MARINE GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS IN SUPPORT TO THE CONSTRUCTION OF NEW HARBOUR INFRASTRUCTURES: THE TRIESTE MARINE TERMINAL EXTENSION

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Introduction. A combination of geographic and historical factors has made the Trieste harbour one the most important commercial terminal in the Mediterranean sea. Thanks to the deep natural draft (about 18 m) modern high capacity vessels can moor to the piers so this area is subject to a modernization project to improve commercial traffic capability. In this expansion plan, the container Trieste Marine Terminal (TMT) - Molo VII, is interested by a extension of about 200 m. The actual terminal were built upon equal-spaced pillars founded in the bedrock. To more effectively support this project new bathymetry, geological/geotechnical and geophysical data were collected.

Geological setting. The Gulf of Trieste, the northernmost sector of the Adriatic Sea, is part of the Adriatic Apulian foreland. It is composed of the Mesozoic Adriatic Carbonate Platform (Vlahović *et al.*, 2005), Paleocene-Eocene carbonates and Eocene Flysch (Onofri, 1982), a turbiditic sequence composed by an alternation of sandstones, siltstones and marlstones. From a structural point of view, two main patterns interest the Trieste Karst area: the Karst Thrust, developed in Dinaric direction (NW-SE), which forces limestones to overlie the Flysch of Trieste, and some minor thrusts in the turbidites. The Gulf of Trieste was extensively recently explored by several offshore seismic lines (Busetti *et al.*, 2010, 2012) that allow to obtain new information to refine previous geological/structural model (Cavallin *et al.*, 1978; Carulli *et al.*, 1980; Carobene *et al.*, 1981).

The Trieste Marine Terminal (TMT) is located in the southern part of the Trieste harbour. Several seismic acquisition were carried in this area. In the 1950s, a single channel reflection seismic (Mosetti and Morelli, 1968) provided information about the Quaternary sediments covering a drainage pattern superimposed on the Eocene Flysch that during the Messinian were emerged favouring the fluvial erosion (Fantoni *et al.*, 2002). This was the first marine geophysical experiment in Italy followed by two refraction profiles (Finetti, 1965, 1967) and, recently, by some single channel reflection seismic campaigns acquired for geotechnical and environmental studies (unpublished data).

In the studied area the bedrock is represented by the Flysch formation covered by Plio-quaternary sediments (Brambati and Catani, 1988; Masoli and Zucchi, 1968). The bedrock is characterized by an alternation of layer of different geomechanical behaviour and by the presence of a weathered zone. The sedimentary sequence covering the Flysch is characterized by an alternation of levels of silt/sandy clay (greenish gray) with fragments of shells and layers of sand fine to medium, and trace of gravel. Silt/sandy clay are saturated with a very soft consistency and sand has a very loose apparent density.

Field investigations. The study area is located on the front of the TMT (about 200,000 m^2) with an average water depth of 20 m (Fig. 1). The marine bathymetric and geophysical survey was carried out in the Autumn 2014 by the OGS boat "Anthea" equipped for shallow water offshore survey. Underwater refraction seismic requires also the onshore access to the pier to record the hydrophone array data. Data were collected in two phases because of the presence of strong Bora wind that inhibits any offshore activities. In the first part were collected bathymetric, side-scan-sonar, magnetometer and sub bottom profile data, in the second the refraction data.

As the front of the TMT is characterized by an intensive maritime traffic, the acquisition phase required a strong coordination with the local maritime authority and the several operators involved in the different harbour activities (berthing/unberthing, loading/unloading , etc.)

Navigation and tidal stage. Navigation data for water-based survey were collected with a Trimble DGPS DSM232 in WGS84 and were passed to the different acquisition tools and the navigational software at a rate of 1 Hz. PDS2000 software with coast line and infrastructure perimeters was used to display the course of the boat and allow real-time navigation along the theoretical predetermined lines.

