Cent. Eur. J. Geosci. • 3(4) • 2011 • 349-357
DOI: 10.2478/s13533-011-0034-2

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Central European Journal of **Geosciences**

Detection of the near surface structure through a multidisciplinary geophysical approach

Research Article

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Received 29 July 2011; accepted 16 September 2011

Abstract: The present survey aimed to image the subsurface structure, including karstic voids, and to evaluate the extent of the heterogeneities that can result in potentially dangerous collapse of road segments overlying these features. A multidisciplinary geophysical approach (seismic refraction, frequency domain electromagnetic and ground penetrating radar) in combination with a detailed geological survey indicated the presence of tectonic faults as well as velocity and conductivity anomalies along an old road within the area of Akrotiri at Chania (Crete). Due to the presence of subsurface fuel pipes, perpendicular to the direction of the road, 2D resistivity imaging was excluded from the applied geophysical methods.
Interpretation of the geophysical data revealed that the section of the road investigated overlies prominent voids attributed mostly to karst features. The conductivity and velocity anomalies are interpreted to indicate an area where the host limestone rock has been downthrown by faulting and associated karstification. The continuation of this fault zone was observed in the slope of the road during later excavations. Interpretation, using geographic information systems (GIS) to integrate data, allowed these controls and relationships to be understood and monitored. The above methodology was proved successful for areas where the application of resistivity method is not possible.

Keywords: Tectonic fault • karstic void • shallow geophysics

1. Introduction

Karstic voids can cause stability problems for many human constructions, in areas underlain by carbonate rocks, such as road and highway subsidence, building foundation collapse, and dam leakage [1]. Structural instability associated with voids can also result in a sudden collapse of the ground surface [2–4] or in a less catastrophic, but recurring drainage problem. Misplaced boreholes can provide inadequate information that can lead to misinterpretation of the subsurface system leading to additional cost for remedial design or further investigation. Remote sensing and surface geophysical techniques [5, 6] can be used to support the proper location of test boreholes designed to identify subsurface features related to karst development within complex geological areas [7, 8] and in urban areas

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All geophysical methods involve the application of physical measurements to address geological issues. The need to scale the geophysical method to the size of the problem becomes an important consideration [10]. In preparing for a geophysical survey, it is necessary to identify the volume of the subsurface area of interest and estimate the size of the features of interest with respect to the resolution of the geophysical methods considered. Geophysical limitations related to resolution relative to the target and site constraints from interferences can dictate the method of investigation.

During the reconstruction of an old road within the area of Akrotiri at Chania (Crete), which is planned to be reused for heavy-load traffic, the constructing group of engineers encountered underground karstic voids at various locations, causing a temporary stop of the contract work. In support of the subsurface investigation, a high-resolution shallow geophysical survey in combination with geological mapping was conducted to identify and map the extent of the underground voids and any weak permeable or highly fractured zones that could contribute to stability problems beneath the road. In this study, three geophysical methods were applied in order to collect information about the geological setting in the vicinity of and below the road: seismic refraction, frequency domain electromagnetic (EM), and ground penetrating radar (GPR). Figure 1 presents the location of the seismic refraction lines, the geophysical grids that were scanned with EM and the GPR transects along the road. Due to the presence of subsurface fuel pipes, the 2D resistivity imaging method was not selected for the subsurface investigations. The novelty of this work with respect to other studies [11–14] is that the proposed methodology is efficient in areas where the resistivity method cannot be applied.

2. Geological setting

The area under investigation (Fig. 1a) is located in the Akrotirion Peninsula, 13.7 km east of the city of Chania. The majority of the study area consists of Triassic – Cretaceous limestones (T-E.k.d) (Fig. 1b) belonging to the Tripolis Geotectonic Zone. These limestones are compact, white grey to bluish, microcrystalline to aphanitic, usually with rudist fragments, sometimes breccias and are in places dolomitized and strongly karstified. Deposits of Quaternary Terra rossa (tr) are also present in karstic hollows. The rest of the area is covered by Miocene marls (M.m) and marly limestones (M.k). The marls are yellow brown to white – yellow, often alternating with beds of marly sandstone and platy limestones, including fossils of sea molluscs. The marly limestones are compact, white – yellow to white – grey and include sea fossils. Two tectonic zones are indicated in the study area (Fig. 1c). Faults, belonging to these zones, which have been measured during field work mainly strike NW–SE with dips in the range of 50-90^o.

