PECULIAR GEOTECHNICAL PROPERTIES OF SUBMARINE SEDIMENTS FROM A POLLUTED SITE

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Abstract

The article presents some of the results of a wide experimental research carried out on submarine sediments sampled down from the Mar Piccolo basin, located within the urban area of Taranto (south of Italy), one of the most polluted towns in Europe. The Mar Piccolo is a semi-enclosed shallow coastal basin, characterised by a rich and unique marine ecosystem. However, the long-lasting industrial activities, together with the waste collection from the densely populated urban centre of Taranto, are responsible for a severe environmental contamination by both heavy metals and organic pollutants. In the field of the actions promoted by the Italian Government to select the most sustainable remediation strategies, the geotechnical characterization of the sediments collected up to 30 m below the sea floor has been carried out, by means of both standard and modified equipment and procedures. The geotechnical laboratory tests have shown that, despite the Mar Piccolo recent sediments have similar origin and composition to those of the Sub-Apennine clay basic formation, their physical and behavioural facets appear to be significantly altered by the presence of contaminants of both natural and anthropogenic origin.

1. Introduction

The contaminated submarine sediments under study have been sampled down within the Mar Piccolo (literally "Little Sea"), a semi-enclosed basin, just behind the coast of the city of Taranto (Fig. 1.1). The town is one of the most important industrial sites in Europe, which has been declared 'at high risk of environmental crisis' and included into the list of the Sites of National Interest (SIN; Italian Law n. 426/1998), to be subjected to environmental remediation (Ministerial Decree n. 468/2002).

The Mar Piccolo is divided into the so-called First and Second bay (Fig. 1); it is characterised by a total surface of about 20km^2 and 13m of maximum water depth. It is connected to the Mar Grande (Ionian Sea) through two inlets (Fig. 1) on the west side and has a limited tidal excursion (i.e. 30–40 cm). Probably, due to the inflow of fresh water by submarine springs (e.g. Galeso and Citrello, Fig. 1) and tributary rivers, the peculiar morphology and the climatic conditions of the area, the Mar Piccolo represents an unusual ecosystem from the naturalistic point of view and the most important area of mussel farming in Italy. In 2016-2017 an ample investigation campaign was funded by the *Special Commissioner for urgent measures of reclamation, environmental improvements and redevelopment of Taranto* (CS_2017 campaign hereafter), aimed to the interdisciplinary investigation of the environmental properties of the sediments in the First bay. The geotechnical characterization of the polluted sediments required the development of innovative solutions to consider their complexity (i.e. highly variable consistency, presence of shells, organic matter and pollutants, pore fluid salinity). The composition, physical properties and compressibility of the Mar Piccolo submarine sediments are presented in the following and the results are compared with those of the Sub-Apennine clay basic formation.

Fig. 1. Mar Piccolo basin in Taranto (Southern Italy) and sampling sites of the investigation campaign supported by the Special Commissioner (CS_2017, green dots). The figure also shows some of the industrial activities around the basin, the mussel farming areas (white contours) and the main submarine springs.

2. Mar Piccolo in-situ campaign

One of the main concerns of the CS_2017 campaign has been that of allowing for the highest possible quality of soil sampling for the chemical, geochemical and geotechnical laboratory investigations. For the first time the in-situ campaign has explored the basic formations, represented by the Sub-Apennine Clay Formation and the Calcarenite di Altamura Formation (i.e. up to 45 m below the sea floor). Nineteen boreholes, located as in Fig. 1, were drilled in the First bay of the basin by means of a drilling machine installed on an offshore elevating platform (Fig. 2a). The difficult goal of the characterization has been to conjugate the necessities to obtain the best possible picture of the site with respect to all the scientific aspects to be investigated and to minimise the costs of the off-shore campaign. To this purpose, the sampling procedures and the laboratory testing programme on the undisturbed samples have been accurately planned by the researchers involved in the project. 1.5 m length polycarbonate liners, on-purpose designed to avoid phenomena of cross-contamination, were analysed by geologists and used for chemical and geochemical testing. At fixed depths, 1.4 m long undisturbed geotechnical samples were collected by means of different devices and methodologies in function of both the sampling depth and soil consistency. The most polluted shallow layer of sediments, characterized by high liquidity index (Vitone et al. 2016) was sampled by means of thin-walled tube samplers, made of transparent polycarbonate, manually pushed into the soil by expert scuba divers (Fig. 2b).

a) b) c)

Fig. 2. CS_2017: a) The offshore elevating platform, b) one of the polycarbonate tube samplers used within the first 1.5m below the sea floor, c) one of the Osterberg tube samplers.

