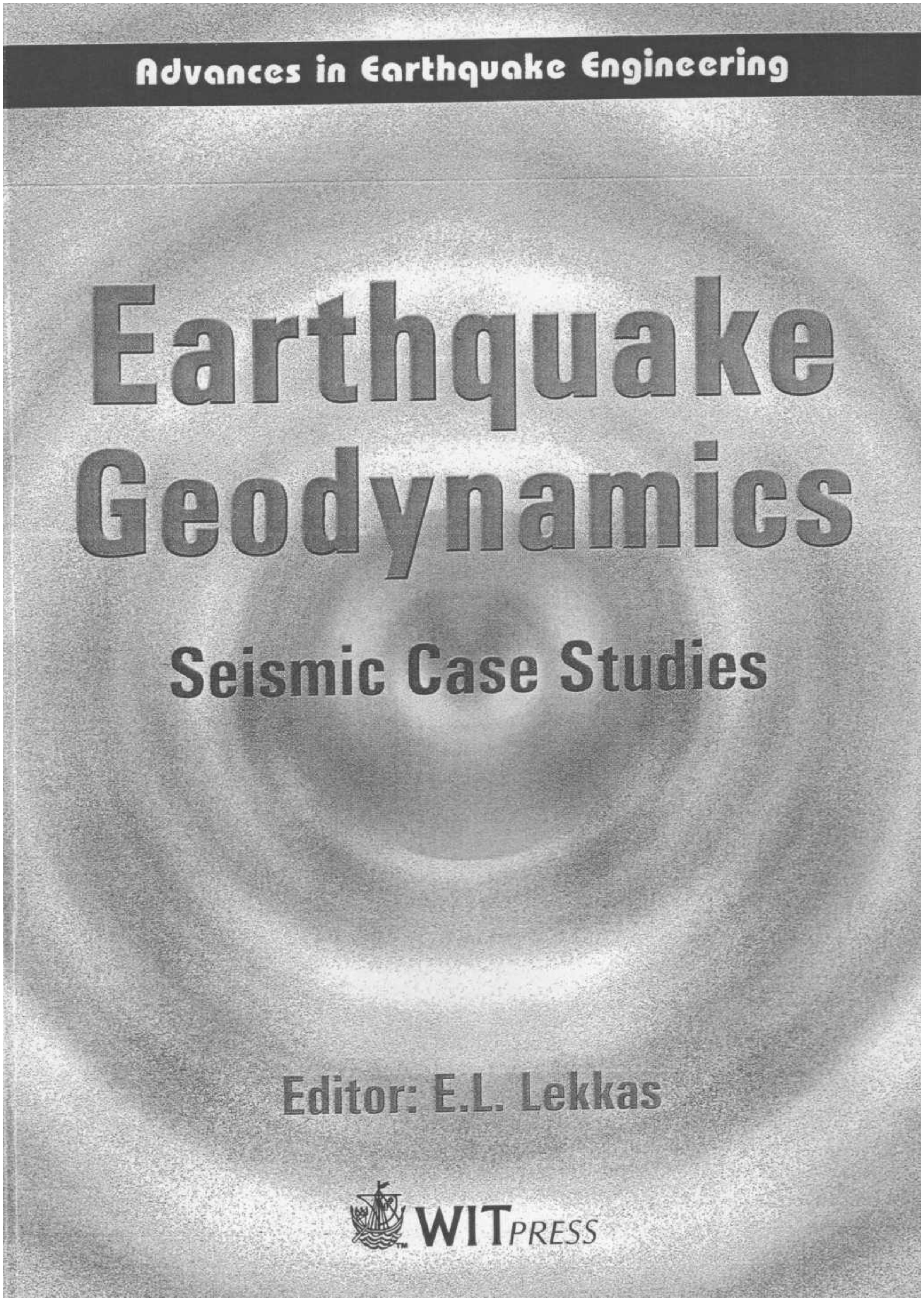

Advances in Earthquake Engineering

Earthquake Geodynamics

Seismic Case Studies

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CHAPTER 10

Low-strain techniques used for microzoning studies in soft rock areas in Greece

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Abstract

For site characterization, and especially in estimating surface strong ground motion, the Vs distribution with depth is a necessary parameter. The distribution also of Vp with depth gives additional information in searching the subsurface conditions, especially when it is related to the structural geometry of the medium. Many geophysical methods have been proposed and have been used worldwide in the past, including surface and borehole techniques. In this paper a synopsis of the methods used by the authors in the last few years are presented, and some case histories of particular interest are described, relating to investigations that have been carried out in the framework of microzoning studies in Greek territory and in a soft rock environment.

