GEOPHYSICAL SURVEY ON THE OFFSHORE MICROTUNNEL ROUTE IN DELIMARA PENINSULA (MALTA)

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ABSTRACT

This paper reports the main result of the geophysical survey performed in the Delimara peninsula (Malta) along the offshore route of the microtunnel realized for the shore approach of the 22” Melita Transgas Pipeline. The main goals of the survey were to assess the seafloor integrity and the possible deteriorations that might arise from the bedrock collapse during the nearshore microtunnelling, and then to identify and avoid cavities during the work.

The preliminary geognostic investigations carried out on this segment through several boreholes highlighted the presence of fractured limestone and possible cavities. A following tomographic analysis (Electrical Resistivity Tomography) allowed the detailed reconstruction of the lithostratigraphic and geomechanics characteristic of the entire corridor. The geoelectric prospect also allowed to verify and evaluate the risk of intercepting cavities along the corridor during the drilling phase.

The installation of seven multielectrode lines were performed: one of them was longitudinal to the microtunnel pathway, two parallel and the rest transversal to it. Six of them were installed on the seabed, with the help of divers, to better mitigate the effects of the marine depth. The post-processing of the data, optimized through the precise knowledge of the electrode positions and the resistivity values of the seawater, led to the definition of a two-dimensional and a three-dimensional predicting model, able to work up to 50 m depth from the seabed. Such models link the values of the resistivity measured and the lithologies of the seabed (known from the stratigraphic logs) to its stratigraphy, allowing to exclude the presence of cavities along the pathway analysed and, thus, to distinguish the karst lithologies (limestone and marly limestone) from the non-karst ones (marls and clays).

INTRODUCTION

The geophysical investigations aim to support the design of a gas pipeline (Melita Transgas Pipeline) in the section interested by the microtunnelling technology. The microtunnel crosses under the Delimara peninsula for 600 m and extends under the seabed for other 600 m. The purpose of the investigations was reconstructing the lithostratigraphic structure of this nearshore section, up to a depth of 50-60 m from the seabed, also assessing the fracturing conditions and any karst processes that affect the lithological formation present,

The activities are subsequent to a first phase of investigations carried out “on the land” (drilling, refraction seismic and geoelectric tomography prospecting). In the nearshore area, two continuous drilling operations and a morpho-bathymetric survey of the seabed have already been carried out, the latter used as a support for the programming and processing activities carried out in this phase. Just starting from the acquired data, it was possible to evaluate the most suitable geophysical methodology for the achievement of the expected objectives. The seabed is featured by a very variable depth between the coast and the outermost part, which reaches 40 m of water depth. It was, therefore, preferred to use the geoelectric resistivity method with tomographic processing (ERT). In addition, considering the need to maintain a high resolution capacity, as well as the considerable depths involved in the outermost area, it was decided to lay the electrode cables for the execution of the measurements directly on the seabed. This entailed the need to use specifically made cable, with an extension of 50 m with respect to the position of the first electrode lying on the bottom.

GEOLOGICAL AND GEOMORPHOLOGICAL FEATURES

The site has been investigated along a line approximately WNW to ESE of about 1200 m. The elevation above mean sea level varies from about 30 metres at the western and decreasing to about -42.0 m, below mean sea level, at the eastern shoreline.
The geological strata (making up the Delimara Peninsula) include the Upper and the Middle members of the Globigerina Limestone formation as shown in Fig 1:

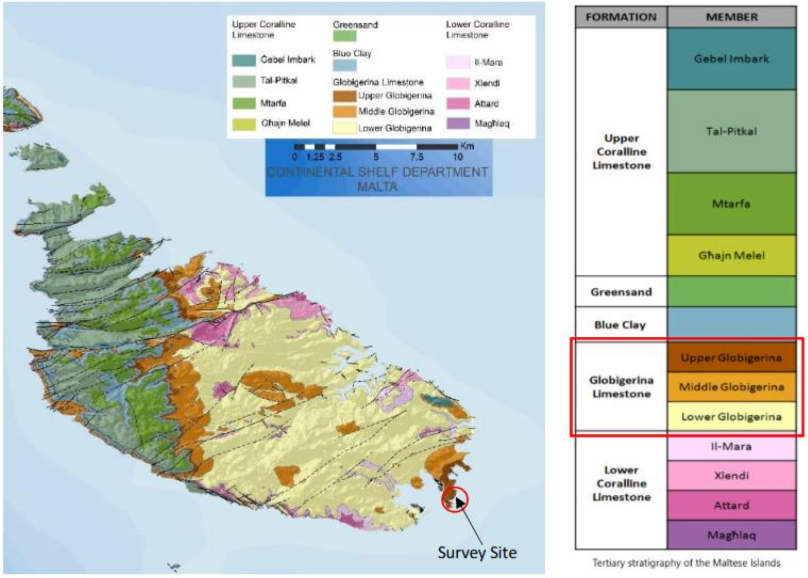

Fig 1: Geological map of Malta (from Continental shelf department) and survey site.