The stream network in the area of study is entered into the autochthonous alpine marly and dolomitic limestone and its pattern is closely related to the tectonic structures and the area is in a mature stage as far as the fluvial erosion cycle is concerned [15]. The aquifer is mainly expected to be inside the fractures developed in the limestone and the free underground water level is located 31–35 m below the surface.

The area around the old road has been geologically mapped (Fig. 1b). The majority of the area of interest is covered by Terra rossa while the rest of it by the Triassic(?) – Cretaceous limestones, according to the geological map of Chania (I.G.M.E.).

Terra rossa is reddish clayey to silty-clayey soil especially widespread in the Mediterranean region, which covers limestone and dolomite in the form of discontinuous layers ranging in thickness from a few centimetres to several meters. It's red colour (5YR to 10R Munsell hues) is a classical diagnostic feature of Terra rossa and is the result of rubification, *i.e.*, formation of hematite [16]. The nature of Terra rossa and its relationship with the underlying carbonates is poorly understood and there are different opinions with respect to its parent material and origin. The most widely accepted theory is that Terra rossa was developed from the insoluble residue of carbonate rocks [17–19]. However, other authors have emphasized that Terra rossa could not have been formed exclusively from insoluble residue of carbonate rocks [20, 21] but rather the Terra rossa of southern Europe might be wind-borne material from Africa.

3. Methodology

The flow chart of the methodology applied to provide information about the geological setting of the study area to a depth of 5-6 m is shown in Figure 2.

Initially, geological mapping using high accuracy GPS, was conducted in order to specify the detailed stratigraphy of the study area, the possible tectonic zones and the drainage network. This was considered as the initial preparatory step for the right design of the geophysical investigations and the subsequent data interpretation.

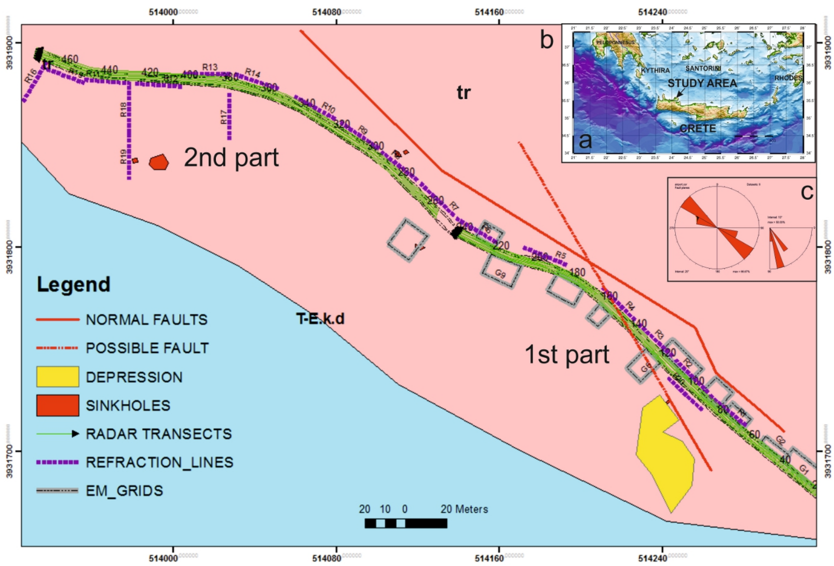

Figure 1. (a) The wide area of Crete (Greece) and the location of the survey, (b) The geological map of the study area and the locations of the geophysical prospecting, (c) Rose diagram showing the strike and the dip of the tectonic features detected in the study area.

