

GEOSTRUCTURAL AND GEOPHYSICAL SURVEYS FOR THE STABILITY ANALYSIS ALONG A ROCK SLOPE IN THE CULTURAL HERITAGE SITE OF ISPICA (SOUTH-EASTERN SICILY)

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Introduction. The aim of this study is to evaluate the degree of fracturing and the stability conditions of the calcareous rock cliff on which the cultural heritage site of Ispica lies. Ispica is a 16.000 inhabitants village belonging to the Ragusa district. It is located in the southeastern coastline of Sicily, where tectonics affects the geology and morphology, as well as the seismicity. Indeed, from a geological point of view, the studied sector is a calcareous horst, with direction NE-SW, bordered by the Gela-Catania foredeep to the west and to the Malta Escarpment to the east (Fig. 1a).

The main structural element is represented by a NE-SW fault system, known as Pozzallo-Ispica-Rosolini system (Ghisetti and Vezzani, 1980; Lentini *et al.*, 1987; Grasso *et al.*, 2000). In the study area, this system is named "Ispica fault system" and shows strike slip motion. Faults are sub-vertical, with maximum throws of 80-100 m. This system mainly adjoins the marls and calcarenites of the Ragusa Formation (lower Miocene) to the west with the blue clays of the Tellaro Formation (middle Miocene) to the east (Grasso *et al.*, 1992).

The seismic activity related to this faults is historically known, with the 1727 and 1903 earthquakes ($M > 5$) (Azzaro and Barbano, 2000). Moreover, on 11 January 1693, Ispica village was destroyed by a $M \leq 7.4$ earthquake (Table 1), which is the strongest shaking ever occurred in the area.

Table 1 - historical earthquakes at Ispica village (<http://emidius.mi.ingv.it/DBMI04/>).

Number of events: 12					
Effects	Earthquakes				
Is	Year Mo Da Hr	Epicentral area	Np	Ix	Mw
10	1693 01 11 13 30	Eastern Sicily	181	11	7.41
3-4	1727 01 07	Noto	14	7-8	5.37
7-8	1818 03 01 02 45	Iblean Mountains	24	7-8	5.63
5-6	1848 01 11	Augusta	33	8-9	5.48
5-6	1903 02 10 08 04	Noto	10	6	4.83
2	1905 09 08 01 43	Calabria	827	10-11	7.06
NF	1908 12 10 06 20	Novara di Sicilia	64	7	5.00
6	1949 10 08 03 08	Noto	32	7	5.18
3	1959 12 23 09 29	Catania Plain	108	6-7	5.23
2-3	1978 04 15 23 33	Gulf of Patti	332	8	6.06
5-6	1980 01 23 21	Modica	122	5-6	4.63
6	1990 12 13 00 24	South-eastern Sicily	304	7-8	5.68

The cultural heritage site comprises several worship constructions such as the Friars Minor Monastery, which had been a Franciscan Friary since 1515 A.D. and now is the headquarter of Friars Minor. The cloister is one of the oldest constructions of the village, so an important tourist attraction.