Tidal stage for data elevation correction were obtained from Trieste Station, belonging to the National Tidegauge Network of "Istituto Superiore per la Protezione e la Ricerca Ambientale – Ispra". The station is located in Trieste's seaport, near the "Lega Navale" wharf. The tidegauge station is equipped with altimetric datum. Each datum is referred to the average sea level, measured in Genoa using the ancient Thompson tidegauge. The datums are metallic check tags, used to determinate the altimetric level by means of high precision leveling, following the guidelines fixed by IGM (Italian Military Geographic Institute). From 07/10/2009 the "hydrometric level" is measured with a new high precision radar sensor SIAP+MICROS TLR.

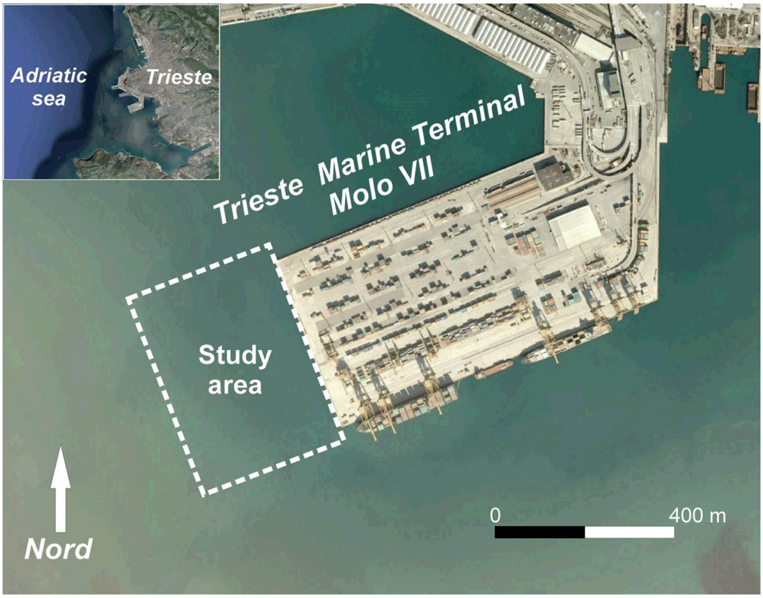

Fig. 1 – Position map.

The data, downloaded from ISPRA web site www.mareografico.it, have been imported in the acquisition software PDS2000, to obtain a full interpolated tidal curve.

Bathymetry. Multibeam echo sounders (MBES) emit sound waves in the shape of a fan from directly beneath a ship's hull. These systems measure and record the time it takes for the acoustic signal to travel from the transmitter (transducer) to the seafloor (or object) and back to the receiver; by the analysis in term of amplitude and phase of the received signal, with beam forming techniques, it is possible to detect the incidence angle and the distance. In this way, MBES produce a "swath" of soundings (i.e., depths) for broad coverage of a survey area. The coverage area on the seafloor depends on the depth of the water, typically three to five times the water depth. MBES is an useful tool to acquire water depth information, to determine least water depths over critical items such as wrecks, obstructions, and dangers to navigation and to detect objects in general.

The morpho-bathymetric survey was carried out with multibeam echosounder, Teledyne-Reson Seabat 7125. This dual frequencies (200 and 400 kHz) instrument utilizes 512 equidistant beams with a maximum ping rate of 50 pulse per second. To correct the raw data, the system has to know precisely, for each pulse, the vessel attitude in terms of pitch, roll, heave, yaw; this is the task of the Motion reference unit model MAHRS, produced by TSS-TELEDYNE. The roll value is also used to steer the acoustic pulse so to insonify always the nadir area of the seafloor. Data acquisition was performed at a velocity of 4 knots along parallel lines allow to obtain an overlap of 20%. As the acoustic pulse can be oriented, we obtained images not only the seabed but also the pillars supporting the wharf. Time to depth conversion was made by real time data from Sound Velocity Probe, Reson SVP71, and sound velocity profiles using the YSI CastAway CTD.