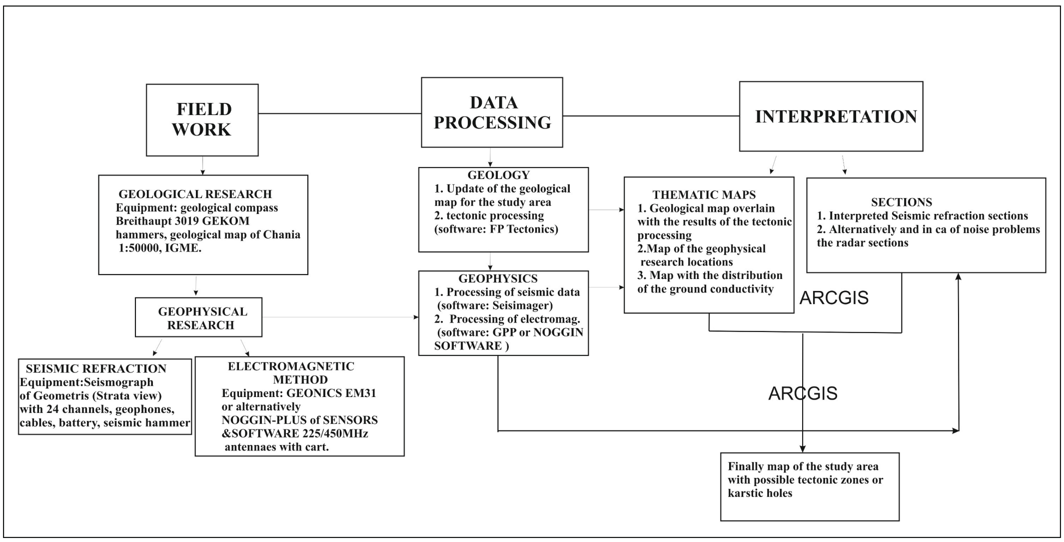

Figure 2. The methodology applied in the present study.

The geophysical research employed seismic refraction, frequency domain electromagnetic (EM), and ground penetrating Radar (GPR). All of these methods are active, non destructive and were not expected to be influenced by external factors during data acquisition. Resistivity imaging was excluded from the applied methodology due to safety reasons (presence of fuel pipes in the subsurface).

The seismic refraction survey is the most familiar method in engineering applications, 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. Seismic refraction data were

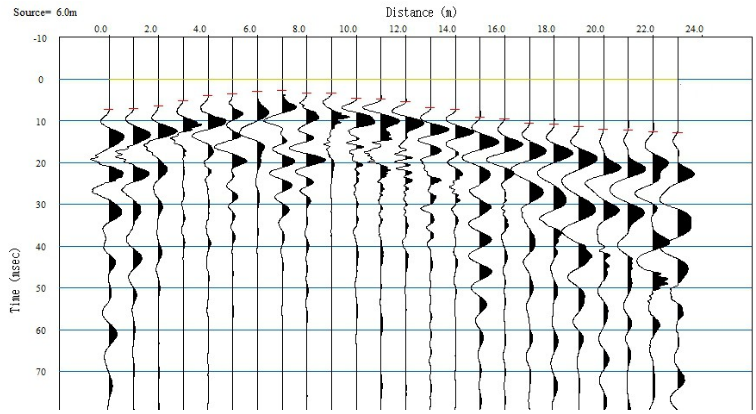

Figure 3. Shot gather showing the picking of the first break.

acquired using a Geometrics R-24 Strataview digital seismograph and signals were recorded by 24 12 Hz OYO-Products geophones deployed at 1 m intervals along the refraction lines (approximately 40). A 7 kg sledgehammer striking a metal plate was used as the seismic source at an offset of 5-6 m. Geophones were buried just beneath the surface to reduce interference from the ground-coupled sound wave. Noise tests had been done in all locations to define the noise level and the best time interval for the data acquisition. A 60 Hz notch filter rejected interferences from power lines. In many cases shot stacking was the best solution in order to obtain high signal/noise records.

Refraction data processing aims at suppressing noise of various types occurring during data acquisition. Picking of first breaks and finally data inversion is undertaken to obtain a velocity section. The recorded seismic data were uploaded to a computer and seismic data processing was performed using SeisImager. The first arrival times were picked (Fig. 3) using the Pickwin module and inversion of the travel time data was carried out in Plotrefa. Shot records were initially processed for geometry correction and bad traces were removed. Thereafter the amplitude of all traces was increased and normalized. Finally first breaks were picked and data were inverted using the time-term inversion method. This method is based on estimation of "delay times" through the use of linear least square inversion method.