The sedimentary sequence is composed of alternating calcareous marls and marly limestones with subordinated prominent bioturbated indurated limestone's that were deposited in a pelagic environment. The stratigraphic sequence is composed by an alternating nature chancing between relatively hard and soft strata of very limited thickness, which may be, in part, the result of selective cementation and neomorphism.
The Upper Globigerina Limestone of Delimara is of a uniform grey colour, lacking the yellow-grey-yellow division that is elsewhere diagnostic of the Member. This correlates with a lack of disseminated iron usually characteristic of the lowermost and topmost Beds. This lack of disseminated iron in turn correlates with an increase in the amount of clay within the Member at this locality. It is atypical concentration of clay minerals that may well be responsible for the formation of the preferential diagenesis within this member as a whole at Delimara. Neomorphism of the lime mud is particularly prominent in the carbonate zones and essentially absent from the marly horizons. As a result, the carbonate zones are more lithified than the marly horizons.
The division between the Upper and the Middle Globigerina Limestone is marked by the presence of a conglomerate phosphate-rich bed named C2 (Pedley 1975) in which most of the pebble material is extensively perforated or pitted and infilled with glauconite.
The Middle Globigerina Limestone is classified as a clayey biomicrite rich in planktonic foraminifera. This member is generally characterised by compact, light grey calcareous marls occasionally altering with massive-bedded marly limestone's layers and dispersed phosphate particles and pebbles.
From a structural system, the area assumes a monoclinal structure, with a slight slope (2-4°) of the bedding planes in the ESE direction. Tectonic dislocations with an outstretched character affect the monoclinal generally very limited shifting, but such as to determine a certain degree of fracturing, resulting in geomechanical degradation and increase of secondary permeability (by fracturing) of the rock mass.
From the geological survey carried out in the surface, the correlation of bibliographic data and what has been identified from the results of the geophysical images on land and sea, the presence of a fault system oriented south-west north-east is presumed for the site of interest, with direction of

immersion southeast. This fault system is probably constituted by a series of fault planes, sub-parallel to each other, which extend towards the southeast. For this reason, the Microtunnel path, will intercept these structures, crossing areas of high fracturing, with probable presence of fine sediment and sea water that have the fractured void.
Additionally, the study area is characterized by eroded cliffs and coves along the coastline in the Delimara peninsula. The geomorphological structures are associated with presence to terraces, paleoshore platforms and shoreline. The terraces are characterized by a concave break of slope at their landward limit that occurs at a regular bathymetric depth. Their landwards limit occurs at three different depths, in the study area: 28-30 m, 35-37 m and 42 m.
These terraces are interpreted as coastal platform formed by subaerial atmospheric agents during the exposure at the bottom and the erosion of the waves (hydraulic pressure and abrasion) that guided the coast towards the ground during the post-glacial sea level rise. As a consequence, the ground edge of these platforms, known as the corner of the coast, provides an indicator of the maximum sea level at the time of formation of the platform. The shallower paleoshoreline, on the other hand, correspond to the notches identified by divers at depths of 25-30 m and 33-40 m, in the study area.

ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

The electrical resistivity tomography (ERT) surveys aims to determine the subsurface resistivity distribution through measurements on the ground surface. The ground resistivity is related to various geological parameters, such as the mineral and fluid contents, porosity and degree of water saturation in the rock. Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. The fundamental physical law used in resistivity is Ohm’s Law that governs the flow of current in the ground. The equation for Ohm’s Law in vector form for current flow in a continuous medium is given by: $\mathbf{J} = \delta * \mathbf{E}$.
Where δ is the conductivity of the medium, **J** is the current density and **E** is the electric field intensity. In practice, what is measured on field the electric field potential. We note that in geophysical surveys the medium resistivity ρ, which is equals to the reciprocal of the conductivity ($\rho = 1/\delta$), is more commonly used.
The resistivity values are largely dependent on the porosity of the rocks and the salinity of the contained water. Unconsolidated sediments generally show even lower resistivity values than sedimentary rocks, with values ranging from about 10 to less than 1000 Ω·m. The resistivity value is dependent on the porosity (assuming all the pores are saturated) as well as the clay content. Clayey soil normally has a lower resistivity value than sandy soil. However, an overlap in the resistivity values of the different classes of rocks and soils can be observed, as the resistivity of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts. The resistivity of groundwater varies from 10 to 100 Ω·m depending on the concentration of dissolved salts. The low resistivity (about 0.2 Ω·m) of seawater due to the relatively high salt content. For this reason, the resistivity method can be considered as an ideal technique for mapping the saline and fresh water interface in coastal areas.
The apparent resistivity measurements in the field have been carried out using an eight-channel georesistivimeter with galvanic isolation (ABEM Terrameter LS2 System) for resistivity, induced polarization and spontaneous potential, with the following characteristics: Automatic or manual selection of the current input from 0.20 to 2500 mA; Energization with max voltage 600 V (1200 V peak-peak); Maximum power to 250 W; Current transmission accuracy to 0.4 %; Current pulse length 0.1%; Impedance 30 MΩ min; Resolution 3 nV; dV/I accuracy to 0.2 % and dV/I accuracy to 0.1%.
To perform the measurements in multielectrode configuration, the system is equipped with an automatic selector, capable of managing 64 electrodes simultaneously. The electrodes were placed manually on the seabed, then connected to the selector via multicore cables. For sea operations, a boat with a length of 12 m was used, engine power of 340 KW (“Simo” dive boat).

DELIMARA ERT SURVEY

Seven ERT surveys were carried out using a multielectrode method. Three of these were carried out in parallel with the pipeline design route, for a length of about 630 m. In particular, one along the pipeline axis (TR02) and the other two at a distance of 10 m from each side. Other four ERT were carried out in the transverse direction, approximately NE-SW for a length of 315 m each one. One of them was executed on land (TR00), it develops between the altitudes of 10 and 13 s.l.m. The other three have been realized offshore, so as to interest transversely the track plan of the microtunnel path and the valley submerged valley present north of the pipeline track. The longitudinal measurement lines (TR01, TR02 and TR03), were carried out by laying 4 cables with 32 x 5.0m-spaced electrodes, for a length of 155 m each. The measurements were carried out at the centre of each pair of cables (simultaneous acquisition on 64 electrodes 315m in length), proceeding from offshore to the mainland, with a roll-along procedure, providing an overlap of 155 m, equal to the length of a single cable. In this way, for each line, three stations will be required (acquisition step).
The acquisition points, coinciding with the central terminations of the cable pairs, have been materialized on the surface by buoys positioned using a GPS-RTK (GR-3 - RTK GPS System from Topcon), anchored to the seabed with special ballasts ("dead bodies"). Both the positioning of the buoys and their anchorage, and the laying of the cables on the bottom, have been performed under control of specialized personnel (divers), see Fig 2:, Fig 3:.

