THE MALTA - GOZO TUNNEL PROJECT: ONSHORE BOREHOLE AND SURFACE SEISMIC SURVEY IN SUPPORT TO THE GEOLOGICAL MODEL BUILDING

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In the frame of the Malta and Gozo tunnel project, OGS collected several geophysical data to provide new information for a more reliable geological model along the planned tunnel trajectory (Petronio *et al.*, 2017).

The geophysical survey was planned: to identify and map the main geological and geomorphological features, to characterize the nature, thickness and spatial variability of geological formations below the seafloor, and to identify the main faults.

The stratigraphy of the Maltese islands consists of five geological formations, ranging in age from late Oligocene to late Miocene: Lower Coralline Limestone Formation, Globigerina Limestone Formation, Blue Clay Formation, Greensand Formation and Upper Coralline Limestone Formation (Galea, 2007). The rock layers in Malta are relatively flat-lying, with the exception of zones where the rock has been folded close to faults. The faults have two main orientations, with the largest faults being northwest-southeast trending, parallel to the line of islands, although these faults are only locally exposed, and a second set that are WSW-ENE trending, with generally small displacements that dominate the topography of the islands.

Multibeam echosounder, Single-channel boomer seismic reflection and multi-channel seismic reflection surveys across study area were carried out between October and December 2016.

The main geophysical product was the offshore reflection seismic sections, natively represents the underground reflectors (layers) depth position in time (two-way time). Obviously the position of the reflectors to be useful for geotechnical application should be expressed in depth. The conversion from time to depth requires velocity measurement of the sediments and rock that are present in the study area.

Surface and borehole seismic data acquisition allow to measurement on-field rock/sediment velocities. Seismic refraction is the main method to obtain velocities information from the surface. This approach is widely adopted for near-surface/medium depth investigations (i.e., portals rock characterization, low coverage tunnel sectors, etc.). In the study area, the presence of the Blue Clay formation between two more competent formations (i.e., the Upper Coralline Limestone Formation at the top and the Globigerina Limestone formation at the bottom) limits the applicability of the refraction method because the velocity inversion. To overcome this limitation borehole measurements were planned.

Seismic borehole technique consists of sending a seismic signal from a surface source down to sensors (geophone and/or hydrophone) located into a borehole. The one-way traveltime from surface to depth is obtained by picking the times of first arrival on the observed records. Repeated measurement are taken at different depth along the borehole in order reconstruct the velocity function along the borehole itself.

The borehole and surface seismic survey took place in February 2018 after the borehole drilling completion.

P- and S-wave vertical seismic profiles (VSP) were acquired in two boreholes located close the sea in the north cost of Malta (BH3 - Marfa Road, Ċirkewwa) and in the south coast of Gozo (BH6 - Zewwieqa Road, Għajnsielem). These boreholes were cased and well-grouted to ensure good seismic coupling between the downhole geophones and the surrounding rock.

P-wave VSP data were acquired by an accelerated weight drop (PWD, about 74 Kg) and hydrophone streamer (24 channels with 5 m inter-trace distance) or 3C borehole geophone, while SH-wave borehole data by a 3C geophone (15 Hz) and a MiniVib IVI T-2500 seismic source (sweep: 12s, 10 – 120 Hz, force 1200 Lb).

In addition to the borehole data two refraction seismic lines has been acquired. The aim of this survey was the measurement the P- and SH- velocity nearby the planned tunnel portals for geotechnical purposes. Two sites were selected: the first one (MA_01) on the Malta Island nearby the borehole BH9, the second one (GO_01) on the Gozo Island nearby the borehole BH8. In both lines was utilized 24 channels spaced 10 m and connected with 10 Hz vertical geophone and 10 Hz horizontal geophone for P- and SH-wave acquisition, respectively. As for borehole data acquisition an accelerated weight drop as P-wave seismic source and Minivib in SH mode for the shear wave acquisition were adopted.

Borehole data allow to compute the seismic velocities of the geological formations present in the study area.