1 Introduction

In the last two decades, emphasis has been placed by earth scientists and urban planners worldwide taking into account the effect of soil on buildings during the occurrence of a strong earthquake. The investigation of soil structure and its dynamic elastic characteristics is of primary importance in estimating expected surface strong ground motion. Many papers have been published on the subject including contributions of geophysical investigations by using surface and borehole techniques (Alvarez *et al.* [1], Bailey & Van Alstine [2], Fertig [3], Helbig & Mesdag [4], Imai & Tonuchi [5], Maurer *et al.* [6], Moony [7], Stoke & Woods [8], Zhang [9]). Each technique presents its advantages and disadvantages depending on accessibility, depth of investigation, surface conditions (pavement, asphalt, cement, etc.) and the cost of the method used.

From surface methods the SASW technique, based on surface waves dispersion, has gained much reliability in the past few years. In Greece there have been a few successful applications in microzoning studies conducted (Pelekis & Athanassopoulos [10], Pelekis *et al.* [11]). Since this method cannot be used in all environments, especially in populated areas and in different surface conditions, there is always the need to develop other surface or borehole techniques. Downhole, crosshole and crosshole tomography techniques have been used equally successfully in some areas of Greece (Kambouris *et al.* [12], Tolis *et al.* [13]). These techniques are based on the detection and selection of P and S-wave arrivals and the determination of Vp and Vs seismic velocities as well as the associated dynamic elastic parameters. The classical crosshole method of using SPT for Vs determination presents difficulties, especially in soft rock environments, and the results obtained are usually doubtful. Nevertheless, engineers find useful, and use, empirical graphs showing the relationship between SPT vs Vs values (Bouckovalas *et al.* [14]) for different geologic formations (clays, sands, clay-sand, marls, etc.).

The scope of this paper is to present the results obtained by the authors in the last few years within the framework of microzoning studies, by developing low-strain surface and borehole techniques in various soft rock environments in Greece.

2 Methodology

Low-strain techniques refer to seismic methods that usually use mechanical sources to produce P and S or PS converted waves. Surface seismic methods utilize mainly SH waves produced by striking a fixed wooden plank (loaded with a heavy weight) on both sides using a sledgehammer. Other modern techniques giving similar results have also been used by utilizing different ways for S wave sources (Deidda & Ranieri [15]). The SASW or Multi-SASW methods are based on the dispersion of surface waves and the dependence of phase and group velocities on their period. The seismic source could be either a sledgehammer or a drop weight. The seismic refraction method, which has been used extensively in the past, gives reliable results for the shallow velocity structure but fails to provide reliable S-wave onsets from deeper horizons. Borehole techniques have been used for detailed structural imaging in areas of special interest. These techniques utilize both surface (sledgehammer) and in-hole (mechanical hammer) seismic sources. Nowadays emphasis is given to developing more sophisticated techniques (e.g. crosshole tomography) in order to obtain detailed, more reliable and 2-D imaging results for Vp, Vs and the dynamic elastic constants, Young's modulus, Ed, rigidity modulus, Gd and Poisson's ratio, σ.

2.1 Surface methods

Different approaches have been used to determine seismic velocities Vp, Vs at depth, which are necessary for the calculation of elastic moduli parameters. The seismic refraction method was the most popular one to have been used routinely in the past, but with limited depth penetration and lower resolution. The seismic reflection method has in the last few years gained much applicability, based on the improvement of seismic sources/instrumentation, the new processing techniques, the deeper depth of penetration and its intrinsic higher resolution. In a recent paper of Deidda and Ranieri [15], SH-wave seismic reflections were obtained from depths of less than three meters. Surface waves have also been used successfully for stratigraphic structure and seismic velocity distribution at depth (Pelekis *et al.* [11]).

In this paper, some earlier efforts conducted by the authors using the seismic refraction method will be referred to. A research project has been put forward by the authors in the last three years to investigate the possibility of getting high resolution shallow structures by generating and detecting S-wave onsets, by applying the seismic reflection method, but the study is still in progress. Surface wave method has been developed greatly in the last few years and is nowadays a useful tool for estimating the subsurface distribution of Vs based on the dispersion of mainly Rayleigh waves. Our experience (Papadopoulos *et al.* [16]) of the subject is strictly limited to only one common project that was carried out in the past including seismic refraction and SASW methods.

2.2 Borehole methods

Borehole methods utilize different techniques such as downhole, uphole, simple crosshole and crosshole tomography techniques. Downhole/uphole techniques are simple and low cost but their applicability presents difficulties based on surface conditions, method of analysis and interpretation and the subsurface structure itself. For the evaluation of soil dynamic properties a new downhole technique was presented recently (Lontzetides [17]) and also a comparison between the results of SASW and crosshole/downhole measurements (Pelekis & Athanassopoulos [10]). An improvement in the method of analysis for downhole measurements has also been presented recently (Kambouris *et al.* [12]). The simple crosshole technique has been applied basically in two ways. The first configuration utilizes a borehole with a triaxial geophone inside it and the seismic source is set at a distance of 3–4 meters away from the first borehole and at the same depth as the triaxial geophone but as a source the SPT device is used. As the Terzaghi test proceeds deeper, the information for the Vs estimation is obtained whenever the drilling device reaches a predetermined depth and produces seismic waves by freely dropping the weight. This method has been widely used in Greece in recent years (Bouckovalas [18]). The ambiguity introduced by this method comes from its inability to check the arrival of secondary waves, taking into account that P and S wave pulses interfere with each other at short distances.