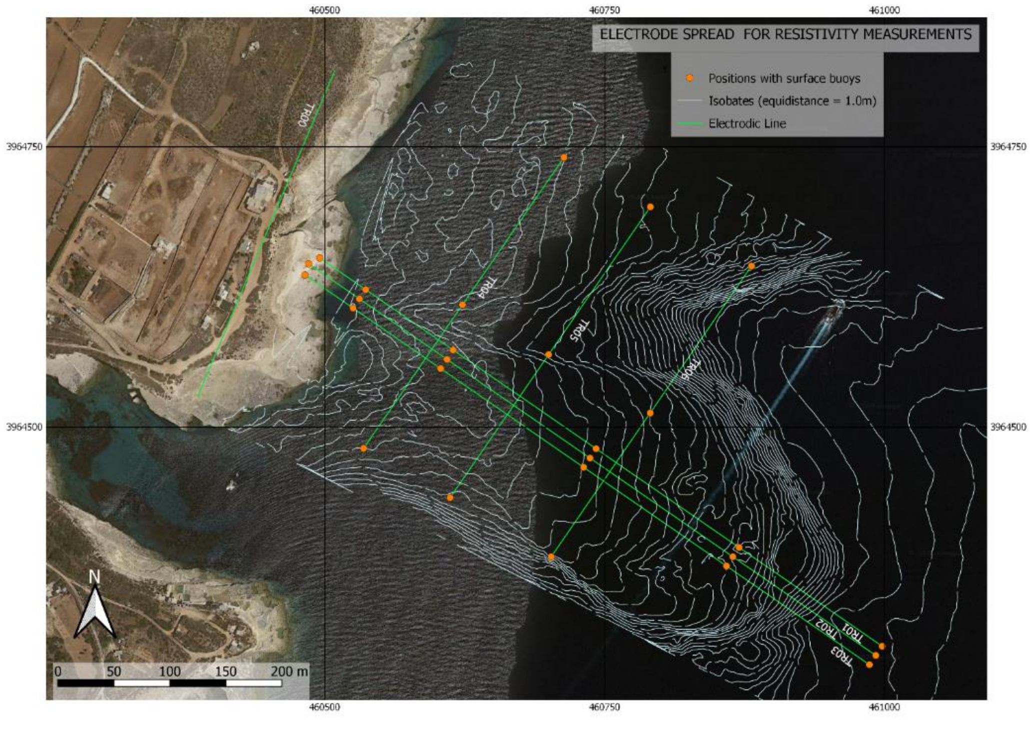

Fig 2: Map of electrode lines realized

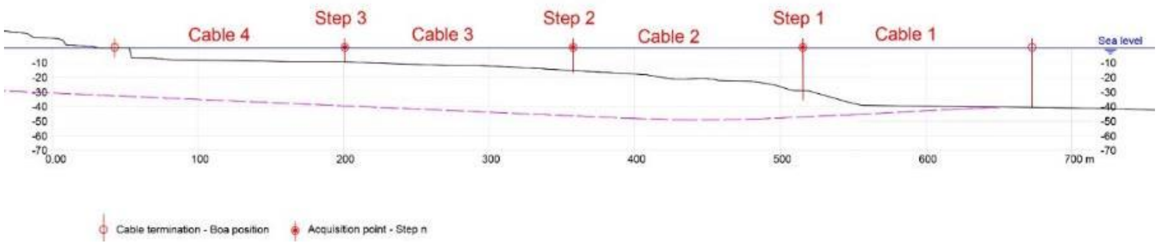

Fig 3: Acquisition scheme for longitudinal lines

In our case, the survey was aimed to the reconstruction of the lithological variations of the sector of interest, and, in particular, to the identification of the calcareous substrate and to identify any cavities and highly karsted areas. An electrode spacing of 5.0 m and a depth of investigation of 55-60 m have been planned. With an electrode spacing of 5.0 m, using 64 electrodes, results in an investigative depth of 55-60 m under the seabed. In order to have as high a resolution of the survey as possible and also increase the depth of investigation, the multicore cables will be laid to the seabed, with the help of geologist's divers. In the measurements a multigradient array was used, which has a good sensitivity compromise between the perception of vertical and lateral variations of underground resistivity. In addition, this array allows the acquisition of multiple measurements simultaneously (up to eight), allowing faster data acquisition. See Fig 4:

Fig 4: Multigradient array (C: Current electrode; P: potential electrode)

For each of the longitudinal lines, 635 m long, 4167 measurements were made, while in the transverse ones, with a length of 315 m, the measurements were 1565. The spatial resolution of the survey depends not only on the spacing of the electrodes and the number of measures, but on a series of factors in a system to be considered complex. In correspondence of possible cavities, being filled with water, there is to expect lower values of electrical resistivity than the carbonate rock in which they are contained. The possibility of solving them is linked to their dimensions in relation to their depth, as well as to the contrast of resistivity between rock and the filling marine water. At a depth of 20-25 m from the seabed, a resolution (ability to detect a cavity) of 4-6 m can be assumed; below this size the electrical anomaly produced, is considered too weak to be perceived by measurements performed on the seabed. See Fig 5:

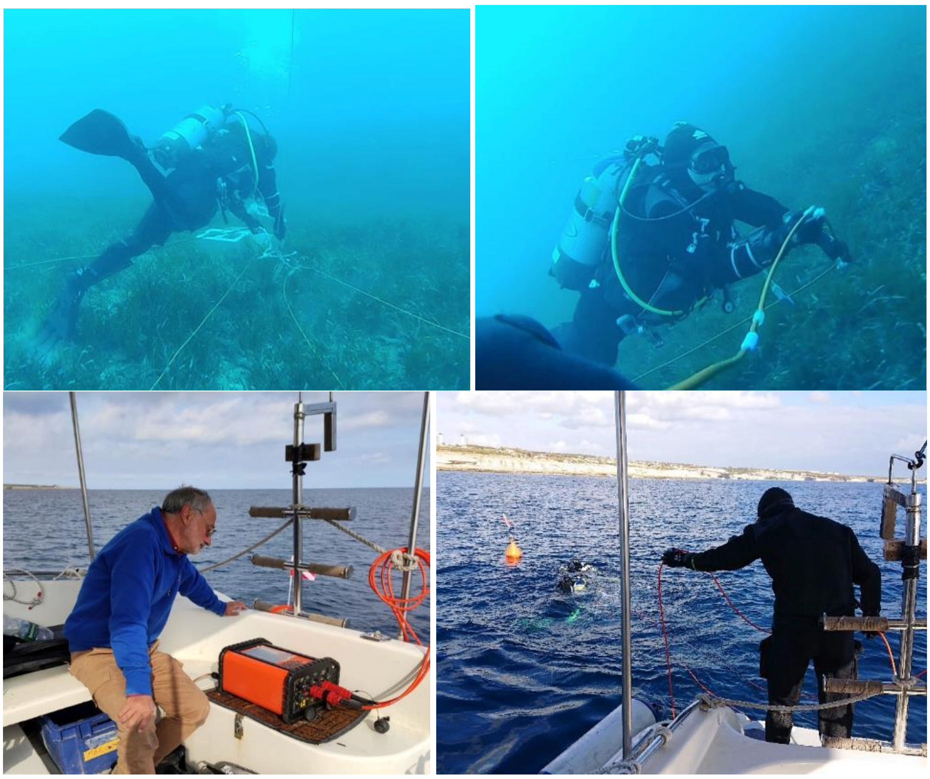

Fig 5: Laying of the cables, arrangement of the electrodes on the seabed and data acquisition

Water depth and resistivity: In order to obtain useful estimates of resistivity in soil and rock, it has been necessary to integrate the water depth and the resistivity of the water in the interpretation model. Errors in water depth or resistivity lead to artefacts in the model, as the inversion program compensates for surplus or deficit in conductance in the water model by the corresponding increase or decrease in the resistivity. In this case, the bottom topography varies greatly; hence, it is of utmost importance to measure both bottom topography for each survey line to avoid misleading results. The water depth in the study area was mapped using multibeam sonar, already carried out in a previous survey; the data acquired by this measure are of good overall quality, with their degradation in the area close to the shore line. This situation has created some problems of elaboration in proximity of the coast. The value of the resistivity of sea water was measured in a laboratory on a taken sample (0.19 Ωm at 15°C).

PROCESSING AND INTERPRETATION

The TR00 survey was carried out on the land, with a length of 315 m, between the elevation of 10 and 13 s.l.m. It falls within the outcrop areas of the Upper Globigerina Limestone Member. The purpose of this prospection was to verify the response from the electrical point of view, of the substrate surfacing as a whole up to depths of over 50 m. Furthermore, as the electrode line passes through a tectonic dislocation (Fig 6:), it has been possible to verify the response, from a geoelectric point of view, of the fracturing band associated with it. The inversion was carried out by providing for gradual variations in resistivity (*L2 norm - smoothness-constrained least squares method*), to better highlight the lithological variations and the fracturing state (residual 2.5%).

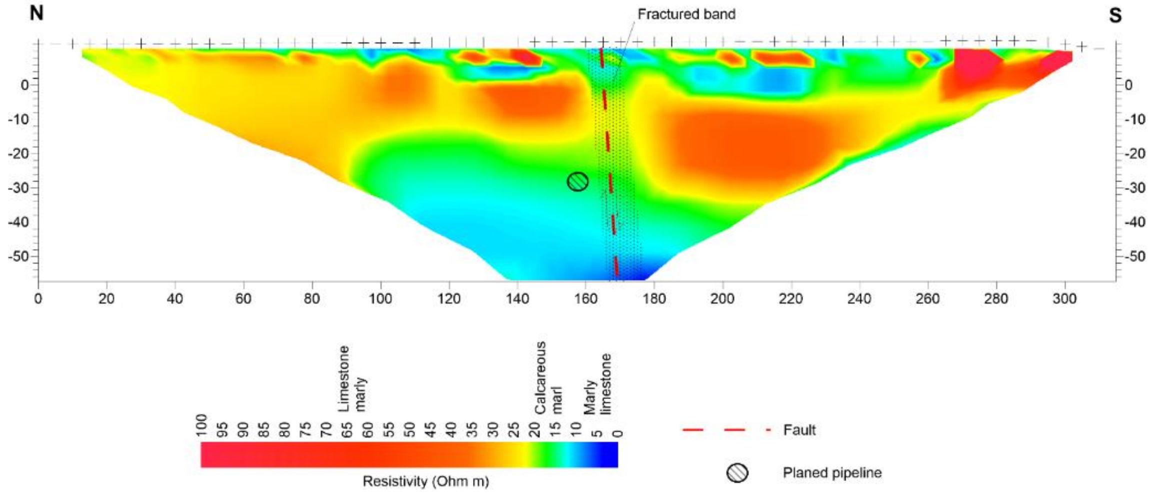

Fig 6: Electrical Resistivity Tomography – TR00.