The sediments of medium consistency (depth larger than 1.5 m below the seafloor) were recovered using either Osterberg hydraulic piston (Fig. 2c) or Shelby samplers. Denison tube piston samplers were also used for the stiff portions of the sediments. The chemical characterization of the undisturbed geotechnical samples was carried out on sub-samples taken soon after the soil sampling.

3. Geological and environmental features of the area

The main geological units outcropping in the area from the bottom to the top are: Cretaceous limestone (Altamura limestone), Upper Pliocene-Lower Pleistocene calcarenites, (Gravina calcarenite, GRA), Lower Pleistocene clays (Sub-Apennine clays, ASP), Middle-Upper Pleistocene calcarenites and sands (terraced marine deposits), Holocene alluvial deposits and coastal deposits. The two depressions of sub-elliptical shape that constitute the Mar Piccolo are supposed to be ancient river valleys that were incised during the continental phase related to the Last Glacial Maximum (20.000-25.000 years BP, Mastronuzzi 2006). They were subsequently submerged by the sea during the Holocene marine transgression. The sediments forming the Mar Piccolo basin have been deposited in time-varying environmental conditions, overlying both the ASP and the GRA. In addition, the remoulding of the top layer of sediments, that is consequent to the anthropic activities carried out in the area, should be also taken into account and it is currently under investigation by the Geologists involved in the research.
In the last decade, several Authors (e.g. ISPRA 2010, Cardellicchio et al. 2007) have provided evidence that the Mar Piccolo submarine sediments contain high concentrations of pollutants. The chemical characterization carried out during the CS_2017 campaign, confirmed that heavy metals (e.g. Hg, Pb, Cd, Cu, Zn) and anthropic organic contaminants (e.g. PCBs, PAHs) in the sediments can even exceed the law limits (D. Lgs. 152/2006). This is particularly the case of the shallow layer (0-1.5m bsf) of some areas in the First bay of the basin. Moreover, the chemical composition of the sediments is also affected by the presence of salt and organic matter. The seawater salinity of the Mar Piccolo ranges between 31g/l and 39g/l depending on the influence of fresh water coming from the submarine springs. The average salinity measured within the pore-fluid of the sediments is 30-32 g/l, even up to 18 m below the seafloor. Concentrations of total organic carbon (TOC up to 8%, ISPRA 2010) higher than those of the Adriatic and Ionian open sea sediments (about 2%, Bartholini 2015), have been found in the sediments by previous investigations carried out in the first 3m bsf. Thanks to last campaign (CS_2017), for the first time, also the organic matter (OM) was detected down to 45m bsf in the samples of the First bay. OM (loss on ignition method, LOI, EPA 160.4) is found to be highly variable, although a general trend of reduction with depth is recorded: OM ranges between 9 and 18%within 1.5m below the sea floor, it is between 5 and 15%, at medium depth (1.5-5m bsf) and tends to the average value of 7% at larger depth (5-32m bsf).

4. Composition and physical properties of the submarine sediments

The grading envelope of the 54 samples collected within the First bay of the Mar Piccolo basin (Fig. 3) essentially represents a fine-grained soil, for which the clay fraction, CF, varies between 22.48 and 65.38%, the sand fraction, SF, between 0.5 and 29.43% and the silt fraction, MF ranges from 30.45% to 69.53%. Specifically, almost all the investigated specimens can be classified as clays with silts, or clayey silts, from sandy to slightly sandy, apart from three samples which testify the presence of a predominantly sandy matrix, located between 1.5 and 5 m bsf in the southwest area of the First bay. It is worth noting that no significant differences in composition occur between the sediments of the shallow layer (0-1.5m bsf, red curves in Fig. 3) and those at lager depth (i.e. 1.5-5m bsf: blue curves and 5-32m bsf: black curves in Fig. 3). In addition, the grading envelop also includes the samples belonging to the basic formation collected in the basin, represented by Sub-Apennine clays, ASP, (green dashed curve in Fig. 3). This data are in agreement with those of the Sub-Apennine clays collected in the Apulian region both in-land (Pappadai Valley, Cotecchia 1996) and in the sea areas (Mar Grande basin, Cotecchia 2005).

