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Construed Geotechnical Characteristics of Foundation Beds by Geophysical Measurements

F. Vallianatos, P. Soupios, J. P. Makris, V. Saltas, I. Papadopoulos
Laboratory of Geophysics & Seismology, Technological Educational Institute of Crete, Chania, Greece

G. Hloupis
Department of Electronic and Computer Engineering, Brunel University of London, United Kingdom

ABSTRACT

The main objective of the present investigation is to demonstrate the potential of ERT (Electrical Resistivity Tomography) and HVSR (Horizontal to Vertical Spectral Ratio) methods as geophysical tools for the monitoring of subsurface cavities. The survey sites are located in Akrotirion Peninsula, almost 7 Km east of Chania town in Crete Island, Greece. At this site, the surface expression of a known cavity with a diameter of about 25 m is visible. The true geometrical characteristics of the cavity were unknown since there are no boreholes in the area. The focus of this survey was primarily of a qualitative nature and the objective was to determine if ERT and HVSR could be used to identify and map near surface cavities (less than 30 meter in depth) in a limestones karstic area such as Akrotirion Peninsula. A 2D/3D model of the resistivity distribution is given for the area under investigation. Furthermore, analysis of microtremors data provides a profile of the seismic response of the tectono-karstic voids.

1. INTRODUCTION

The last couple of decades, geophysical prospecting has met with wide use for many applications in geotechnical and geo-environmental investigations. The expeditiousness and effectiveness of the methods together with their non-destructive mode of implementation, made them necessary and adequate. The application of geophysical methods, is able to investigate, detect and determine soil properties, inhomogeneties of the subsurface, cavities, ancient relics and generally any underlying structures or bodies that have different physical properties from their geological surroundings (Aubert et al, 1984; Roka and Tsokas, 1987; Carrara et al, 2001).

In civil engineering, a most important aspect is the depth of the building foundations, and whether any irregularities of the subsurface revealed during excavation, might change the planning, or even cancel the founding. Geophysics is able to provide answers to such kind of problems, and even more may disclose several types of discontinuities that other geotechnical methods, like simple geotechnical tests, or geologic field reconnaissance, probably would miss (Soupios et al, 2005, 2006a,b).

However, the application of the appropriate geophysical tool for the detection of karstic cavities is not always straightforward, due to the highly variable and unpredictable target characteristics. ERT is one of the most promising techniques for solving the cavities problem and is a proven imaging technique where the theory and application are well documented in geophysical research literature.

It has, in general, been observed, that damage associated with the occurrence of earthquakes is the result, not only of the magnitude of the earthquake and its epicentral distance, but also of local site effects caused by the topography and geology of the site. These local effects are frequency dependent. The reaction of the local geological conditions to the incoming seismic energy is known as the “site response”. Various techniques have been applied to assess site effects: numerical models, the spectral ratio method and the HVSR method. Its principle is based on recording the ambient vibrations of the
ground during a period of time and calculating the spectral ratio of the horizontal component (H) over the vertical one (V). The resulting H/V spectral ratio (HVSR) highlights the resonance frequency of the sites and their corresponding level of amplification as well.

In the case study reported here, ERT was implemented in order to determine the different electrical properties of the sub-layers. Furthermore, the ERT results have been correlated with available geotechnical borehole data, in order to associate the different electrical properties with the geological layers aiming to reliable identification and interpretation of the underground structures. In addition, HVSR method was applied, in order to check its validity as a supplementary technique to electrical resistivity tomographies.

2. GEOLOGICAL SETTING

The area under investigation is located in the Akrotirion Peninsula, 12 km east of the city of Chania (Fig. 1). The broader area of Akrotirion Peninsula consists mainly of two sub-areas (Fig. 2). The northern area is composed mainly of karst water-bearing carbonate rocks (limestones, marly limestones and a clayed weathered layer) of Late Triassic to Early Jurassic age (Trypalion Carbonates) overlying Permian Plattenkalk Limestones (Fig. 2). The southern part is composed of Neogene sediments while Quaternary deposits are present all over the Akrotirion Peninsula (Fig. 2).