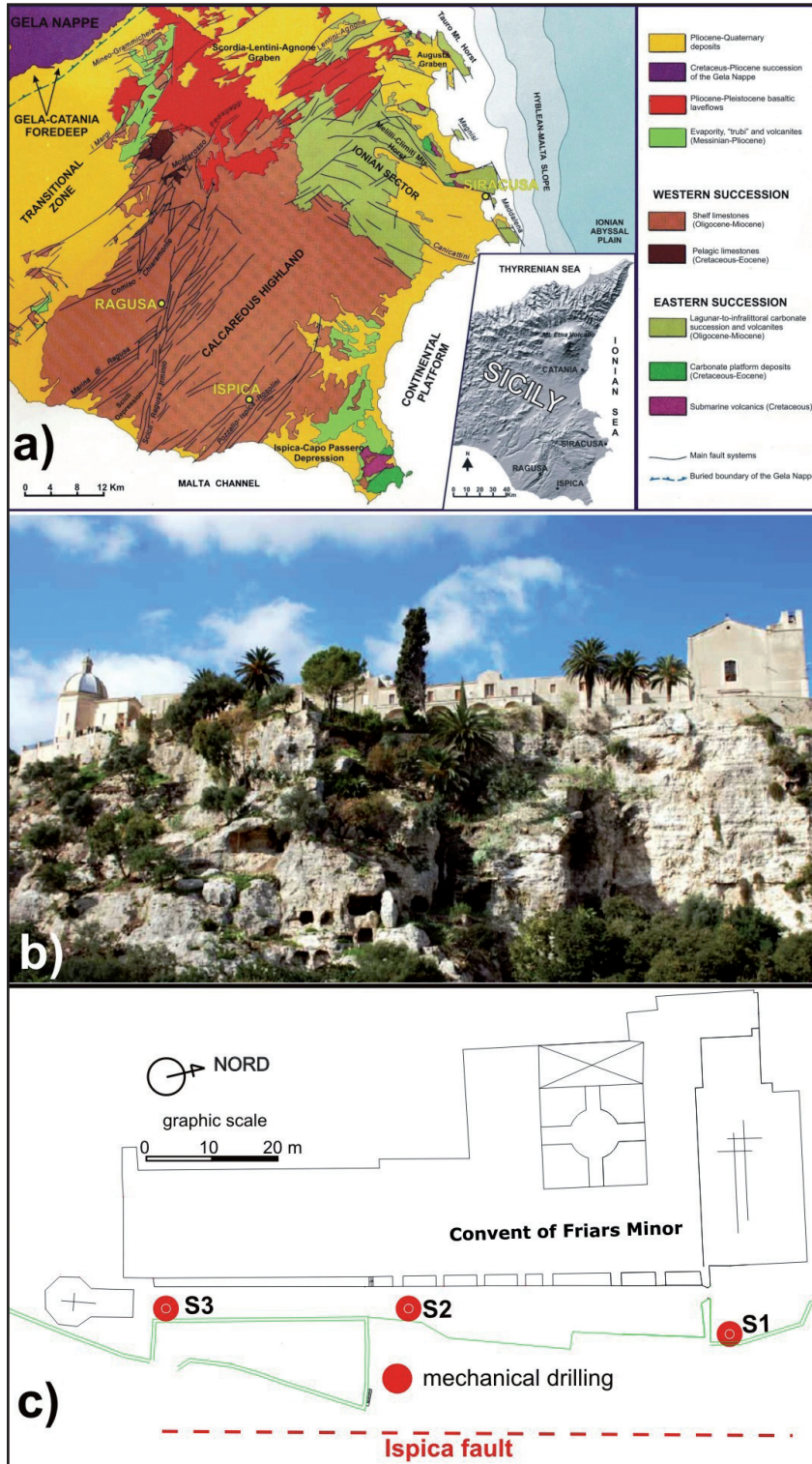


Fig. 1 – a) Geological map of south-eastern Sicily (Lentini *et al.*, 1987); b) convent of Friars Minor photo; c) map of the mechanical drilling location.

This site stands on the top of a 35 m high calcareous cliff (Fig. 1b), located in the eastern sector of Ispica village, showing instability conditions since the presence of deep fracturing and karst, as well as of several blocks about to fail. For the reconstruction of the stratigraphic succession, 3 geognostic mechanical drillings were performed in front of the monastery (Fig. 1c).

The resulting stratigraphy is represented by a succession of calcarenites with different degree of fracturing; particularly, under a thin talus level, 5 meters of intensely fractured calcarenites are present; between 5 and 20 m b.g.l. the succession shows a lower degree of fracturing; from 20 to 30 m b.g.l. intensely fractured calcarenites were drilled.

Deep fracturing, especially close to important tectonic structures, is one of the main causes of slope instability (Barbano *et al.*, 2014; Pappalardo, 2014). Furthermore, the high seismic activity of the study area (category II according to the Italian Ordinance OPCM 3274) may be regarded as one of the potential triggers for rockfalls.