Side scan sonar and magnetometric survey. The Side Scan Sonar (SSS) is a technique based on the emissions conical or fan-shaped pulses down toward the seafloor across a wide angle perpendicular to the path of the sensor through the water. SSS produces images of the sea floor similar to a large-scale aerial photographs useful to detect seafloor installations (i.e., cables, pipelines, etc.), shipwreck and other obstructions that may be hazardous for navigation. Depending on the different acoustic response it is possible to obtain also indirect information about the nature of the sediment (sand, mud or their mixtures) or the presence of outcropping bedrock, metal bodies, etc.

We utilized the EdgeTech DF-1000 / DCI Digital Side Scan Sonar Sistem (100 and 500 kHz) controlled by CODA DA-50 (Coda Technologies). Data were acquired with the tow fish at the depth of 4 m with a cruise velocity of 4 knots. The investigation involved the generation of six sonograms NW-SE oriented (i.e, parallel to the TMT front) with a length of 500 m and a lateral range of 75 m. The tie line interval was about 50 m that permits a full coverage with overlapping of the study area.

The acquired data were processed through Coda Octopus Geokit Mosaics software and graphically represented in a mosaic in order to locate objects on the sea floor and to define the morphological and sedimentological characteristics of the seabed that confim/complete the information coming from the bathymetric multibeam survey.

In addition to SSS data acquisition, a magnetometer survey has been carried out to obtain a magnetic map in front of TMT. The survey was conducted from "Anthea" boat with NW-SE tie lines spaced 25 m interval. Magnetic data were acquired using a Marine Magnetics SeaSpy magnetometer towed at a distance of 20 m behind the boat. The sensor elevation was recorded with each magnetic measurement to allow for later correction of the water-depth related changes in magnetic intensity. The magnetometer was cycled at 4 Hz providing about one sample per metre.

The magnetometer survey was preparatory to an UXO (Unexploded Ordinance) survey performed by certified personnel.

Sub bottom profile. A dense grid of sub-bottom-profile (SBP) data was recorded to identify recent sediments up to the top of rock basement (Eocene Flysch). A total of about 11 km distributed along 30 lines (11 NW-SE direction and 19 NE-SW direction) was acquired by a Sub Bottom Profiler Edgetech SB-216S (tow fish) and Edgetech 3200-XS topside (control/acquisition unit) with a cruise velocity of 3.5 knots. After several tests we acquire data with the following parameters: up-sweep 2-10 kHz, 20 ms length with a source rate of 2Hz, tow fish depth 1.5 m. SBP data penetration allows to obtain information of sediments/Flysch interface which in the studied area ranges from 30 to 50 m below the sea level.

The two-way-time data were converted in depth below sea level using the velocity of 1530 m/s for the water column and 1610 m/s as an average for the sediments from sea-bottom to the Flysch top. This velocity was obtained by underwater refraction (see next paragraph) and by a check-shot measurement performed in a drilled hole. The SBP lines were analyzed more than once to avoid misinterpretation of multiple events and to test the repeatability of the interpretation. The sediments/bedrock interface were detected and correlated with to the borehole data and to tie-line crossings in correspondence of the line intersections.

In the SW sector, where the bedrock is deeper, we compared SBP data with single channel reflection data acquired with boomer source in a previous unpublished study.

Underwater seismic refraction. From a geotechnical perspective a more important problem is that it is very difficult to determine engineering properties from reflection records. Refraction seismic survey are routinely acquired on land for geotechnical purposes. S-wave data are preferred because are strictly connected with geotechnical parameters but the generation of shear wave at the sea bottom is not a trivial issue. To obtain information about the bedrock nature and alteration, an underwater P-wave seismic refraction was planned.

Seismic survey has been carried out along seven profiles with hydrophone cables deployed on the sea-bottom. Acquisition geometry (i.e., trace interval and maximum offset) was defined after a feasibility study to estimate the minimum offset to detect refraction coming from the bedrock. This preliminary analysis was performed by the use of synthetic seismic data computed with different simplified velocity models.