Electromagnetic induction (EM) uses the principle of induction to measure the electrical conductivity and the magnetic susceptibility of the subsurface. EM has the advantage over other methods, of speed and a crew size of only one. EM data are typically collected at one second intervals as an operator walks across the ground surface. This permits several miles of data collection per day. The principal limitation of the method is the qualitative result and depth estimates are normally limited to shallow or deep. The presence of utilities, fences, cars or buildings poses potential interference for EM surveys, limiting the use of this method at developed properties. The depth of penetration is governed by the coil separation and orientation. Unlike conventional resistivity techniques, no ground contact is required. This eliminates direct electrical coupling problems and allows much more rapid data acquisition. A Geonics, Inc. GEONICS EM31 was used in this study in order to map part of the study area (in the vicinity of the old road, Fig. 1b) up to a depth of 4-5 m below the ground surface, with a sampling interval of 1m. It was impossible to apply this method to the rest of the area because of very dense vegetation. Noise problems arose in the eastern part of the road which was constructed by cement with metal frame reinforcement below it. EM data were processed using the GPP Package [22]. The basic operations of GPP Package are:

1. *Pre-processing:* In general, the GPP package runs by creating a list of the files to be processed. In case there is a need for reversing the X and Y columns (in order to bring grids in the right alignment with respect to the north), the pre-processing option may be chosen. Thereafter the geometry of the grid is checked and mean and standard deviation values are computed. Maximum and minimum values of the measurements, mean, standard deviation, X and Y coordinates and X and Y sampling intervals are displayed. At this phase of the processing, peak values can be muted and the benchmarks can be relocated by shifting the X, Y coordinates.

2. *Main Processing* constitutes the most important phase of the processing and manipulation of the

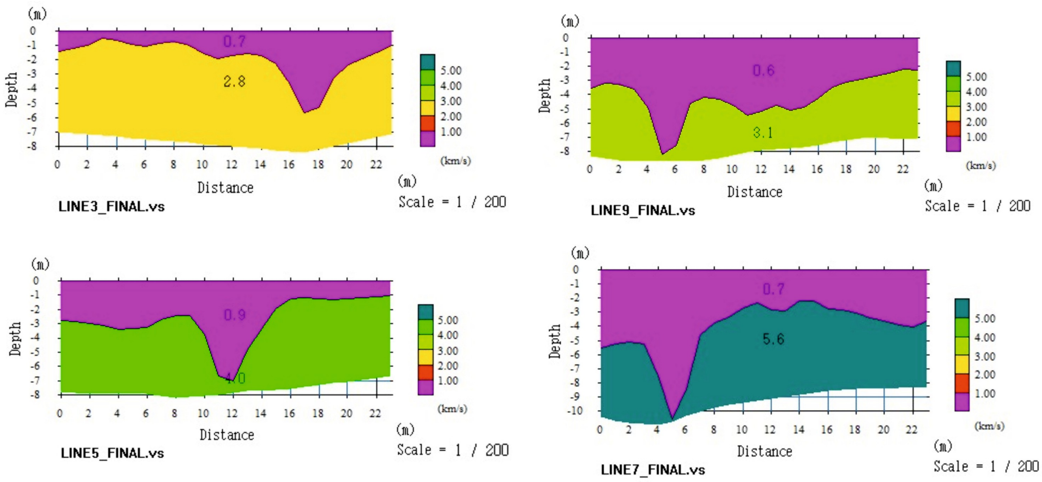

Figure 4. Examples of the seismic refraction sections showing the velocity distribution in the study area and the detection of the possible weakness zones. The beginning of the Lines 3, 5, 7 and 9 correspond to 120 m, 190 m, 250 m and 300 m of the road (Fig. 1b). The weakness zones are approximately located at 18 m (Line3), 12 m (Line5) and 5-6 m in Lines 7 and 9.

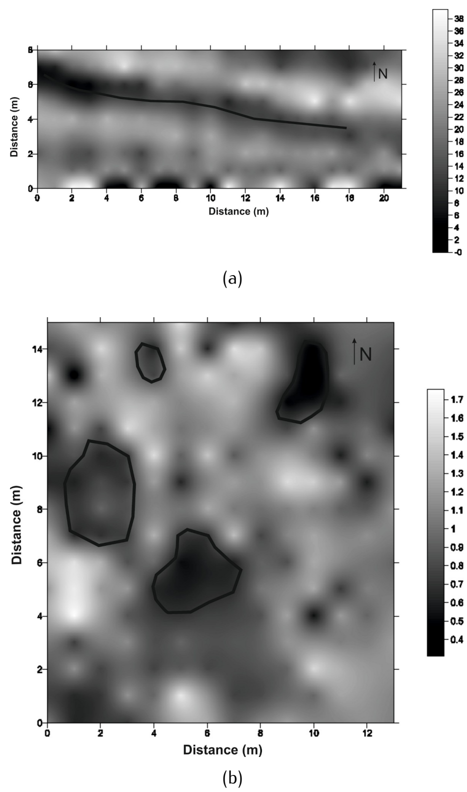

Figure 5. Responses of the conductivity (mSiemens/m) corresponding to the traces (black lines) of a fault (a) and karstic voids (b) at depth 1.5-3 m. The upper grid is located between 60-80 m along the road while the lowest one between 260-273 m (Fig. 1b).