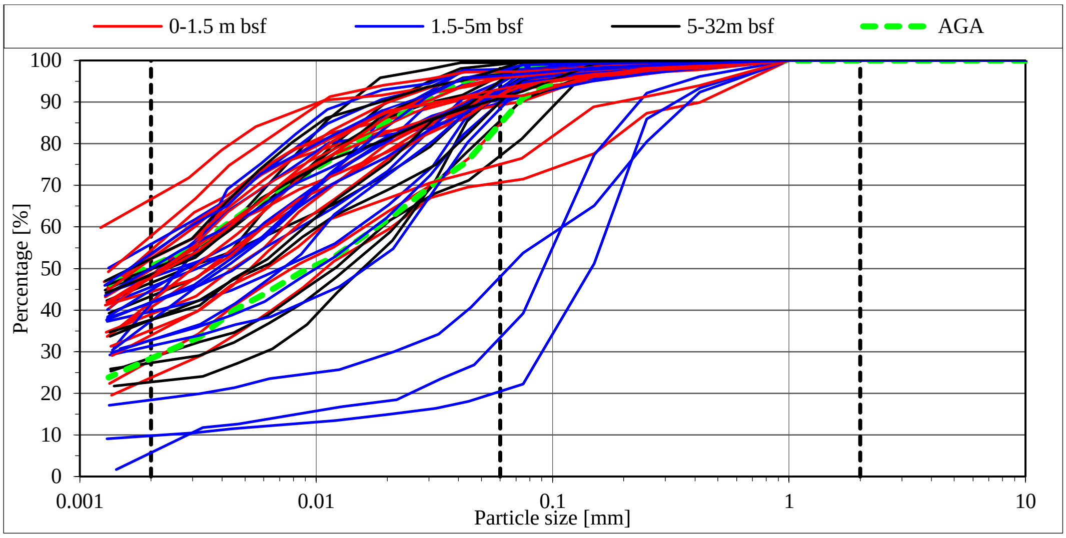

Fig. 3. Grading curves of the Mar Piccolo sediments.

A widespread presence of illite, interstratified illite/smectite, I/S, and chlorite/smectite, Chl/S has been detected within the clay fraction of three samples collected along one borehole in the south of the First bay during a preceding campaign (Vitone et al. 2016). This finding is similar to what found for the ASP Formation outcropping in the Taranto area, where the clay minerals (46%) are mainly represented by illite (De Marco et al. 1991, Cotecchia 1996, Cotecchia 2005).
All these evidences seem to suggest that there is no indication of significant differences in composition not only with depth throughout the basin but also between the recent sediments and the basic AGA Formation, from which the sediments were originated in consequence of geological processes (i.e. erosion and subsequent deposition, Mastronuzzi et al. 2006, Lisco et al. 2015). However, the forthcoming data of mineralogical composition of the Mar Piccolo sediments will better clarify this aspect of the research.
The Mar Piccolo samples taken during the CS_2017 campaign show a great variability in the Casagrande's plasticity chart (Fig. 4a) and the Activity chart (Fig. 4b). Despite the similar mineralogical composition, the sediments from the most contaminated shallow layer are characterised by unexpected index properties if compared to those taken at larger depths within the same site and those typical of Sub-Apennine clays (i.e. AGA).
According to the BS 5930 (1999), the samples from the deeper (black x in Fig. 4a), intermediate (blue rhombus in Fig. 4a) and AGA (green triangles in Fig. 4a) layers can be classified as fine soils from high ($50\%<w_L<70\%$), to very high plasticity ($70\%<w_L<90\%$), except for few samples having clay fraction lower than 30% and w_L lower than 50% (i.e. intermediate plasticity). In Fig. 4b, the activity for the samples in these layers ranges from low (A = 0.56-0.75) to medium values (A = 0.75-1.25). On the other hand, the shallow layer of the Mar Piccolo basin (red circles in Fig. 4, 0-1.5m bsf), where the pollutants reach values often above the law limits and the organic matter content is high (OM=9-18%), is also characterized by huge variability and highest values of plasticity and activity indexes. In particular, within 1.5m bsf, w_L varies between 62 and 117%, PI between 34 and 79% and A ranges from 0.60 to 2.49 (Fig. 4a and 4b). The activity of the shallow layer is also above the values expected for illitic mineralogy reported by Mitchell & Soga (2005) (i.e. Smectites A=1-7; Illite A=0.5-1; Kaolinite A=0.5). The variability of the index properties of the sediments is higher than that of the AGA Formation from which the sediments were originated, measured either on in-land samples (Cotecchia 1996) or in submarine samples taken from both the Mar Grande (Cotecchia 2005) and the Mar Piccolo basin (AGA samples). Both the Mar Grande and the Pappadai clay sites are characterized by lower organic content and, if the Pappadai clay site is an unpolluted site, the Mar Grande is characterised by much lower