A geophysical survey has been performed to obtain information on the degree of fracturing of the deep rock mass and to estimate the resonance frequency of the site.

Geostructural surveys, kinematic and stability analysis allowed us to better understand the main instability features, as well as to evaluate the safety factors for the most unstable blocks.

Methodologies. The study of the environmental microtremors (noise), through passive seismic recordings of single-station H/V (or HVSR), is a non-invasive technique for the investigation of the underground. It allows highlighting the frequencies at which the ground motion is amplified by stratigraphic resonance. The spectral ratios of the vertical and horizontal components of the ground motion, recorded at each measurement station, are taken into account by this technique (Nogoshi and Igarashi, 1970; Nakamura 1989). The amplitude ratio associated with the resonance frequencies of the site is an indicator of the “minimum” amplification expected at the site in case of earthquake.

In a simple two-layer system, characterized by two different speeds (V_1 and V_2) and by two different densities (ρ_1 and ρ_2), the equation linking the resonance frequency “ f ” to the thickness “ H ” of the resonating layer, depends on the shear waves velocity, as shown by:

$$f = nVs/4H \quad (1)$$

where n ($= 1, 3, 5 \dots$) indicates the order of the mode of vibration (fundamental, first superior etc.), V_s and H represent the shear waves velocity and the thickness of the resonating layer respectively.

Eq. (1) allows understanding how the H/V technique can also provide information on stratigraphic characters. Indeed, starting from a noise measurement providing f , once known the V_s of the coverage, the depth of the main seismic reflectors or vice versa can be easily estimated (Ibs-von Seht and Wohlenberg, 1999); each peak in the H/V graph corresponds to a possible reflector (seismostratigraphic level) that presents an impedance contrast compared to the neighbor level; the greater the impedance contrast, the greater the amplitude of the peak would be. However, this report does not follow a linear trend.

The measurements of environmental microtremors were carried out through the use of a portable digital tromograph TROMINO (Micromed S.p.A.), equipped with three electrodynamic orthogonal sensors (velocimeters) responding in the band $0.1 \div 1024$ Hz. Seismic noise has been acquired with sampling frequency of 128 Hz, and recorded for 20 minutes at 3 measurement stations (N1-N2-N3) (Fig. 2).

These were placed close to the previous drilled boreholes (S1-S2-S3), to verify if such a survey could detect any difference in the physical-mechanical properties of the lithology (i.e. changes in the degree of fracturing), already pointed out by the stratigraphy successions (Fig. 2).

The instruments were located on the ground, with the major axis oriented toward north. Recordings were processed through the software Grilla, to evaluate the relationship between the spectral components of the ground motion.

Data were then processed by dividing the acquired traces in 20 seconds time-windows. Then, a triangular smoothing of 10% was applied, and the signal was “cleaned”, eliminating