Two 24 channels hydrophone cables, 5 m interval, and a mud gun (Bolt DHS 5500, 7.6280 in^3) with a pressure of 70 bar were used. Hydrophone cables was deployed by the boat starting from the TMT head along the planned lines. Five to eleven shot points was performed for each line lowering mud gun to the sea bottom. A precise time-break identification was obtained by

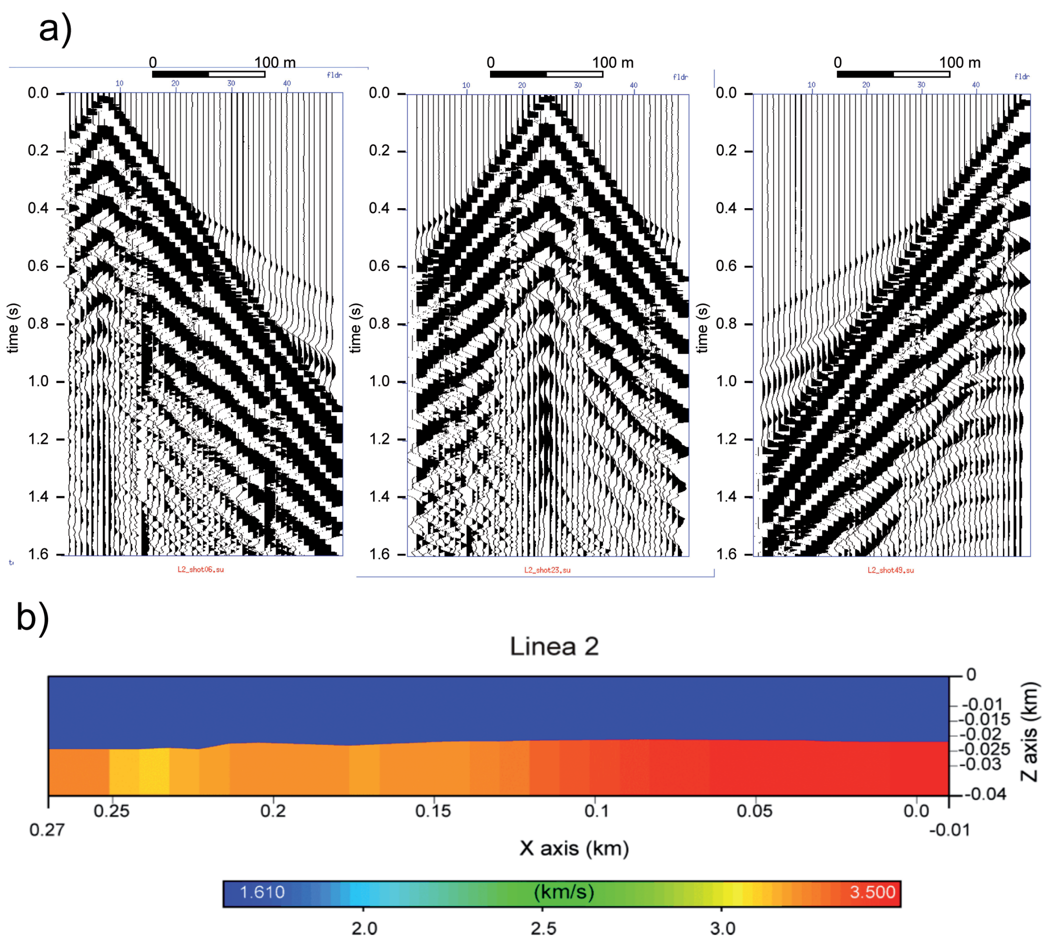

Fig. 2 – Underwater refraction seismic data: a) three common-shot-gathers recorded along the line 2 (perpendicular to the TMT front) and b) P wave velocity model obtained by the first arrivals tomographic inversion (line 2).

the near-field hydrophone. These data were transmitted by a radio-link (RTS-100) to a dedicated onshore seismograph. We used three Seismic Source Daq Link III seismographs (two for the 48 hydrophones, the third one to record the near-field signature and GPS PPS signal) with 0.125 ms sampling rate and 5 s data length.

