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Exploring the Geological Parameters of Urbanized Centers at the Island of Crete through Geophysical Approaches

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Abstract: The application of geophysical techniques in urbanized environment encounters a suite of problems depending on the structure and the construction density of the urban centers. On the other hand, information resulting from the different geophysical methods can become a valuable tool for the management and planning authorities. This kind of information is critical in areas exposed in different risks, such as earthquake, erosion, landslides, a.o. This paper investigates the suitability of a range of different methodologies applied in the urban centers of the island of Crete, Greece, in order to explore and define the geological characteristics of them. Emphasis is also given in the way of dissemination of the data through the WEB.

Key-Words: Refraction Seismics, Geolectrical Tomography, Microtremors, WEB_GIS

1 Introduction

The provision of geo-information is of critical importance in the development of the urban infrastructure, especially when we encounter problems related with the sustainable development and planning of the particular regions. Geo-information is even more important when urban centers are located in areas which are facing various environmental risks. The definition of the geological parameters can help developers and planning authorities in avoiding areas of high risk and in taking the appropriate measures in geo-technical works.

Within this framework, geophysical techniques can be applied to provide valuable information regarding the properties of the subsurface, in correlation to other historical and statistical data, such as seismic activity, geological drillings, etc. On the other hand, not all geophysical techniques are appropriate for the specific context of urban environments. Electrical tomography, seismic prospection, microtremor measurements, multi-frequency electromagnetic methods, a.o. are mainly those which are best suited for the investigation of the geological parameters and the determination of the site response to the earthquake activity. Some of the above techniques were used in the particular project as demonstration study to examine their feasibility in the urban centers of the island of Crete in the Aegean Sea.

2 Geological Settings of Crete

Crete is a mountainous island, the largest of the Greek islands, located south of the Aegean Sea and consisting of a link between Asia, Africa and Europe. The island of Crete is characterized by the presence of pre-alpine and alpine rocks that constitute a complex nappe pile, and of late alpine, neogene sediments that fill the basins occurring between the high mountains (Fytrolakis 1980, Bonneau 1984) (Figure 1). A number of different, fault bounded units constitute the nappe pile of central Crete. According to their tectonostratigraphic position and their tectonometamorphic history, these nappes are divided into two major groups; the upper nappes and the lower nappes, separated by a major normal detachment fault (Fassoulas 1995). The alpine and pre-alpine rocks of Crete (the rocks which were formed prior or during the alpine orogenessis) occur in the different nappes of the island. The post-alpine rocks of Crete occur as Neogene and Quaternary sediments in the east-west and north-south trending basins, resting on the upper and lower nappes. A more thorough description of the geological settings of the island is given by Sarris, *et al* (2005)

Fig. 1 Geological map of Crete created through digitization and processing of the available 1:50,000 scale geological sheets of the Institute of Geological and Mineralogical Exploration. These data were further refined in order to create a more updated and homogenized form of the geological settings of the island, which were ultimately used in relation to the geophysical measurements in order to define the geological parameters of the urban centers. The geological maps of Crete are available in http://www.ims.forth.gr/website/geology.

3 Electrical Tomography

One of the most popular methods used for geophysical prospection is the Electrical Resistivity Tomography (ERT). It has been widely used either for shallow or deep subsurface investigation, identification of buried artifacts and environmental studies.

ERTs were conducted in the three larger cities of Crete, Chania, Rethymno and Herakleio. The main purpose of the electrical tomography survey was the identification of the subsoil stratigraphic structure to depths varying from 10 to 50 meters. Measurements took place within the urban environment, either by direct penetration of iron electrodes in soil or by the use of indirect induction of electric current to the ground, using very conductive materials, like betonite.

3.1 ERT Interpretation

Processing and interpretation of ERT data was carried out using an inversion algorithm originally proposed by Constable, *et al* (1987). Data were filtered to eliminate bad datum points and in addition, a smoothness constrain was applied on the model resistivity values in cases of high noise levels. Transect RETH 05 (Fig. 2) is typical of the results obtained at the city of Rethymno. Resistivity values indicate that the urban center of Rethymno is covered with a thin layer of neogenic alluvial sediments with resistivity values of less than 50 Ohm.m, overlying cohesive yellow marl to marly limestone, with resistivity values varying between 80-300 Ohm.m. At some places layered marly limestone at depths less than 30m is present, with representative resistivity values of more than 500 Ohm.m. In the cases of Castle Forteza (at the north section of the city) and towards the south parts of the city, carbonates appear near the surface, with representative resistivity values of 900-1500 Ohm.m.