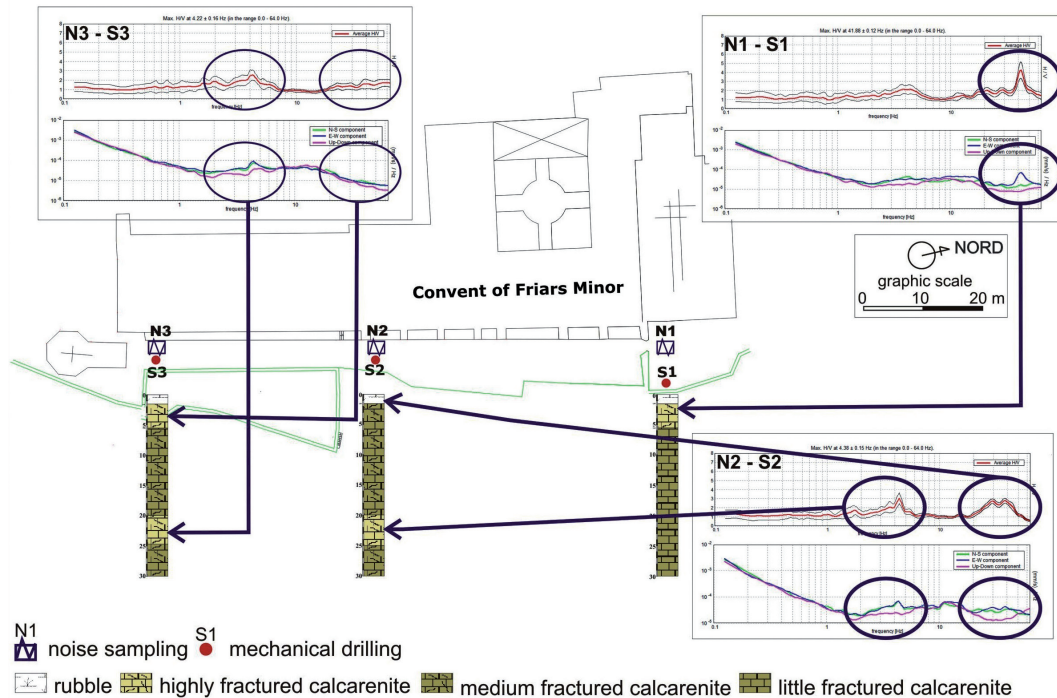


Fig. 2 – Map of the geognostic and geophysical surveys location and the relative stratigraphic sections and H/V spectral ratios.

the transients, (i.e. anthropogenic disturbances). For the analysis, only the stationary portion of the signal has been taken into account. The final functions HVSR of each measurement are represented by frequency (x-axis the 0 to 64Hz) - amplitude H/V spectral ratios (y-axis) graphs.

For each station the outcome of the statistical tests (guidelines SESAME, 2005) showed that all measurements have met the 3 criteria experiencing the reliability of the H / V curve and the goodness of implementation of the measure. For 2 of the 3 recordings also the main peaks of resonance were significant and clear for all the six criteria analyzed; only the recording N3 does not meet the first of the 6 parameters assessing the clarity of the peak.

In order to obtain stratigraphic information from the H / V spectra, which could be compared with those obtained previously by mechanical drillings, the average velocity of shear waves in the investigated sector had to be estimated. It was obtained by down-hole prospecting, performed in correspondence of the drillings. In this way, the inversion of equation 1 allowed obtaining information on the depth of the impedance contrast causing the peak observed in the spectra of our recordings.

Geostructural surveys have been performed at two measurement stations (SL-1 and SL-2) located in the SE portion of the cliff (Fig. 3), according to ISRM (2007) recommendations. Scan lines were placed at the most fractured portions of the slope and inside a karst cave. For each discontinuity dip-immersion, spacing, persistence, opening, in-filling, roughness, uniaxial compressive strength (UCS) and hydraulic conditions have been measured.

Moreover, several unstable blocks, with volumes ranging between 2 and 460 m³, have been surveyed along the southeastern portion of the slope. All the surveyed factors were used for the Bieniaski (1976) classification, to assign a quality class to the rock mass, as well as to calculate its main geomechanical parameters. Bieniaski's Rock Mass Rating (RMR) system