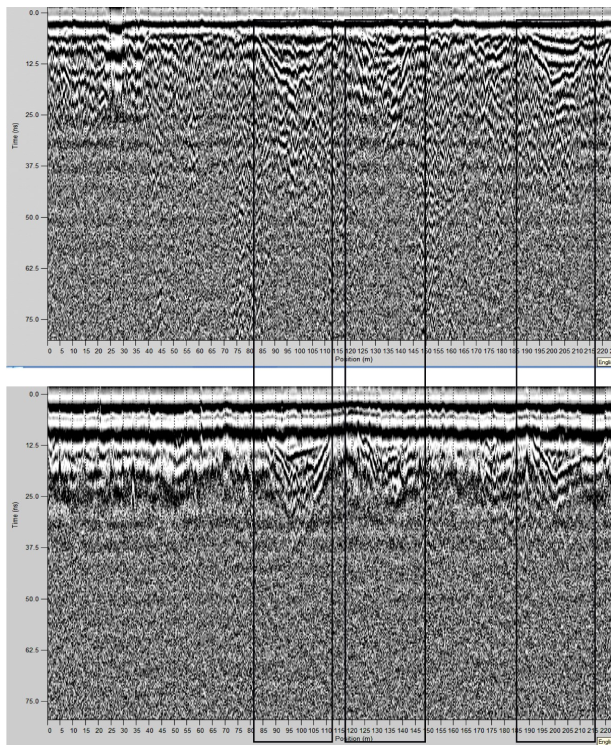

Figure 6. Typical examples of disturbed stratigraphy (black boxes) for the 1st part (east section, Fig. 1b) of the road.

data. The Main Processing procedure is divided into three steps. In the first step (Level Correction) the dynamic range of all files is specified according

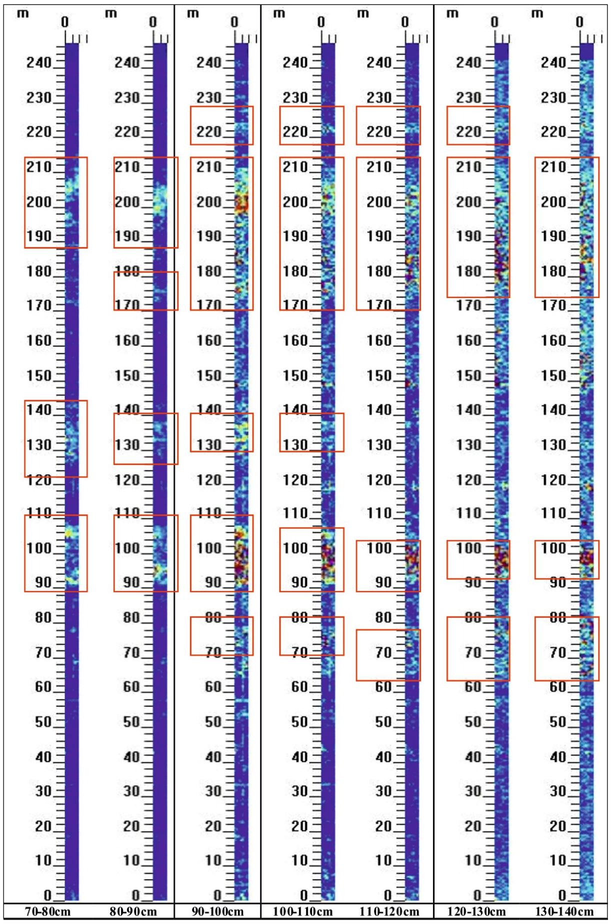

Figure 7. Horizontal Slices with increasing depth for the 1st part (east section, Fig. 1b) of the road. Red boxes indicate locations of disturbed stratigraphy.

to the Grid Level Correction Factor. Thereafter the de-spiking technique can be applied according to the noise level. In case of noisy data the De-spiking Factor must be smaller than one standard deviation in order to eliminate the extreme measurements. In the case of less noisy data the De-spiking Factor can be greater than one standard deviation. Finally, Line Equalization is applied to the data in order to avoid stripping effects.