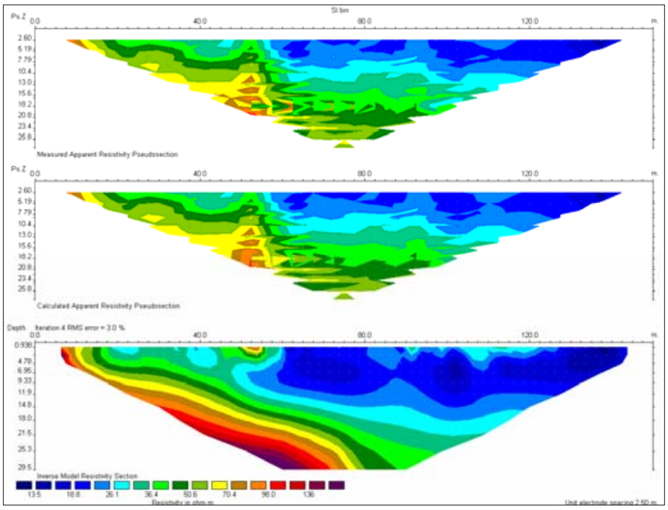

Fig. 2. Electric Resistivity Tomography at site RETH 05.

At the city of Herakleio, the surface cover consists of alluvial sediments and anthropogenic material, having resistivity values with great variance, ranging between 20 and 180 Ohm.m. Deeper layer consist of mainly quaternary cohesive sediments overlying yellow marl. At the north part of the city, near the coastline, evidence of sea water intrusion has been found, with layers having resistivity values within the range of 1.5-10 Ohm.m. Since the ERTs maximum penetration depth did not exceed 40m, no evidence of marly limestone was found at the particular depths, especially at the southern parts of the city where they were expected.

In the city of Chania, a more complex geology exists. Cover layer consists of quaternary sediments, anthropogenic materials and sand. Representative resistivity values range between 50 Ohm.m (for the anthropogenic materials) and 150 Ohm.m (for marles). Under that cover layer, cohesive marles and marly limestone is present, with resistivity values of more than 300 Ohm.m. No evidence of the basement has been found, since the maximum penetration depth didn't exceed 50m.

4 Seismic Prospection Techniques

Seismic geophysical methods have long been used by geologists and geophysicists to delineate subsurface features. The seismic refraction survey is the most familiar method in engineering applications which is employed to obtain the elastic properties of subsurface layers. Seismic methods have evolved into a cost-effective tool for rapidly determining depth to bedrock in engineering and construction projects. The method is best suited to sediment thickness estimation and bedrock quality determination.

Six and ten seismic profiles were conducted over the broader area of Rethymnon and Herakleion respectively. The selection of the location of the profiles was accomplished according to the geology of the study area and the accessibility of the areas in order to apply the method (no high and thick vegetations, no surface construction activities and no steep topography).

4.1 Data Acquisition - Processing

Seismic refraction data were acquired along 16 profile lines, using a Geometrics R-24 Strataview digital seismograph and signals were recorded by 24 12Hz OYO-Products geophones deployed at 10m and, occasionally, 7m intervals along the refraction lines. A 7kg sledgehammer striking a metal plate was used as the seismic source. Geophones were almost buried just beneath the surface to reduce interference from the ground-coupled sound wave. Data were further downloaded to a computer for processing and interpretation.

Selected shots were used to build velocity profiles for each line using the SIP family of routines (Rimrock Geophysics, 1995). The SIPT-2 code allows co-processing of up to 7 shots for each geophone spread. First arrivals were picked using the SIPIK code. Picking of first arrivals proved to be a difficult task due to their very low frequency content, and thus they are “emergent” (the amplitude builds slowly, rather than abruptly). These attributes of the first breaks result in a higher likelihood of having a few milliseconds of error in the selected arrival times and can result in a final model that is less precise. Once arrival picks were selected, they were incorporated into a data file for each profile line, using the SIPIN and SIPEDT codes.