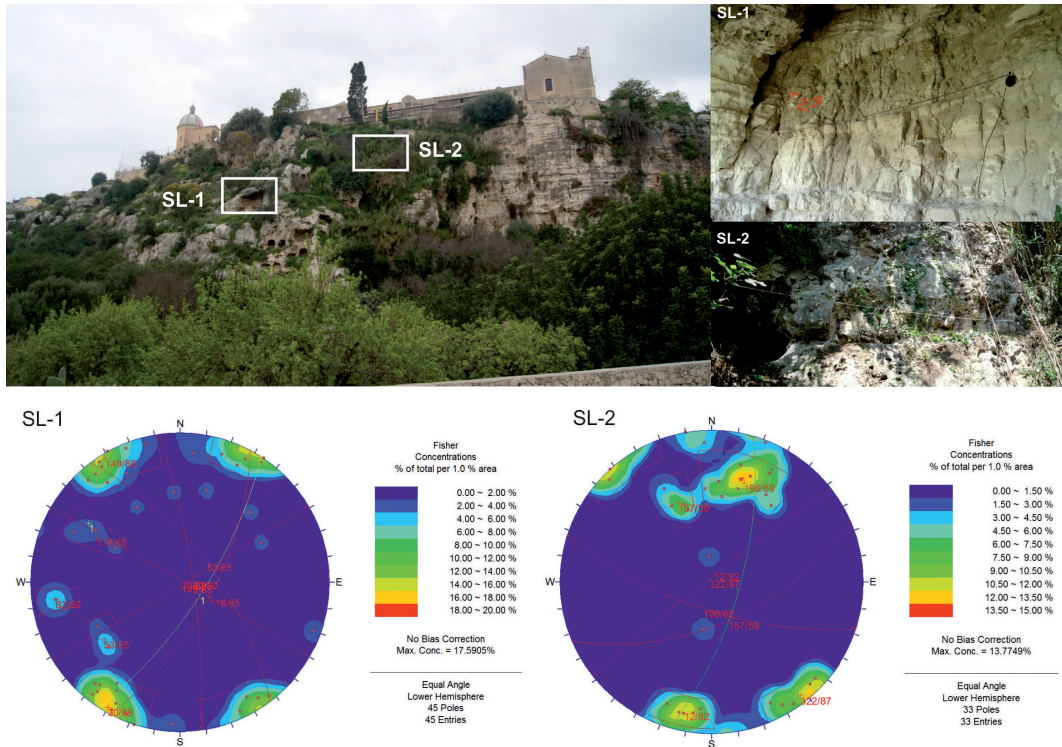


Fig. 3 – Location of geosstructural measurement stations with corresponding stereoplots showing the pole density with respect to the surveyed discontinuity sets.

(1976) is a geomechanical classification system for rock masses, which takes into account 6 parameters: Uniaxial Compressive Strength (UCS) of rock material; Rock Quality Designation (RQD); Spacing of discontinuities; Condition of discontinuities; Groundwater conditions; Orientation of discontinuities.

In particular, UCS is one of the most important parameters since it depends on physical properties of the rock (i.e. porosity, micro fracturing, texture) (Pappalardo *et al.*, 2013). Spacing of discontinuities affects the degree of fracturing, while their orientation plays a significant role in the stability analysis. Each of the six parameters is turned into a value corresponding to the characteristics of the rock. These values are derived from field surveys and laboratory tests.

The sum of the six parameters is the “RMR value”, which lies between 0 and 100 and identifies 5 classes of quality, from “very good” to “very poor”. Furthermore, on the basis of RMR, mean cohesion and internal friction angle of the rock mass can be calculated (Bieniawski, 1976) through:

$$c' = 5RMRb \tag{2}$$

$$\phi = 0.5RMRb + 5. \tag{3}$$

Stereographic projections of the discontinuity poles allowed grouping all the surveyed discontinuity into sets for the kinematic and stability analysis (Fig. 3).

Kinematic analysis, according to Hoek and Bray (1981), is a graphical procedure allowing the identification of the main failure mechanisms with respect to the geometric relationship between the discontinuity and the slope. If the discontinuity has the same orientation of the slope ($\pm 20^\circ$) but a lower inclination, planar sliding is the possible failure mechanism; if the discontinuity has the same orientation of the slope ($\pm 20^\circ$), but an opposite immersion, toppling may occur; if two discontinuities intersect, with a plunge of the intersection lower than the dip angle of the slope face, wedge sliding may be the potential failure mode.

On the basis of these stereonets, Markland Test (1979) allows identifying the unstable mechanisms, with respect to the internal friction angle of the rock mass. In fact, the graphical representation of the discontinuities (as poles or cyclographics), slope (as a cyclographic) and friction angle (as a circle) leads to the delineation of “critical areas” in the stereogram. Each discontinuity, whose pole falls inside of these areas, is to be considered unstable.