Velocity versus depth information were used to convert time to depth in order to assign reliable depths to the events seen in the offshore seismic reflection profiles. Further borehole data give also insight into seismic wave propagation/reflectivity and provide a guide for interpretation of the offshore seismic data.

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GEOELECTRICAL SURVEYS FOR GROUNDWATER INVESTIGATION IN TOGO (AFRICA)

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Introduction. Despite an increase of drinking water coverage in the last 20 years, rural areas in developing countries have still difficult access to safe water. In this context wells represent an important alternative to improve the water supply. In order to deal with this problem, during August 2012, in the framework of a collaboration with the no-profit organization "Il Pozzo della Farfalla", based in the town of Potenza (Italy), the Institute of Methodologies for Environmental Analysis of the Italian National Research Council (CNR-IMAA) carried out a geoelectrical survey, by means of the Electrical Resistivity Tomography (ERT) method, in some rural villages of Togo (Africa) for groundwater investigation (Fig. 1).

The main aim was to obtain information about the lithological-stratigraphical setting and the presence/depth of both groundwater and crystalline bedrock. These information were crucial in order to support the construction of two new wells, which was the main objective of the project "Costruiamo il 2° Pozzo della farfalla".

Fig. 1 shows the location map of the investigated sites: Apu Kedji, Kevè, Tonouvè, Hagblevou and Dzoto.

All the investigated sites are located in the administrative Maritime Region of Togo. From a geological point of view, Apu Kedji, Hagblevou and Dzoto are placed in the sedimentary coastal basin, whereas Kevé and Tonouvé are located on the Panafrican basement (Affaton, 1987).

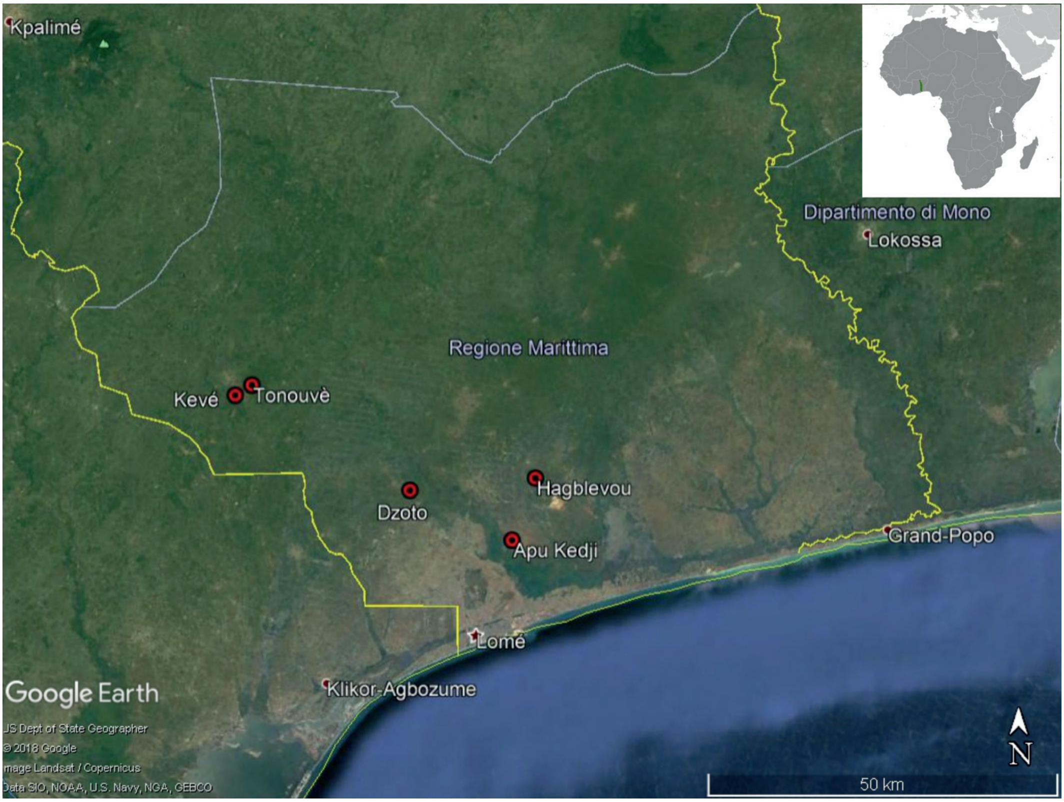

Fig. 1 - Location map of the investigated sites in Togo.