contamination than that of the Mar Piccolo basin. In particular, Cotecchia (2005) report that the Mar Grande clays (sampling depth from 1 to 33 m bsf) are characterised by w_L varying from 38 to 70%, PI from 19 to 40%, and activity values A from 0.49 to 0.93. Similar values were found in the Sub-Apennine Clay Formation in the Pappadai Valley: w_L= 30-67%; PI=11-37%; A=0.42-0.72 (Cotecchia 1996).

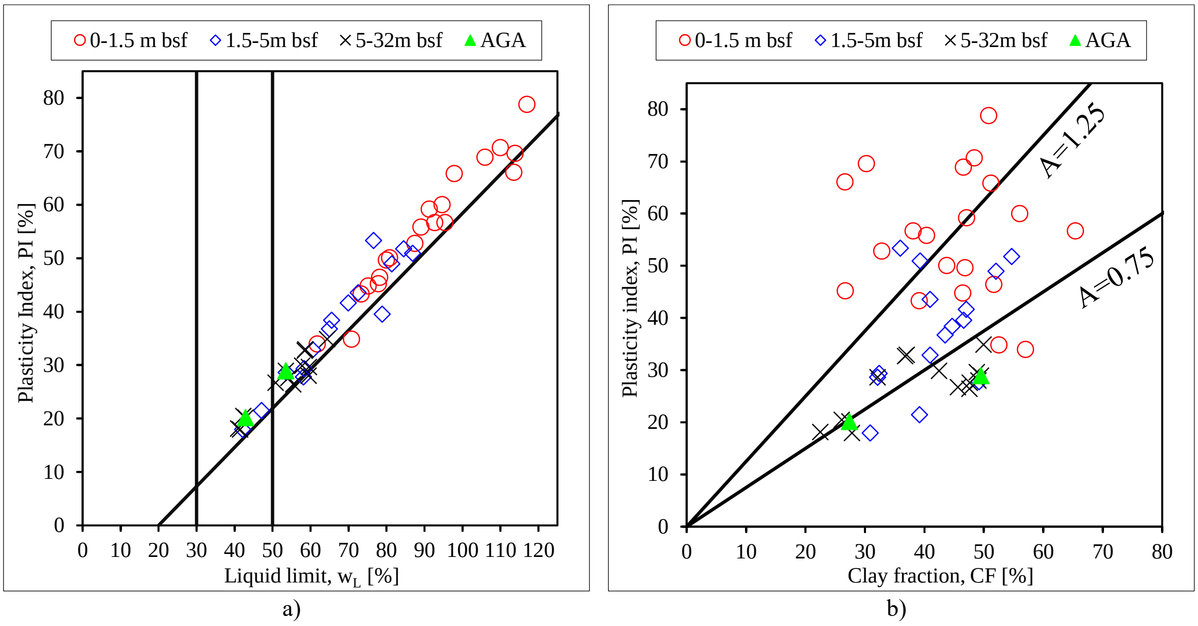

Fig. 4. Casagrande's plasticity chart (a) and Activity chart (b) of the Mar Piccolo sediments.