Safety factors have been calculated, for the main unstable mechanism, by the limit equilibrium analysis, where the full shear strength is assumed to be mobilized simultaneously (Hoek *et al.*, 1973):

$$FS = \frac{3}{\gamma H} (c_A X + c_B X) + \left(A - \frac{\gamma_w}{2\gamma} X \right) = \tan \varphi_A + \left(B - Y \frac{\gamma_w}{2\gamma} \right) = \tan \varphi_B \quad (4)$$

where C_A and C_B are the cohesive strengths of planes A and B along the base of the rock wedge; φ_A and φ_B are the internal friction angles of planes A and B along the base of the rock wedge; γ is the unit weight of the rock mass; γ_w is the unit weight of water; H is the total height of the rock wedge; X, Y, A and B are dimensionless factors depending upon the geometry of the rock wedge and the slope.

Results. The spectrum of the noise recording N1, located in the northern sector of the cultural site, shows a clear peak at a high frequency (41.88 Hz) with an amplitude of the H/V spectral ratio greater than 4. On the contrary, the spectra of the recordings N2 and N3, respectively located in the central and southern portions of the site, show two peaks at different frequencies. The first has an amplitude of the H/V ratio of about 3, at frequencies between 4 and 4.5 Hz; the other has an amplitude ranging between 2 and 3 at frequencies around 40 Hz.

The comparison of the results obtained from noise measurements and the stratigraphic succession (Fig. 2) indicates the presence of one peak in the N1 spectrum, corresponding to transition between low fractured calcarenites and medium fractured calcarenites. On the other hand, spectra N2 and N3 show a low frequency peak (4 Hz) corresponding to the transition between intensely fractured and low fractured calcarenites (Fig. 2). These results are comparable with the stratigraphic succession reconstructed through mechanical drilling S1-S2-S3 (Imposa *et al.*, 2010, 2014).

Thus, it can be stated that noise survey, followed by H/V analysis can give information on the stratigraphy (Amorosi *et al.*, 2008), since it allows detecting the depth of impedance contrast related to lithological transitions, if the shear wave velocity is known.

Results of geostructural analysis allowed identifying 5 main discontinuity sets at SL-1 and 4 systems at SL-2. These showed a close spacing, modest aperture and slight roughness. Sometimes discontinuities are filled with soft material. Geomechanical classification, according to Bieniawski (1976), allowed the estimation of the RMR index, which classifies the rock mass as “Fair Rock” (III class). Calculated values of cohesion and internal friction angle range between 200 and 300 kPa and 25° to 35° respectively.

Kinematic analysis and Markland Test (1979) showed that planar sliding, wedge sliding and toppling are to be considered potential failure mechanisms. In particular planar sliding are mainly possible at SL-1, at those discontinuities with direction matching to the slope. The main unstable mechanism, at both stations, is the wedge sliding, occurring along two intersecting discontinuities, with a plunge of the intersection lower than the dip angle of the slope face.

Calculated safety factors (FS) for the main failure mechanism (wedge sliding) are lower than 1, both in static and pseudostatic conditions, highlighting the high instability of the slope. It has to be noted that the pseudostatic conditions are the most reliable in this case, since the high seismic activity of the study area.

Conclusions. This study aims to evaluate the degree of fracturing, as well as the stability of a rock cliff in an area with a high seismic activity. The Convent of Friars Minor, considered among the cultural heritage sites of Ispica Village, stands on the top of the cliff, which is bordered by an important tectonic alignment striking NE-SW. Several rockfalls occurred in

the past years, threatening the stability of the rock cliff, as well as the static of the cultural heritage site.

From the analysis and the interpretation of the seismic noise, it is clear that the adopted geophysical methodology allows highlighting the presence of a different degree of fracturing in the rock mass. Indeed, it is function of the spectral response. These results, however confirmed by the stratigraphy obtained by mechanical drillings, allow us to say that the Convent of Friars Minor stands on a fairly fractured area and the resonance frequency has values of 4 Hz (S2 and S3) and 41.88 Hz (S1).

