THE UNDERSEA MALTA - GOZO TUNNEL PROJECT: GEOPHYSICAL INVESTIGATIONS

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Introduction. Between the autumn of 2016 and the winter 2017-2018 OGS and the University of Malta carried out a series of geophysical investigations in the Gozo Channel (Malta). These surveys are part of the study commissioned by the Ministry of Transport and Infrastructure of Malta to evaluate the feasibility of an undersea tunnel between the islands of

Malta and Gozo in the Mediterranean Sea. Final interpretation and modelling will be completed by University of Malta.

The general aim of this study is to provide a new contributions and improvements to the geological model of the area, so as to better plan and design the final proposed route.

Specific objectives of the project are as follows: to characterize the nature, thickness and spatial variability of the geological formations below the seafloor; to characterize the geologic, geotechnical and hydraulic properties of these formations; to detect features of geologic and geomorphic relevance within them (e.g. faults, Karstic formations); to build a 3D geologic model of the study area.

Geological settings of the study area and its implications for tunneling. The islands are composed almost entirely of marine sedimentary rocks, mainly limestone of Oligo-Miocene age. Some minor quaternary deposits of terrestrial origin are also present.

The rock sequence comprises five main distinct formations which, although slightly disturbed by almost vertical faults displacements, lie almost horizontally across the islands with a minor generalized NE dip. The five main rock types are (in order of decreasing age):

- Lower Coralline Limestone: this is the oldest exposed rock type in the Maltese Islands and started being laid down during Oligocene age. It is a 140m thick, hard limestone unit that forms sheer cliffs that may be from ten to over a hundred meters high;
- Globigerina Limestone: this formation is subdivided into three units (Lower, Middle and Upper Globigerina Limestone) by two pebbles beds. It is a softer fine-grained limestone unit that forms irregular slopes, and that start being deposited during Miocene (Langhian to Aquitanian). Its thickness varies from 23m to 207m;
- Blue Clay: this is a very soft unit that within the islands normally forms rolling low slopes that are mostly covered by carbonate raw soil or scattered rubble. The age is Langhian to Tortonian, in the Miocene. Blue Clay is generally impermeable and holds water, with a thickness up to 65m;
- Greensand: even if not sufficient thick (12m), this formation proved distinctive enough to have deserve a separate name. It consists of massive, friable, intensely burrowed marly limestone, deposited during the Tortonian age in the Miocene;
- Upper Coralline Limestone: this formation is a complex association of limestone. The deposition of these marine sediments stopped around 10 million years ago when the seabed rose above sealevel. This formation constitutes the coralline plateau that top most of the hills of Gozo and Malta. It overlies the Blue Clay in an irregular pattern and its thickness can reach 162m.

A system of horst and graben structures of E-NE trend characterizes the area interested by the project. These structures are indicated by prominent ridges and valleys, with sub-horizontal strata dominating. Rock faulting and displacements are widely present in north Malta and south Gozo and in the channel between them, where the geology is not clearly understood yet.

There are a series of geological implications for tunneling in this area. The most relevant are:

1) The presence of faults, that degrade the rock quality and its mechanic characteristics. This represents a potential risk for the tunnel excavation in areas where the faults positions are either unknown or poorly mapped;
2) The presence of Blue Clay formation, that would be preferable to avoid during the tunneling because of its softness and its generally poor mechanic characteristics.

Where possible, in fact, the tunnel alignment should be developed below the impermeable Blue Clay layer, and extend as far as possible within the Globigerina and Lower Coralline Limestone formations, that are harder and where karsts formations are understood to be scarce.

Plan of work and methodologies. The geophysical investigations have been completed in two different phases. The first phase took place in autumn 2016, and comprised all offshore operations. The second phase was planned after the borehole drillings, and was completed during winter 2017-2018.