The other configuration resembles the first but differs in that it uses two boreholes (instead of one) and a mechanical hammer inside one of them is used as a seismic source. The seismic pulse has higher frequency content, and using several triaxial geophones located at different depths for each shot, one can obtain recognizable and more reliable secondary arrivals. This method has been successfully used by the authors (Kambouris *et al.* [12]). A more sophisticated and effective method is the crosshole tomography method, which utilizes many shot points and geophone locations so that dense seismic traces cover the area between the two boreholes. Thus, a receiver chain of eight triaxial geophones is lowered into one borehole and a number of shots are fired into the other borehole every two meters by using a mechanical seismic hammer. The seismic source operates by a spring-driven hammer striking an anvil producing signals for P- and S-waves. A converter fixed at the lower part of the hammer transforms the axial movement of the anvil-rod assembly into hydraulic shock. The fluid between the converter plates is pushed into the borehole walls, producing radially directed stresses and consequently compressional and shear waves (Cosma [19]). The frequency content of the waves of the mechanical hammer is in the range 200–1500 Hz. The dominant frequency of the recorded shear waves is in the range 200–350 Hz. In this way it is possible to detect low and high velocity regions between the two boreholes as well as the corresponding distribution of the elastic moduli (Papadopoulos *et al.* [20]). Limitations to this method can be imposed mainly by two factors, (a) the prerequisite of at least one watertight borehole where the seismic hammer enters and (b) the cost of the two boreholes.

All the above-mentioned techniques have been formulated by the authors and the results obtained from different parts of Greece will be presented below. The measurements have a common character in that they were conducted in lowland areas and in a soft rock environment. The importance of conducting such measurements arises from the need to incorporate the results obtained (e.g. elastic moduli parameters) in microzoning studies that are developed for seismic hazard assessment and protection in vulnerable areas.

3 Elastic moduli determination

The upper 2–3 meters are usually composed of loose material that behaves in an inelastic way and the seismic velocities (Vp, Vs) show much lower values, even below the velocity of sound in the air (340 m/s) for P waves. Reliable results can be obtained below three meters' depth for both surface and borehole geophysical methods. Consequently reliable elastic moduli constants can be obtained at deeper depths where the material starts to behave elastically, although other factors (e.g. water content, fractures) can affect them. The presence of water content in soft rocks can be indicated by the higher Poisson ratio values, σ (Papadopoulos [21]). Under the water table of a formation, the ratio of seismic velocities Vp/Vs will be higher causing a higher Poisson ratio even if the rigidity strength of the rock increases in absolute values. The density of the medium should be known for the rigidity modulus determination. In most cases an average density is obtained, introducing a small error in the calculations since only small density variations are observed in soft rocks (1.6–2.1 gr/cm^3). In earlier times empirical relationships were used to calculate the Young's modulus from seismic velocities, Vp (Brown & Robertshaw [22]). Errors in the determination of elastic moduli parameters are introduced mainly from the errors derived from the estimation of seismic velocity Vs. Emphasis has been given in recent years to obtaining reliable Vs distribution at depth and laterally by utilizing seismic reflection and crosshole tomography methods.

4 Case histories

Some case histories will be described below for areas where temporary or extensive investigations have been conducted in the framework of site characterization or microzoning studies (Figure 1). For the areas of Grevena-Kozani and Aegio, only surface geophysical investigations were carried out due to the need to provide data for soil conditions in a short time, in order for the local authorities to undertake immediate measures for house repairs or for moving the population to safer regions after the occurrence of the large earthquakes (13 May and 15 June 1995) which struck these areas.

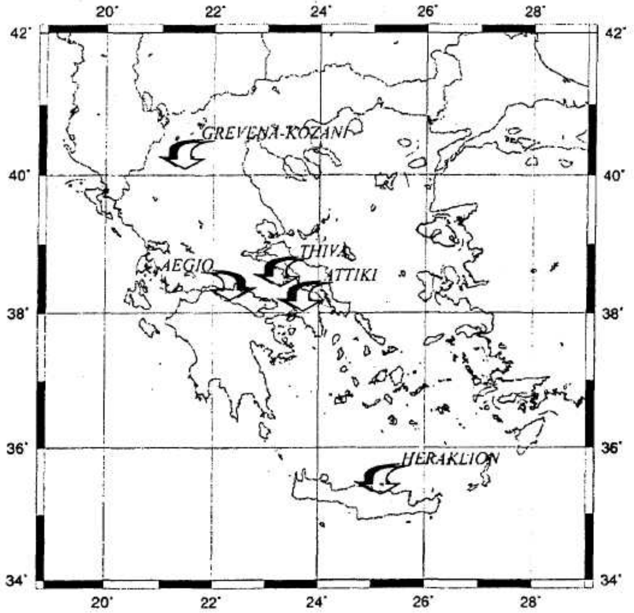

Figure 1: Map of Greece showing the sites where surface and borehole techniques were carried out, in the framework of microzoning studies.