A ground penetrating radar (NOGGIN-PLUS of SENSOR & SOFTWARE 225/450 MHz antennas with cart) was also used in this study. The purpose of the GPR survey was to map the intense under surface reflectors along the path of the road that could be caused by disturbances of the normal stratigraphy of the ground. Radar transects were separated by a distance of 0.5 m and the sampling interval along each profile was 10 centimetres. The GPR transects, scanned along the road, are shown in Figure 1b. The radar signals collected were processed through special software packages provided by Sensors& Software Ltd. Each radar section was pre-processed in order to check any errors in the starting and end position of each transect. A value of 5-10% of the peak amplitude of each transect was specified as the threshold value in order to re-define the time-zero level of each trace. A constant gain (AGC, automatic gain control) of 50 was applied to all data in order to amplify the weak reflection signals. Processing also involved the removal of the low frequency signal saturation (Dewow). The velocity of propagation of the electromagnetic waves was estimated to 0.08 m/nsec based on the hyperbola matching method. Each transect was visually examined in order to analyze the particular signals and any disturbances of the subsurface stratigraphy. There was an obvious difference in the signals obtained from the first part (Fig. 1b) of the road (east part) and those obtained from the second part (Fig. 1b) of the road (west part) originating mainly by the construction material of the road. The east part of the road was constructed by cement that had a metal frame below it (probably for stability purposes), which can be seen in the surface sections of the road and the radar signals that were registered along the parallel transects. This created a number of strong surface reflections and strong attenuation of the signal. Still, it was possible to penetrate below the metal grid and obtain some information about the subsurface reflectors. The quality of the signals was compared to a GPR transect scanned to the south of the cement coverage of the road and parallel to it. In contrast, the west section of the road, which was covered by asphalt, did not create any serious problems (strong surface reflections, signal attenuation) in the signal propagation. Migration process was applied with a velocity of 0.08 m/nsec and a scale factor of 0.2 in order to enhance the spatial extent of the reflectors. A 3 point down trace average filter was applied along the profiles acting as a low pass temporal filter for removing the high frequency noise induced in the collected data. Background subtraction and trace-to-trace averaging were also applied in order to further smoothen the data. At the end, slices were produced by averaging the amplitude over a specific depth range though an envelope filter, which simplifies and smoothens the display of a radar section by converting the sinusoidal components of the wavelet to positive average amplitude.

GIS techniques were used for mapping the geophysical properties on the various topographic and geological features of the area. Maps were created through interpolation algorithms (kriging) to show the spatial distribution of the above measurements. Time slices were formed and

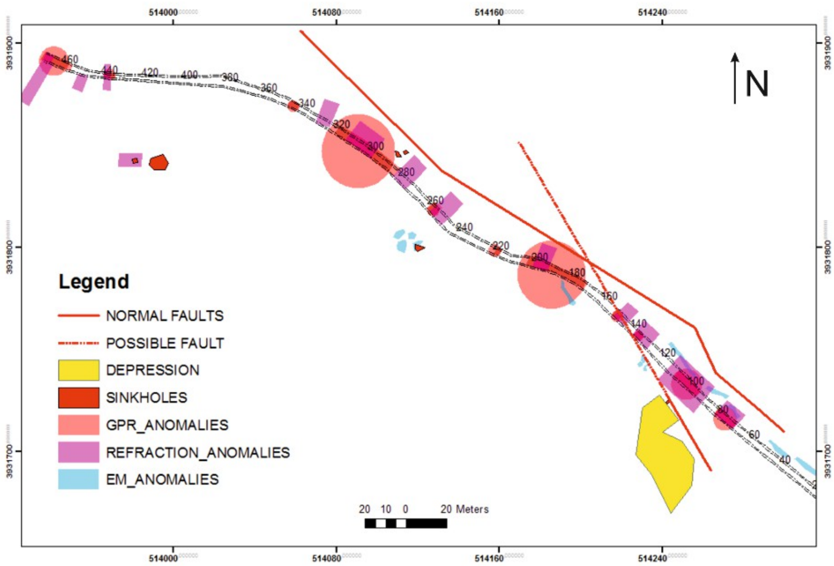

Figure 8. Map showing the combined interpretation of the applied methodology. Disturbed stratigraphy is mainly indicated in locations of the overlapped Refraction, GPR and EM anomalies.

together with the rest of the geophysical maps, were rectified in GIS, converted to polygons and through spatial adjustment they were projected along the bending course of the road.