Each of data files includes precise positions for each geophone and shot point and all of the first arrival picks. Each pick was assigned to a specific subsurface layer in the data file in order to produce the Time-Distance (T-D) plot. SIPT-2 processing assumes that there are discrete layers that are laterally continuous and have constant velocity. SIP software package was employed for the determination of the cross-section of the above mentioned lines.

4.2 Interpretation

T-D plots were constructed in order to assign the refractors (layers) and finally an iterative non-linear algorithm was applied to estimate a cross section of the resulted velocity model (figure 3).

For the interpretation of the selected data sets, each arrival was corresponded to a layer where the deepest refraction of the seismic wave has been recorded. Thus, the first arrivals (close to the seismic source) correspond to the direct waves which give information about the velocity of the first (superficial) layer. The first refracted waves correspond to the second layer. The same procedure was applied for deeper layers.

The final interpretation of the profiles (as long as P-waves are concerned) is based on the morphology of the discontinuities (refractors) and the velocities of the space waves. Taking profile HER02 for example, two layers are noticed (Fig. 3). The first, a medium velocity layer (957m/sec), corresponds to the quaternary cohesive sedimentary formations. The second layer appears with a much higher velocity (5395m/s) and corresponds to the massive and possible karstified limestone.

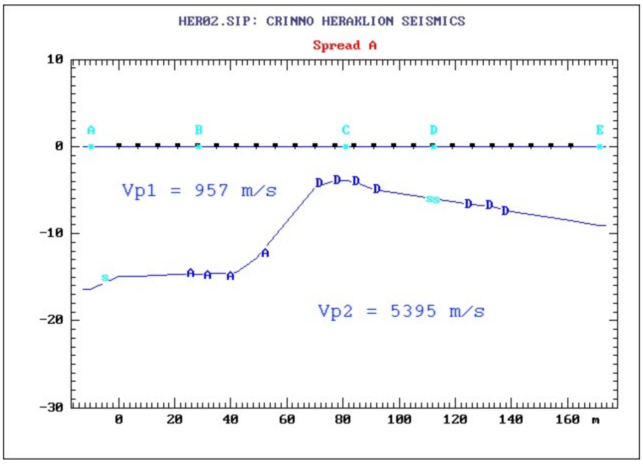

Fig. 3. Resulted geophysical structure for SITE02 in Herakleion city.

Trying to classify the resulted velocity models based on the geological formations found at the cities of Rethymnon and Herakleion, the velocity models were distinguished in five different geological formations as is shown in Table 1.

Specifically, the surficial geology at Rethymnon is mainly composed of quaternary and neogenic deposits that form depositional plains oriented from south to north with low to medium velocities which vary within the range of 500-1100m/sec (RETH 01, 05, 06 and 10). A higher velocity layer crops out at the

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eastern part of Rethymnon, consisting of Miocene to Pliocene sedimentary sequence of marls and marly limestones (RETH 02, 06, 08 and 10), forming hilly areas in the southern neritic zone. Carbonates of the Trypalion nappe and cohesive layered marly limestove are exposed towards the west-southwest area of Gallos, to the south of Koubes and around the Fortetza Castle (RETH 05).

CRINNO EMERIC I – REFRACTION SEISMICS					
HERAKLION			RETHYMNON		
LOC.	1st Layer (m/s)	2nd Layer (m/s)	LOC.	1st Layer (m/s)	2nd Layer (m/s)
HER 01	704	1994	RETH 01	500	
HER 02	957	5395	RETH 02	2100	
HER 03	905		RETH 05	763	3939
HER 04	590	1991	RETH 06	798	2822
HER 06	1023	2415	RETH 08	1765	
HER 07	792		RETH 10	671	1924
HER 08	574	1976	P-waves (m/s)	Description	
HER 10	687	2617	500 – 700	Neogenic allouvial sediments	
HER 11	509	2202	700 – 1100	Quaternary cohesive sediments	
HER 12	628	1707	1700 – 2600	Cohesive yellow marl to marly limestone	
			2600 - 4000	Layered marly limestone	
			> 5000	Massive/carstified limestone	

Table 1. Classification of the resulted P-wave velocities with respect to the corresponding geology at the study area.