4.1 Area of Grevena-Kozani

A surface geophysical investigation was carried out at selected and heavily damaged sites after the earthquake occurrence of 13 May 1995 of magnitude 6.6 R. Macroseismic observations showed that the heavily damaged areas were affected very much by the bad soil conditions. For immediate restoration of damage or for urban planning decisions regarding whether or not to move the population to other, safer, areas, an integrated geophysical study was proposed among the other investigations including the seismic refraction method and electrical soundings, in order to investigate the thickness of the loose soil material and the presence of the water table at shallow depths. The results obtained could be used for an immediate estimation of the hazard assessment due to landslide or liquefaction phenomena. Since only Vp velocities were determined and in order to get a gross estimation for at least one elastic parameter, the following empirical formula by Brown, Robertshaw [22] was used to estimate the Young's modulus of soil material:

$$Ed = 1.163Vp^{2.34}10^9(Newtons / m^2) .$$

In Table 1, the range of Vp seismic velocities for the upper two layers and the corresponding lithologies are shown, obtained from various selected sites of heavily damaged villages in between the Grevena-Kozani area.

Table 1: Range of Vp seismic velocities for the upper two layers and the corresponding lithologies in the Grevena-Kozani area.

Layer no.	Seismic velocity, Vp (m/s)	Lithological description
1	550–900	Loose surface material composed of clay, sand, gravel, etc.
2	1250–4500	Alternative layers of conglomerates, sandstone and marls. Higher values correspond to cohesive ophiolitic conglomerates.

In Table 2 the seismic velocities, Vp, and the corresponding values of Young's modulus, Ed, are shown for every investigated village (Figure 2).

Table 2: The seismic velocities, Vp, and the corresponding values of Young's modulus, Ed, for every investigated village in the Grevena-Kozani area.

Village	Layer 1		Layer 2	
	Vp (m/s)	Ed ($Nt/m^2 \times 10^9$)	Vp (m/s)	Ed ($Nt/m^2 \times 10^9$)
Chromio	600–900	0.4–0.9	1250–1350	2.0–2.4
Knidi	800–900	0.7–0.9	3600–4500	23.3–39.3
Baris	550	0.3	1600–1800	3.5–3.9
Nisi	600	0.4	3000–3400	15.2–20.4
Messolakos	650	0.4	1500–1700	3.0–4.0
Sarakina	700	0.5	1550–2000	3.2–5.9
Kozani	500–700	0.2–0.5	1800–1900	3.9–5.2

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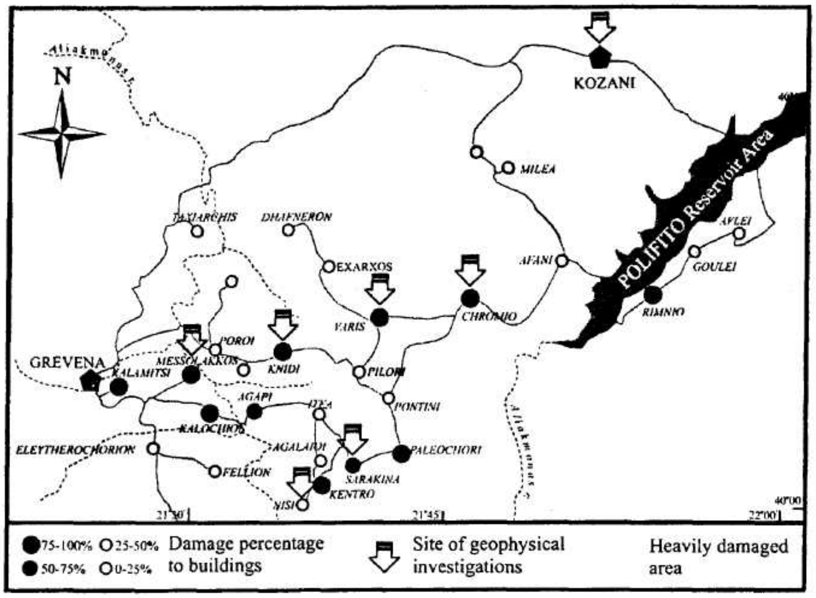

Figure 2: A sketch map of the Grevena-Kozani area, showing the distribution of damage and the investigated geophysical sites.

For loose material composed of clay, sand, gravel, etc., with seismic velocities Vp, 550–900 m/s, the Young's modulus ranges between 0.29–0.91 Nt/m^2 and for conglomerates, sandstone with seismic velocities 1,250–4,500 m/s, the Young's modulus ranges between 2.0–39.3 Nt/m^2. The thickness of the first layer ranges between 13–26 m. The low seismic velocities and the bad geotechnical conditions of the first layer, associated with its relatively small thickness, probably caused the heavy damage that was suffered by the Grevena-Kozani area.