The resulting model shows a discrete lateral continuity of the electrical horizons, characterized by low resistivity bands (5-20 Ωm), alternated with higher resistivity horizons (20-60 Ωm). The low values can be correlated to the presence of a pelitic component (marl and marly limestone), while where it tends to increase, it can be attributed to the prevalence of the coarse and calcareous component (limestone marly). The effect of the fault is visible both in the displacement of the electrical/lithological horizons, and in the definition of a slightly less resistive sub vertical band, about eight meters wide, which can be correlated with the fracturing band. See Fig 7:

Fig 7: TR00 prospecting (on land) and fault position

The three ERT surveys parallel to the pipeline (TR01, TR02 and TR03), are laid on the seabed, for a length of 630 m. The numerical modelling was performed by adopting the electrical resistivity of the sea water as determined in the laboratory, with a value of 0.19 Ωm at 15°C; while for the depth of the seabed, and of the electrodes, reference was made to the data of the existing bathymetric survey. The numerical inversion was always carried out using the Res2DInv64 software, *L1 norm inversion method* (robust). Despite the relatively low residual error values (6-7%), the inversion produced artefacts (see Fig 8:) in the area closest to the coast, presumably due to the incorrect estimate of the depth of the seabed near the shore line.

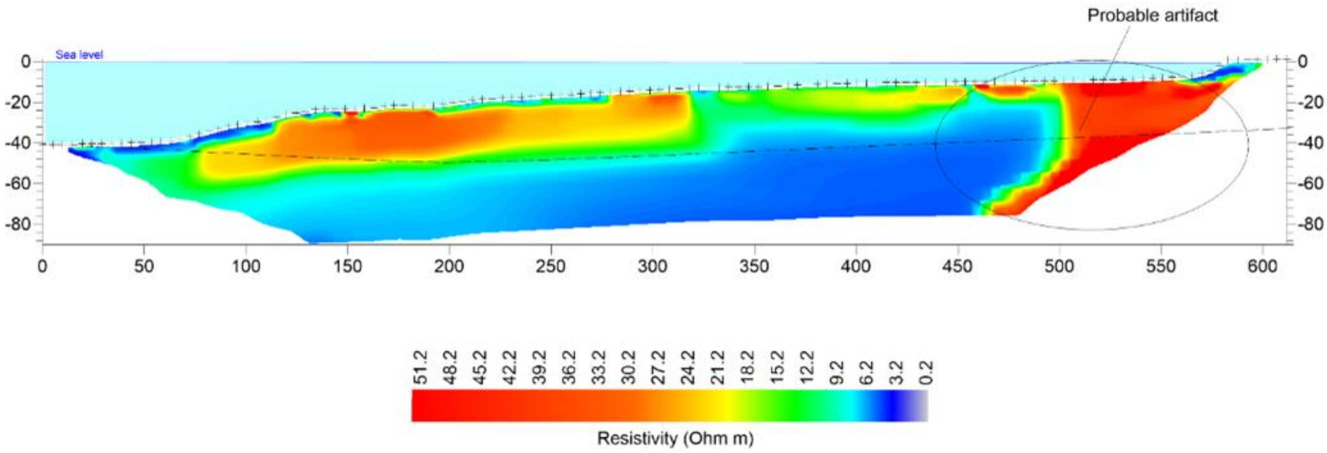

Fig 8: Electrical resistivity tomography – TR02

For this reason, it was decided to "cut" the length of the longitudinal prospections to 560 m, excluding in the elaboration the section close to the shore line and that on land. The results thus obtained are more reliable and consistent with the local lithological context. The inversion was carried out always providing for abrupt changes in resistivity (L1 norm - robust) and the models obtained have residual between 7% and 8%.

The three resistivity 2D models, parallel to each other and spaced 10 m laterally, show good lateral continuity of the electric horizons. A first horizon, slightly inclined in the SE direction, has a thickness of 20-22 m and a resistivity between 20 and 40 Ωm, correlated with the lithologies of the Upper Globigerina Limestone Member, as found in coring, consisting of limestone, weak to very weak, with grey marly. An underlying horizon, whose base is located at about 35 m depth, shows a reduction in the value of electrical resistivity, which is between 12 and 18 Ωm, attributable to the increase in marly intercalations.