Method and Results. The ERT surveys were performed by means of a Syscal Junior (Iris Instruments) resistivity meter, coupled with a multielectrode acquisition system (48 electrodes). A constant spacing "a" (2.5 or 10 m) between adjacent electrodes was used. Along each profile, Wenner (W) and/or Wenner-Schlumberger (WS) configurations were adopted with different combinations of dipole length (1a, 2a and 3a) and number of depth levels "n" ($n \le 6$). The investigation depths were about 15 m (for a = 2.5 m) and 80 m (for a = 10 m).

The apparent resistivity data were inverted using the RES2DINV software (Loke, 2001) to obtain the 2D resistivity images of the subsurface. The inversion routine is based on the smoothness-constrained least-squares inversion method implemented by using a quasi-Newton optimisation technique (Sasaki, 1992; Loke and Barker, 1996). The optimisation method adjusts the 2D resistivity model trying to iteratively reduce the difference between the calculated and measured apparent resistivity values. The root-mean-squared (RMS) error provides a measurement of this difference.

The ERT interpretation has been almost based on the scarce geological and stratigraphic data found in literature and on the information of local people. In particular, from a comparison between the ERT and borehole data, reported in the work of Da Costa *et al.*, 2012, it has been possible to approximately associate resistivity values/patterns to different litho-stratigraphic setting.

Apu Kedji. The first ERT was carried out at Apu Kedji site, a rural village located about 15 km north-est of Lomé, capital of Togo, where the no-profit organization "Il Pozzo della Farfalla" realized the first well for water supply in 2010 (Fig. 2). In this site, the main aim of the survey was to test and calibrate the results obtained from the electrical image of the subsurface with the presence of groundwater at a depth of about 5-6 m below ground level (bgl) as roughly estimated through the water well.

The electrical images were performed with an electrode spacing of 2.5 m and 48 electrodes, reaching a total length of the profile of 117.5 m and an investigation depth of about 15 m.

Fig. 2 shows the 2D resistivity model related to the ERT profile centred on the existing water well.

For the achievement of best fit between the calculated and measured apparent resistivity values, three iterations were performed, obtaining a resistivity model with a relatively low RMS error of 4.2%.The electrical image is characterized by a relatively low resistivity range, varying from 5 to over 127 Ωm, and by an almost piano-parallel electrostratigraphic pattern. The shallow irregular and thin resistive layer can be associated to sediments (clayey sands?) with low water content, whereas the underlying conductive layer can be associated to the same saturated sediments, as testified by the presence of water into the existing well.

Kevè. The second site is a populated zone, near to the village of Kevè, located about 45-50 km north-west of Lomé, where the no-profit organization "Il pozzo della Farfalla" aimed to realize the second well for water supply.

In this site, two ERT were acquired close to the catholic parish of "Sacré-Coeur de Jésus": the first one, centred on Rectory, at relatively low resolution, with an electrode spacing of 10 m and 48 electrodes, reaches a total length of the profile of 470 m and an investigation depth of about 80 m; the second one at relatively high resolution, with an electrode spacing of 2.5 m and 48 electrodes, reaches a total length of the profile of 117.5 m and an investigation depth of about 15 m.

The first deeper ERT was performed to obtain information about the depth of the crystalline bedrock, whose presence was supposed on the base of geological data, whereas the second shallow ERT was carried out in order to characterize the near surface lithological, stratigraphical and hydrogeological setting.