Quaternary and Neogene formations, as well as alluvial deposits prevail in the wider area of Herakleion city (Sarris et al., 2005) and close to the streambed of the Knossanos stream (Polyhronakis *et al.*, 1999). These sedimentary formations correspond to a low velocity layer found in all seismic locations (509-1023m/sec). In the eastern part of Herakleion (HER 01, 04, 06, 08 10, 11 and 12), a low to medium velocity layer appears (1707-2617m/sec), corresponding to limestones, which alter to calcareous marls, or marly limestones. Same results are drawn for the central part of the area where the port of Herakleion was constructed. The specific region seems to consist of homogeneous marls, marly limestones and clays with plant or animal organic remains. Cohesive and massive limestone is also suggested in the western ancient fortress with high velocity (5395 m/s, HER 02).

The results of geoelectrical tomography are in good agreement with the seismic sections as far as the identification of the above mentioned geological units (Table 1) is concerned. As an example, the comparison between the resulted tomographic image of HER11 seismic profile and the 2D resistivity image for the same location is given in figure 4. The top layer, having a thickness of approximately 5m, is a low resistivity/ low velocity layer with values ranging between 40-180 Ohm.m and 509 m/s, respectively, and it is composed of alluvial sedimentary deposits. Below this layer and down to 20m, there is a high resistivity/ high velocity layer with resistivity values ranging between 200-800 Ohm.m and velocity equal to 2202 m/s, respectively, and it is composed of cohesive marl to marly limestone (Fig. 4).

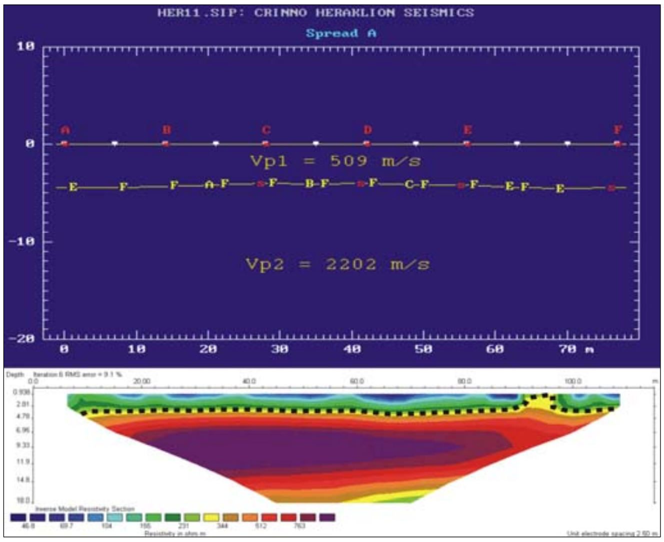

Fig. 4. Comparison of the resulted tomographic images from refraction seismics (upper) and geoelectrical tomography (lower) for the same HER11 location.

5 Geophysical site characterization using ambient noise array measurements.

The method of microtremor array measurements was employed in order to investigate the behavior of the shear wave velocity with respect to depth. The particular measurements are particularly useful in the evaluation of the seismic risk of the urban environment. Microtremor data can be used to verify the underlying geological formations and the corresponding propagation velocities of potential earthquake activity.

Microtremor data were collected at the historical centers of the 3 major cities of Crete. Array measurements were acquired through the night period using twelve stations consisting of Reftek130-01/3 loggers and Guralp CMG40T (1Hz) sensors. The layout of the sensors was based on three co-centric circles of different radius and one station at the center. The inner circle consisted of 6 sensors for the better evaluation of the shear wave velocity of the upper layers, whereas the other two circles consisted of three stations each. The corresponding layout for the city of Chania is shown in Figure 5.

After visual inspection of the data, the appropriate time windows were selected for processing. The method of frequency-wavenumber (F-k) (Aki, 1957) was applied and a software tool provided by the Sesarray project (www.geopsy.org) was used for processing the data and modeling the dispersion curve (DC) information for each site. In addition, an inversion algorithm (Wathelet, *et al.*, 2004) was applied to the DC data and a set of shear wave models was proposed.