Below 35-38 m of depth, there is a sharp decrease in resistivity values, between 2 and 6 Ωm, which can be attributed to a lithological variation, where pelites (marls and clayey marls) are prevalent, such as also found in coring.
Regarding the evaluation of the state of fracture and of karst forms that may affect subsoil sectors, it must be considered that the increase in the state of fracture and karst have the effect of increasing the porosity of the rock mass. This condition determines, from the electrical point of view, a sudden reduction in the resistivity values, as the conduction of the electric current is made easier by the interstitial water, even more so if it is high in salt content, being sea water. This condition will be particularly evident when the lithology is of higher resistivity (limestones), in which the contrast with the fractured bands and, even more, in the karst areas filled with water, is higher. In particular, the detectable cavities will be characterized by particularly low resistivity values, close to those of sea water (<0.5 Ωm). In this perspective, therefore, the lateral variations of low resistivity within the electric/lithological horizons, can be interpreted as more fractured and possibly karst areas.
In the attached models, some areas with lower resistivity are observed within the limestone horizons, which can therefore be interpreted as more fractured. One of them coincides with the escarpment between the platform and the underlying bottom, from 10 m up to the progressive 150 m where the limestone mass is probably more disarticulated due to the morphological condition. Other areas where the resistivity decreases are between the progressive 260 m and 450 m, in which the rock mass is presumably affected by fracture due to tectonic causes. There are no localized sectors with resistivity lower than 0.5 Ωm, so there is no indication of detectable cavities.
For the purpose of further evaluations on the geometric distribution of the values of the real electrical resistivity of the sector investigated with the longitudinal ERT (TR01, TR02 and TR03 (See Fig 9:)), the data of the three survey lines have been merged into a volume (3D) included between the bottom of the sea where the electrode lines fall to a depth of about 60 m from the seabed. The geoelectric data thus placed in space have been subject to 3D inversion through the use of the Res3DInv64 software. The inversion parameters have remained the same as those used in the 2D inversion (L1 norm robust and 0.19 Ωm for sea water resistivity).
As seen also in 2D models, and presumably for the same reasons, an artifact near the coast is produced in the calculation. This is characterized by an area, between progressive 450 and 500 m, with an abrupt lateral passage between a low-resistive and a high-resistive side by side, with unrealistic values and distribution not consistent with the local lithostratigraphic context. In the remaining parts of the model the result obtained is similar to that seen in the 2D lines. The values of the electrical resistivity are presented by volumes in transparency, with perspective views (from the East and South); in vertical slices (clip-planes), one of which is aligned with the pipeline, one located 5.0 m towards the NE and the other 5.0 m towards the SW. Finally, in order to have a perception of the variation of the resistivity values within the homogeneous lithological/electrical horizons, clip plane of a structural plane was used, with geometry similar to that of the outcropping Formation (DIP/DIPDIR - 04°/144°), at various depths. (See Fig 10:)