4.2 Area of Aegio - Achaia

The seismic refraction method was used to investigate the shallow soil conditions in two heavily damaged sites in the Aegio - Achaia area. A five-story apartment building in the city of Aegio and the Eliki Hotel in Valimitika partially collapsed during the large earthquake occurrence on 15 June 1995 of magnitude 6.1 R. Among other research studies that were carried out to investigate the causes of the heavy damage to buildings, a geophysical program was executed along traverses close enough or across the damaged buildings wherever possible. According to the results obtained for soil conditions at the five-story building site, a uniform depth (approximately 2 meters thick) of the upper surface and low velocity layer (650 m/s) was detected west of Despotopoulou Street that abruptly deepens eastward to a depth of up to six meters under the damaged L-shaped building (Figure 3a,c). There is a linear trend in isopach lines along a N–S

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direction, revealing that the western foundation of the building rested on a higher velocity basement (1,300 m/s) that dips eastward (Figure 3b).

The upper surface layer is composed of sand-gravels and clay sand-gravels and the lower layer of clays, clay sands and silty sands. The unfavorable shallow structure, due to the eastward abrupt deepening of the basement and the low seismic velocity values of the overburden, caused extra horizontal forces to be applied to the western foundation of the partially collapsed building, without ignoring the additional effect of the deeper structure that might modify the strong ground motion as well.

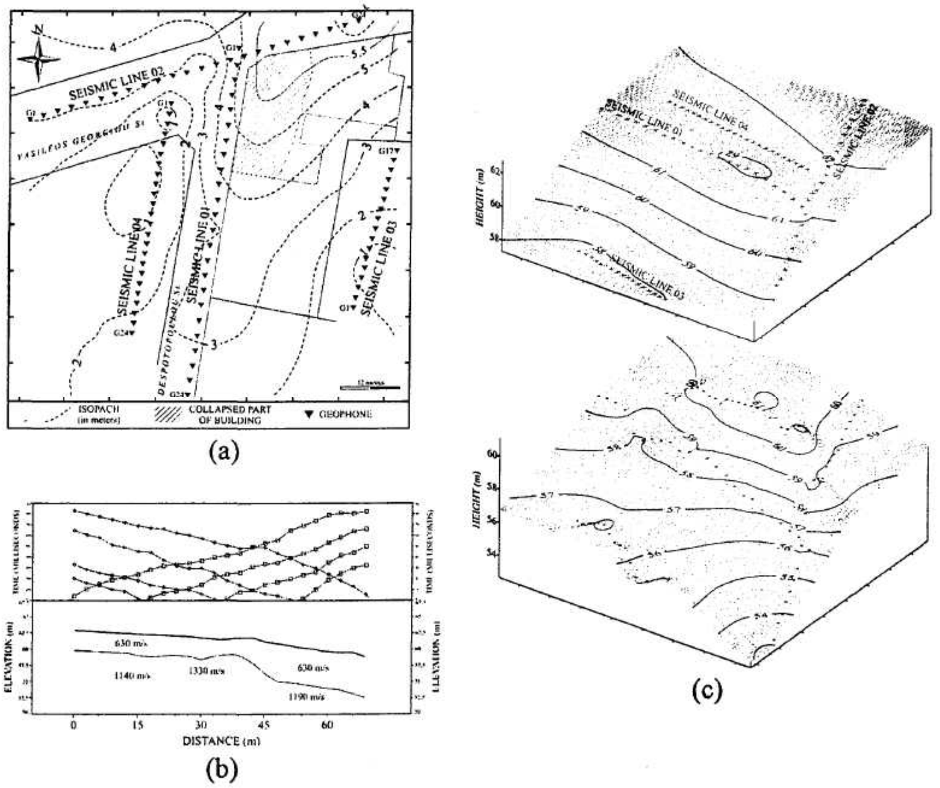


Figure 3: (a) A sketch map showing isopachs and the collapsed part of the five-story building (hatched area), (b) time-distance curves and the corresponding structure along seismic line 03, and (c) 3-D presentation of surface and subsurface (basement) based on seismic results.

At the site of the Eliki Hotel (Figure 4), which also partially collapsed, two distinct subsurface seismic layers were also detected. The upper surface layer with low velocity (700 m/s) is composed of sand gravels, sandy clay and clay sand and the deeper layer had an average seismic velocity of 1,550 m/s. This layer corresponds to the sea water front which intrudes from east to west

(Corinthian Gulf) which is found at a depth of two meters east of the hotel (G24) and deepens further to six meters' depth west of the hotel (G7). Large Poisson ratio values were determined along Seismic Line 3 (>0.4), where seismic velocities Vs were measured, indicating that the surface materials have been affected by sea water intrusion. In general, the soil formations around the Eliki Hotel area are homogeneous with low values of Young's and rigidity moduli.