Both sub-areas and especially the northern one are characterized by abundant karst depressions (sinkholes) such as dolines and uvallas (Fig. 2) interpreted as the result of karstic erosion combined with the tectonic stress on the Trypalion limestones. The sinkholes in Figure (2) were extracted subtracting the Digital Elevation Model (DEM) of the study area with a cell size of 30 meters, from the hydrologically corrected DEM (Fig. 2) with the same cell size. Many of the extracted tectono-karstic voids correspond well with the previously observed cavities while their existence was further confirmed during the field observation.

Many different tectonic movements have affected the exposed rocks. The major WNW-ESE direction (Fig. 2) mainly represents limestone bedding and is responsible for the formation of the karstic structures. The photo-lineaments extracted from the on-screen interpretation of the panchromatic band of the Landsat-ETM satellite image of the study area with a spatial resolution of 15 m, are of a NW-SE and a NE-SW direction (Fig. 2), inferring the presence of a well developed joint system in the area.

3. GEOPHYSICAL EXPLORATION

Surface-geophysical methods offer quick, inexpensive, and non-invasive means to help characterize the subsurface geophysical
characteristics. They provide information on subsurface properties, such as soil thickness and saturation, depth to bedrock, location and distribution of conductive fluids, and location and orientation of bedrock fractures, fracture zones, and faults.

However, there are numerous limitations to the information obtained by the geophysical techniques and they shall not be expected to provide reliable results under all circumstances. All geophysical information should be cross-checked by borings and/or other direct methods of exploration.

Surface-geophysical surveys were conducted in the political/military airport of Chania Crete Island, from March 2004 to May 2004 (Figure 3). Data were collected for thirty (30) 2D geoelectrical profiles along the axis of undefined anomaly of the subsoil and one profile consisted of seven ambient noise measurements (Mictrotremors - MT).

3.1 Electrical Resistivity Survey

In many cases the ground can not sensibly be resolved into plane homogeneous layers, as required for VES (Vertical Electrical Sounding) work, or into simple zones of lateral conductivity variation as required for profile interpretation.

A combination of the two techniques is required. Electrical resistivity imaging (Griffiths & Barker 1993; Loke 1999; Acworth 1999) is one approach to this problem. Electrical images can be measured in 2-dimensions with the assumption that little variation exists in bulk material values in the third (normally the -y-) dimension; or in 3-dimensions.

Two dimensional work is routine and the field and interpretation procedures have been developed to the extent that the process is now almost as rapid as for one-dimensional sounding investigation. Three-dimensional surveys are not yet routinely carried out as they require correspondingly larger amounts of field equipment and the interpretation times for the large data sets acquired are still considerable.

For imaging depths of about 30m it is convenient to use electrode spacing of 5m to 10m, depending on the subsurface resistivity. The electrodes (all the combinations of C1–P1–P2–C2) are each connected to a take out on the multicore cable and the cable is connected to a switching box which is manually controlled, or to a switching module which is computer controlled. Typical cables have between 20 and 25 take outs with 2m, 5m or 10m separation between each take out. ERT survey was conducted by using the dipole–dipole electrode configuration. The Syscal Jr. Switch 48 – IRIS Instruments resistivity imaging system was used in this project.

A resistivity traverse is carried out with the electrodes separated by single electrode spacing. Figure 4 shows the arrangements for an eight take out cables. A convention exists in that measurements taken with adjacent electrodes connected are referred to as N = 1a (5) measurements, N = 2 (4) to N = 4 (2). The numbers in parenthesis show the number of readings in each traverse. As the electrodes are all connected to the switching module, it is not required that the measurements be collected as a traverse.

At the prospected area an ERT survey has been carried out in four areas in order to examine and give solution in different geotechnical and environmental problems. The geoelectrical data were collected using an IRIS-Syscal Jr. Switch 48 instrument with accuracy of 0.1Vm. The system features 48 electrodes, enabling fully automated measurements of the shallow subsurface apparent resistivity using the dipole–dipole configuration. This technique has
the advantage of a very good horizontal resolution, but its main disadvantage is the relatively low signal strength. Thirty geoelectrical profiles were carried out which are presented in Figure 3. The logs from geotechnical boreholes were also used in order to verify the resulted tomographic images in the study area. The dipole–dipole spacing a was 2 to 5m enabling the possible detection of bodies and/or structures till 30m depth, which could be considered satisfactory for the required information about the near-surface geotechnical anomalies.