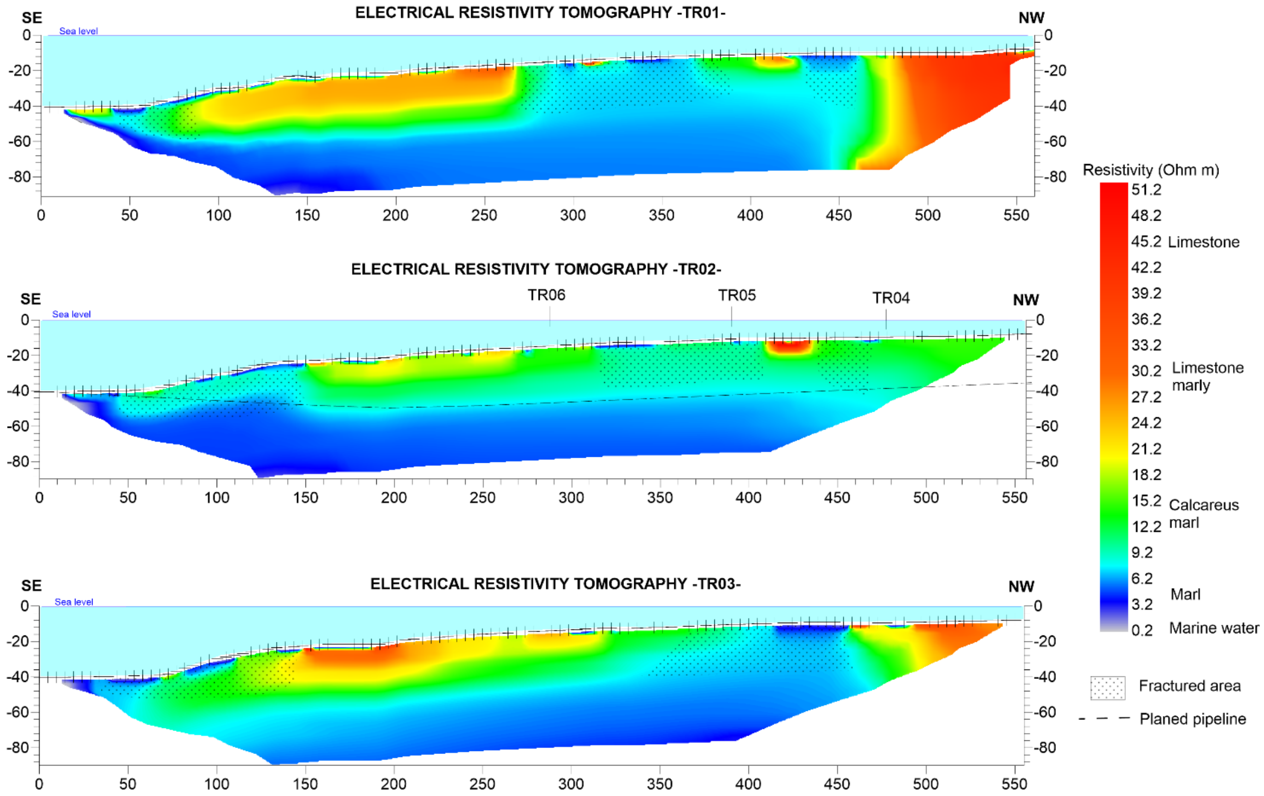

Fig 9: Electrical resistivity tomography – TR01-TR02-TR03

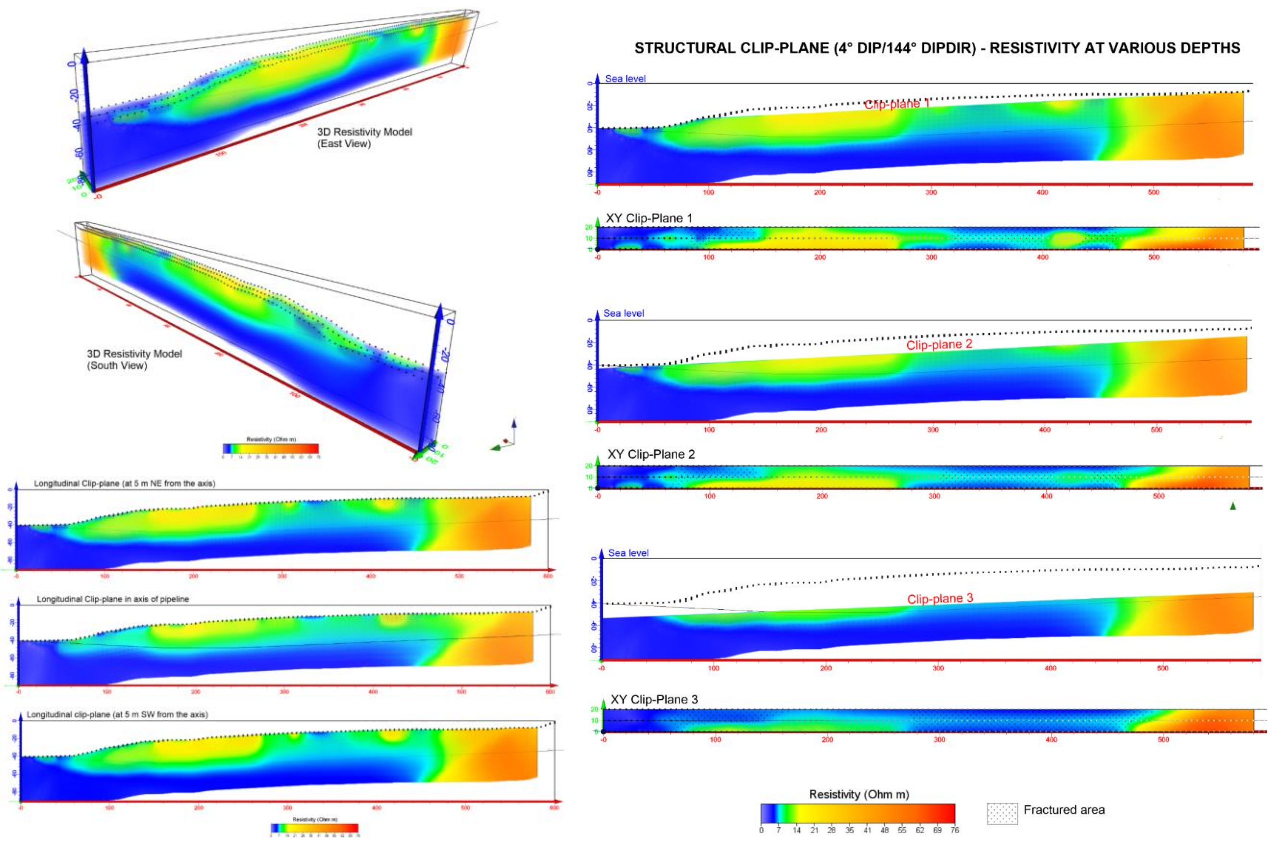

Fig 10: 3D Resistivity model and structural clip-plane (4°DIP/144° DIPDIR) – Resistivity at various depths

The three geoelectric prospections transversal to the direction of the pipeline axis (TR04, TR05 and TR06 (See Fig 11:)), cover the entire area of the submerged morphological platform and the valley present in the north side. The models, always elaborated with the same boundary conditions used for the longitudinal models, show a distribution of the resistivity values similar to those already described, therefore consistent with a sub-horizontal monoclinal structure of the lithologies. An electrically relatively higher resistive first horizon (>10 Ωm) is always observed, laterally affected by slightly more conductive/fractured bands.
Two particularly low-resistive cores are present in the initial part of the TR04 and TR05 models, with resistivity values lower than 1.0 Ωm, attributable to highly fractured and karst areas. As also observed in the longitudinal models, in depth (25-27 m in the platform area) there is a marked decrease in the resistivity values, correlated with the increase in the frequency of the marly intercalations.