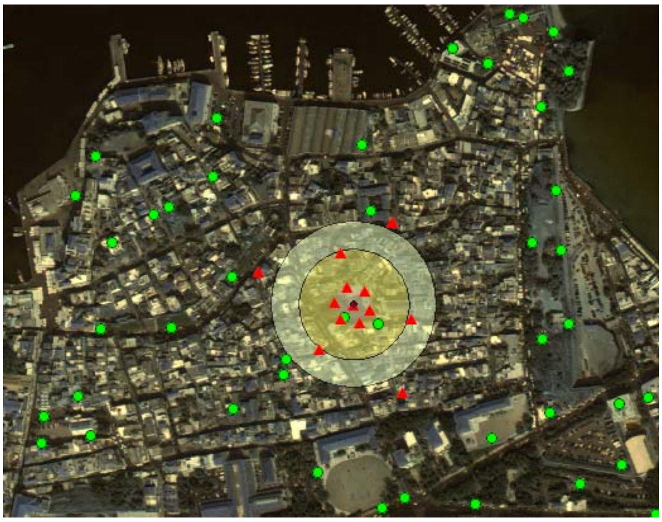

Fig. 5. The layout of the microtremor array measurements for the city of Chania. Measurements were carried out within the historical center of the city, between the Venetian fortification walls and the port.

In Figure 6, the shear wave velocity model for the city of Chania is presented. The particular model resulted from an array of circles of radii 20, 60 and 100m (Fig. 5). According to the available data regarding the geology of the urban center of Chania, the following stratigraphy model is proposed: a. The upper layer with a gradient increasing velocity from 200m/sec to 600 m/sec up to a depth of 12m below the surface corresponds to the Pliocene yellow to brown sandstone, b. Following till the depth of 140-155m, a shear wave velocity of 1200-1400m/sec is suggested, related to limestones of Miocene age with alterations of sandstone. c. Right below the limestones, the layer with shear wave velocity greater than 3400m/sec corresponds to the massive limestone.

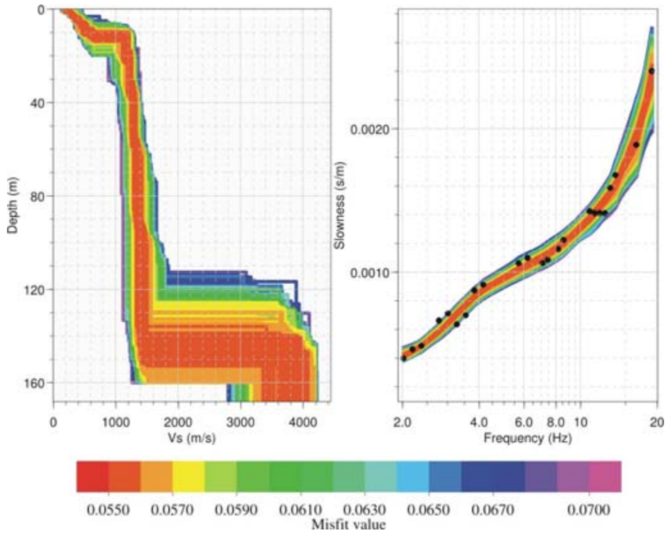

Fig. 6. One-dimensional model of shear wave velocity behavior with depth (left) and the corresponding dispersion curves (right). The dark circles present the results of the F-k processing.

6 Individual ambient noise measurements

The best procedure for determining the site response of a particular sedimentary location to the earthquake activity is to record ground motion during an earthquake and calculate the spectral ratio of the sediment site recording to a nearby reference site located on rock (e.g. Borcherdt, 1970). However, in order to achieve site response surveys in a reasonable period of time using the particular technique may be a difficult task, especially in regions of low seismicity. Of similar difficulty is the numerical prediction of site effects within a reasonable confidence level, since it requires a detailed knowledge of some key geotechnical and geophysical parameters (Panou et al, in press).

An alternative approach of characterizing site response in domestic areas, involves the use of the horizontal to vertical spectral ratio of ambient noise recordings. Ambient noise is low amplitude vibrations of soil generated by natural disturbances. The spectral ratio of the horizontal to vertical component of ambient noise usually shows a peak, which indicates the fundamental frequency of the investigated site (Nogoshi and Igarashi, 1971; Nakamura, 1989).

Within the frame of the CRINNO EMERIC-I, several single station measurements were conducted in the three major cities of Crete. In Figure 7, a map of the urban area of the city of Chania is presented, together with the corresponding overlay of the fundamental eigen-frequencies map, created through a nearest neighbour gridding algorithm.

Fig. 7. Map of the fundamental eigen-frequencies in the area of Chania.