The geoelectrical data collected have been processed by means of the RES2DINV (Loke 1997) and the 2DINVSCR (Tsourlos 1995; Tsourlos and Ogilvy 1999) modelling software in order to perform 2D geoelectrical data inversion. The inversion routines are based on the smoothness-constrained least squares method (deGroot-Hedlin and Constable 1990; Constable et al. 1987; Sasaki 1989, 1992; Loke and Barker 1995, 1996a,b; Tsourlos 1995) and the forward resistivity calculations, were executed by applying an iterative algorithm based on a Finite Element Method (FEM). The inversion program divides the subsurface into a number of small rectangular prisms, and attempts to determine the resistivity values of the model prisms directing towards minimizing the difference between the calculated and the observed apparent resistivity values. The goodness of fit is expressed in term of the RMS error. In this work, the RMS errors for all the conducted profiles ranged from 3% to 25%.

3.2 Ambient Noise Measurements

Ambient noise recordings have been nowadays widely used for site response estimates, taking advantage of the fact that it is fast, low cost, effective method. It has been extensively analyzed in geophysical literature that using microtremors and taking the horizontal to vertical spectral ratio, the fundamental frequency of the sediments overlying bedrock can be estimated (Bard 1999). There is still an open issue among geophysicist whether the amplitude of the frequency peak of the spectral ratio using HVSR can be identified as the corresponding site amplification. Numerous papers give contradictory results (Fischer et al. 1995; Riepl et al. 1998), though almost all agree that spectral ratio amplitude underestimates the site amplification (Goula et al. 1998; Volant et al. 1998).

The basic principles of the method are based on one basic assumption: ambient noise consists of surface waves. Vertical motion of particles is primarily dominated by Rayleigh waves, and horizontal motion is dominated by Love and Rayleigh waves (Aki 1957). During the past decades numerous studies, especially in Japan (Nogoshi and Igarashi 1971; Horike 1996), showed that by measuring ambient noise recordings and dividing the horizontal motion spectrum by the vertical one, the ratio can provide useful information regarding the resonance frequency of the location of the measurement. If the impedance contrast ratio at depth is high enough, then a distinct peak is observed at the spectral ratio, which is very close to the resonance frequency (Nakamura 1989).

Regarding the nature of the noise wavefield, at frequencies below 0.3-0.5 Hz microtremors are caused by ocean waves at long distances. At intermediate frequencies, between approximately 0.5-1 Hz, they are mainly generated both by close coastal sea waves and by the wind, while beyond 1 Hz they are linked to human activities.
Since the area under investigation in this study is very close to the coast, and also very close to the airport, one can expect surface waves originated at various frequencies, from 0.3 to 20 Hz, covering the frequency band of our interest.

Irikura and Kawanaka (1980) report an important change in microtremor spectral characteristics when crossing a fault along a profile, proposing an explanation in terms of reflection and transmission of surface waves through a lateral discontinuity. They also proposed to use microtremor profiles as a means to detect lateral irregularities of underground structures (Bard 1999). In the area under investigation, a profile consisting of 8 single station ambient noise measurements has been conducted. The purpose of using microtremors was: a) to examine if HVSR can determine cavities as lateral discontinuities and b) to have a combination of geophysical methods over the karstic voids/network, in order to have better results. For this purpose, the microtremors profile was located at the same place where ERT 4 of Area1 was conducted.