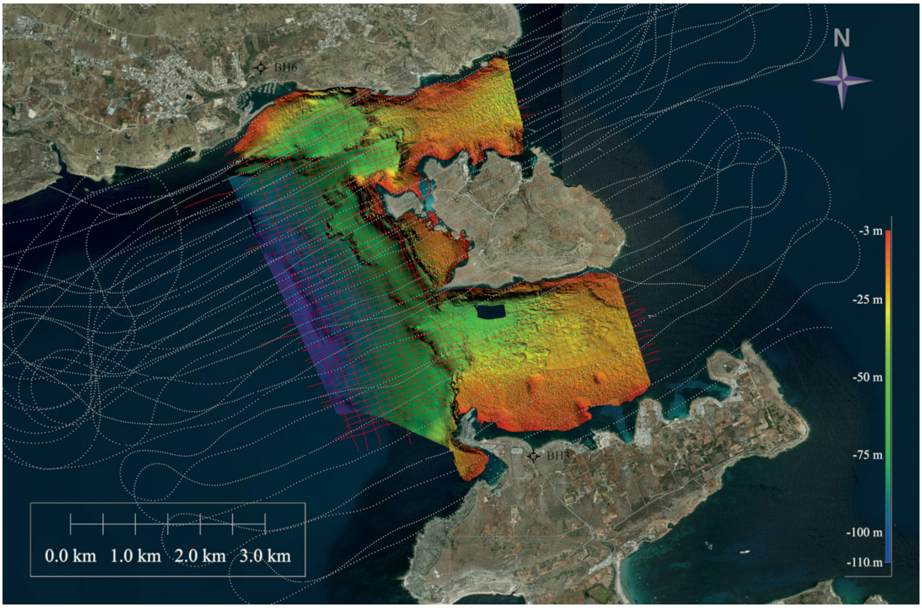

Fig. 1 - Acquisition Map. Bathymetric data, Seismic Lines (Red), Airborne Survey (dotted White), and Borehole location.

The first phase comprised morphological and seismic data acquisition.

The project area (Fig. 1) was fully covered with a Reson Seabat 7125 Multibeam (500kHz). The bathymetric data was acquired and processed with Teledyne PDS software that provide, during acquisition, some automatic tools to detect and delete data with a bad quality level. All the data set was processed with the following steps: sensor calibration and geometry validation; sound velocity profiles control; positioning and tidal control, application of Statistic, Slope, Flying Object, and Beam Quality automatic filters; data replay, with different point of view, to detect residual spikes and anomalies. Finally Digital Terrain Models, with square cell from 2 to 20 meters, were created. A centimetric scale 3D map of the seafloor was achieved.

To image the subseafloor with a fine scale up to few tens of meters, a High Resolution Seismic survey was performed using a boomer source with a single-channel streamer (8 piezoelectric elements connected in series with a 2.8 m active array). The boomer plate (AA301) produces a theoretical minimum phase wavelet with amplitude spectrum between 400 and 4000 Hz. With this frequency range, under favourable conditions, we can obtain data with decimetric resolution. Boomer data was processed with conventional mono-channel processing sequence: after DC removal (continuous noise from electrical devices) and filtering (time variant band-pass in a range 100-6000 with slope in dB/octave), we applied a gain (spherical divergence and balance gain obtained by inverse of amplitude decay curve) to recover the seismic energy. The weather condition affected the HRS data: the sea waves lifting and lowering the streamer and the plate, creating a wavelet effect on data. These undulations modified and destroyed the reflectors. To attenuate this effect in several profiles we applied a static correction calculated on a plot trace within a predetermined window.