In terms of in situ state, the sediment samples taken with the top 2-3m bsf have generally natural fluid content much higher than the liquid limit and the liquidity index, LI, varies between 1 and 2.7 (the maximum value is LI=4). In the layer of sediments between 3-5 m bsf, LI is still higher than one (i.e. liquid consistency), ranging between 1 and 2, even when the real consistency is clearly plastic. At larger depths (5-32m bsf), LI is either close to one or slightly smaller, indicating a plastic consistency. If compared with the ideal profile of reconstituted Pappadai Clays, the Mar Piccolo sediments exhibit high water content than expected for normally consolidated sediments under their own weight up to 20m bsf.

5. Compressibility of the submarine sediments

The results of the one-dimensional loading tests carried out on 53 oedometer specimens, are reported in the void ratio, e, vertical effective stress, σ'_v, semi-logarithmic plot in Fig. 5. As expected, the curves are characterised by a huge variability in both initial void ratio and compressibility. The compressibility of the shallow layer of sediments (i.e. C_c=0.8-1.5) is slightly higher than what expected for illite (C_c=0.50 to 1.10, Sridharan & Nagaraj 2000), although the shallow sediments have silt fraction (MF) between 30 and 59%. The intermediate (i.e.1.5-5.0 m bsf, blue curves in Fig. 5) and the deep (>5m bsf, black curves in Fig. 5) layers are characterized by average compressibility indexes C_{c_av} equal to 0.7 and 0.4. These values are higher than those of the AGA samples (green curves in Fig. 5) collected in the basin for which C_{c_av} is equal to 0.23. The secondary compression coefficients, c_α, of the shallow samples vary with vertical effective stress according to a *bell shape* trend: from 0.002 to 0.04 (σ'_v < 6 kPa) to maximum values of 0.011 to 0.073 (σ'_v = 10 - 50 kPa). The c_α values of the shallow Mar Piccolo sediments are above the range 0.005-0.02 suggested in the literature by several authors for normally consolidated soils (e.g. Lambe & Whitman 1969), but included into the range of variability (0.01-0.1) recognised for organic peats (e.g. Madaschi & Gajo 2015). On the contrary, samples taken from larger depths both in terms of values (z>3.7 m bsf, c_α = 0.002 – 0.024) and trend (almost constant) with vertical effective stress behaved similarly to the reconstituted Sub-Apennine Clays (of same origin and mineralogy), that have an almost constant c_α equal to 0.012 in the normal compression phase.

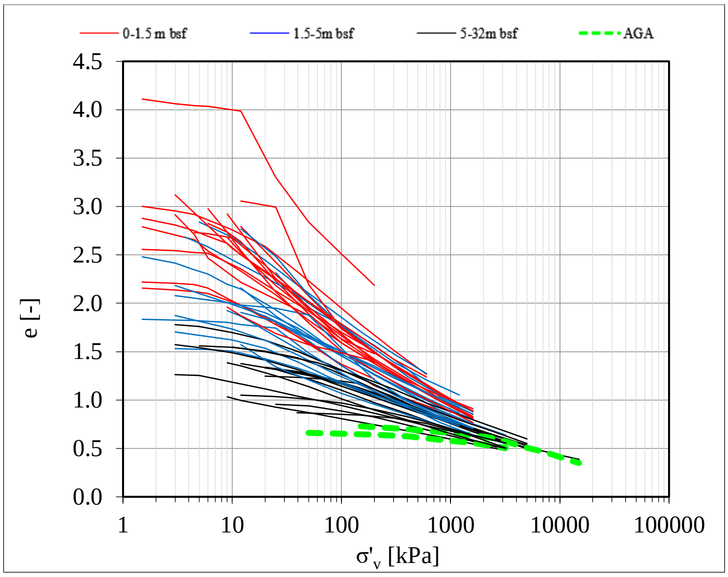

Fig. 5. Mar Piccolo submarine sediments: OED test results.

From what above, it emerges that the altered geomechanical properties of the Mar Piccolo sediments reflect the presence of organic matter, OM, of both natural and anthropogenic origin as well as that of other factors and their combination (e.g. sediment composition, water salinity and pore water chemistry).

Acknowledgements

The activities described were funded by the *Special Commissioner for urgent measures of reclamation, environmental improvements and redevelopment of Taranto* (South of Italy), Dr Vera Corbelli.

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