The equipment used was a Lennarz 3D-Lite (1Hz) velocimeter sensor, coupled with a 24-bit digital acquisition unit. All measurements had 20 minutes time length, using 100 Hz sampling rate. Data were filtered using a high-pass Butterworth filter at 0.2 Hz. Then time windows with constant length of 40 sec were manual picked, in order to exclude obvious transient disturbances from nearby sources (people who walked, moving vehicles, etc). Fourier spectra in all three components (N–S, E–W, U–D) were computed, and a cosine taper with width 0.10% was applied. Finally, smoothing of the Fourier amplitude spectra was carried out using Konno–Ohmachi algorithm (Konno and Ohmachi 1998). At the end, calculation of the horizontal to vertical spectral ratio for each frequency was made, in order to have the spectral ratio in the frequency band of interest, between 0.2-25 Hz.

4. RESULTS OF GEOPHYSICAL INVESTIGATIONS

Thirty 2D geoelectrical measurements were carried out in four areas (Fig. 3) aiming to mainly address geotechnical problems. The results of tomography profiles are displayed as cross sections of the “true” resistivity distribution of the earth. Individual features, such as fractures, weak rock mass and cavities could be easily resolved. Comparison of these tomographic images with the available boring logs and the ambient noise measurements is also given.

Figure 5: Combined tomographic results from all ERTs conducted in Area1. Dark colors correspond to low resistivity values. The areas of interest i.e., possible karstic voids and karstic network, are indicated with dashed lines.

4.1 2D Geoelectrical Modeling

In Figure (5) the results of the ERTs acquired in Area1, where dark colors represent low resistivity values are depicted. As it is shown, resistivity values of 50-500 kOhm.m define areas of intense interest, indicating probable cavities and karstic network as it shown in Figure (5). The resulted tomographic image is in great agreement with the information gained from the borehole logs.

Same results were established in the other study areas (Area2, Area3 and in the area of the Air corridor). We should mention that, the karstic voids in all tomographic images appears with very high (more that 100 kOhm.m) resistivity.
4.2 3D-Inversion Geoelectrical Modeling

In order to obtain a more and realistic representation of the subsurface structure, processing of the 2D-data was made with the advanced 3D-algorithm Res3dinv (Loke and Barker, 1996b). The result is a pseudo-three dimensional model where data are interpolated between the profiles. Horizontal resistivity slices are obtained at ten different depths, starting from the surface down to 6.85 m (Fig. 6).

From the results we can see that the main karstic body is located at the center of the study area, having dimensions approximately 30x25 m, starting at a depth of 3 m. Due to the shallow investigation of the area, there is no possible determination of the floor of the karstic body.

4.3 Microtremors Interpretation

Figure 7 depicts the locations where microtremors recordings were taken place along ERT 4 profile.

Some of the initial measurements were removed since they were too noisy due to the wind. The results from the remaining recordings presented at figure 8. As it can be seen as the profile crosses the assumed karstic void/network there is a change in the spectral shape and intensity. More specific at locations 1 and 2 where limestone assumed there is a rather flat amplification response (amplification ration between 1 and 1.5). At locations 3, 4 and 5 where we are above voids an increase at amplification ratio observed from 1 to 10Hz. Moreover at location 6 where we pass the void the amplification ratio behaves again as at locations 1 and 2.

The correlation of these measurements with the tomographic results of ERT 4 profile is a
very good indication that the supposed karstic void works as a resonator for the ambient noise. The application of ambient noise measurements in such cases (surficial detection of karstic void) could be very promising since this method is cost-effective, non-destructive and easily applied.

5. CONCLUSIONS

This paper reports the results of a geophysical survey performed in the political airport of Hania in Crete Island. The results provide evidence that the use of non-destructive geophysical techniques can be implemented in order to resolve numerous geotechnical, geological and hydrogeological problems. It has been demonstrated that the electrical resistivity tomography (ERT) could be applicable to investigations in geological and engineering issues. This method could also be used in various phases of engineering and geological projects for determination and characterization of local geological structure. The results of the geoelectrical survey were validated through the use of the borehole’s logs. The 3D model of the karstic network as resulted from the application of the geoelectrical methods in the study area is also presented. Ambient noise measurements were carried out on a sector of the studied area over the ERT4 in Area 1, geoelectrical profile in order to obtain a better characterization of the anomaly previously detected. A good correlation between the frequency and geoelectrical anomalies emerges from the results presented.

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