Underwater seismic refraction data have a good signal to noise ratio and the first arrivals are clearly detectable also a larger offsets (Fig. 2a). Travel time tomography was applied to each seismic line to obtain the corresponding 2D depth velocity section and to estimate the depth of the sediment/Flysch interface. We invert the first arrivals picked in each seismic line. First, we separated two different arrivals in the picked travel times for each common shot gather: the direct arrivals and the refracted arrivals from an horizon below the sea bottom, interpreted as the top of Flysch. For this purpose, we applied a procedure which automatically identifies the knee point (crossover distance) separating the two different arrivals. Then, we inverted the refracted arrivals by using an inversion approach based on minimum dispersion of the refracted points (Carrion *et al.*, 1993): depth and geometry of the refracted horizon are defined by an iterative procedure which minimized the difference between the refracted points and the estimated surface. The same procedure reconstructed also the lateral velocity gradient of the layer below the refracted interface. In the inversion we constrained the sediment velocity (1610 m/s) associated to the first layer below sea bottom.

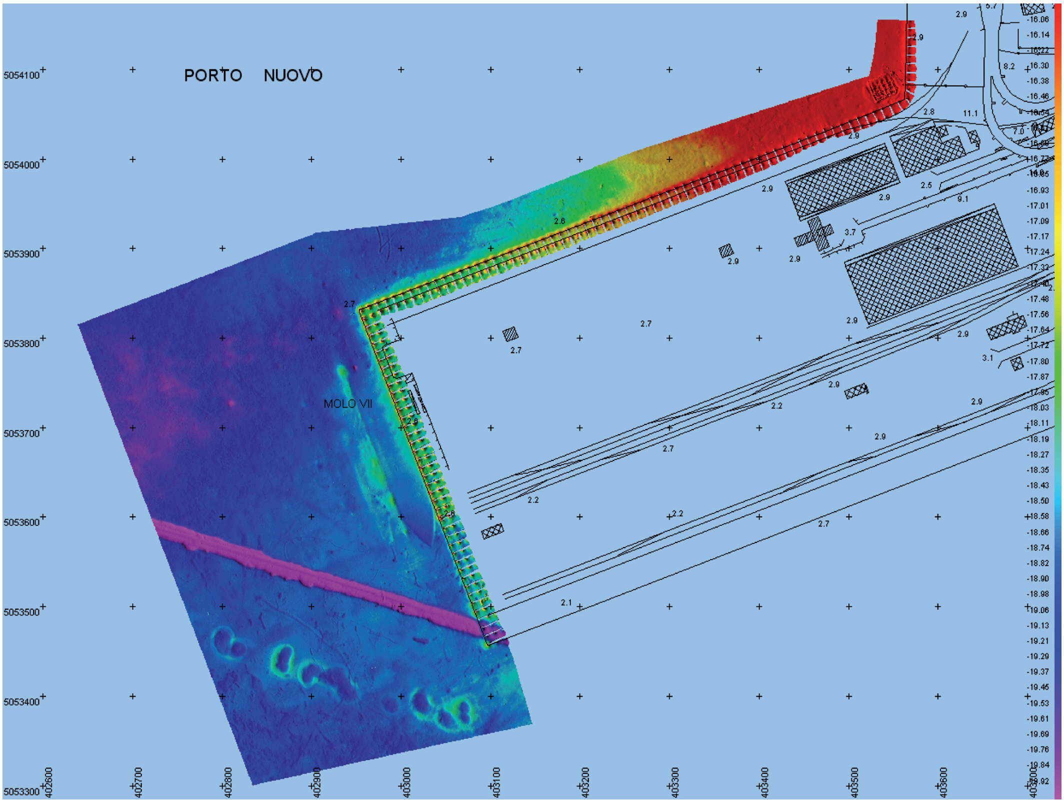

Fig. 3 – Bathymetric map.