4. Results and conclusions

This survey was carried out to provide information about the geological settings in the vicinity of and below an old road (Fig. 1b) that is to be reused for heavy-load traffic. The majority of the study area is covered by Terra Rossa.

By studying the velocity models (examples presented in Figure 4) deduced from the seismic refraction lines and taking into consideration the geological structure of the study area, three layers could be detected. The upper layer (0.6-0.9 Km/s) possibly represents Terra Rossa revealing a thickness of about 0.5-2.5 m. Terra Rossa is locally underlain by a layer (1.3-3.1 Km/s) with a maximum thickness of about 1-3 m, that possibly represents a limey conglomerate (where tectonic zones are present) or a disturbed layer due to anthropogenic activities. The deepest layer, detected in these sections, is present at a depth of about 2.5-4 m, and has a velocity of about 3.6-5.6 km/s, possibly corresponding to limestone. Weakness zones are interpreted at various locations (Fig. 4).

NW-SE striking linear features in the conductivity maps resulting from this study (Fig. 5a) may be interpreted as tectonic zones, while the low conductivity zones possibly correspond to sinkholes (Fig. 5b).

Visual inspection of each radargram helped to identify regions of disturbed stratigraphy that were correlated to each other and to the surface features that exist in the area. Zones of disturbed stratigraphy were marked and correlated to the results of slicing that followed. Examples of such regions of disturbed stratigraphy are shown in Figure 6. The horizontal slices (Fig. 7), at depths of greater than 0.7 m and in the east section of the road, show anomalies of the stratigraphy at 65-75 m, 90-100 and 175-215 from the beginning of the road.

The combined georeferenced geophysical maps were cross-correlated and areas of highly disturbed stratigraphy were marked and pinpointed (Fig. 8). It is obvious that highly disturbed stratigraphy characterizes the study area. This is interpreted to be due to faulting and anthropogenic activity. Two tectonic zones are indicated in the study area. These faults are mainly striking NW–SE showing dips in the range of 50-90°. The presence of these tectonic zones is supported by the results of the geophysical survey. Possible karstic voids and tectonic zones are present especially in the vicinity of the eastern part of the road and they are interpreted to be situated at depths ranging between 0.7 – 2.8 m (Table 1). All three

Table 1. Showing the depth of the detected features.

Location (m)	Depth (m)
68-77	0.9 – 2.1
100 - 108	0.9 – 1.4
172 - 187	1- 1.80
216 - 221	1 – 1.30
251 - 257	0.9 – 2.8
280 - 320	0.9 – 2.8
340 - 344	0.4 – 1.7
434 - 438	0.7 – 2.8
464 - 468	0.7 – 2.8

geophysical methods, combined with geological mapping, were effective in detecting anomalous features. The seismic refraction tests estimated the stratigraphy of the study area and found weakness zones such as faults; meanwhile EM conductivity and GPR were able to distinguish finer features including faults and karstic cavities, most of which are greater than 50 cm in diameter. Under favourable conditions (high electrical contrast) the EM method is able to detect even smaller anomalies (5-20 cm size). The above result encourages the integration of geological and geophysical approaches to investigating the subsurface.

In conclusion, the combination of geological and geophysical (Seismic Refraction, EM conductivity and GPR) surveys proved to be a successful tool for the detection of highly disturbed stratigraphy and proved to be of value for subsequent construction works. Taking into account that resistivity imaging could not be applied in the study area due to safety reasons, the above methodology is suitable for such areas. GIS techniques provide an excellent tool for studying the spatial distribution and relationship between the various geophysical properties and the geological settings of a study area.

Acknoledgements

Many thanks to Chatziaugousti D., Tzanaki I., Papadopoulos I., Stavroulaki I., Seferou P., Pegga G., Kanellopoulos P. and Sarridou P. for being involved in the fieldwork measurements. We are grateful to an anonymous reviewer and to Dr. Jan Simkanin for the critical review and the constructive comments.

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