As shown in the above figure, at the city of Chania the frequency band for the fundamental eigen-frequency lies between 0.20 and 0.50 Hz. This is an indication of the presence of seismic contrast between the marly limestone and limestone at great depths, located probably more than 300 m below the surface in certain places at the centre of the city. Since no second peak was observed at all measurements, the seismic velocity transition between superficial layers is considered to be smooth until the marly limestone is met.

In the case of the cities of Rethymno and Heralkleion, the data sets obtained were rather sparse and no safe results can be concluded from this study regarding the seismic velocity contrast between the layers of the subsurface.

7 Dissemination of data

The above data were integrated with the rest environmental, topographic and statistical information that were gathered within the framework of EMERIC-I. Dissemination of the data was achieved through the accessibility of technical reports describing the methodology, instrumentation and the corresponding results of the measurements. Furthermore, cartographic products are served through a WEB_GIS platform, based on customization of ArcIMS. More particularly, ground control conditions for each city are accessible in different windows through HTML viewers, which provide different navigation tools through the maps. Each window consists of a Quickbird satellite image of the city, a layer with the road network information, the specific points of measurements and the low frequency map (see Figure 7). Query tools can provide information regarding the location and the coordinates of the measurements and the corresponding frequencies.

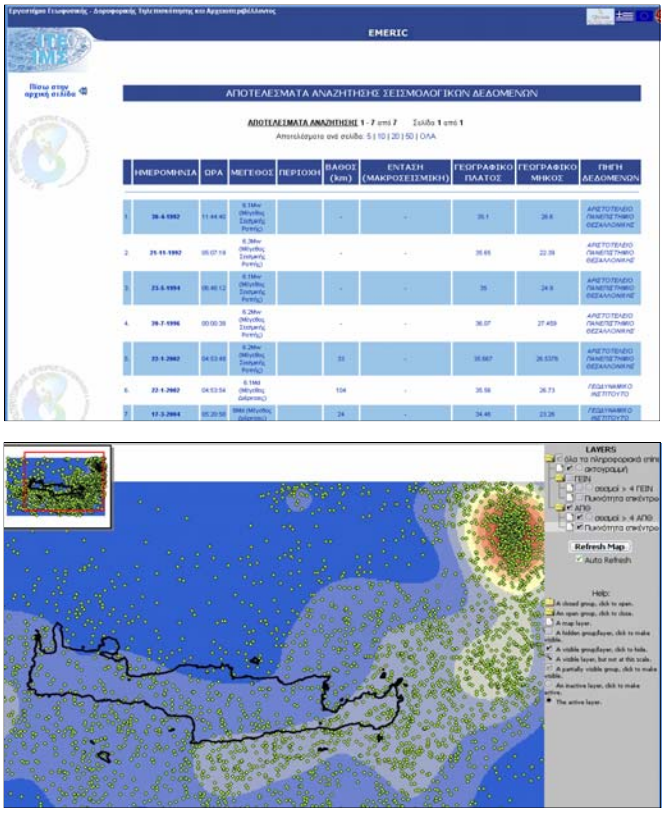

Fig. 8. Query results screen for the earthquake database (above) and spatial distribution of earthquake epicenters for the area of Crete (below).

A seismological database is also available for earthquake registries coming from both the Aristotle University of Thessaloniki and the Geodynamic Institute of Athens, covering both historical and more recent earthquakes (http://www.ims.forth.gr/joint_projects/emeric/crinno_earth_search_gr.php). Queries are based on the time window and the earthquake magnitude. The same data (epicenters of earthquakes and the epicenter density) is available for both datasets for earthquakes of magnitudes larger than 4, through an ArcIMS server (Fig. 8)

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8 Conclusions

The compilation of a geo-information inventory which can provide information within an urban context is of extreme importance for a wide range of applications. Within this context, different types of data can be gathered spanning from fieldwork measurements to geology maps or even historical and statistical data. Geophysical measurements play a critical role in the refinement of this information within the high-resolution scale range required for the urban centers.

The particular project can contribute significantly to the urban and regional planning and development of the major cities of Crete. It can be used as a pilot one for the expansion of the application of geophysical techniques in providing the infrastructure for the technical construction works and helping local authorities in developing specific strategies for the open dissemination of information to both public and private bodies. This public/free release of information, through the help of GIS and WEB_GIS platforms, can guarantee the high impact level of the geophysical data to the end-users, enhancing also the potential use of the above data to a wide range of applications such as the management of the natural resources or the geological hazards of the urbanized environments.

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