We applied the staggered grid method (Vesnaver and Böhm, 2000) for all lines, using a base regular grid with low lateral resolution (28 m) obtaining a final high lateral resolution grid (7 m).

As inversion algorithm we used the SIRT method (Simultaneous Iterative Reconstruction Technique) and the minimum time approach for the ray tracing (Böhm *et al.*, 1999). We estimated the reliability of inversion by computing the time residuals (difference between picked and computed travel times); we obtained 1.4 ms rms residual (equivalent to 2.6 % on picked travel times). An example of 2D velocity model is shown in Fig. 2b.

Geological/geotechnical borehole data. In addition to geophysical acquisition, a geological-geotechnical survey and geotechnical laboratory analyses were carried out in order to define the geolithologic, lithostratigraphic and geotechnical features of the area. In particular, eleven sea drillings reaching the first metres of the Flysch bedrock were performed. Of these, four were carried out onshore along the edge of the pier by positioning the drilling rig at the TMT head. The other seven were performed offshore with a barge. In addition to geolithologic and lithostratigraphic identification and classification, various tests were performed on core samples with the use of a pocket penetrometer and pocket vane in order to identify the Uniaxial Compressive Strength (UCS) and Undrained Shear Strength (Su) values and assess the cohesive soils. During the drilling, seventeen undisturbed samples were also extracted, with a Shelby-type tube sampler, along with twelve semi-disturbed samples, which subsequently underwent geotechnical laboratory analyses, as well as twenty Standard Penetration Tests (SPT). The SPT data revealed values between 1 and 32, with rejection on the lithological contact with the Flysch. From the SPT data, Phi values for sandy lithologies were assessed with various methods and revealed an average range of 20°-30° for levels which were less dense, and 30°- 40° for the remaining. Regarding the finer silt-clay materials, a consistency ranging from soft to plastic was detected.

The Flysch was also classified by the Rock-Quality Designation (RQD) index and, where possible, data regarding sedimentation, fracturing and Joint Roughness Coefficient (JRC) was also collected. The RQD index data revealed that the first metres of Flysch bedrock are characterised by poor quality, which generally moves towards average and, at times, fair quality as further depths are reached.

Based on the assessments carried out, a lithostratigraphic model of the area was defined, and several geological sections were drawn. Specifically, the geolithological features are as follows: 1) from 0.0 to -15.80 / -28.80 m below seafloor (mbsf): silt-clay-sand complex; 2) from -15.80 / -28.80 to -18.80 / -32.00 mbsf: altered marlstone-sandstone Flysch; 3) from -18.80 / -32.00 mbsf: unaltered sandstone-marlstone Flysch.

Geotechnical laboratory tests were performed on the undisturbed and semi-disturbed samples extracted during the drilling, which allowed for the identification of the principal geotechnical parameters. Lastly, regarding the silt-clay-sand complex overlying the Flysch bedrock, the susceptibility to liquefaction based on grain size was assessed (Sherif and Ishibashi, 1978). The results showed that for four samples there is a possibility of liquefaction. Additional tests were performed based on the Liquid Limit (LL) and Plasticity Index (PI) (Seed *et al.*, 2003), which revealed the potential risk of liquefaction of some samples.

Results and conclusions. The results of the bathymetry survey are shown in a colour-shaded map in Fig. 3. Seaward of the TMT front, the bathymetry shows a smooth, gently sloping to SW with a water depth ranging from about 18 m to 21 m. Some interesting features can observed on MBES data as well as on SSS data: a ship footprint located along the pier and an abandoned pipeline channel with NW-SE direction.

SBP data in conjunction with borehole data allow to obtain the depth and the morphology of the top of the bedrock. The assessment of geotechnical conditions was performed mainly on the base of the borehole data and by underwater refraction data.

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