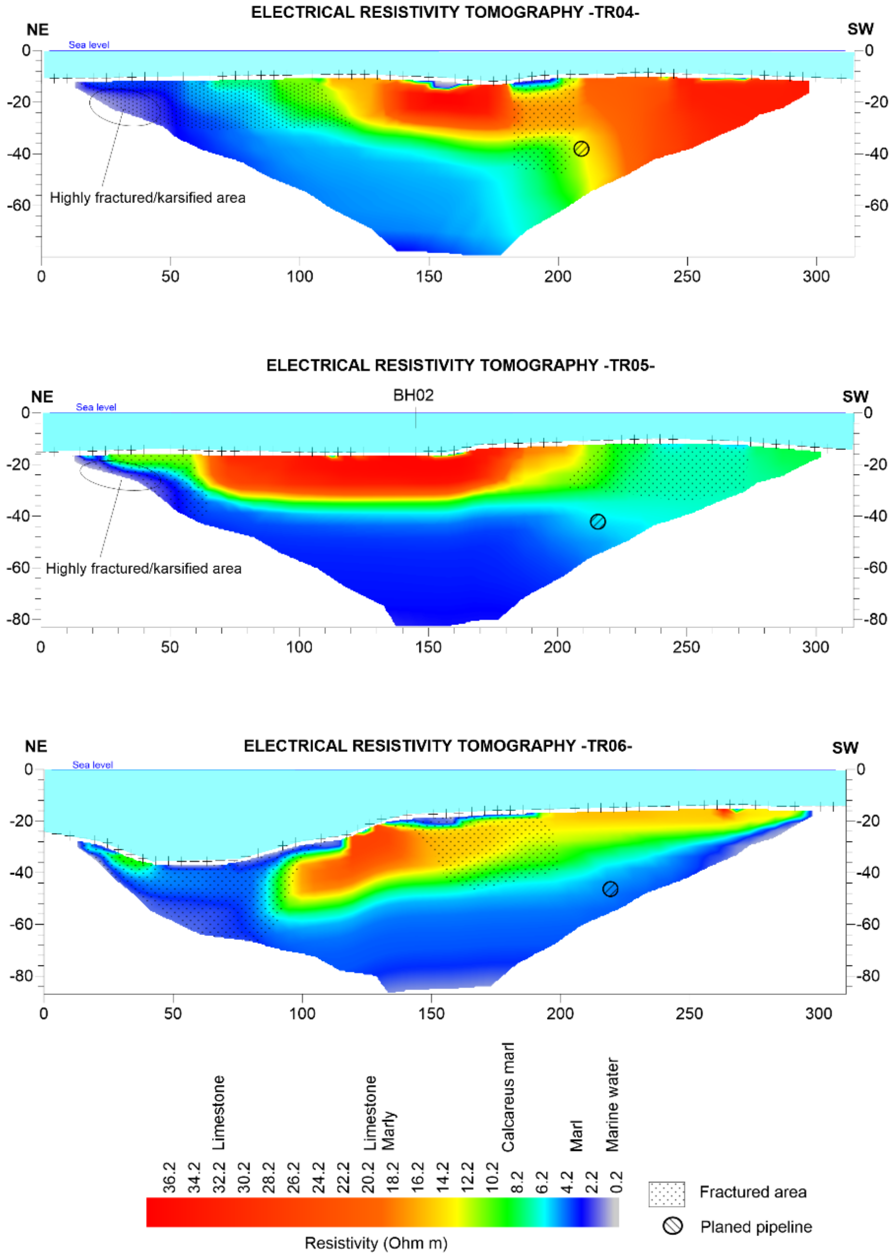

Fig 11:Electrical resistivity tomography – TR04-TR05-TR06

CONCLUSIONS

Geophysical surveys through geoelectric resistivity method (ERT) have been carried out in the nearshore area of the Delimara Peninsula, where a microtunnel is planned to be realized for the offshore approach of the 22” (Melita Transgas Pipeline).
The measurements were carried out in extreme conditions, from a technical point of view: the presence of significant water depths, with high electrical conductivity, limits the resolution capability of the methods due to short circuiting in the water layer. However, these difficulties have, at least in part, been avoided thanks to adequate equipment, careful planning, and attention to details (precise positioning on the seabed and measurement of sea water resistivity). The electrical resistivity models obtained have a good quality level (residual 7-8%) and are consistent with the lithostratigraphic context of the investigation area.
The correlation of the electrical resistivity values of the 2D and 3D models with the lithologies, as reconstructed also in the executed coring, allowed to hypothesize the geometric arrangement of the lithologies up to depths that reach 50-60 from the seabed. In the offshore area, the lithological structure is characterized by the presence of a horizon with relatively high resistivity, attributable to the predominantly calcareous and marly limestone lithologies (Upper Globigerina Limestone Member), with a thickness varying between about 22 and 30 m, in which a gradual decrease is observed of the resistivity values in its lower portion, attributable to the presence of more frequent pelitic intercalations (marly). Even deeper, resistivity values are observed to decrease further, a condition attributable to a lithological change (marls and clayey marls - Middle Globigerina Limestone Member).
For the identification of the fractured and karst areas in the rock mass, it was considered that they led to an increase in porosity, and that in the presence of sea water there was a reduction in the electrical resistivity values. This condition is extreme in the presence of cavities filled with sea water, in which calculated resistivity values lower than 0.5 Ωm are to be expected. These values are not found in the resistivity models, except for two small nuclei present in the ERT TR04 and TR05, in their initial portions, attributable to areas of strong fracture and karst.

REFERENCES

Pedley, H.M., The Oligo-Miocene sediment of the Maltese Islands, Unpublished PhD thesis, University of Hull.

Micallef et al., The submerged paleolandscape of the Maltese Island: Morphology, evolution and relation to Quaternary environmental change, Marine Geology (2012), http://dx.doi.org/10.1016/j.margeo.2012.10.017.

Dahlin T., Bjelm L. and Svensson C. 1999. Use of electrical imaging in the site investigations for a railway tunnel through the Hallandsås Horst, Sweden. Quarterly Journal of Engineering Geology and Hydrogeology 32, 163–173

Dahlin, T., & Loke, M. H. (2018). Underwater ERT surveying in water with resistivity layering with example of application to site investigation for a rock tunnel in central Stockholm. Near Surface Geophysics, 16(3), 230-237.

Loke M.H. 2020. Tutorial: 2D and 3D electrical imaging surveys (www.geotomosoft.com). Revision date 17 Agust 2020.

Loke M.H. and Lane J.W. 2004. Inversion of data from electrical resistivity imaging surveys in water-covered areas. Exploration Geophysics 35(4), 266–271.

Simyrdanis K., Papadopoulos N., Kim J.-H., Tsourlos P. and Moffat I. 2015a. Archaeological investigations in the shallow seawater environment with electrical resistivity tomography. Near Surface Geophysics 13(6), 601–611.