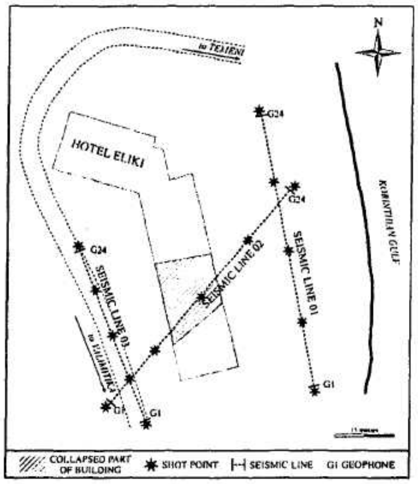


Figure 4: A sketch map showing the seismic lines and the collapsed part (hatched area) of the Eliki Hotel.

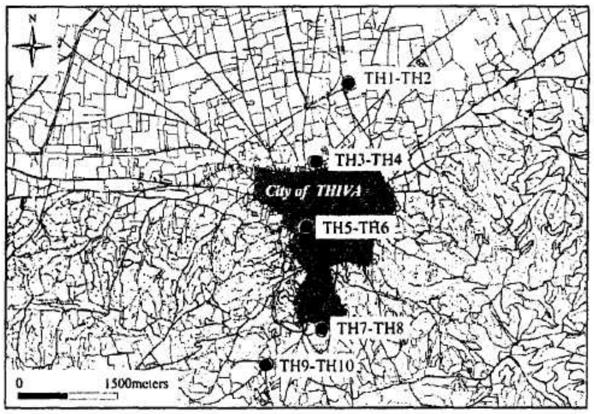


Figure 5: A map showing the broader area of Thiva and the sites of borehole pairs used for crosshole tests.

4.3 Area of Thiva Beotia

In the framework of the microzoning study for the area of Thiva Beotia, crosshole investigations were carried out at selected sites (Figure 5) based on the existing geological/geotechnical maps.

The crosshole results are shown in figure 6. Higher Vs values (> 500 m/s) are due to fresh marl formation (TH3-TH4 borehole pair) or to the presence of micro-breccia (TH7-TH8, TH9-TH10 borehole pairs) and conglomerates (TH1-TH2, TH5-TH6 borehole pairs). Seismic velocities, Vs, for micro-breccia and conglomerates are generally low due to fractures and bad rock quality. A slight linear increase in velocity with depth is observed, although local deviations are present.

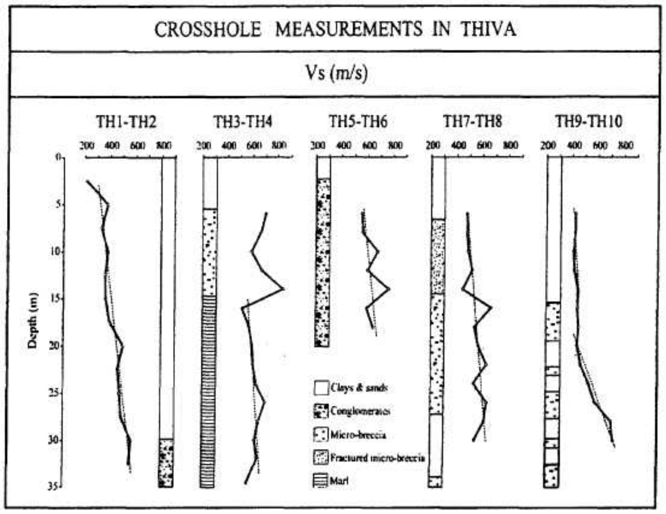


Figure 6: Crosshole results for the area of Thiva and their correlation with lithologic borehole data.

4.4 Area of Athens Attiki

Quite a number of site investigations were conducted (Figure 7) by applying crosshole and crosshole tomography techniques for estimating the seismic velocities Vp and Vs as well as the dynamic elastic parameters of the medium between a pair/s of boreholes. In addition, downhole measurements were also conducted at some sites, in an attempt to correlate and improve modified processing techniques with crosshole and crosshole tomography results.

In figure 8a, compiled crosshole results of Vs distribution with depth for different sites of Attiki are shown. A slight linear increase in velocity with depth is observed for the Ag. Anargiri and Maroussi sites, but a more complicated picture appears for the Elefsis and Thrakomakedones sites. At the Elefsis site the surface material is highly inhomogeneous and in Thrakomakedones the first 15 meters are composed of cohesive breccia. In these two areas the seismic velocities, Vs, are abnormally high at shallow depths. A correlation between crosshole and downhole results for the Thrakomakedones site showed that there is a good agreement for the first 25 meters' depth but weak fit below it (Figure 8c). Crosshole results showed good correlation with borehole data. Classical downhole measurements including data acquisition and processing techniques must be further improved to obtain more reliable results.