The 2D resistivity models were showed to the local drill company, that searched for an appropriate area to drill under the approval of the population. The ERT gave important guidelines to the company in preparatory and operational phases. The aquifer was founded at about 55 m

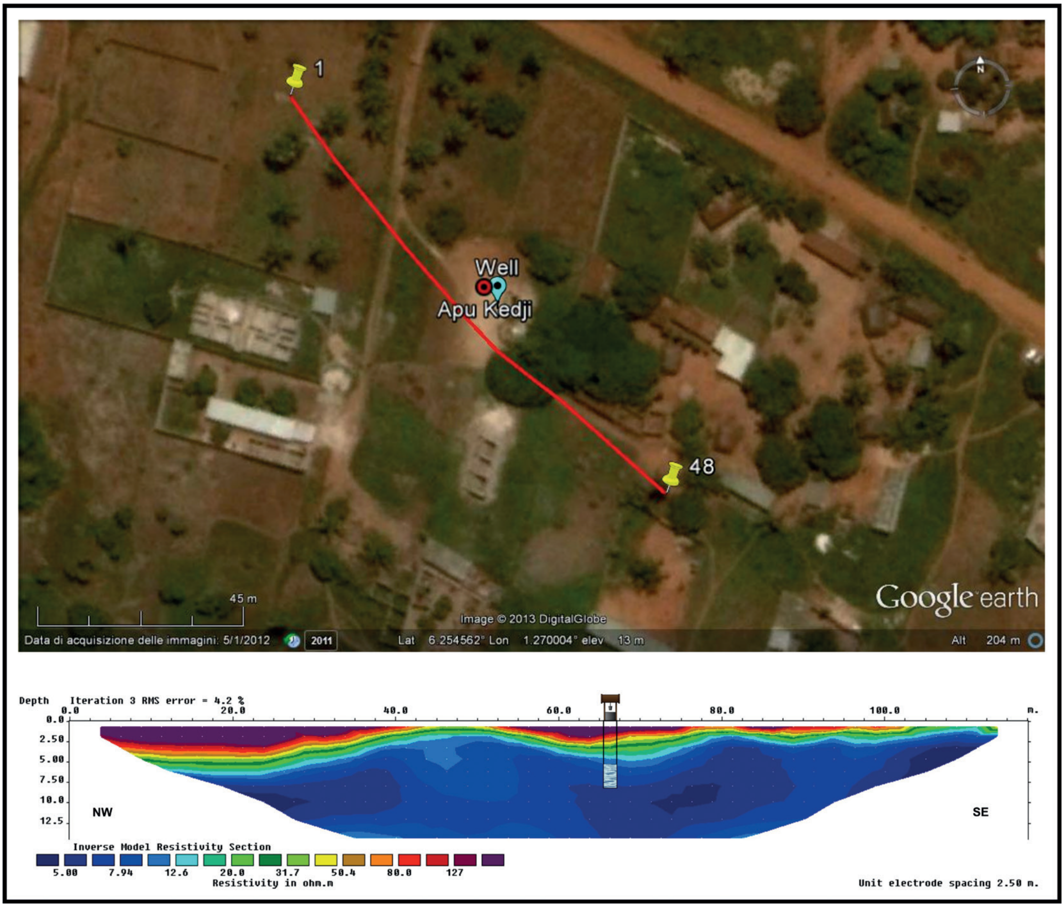

Fig. 2 - Map of Apu Kedji site in which are reported the ERT profile (red line), position of first (1) and last (48) electrode (yellow icon) and the well for water supply (cyan icon) (top). 2D resistivity model of ERT carried out in Apu Kedji with the position of the water well (bottom).

of depth and it was drilled 5 m below the aquifer level. A 10 cm diameter polyvinyl chloride casing was installed to protect the well from collapse and debris. Subsequently, a temporary pump was placed over the well to monitor the water quality and output. It was, then, finished at the surface with a stainless steel positive displacement pump and mounted on a concrete slab. Finally, a piping system was installed to bring water into a tank located at the top of an expressly built concrete water-tower (Fig. 3).

Fig. 3 - Picture of the water well built in Kévé.

The no profit organization Il Pozzo della Farfalla believes in utilizing technology that suits the economic environment and encourages the community's self-reliance and determination, so everything was chosen for giving long-life to the project: the pump system, for example, has an average life of 20 years and all replacement parts are easily found in rural areas at affordable costs.

The results show how collaborations between research institutions and no profit organisation can specifically improve drinking water supply in developing countries.

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