A multichannel Reflection survey was conducted to characterize the nature and stratigraphy of the bedrock, the main issue was to identify the main faults and the interface between the Blue Clay and the underlying rock. As a whole 108 seismic lines were acquired (236 km). The grid was constituted by lines spaced 75m (Fig. 1, Red Lines), along 70°N and 160°N directions (Fig.1). To reach the "target depth" of 300m below the seafloor, a 60 cu.in. Sercel Mini GI-Gun was used as source. The gun was feeded by three high pressure Coltri compressors, capable of

320 l/min at 140 bar each, and was activated in "Harmonic mode" every 18.75m or 15.625m when possible. The data were collected by a 96 channel 300 m long Geometrics GeoEel digital streamer, with a trace distance of 3.125m. Both the source and the seismic cable were towed at a depth of 1.5m, to keep the spectra as broad as possible. During the Multi-Channel Seismic acquisition, a realtime QC was performed onboard. After survey completion the dataset was processed in OGS facilities. The processing sequence was briefly as follow: editing; geometry assignment; water bottom picking; surface-related multiple elimination (SRME); amplitude recovery; predictive deconvolution; velocity analysis; normal moveout correction (NMO), manual stretch mute and Stack. The "Post-stack" processing consisted in the following steps: F-X deconvolution; time varying bandpass filtering; Kirchhoff time migration followed by amplitude balancing.

The second phase of the survey took place in winter 2017-2018 after borehole drilling, completing the dataset with onshore seismic data, and borehole seismic (VSP) for validation, calibration and time to depth conversion. In two boreholes located in the north coast of Malta island and in the south coast of Gozo island (Fig. 1, indicated as BH3 and BH6) a total of five VSP, three for P-waves and two for SH-waves has been acquired.

For P-waves an hydrophone streamer down the hole, and a PWD (accelerated Weight Drop, about 74kg) mounted on a tractor as impulsive source were used.

For SH-waves a 3C geophone down the hole, and a MiniVib source (11kN peak force) as vibrational source were used.

Two refraction seismic lines has been acquired close to BH8 and BH9, to determine the P and SH velocity nearby the planned tunnel portals.

In November 2017 an extensive airborne gas concentration survey has been carried out in the area between Gozo and Malta islands. The mission was focused to map CH4 and CO2 concentrations. The acquisition has been carried out with a Los Gatos Research (LGR) Ultraportable Greenhouse Gas Analyzer (UGGA) carried on-board of a Cessna 172 aircraft. The flight pattern consisted in 22 parallel lines (Fig. 1, dotted white lines) over an area of 30 km^2 with a set flight altitude of 500 ft at a speed of 70 Kts IAS in VMC and low wind intensity. The LGR inlet pipe has been placed on the wing leading hedge to sample undisturbed and uncontaminated samples of air. OGS technicians implemented a specific LGR data logger based on Arduino platform. The LGR's UGGA reports and store all measured fully resolved absorption spectra which allows the instrument to accurately correct for water vapor dilution and absorption line broadening the effects and thus to report CH4 and CO2 on a dry (and wet) mole fraction basis directly without drying or post processing. CO2 and CH4 data have been plotted using simple moving average filter, over a period of 10 seconds, in order to remove short-term fluctuations. Also, data from LGR's UGGA have been interpolated over a 100x100 m grid, in order to produce a map concentration stackable with other significant data, e.g. trajectory information, or pockmarks detected at seafloor. The data shows some local anomalies where a major increase in concentration of CO1 (up to 403 ppm) and CH4 (up to 1890 ppm) are observed.

Results. A complete dataset including offshore multichannel seismic, HR seismic, VHR seismic, bathymetry, aerial CH4 and CO2 concentrations, land seismic, borehole stratigraphy, and VSP has been acquired over two years. The overall data quality is good. The objective "target depth" has been successfully reached with seismic penetration up to 600 m below seafloor. The seismic velocities have been determined through the VSP and refraction seismic acquisition.

Conclusions. The dataset will allow to build a 3D geological model to fully characterize and better understand the structures in the area and to determine the Blue Clay formation limits. The integration of seismic sections with VSP data will give useful depth information for the correct tunnel planning. Aerial gas measurement will provide a tool to better understand the features revealed from seismic and bathymetric data.