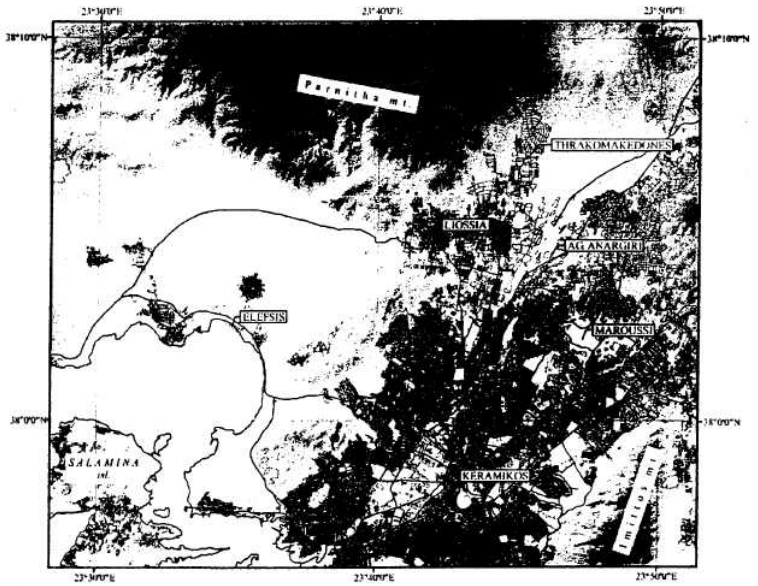
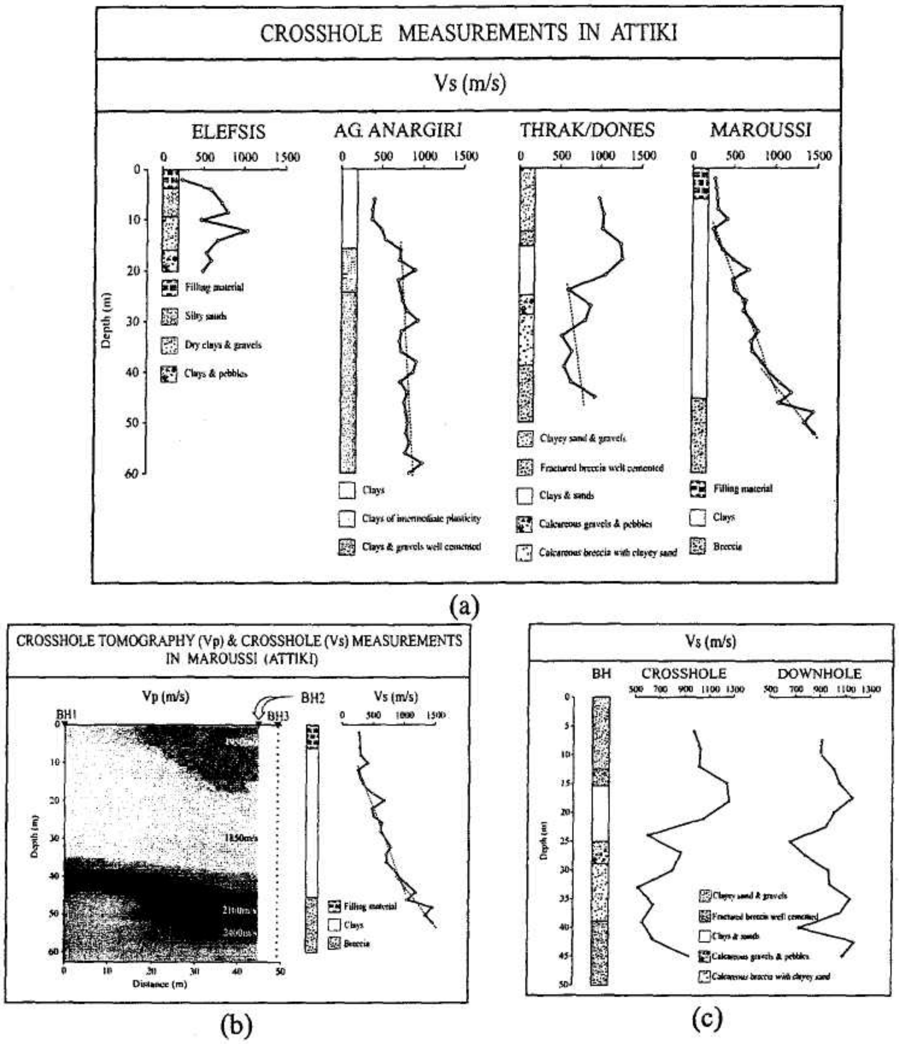


Figure 7: A broader map of the area of Athens, showing the investigated sites.