Geostructural analysis pointed out the presence of several discontinuity systems. One of them shows an orientation matching with the direction of the NE-SW main fault system. Geomechanical properties of the rock mass are to be considered poor, according to the RMR classification. Moreover, stability analysis highlighted a widespread instability, with planar sliding and wedge as possible failure mechanisms. The limit equilibrium analysis led to the calculation of FS whose values are lower than 1 both in static and pseudostatic conditions. Furthermore, the main instability conditions are related to the southeastern portion of the surveyed slope, where several karst caves are also present.

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TOMOGRAFIA SISMICA MARINA MULTICANALE AD ALTA RISOLUZIONE: ESEMPIO DI APPLICAZIONE PRESSO IL “PORTICCIOLA DELLA TONNARA”, CAPO GRANITOLA (TP)

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Introduzione. Le zone di transizione marino-costiere, le aree alluvionali o vulcaniche sono generalmente caratterizzate dalla presenza di terreni sciolti e forti variazioni geometriche latero-verticali, che si ripercuotono sul campo di velocità del sottosuolo in questi casi estremamente variabile.

La tomografia sismica multicanale a rifrazione è una tecnica di prospezione sismica che permette di definire un modello bi-dimensionale del sottosuolo, grazie l'individuazione delle anomalie di velocità di propagazione delle onde sismiche. Questa metodologia possiede un potere risolutivo nettamente superiore agli altri metodi convenzionali a rifrazione [es: Metodo Reciproco Generalizzato (GRM), metodo del tempo di ritardo (*delay time*), metodo del tempo intercetto], i quali si basano su un modello di sottosuolo costituito da strati regolari e con proprietà elastiche costanti, e che di conseguenza risultano inadeguati quando si è in presenza di forti variazioni laterali della velocità o inversioni di velocità con l'aumentare della profondità, cioè in presenza di situazioni geologicamente complesse.

Il metodo sismico multicanale a rifrazione, grazie alla sua versatilità, è uno dei metodi geofisici più comunemente utilizzati per l'esplorazione del sottosuolo. Tale tecnica permette, infatti, di ricostruire in maniera dettagliata le morfologie sepolte e definire la presenza di eventuali discontinuità in sottosuolo (faglie, fratture). La tomografia sismica viene ampiamente adoperata a terra a scopi ingegneristici; invece in mare ha un'applicazione limitata, in particolare nelle zone costiere e di transizione come porti, lagune e baie. Recentemente, è stato dimostrato che le indagini sismiche a rifrazione in ambiente marino superficiale, possono fornire contributi importanti per la caratterizzazione degli strati del sottosuolo in termini di spessore e di velocità delle onde compressive V_p (Whiteley e Stewart, 2008). La velocità delle onde P, infatti, è legata alla rigidità dei materiali e costituisce, quindi, un parametro importante per individuare il bedrock sismico ed i rapporti stratigrafici tra questo ed i sedimenti di copertura. La ricostruzione accurata del tetto della morfologia del bedrock sismico e quindi la valutazione della variazione degli spessori delle unità più superficiali è indispensabile nei progetti inerenti lo sviluppo di un'area portuale come ad esempio la costruzione di ponti o banchine e soprattutto nella stima degli interventi di dragaggio e ripascimento (MacGergor *et al.*, 1994, Young Ho Cha *et al.*, 2003).

Al fine di dimensionare un intervento di dragaggio da eseguirsi nello specchio d'acqua del “Porticciolo della Tonnara” di Capo Granitola, a Campobello di Mazara (TP), l'Istituto per l'Ambiente Marino Costiero del CNR di Napoli ha eseguito un test di sismica marina multicanale a rifrazione. Sono stati realizzati 4 profili sismici, di cui tre seriati e paralleli alla costa ed incrociati da un quarto profilo, al fine di ottenere dati di tomografia sismica da elaborare mediante tecniche 2D e 3D.