An effort was made to correlate crosshole tomography results covering a wider area (between boreholes BH1-BH2, 45 meters apart), based on P-wave data and normal crosshole measurements (between borehole pair BH2-BH3) based on S-wave data (Figure 8b). It is obvious that for the upper 10 meters there is no good correlation but for the deeper structure the higher Vs values correspond nicely to higher Vp values. So, we can get a gross estimation of Vs values for the area between the borehole pair BH1-BH2 based on the above-mentioned correlation.

4.5 Area of Heraklion Crete

In the area of Heraklion Crete an integrated geophysical program, including seismic and electrical methods, was conducted in the framework of the microzoning study, carrying out surface as well as borehole techniques. The results obtained from one borehole pair will be presented here, where the crosshole tomography technique was used. The spacing of this borehole pair was 40 m, much longer than the usual one used for normal crosshole measurements (3–4 m apart). The scope of this effort was to investigate the possibility of getting reliable S-wave arrivals in longer distances and in a soft rock environment by using the mechanical hammer as a source.



(a)

(b)

(c)

Figure 8: (a) Crosshole results for selected sites in the area of Athens, (b) A comparison between P-wave crosshole tomography results (BH1-BH2) and S-wave crosshole results (BH2-BH3) for extrapolating the S-wave distribution in the area between borehole pair BH1-BH2, and (c) Crosshole/downhole comparison based on modified crosshole processing technique (Kambouris *et al.* [12]).

In figure 9 are shown the results obtained for the distribution of Vp, Vs, Poisson Ratio, σ, Rigidity Modulus, Gd and Young's Modulus, Ed. An average density of 2.1 Kg/m^3 was used for the Rigidity Modulus calculation. The estimated Vp and Vs velocities are generally low and this is in accordance with the lithology of a medium composed of loose material, clays and locally sands and gravels. The high σ values are attributed to either the shallow depth of water table for areas close to Giofiro torrent or the loose material of the overburden and the bad quality of the upper part, of marl up to 50 meters depth.

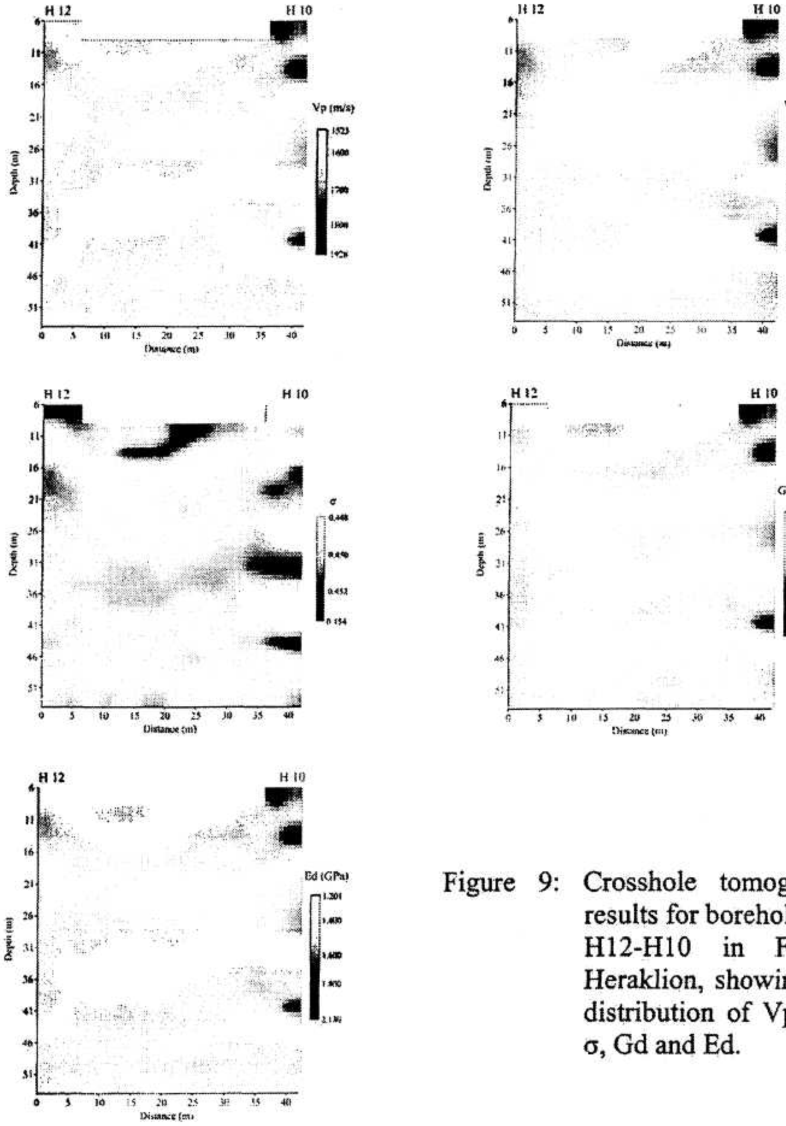


Figure 9: Crosshole tomography results for borehole pair H12-H10 in Finikia Heraklion, showing the distribution of Vp, Vs, σ, Gd and Ed.

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