ORIGINAL PAPER

Engineering geological 3D modeling and geotechnical characterization in the framework of technical rules for geotechnical design: the case study of the Nola's logistic plant (southern Italy)

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Abstract

In the design and construction of buildings and infrastructures, the reconstruction of a reliable 3D engineering geological model is an essential step to optimize costs of the construction and limit risks from failure or damage due to unforeseen ground conditions. The modeling of ground conditions is a challenging issue to be tackled especially in the case of geological units with complex geometries and spatially variable geotechnical properties. In such a direction, coupled geological and geotechnical criteria are usually adopted to define engineering geological units.

These concepts are considered by the current technical rules for geotechnical design such as the Eurocode 7 and in the national regulations which have followed it, known in Italy as "Norme Tecniche per le Costruzioni (NTC)." Notwithstanding this advanced regulatory framework, no comprehensive indications on methodological approaches were given for the 3D engineering geological modeling and geotechnical characterization of a design and construction site. In this paper, the case study of the highly heterogeneous and heteropic pyroclastic-alluvial stratigraphic setting of the Nola plain (Campania, southern Italy) characterizing the site of the Nola's logistic plant is dealt with. The approaches are based on the engineering geological modeling analysis of a high number of stratigraphic, laboratory and in situ geotechnical data, collected for the design of the plant, and the use of a specialized modeling software providing advanced capabilities in spatial modeling of geological and geotechnical information, as well as in their visual representation. The results obtained, including also the analysis of statistical variability of geotechnical properties and the identification of representative geotechnical values, can be potentially considered a methodological approach, consistent with the current technical rules for geotechnical design as well as with fundamental concepts of engineering geological modeling and mapping.

Keywords Engineering geology · 3D modeling · Complex stratigraphic setting · Civil engineering works

Introduction

For the design and construction of civil engineering works, the 3D engineering geological modeling consisting in the recognition of geological materials, characterization of their physical and mechanical properties, and the reconstruction of three-dimensional geometries represents a fundamental step for the optimization of costs and minimization of related risks. At this scope, lithological/stratigraphic characteristics and not overlapping geotechnical properties lead to identify engineering geological units, which are conceived as a specialized category of geological units with homogeneous lithological/stratigraphic and engineering properties (UNESCO-IAEG 1976) to be used for mapping and applicable to the design, construction, and service of civil engineering works. Moreover, the recognition of engineering geological units is conceived enabling the reconstruction not only of engineering geological maps but also 3D models of the subsurface. In particular, engineering geological mapping assumed a great relevance after the proposal of a nomenclature of engineering geological units (UNESCO-IAEG 1976), which was set homologously to that of lithostratigraphic ones (ISSC 1976) as dependent on the scale of analysis.

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Consequently, different types of engineering geological units, varying from qualitative to quantitative, were established according to the type of investigations to be carried out depending on the scale of survey and representation (González de Vallejo and Ferrer 2011).

As a further conceptual advance, Fookes (1997), following the intuitions of Terzaghi (1946), highlighted the importance of geotechnics in the field of geology applied to civil engineering by underlining the lack in classic geological maps of quantitative information on geotechnical properties of soils and rocks, such as shear strength, permeability, and compressibility. Accordingly, the purpose of the engineering geological mapping was focused more clearly in recognizing engineering geological units, characterized by homogeneous lithostratigraphic and geotechnical properties, whose geometrical boundaries correspond to changes in their geotechnical features.

Further advances in the definition of engineering geological models were established by the International Association for Engineering Geology (IAEG) and the Environment Commission C25 (Parry et al. 2014) which distinguished conceptual, observational, and analytical engineering geological models specifying their applications.

The concepts of the engineering geological units and 3D modeling of the subsurface can be considered very consistent to guidelines of the Eurocode 1997, EN 1997–1:2004 (CEN 2004) and in the national regulations which have followed it, such as Italian "Norme Tecniche per le Costruzioni" (NTC), issued in 2008 and 2018 (Ministero delle Infrastrutture e dei Trasporti 2008), in which the rules for planning geotechnical surveys and the treatment of their results were established. In such a framework, the reconstruction of 3D engineering geological models is become an important cognitive support, with greater capabilities in displaying spatial variations of engineering geological properties of the subsoil (Kolat et al. 2012; Donghee et al. 2012; Parry et al. 2014). Therefore, in recent years, many progresses have been made in the field of 3D geological modeling. Alan and Norman (2003) proposed the Horizons Method to build solid models. Some researchers tried to develop 3D geological modeling software using 3D graphics platforms such as OpenGL (Zhang and Liu 2003) and GOCAD (Douglas et al. 2007). Moreover, the British Geological Survey achieved 3D geological models at a wide range of scales with a 3D geological information system (Lelliott et al. 2006, 2009; Robins et al. 2008; Royse et al. 2009). In Paris, a multilayer 3D geological model of the city was developed from The General Inspectorate of Quarries of France (Thierry et al. 2009). The reconstruction of 3D geological models was proposed to show the distributions and volumes of exploitable mineral in Quaternary deposits of southwest Germany (Kostic et al. 2007) and coal in western Greece (Krassakis et al. 2022). Some authors (Dong 2008; Apel 2006; Choi et al. 2009) improved data management

and a plug-in for 3D geomodeling of the capital city of China. In more recent studies, the engineering geological models are built using drilling, geotechnical or geophysical data from site surveys using 3D modeling software packages such as *Leapfrog* (Rose et al. 2018; Whiteman 2021). The advances in computational speed, collection and digitalization of an increasing number of geological and geotechnical data have led to the improvement of their 3D representation, thus allowing a better assessment of related hazards and uncertainties involved in urban planning (Kessler et al. 2009; Marache et al. 2009; Royse et al. 2009; Royse 2010; De Beer et al. 2012a, b). This has allowed to pass from the conceptual model to the realistic one (Culshaw 2005) through the combination of spatial information with physical and geotechnical properties, to be attributed by statistical approaches.

Finally, Baynes et al. (2020) tackled the problem of uncertainty in the engineering geological model considering it as an interlinked mixture of conceptual models and observational data characterized by epistemic and aleatory uncertainties respectively (Bowden 2004; Lee 2016) in which the greater the amount of observational data, the more the accuracy of the model increases. The accuracy also depends on the data structure that determines the modeling algorithm and visualization (Wang 2021).

For this study, starting from a wide database of lithological and geotechnical data, derived by detailed campaigns of stratigraphic and geotechnical surveys, carried out for the design of the C.I.S — Interporto Campano — Vulcano Buono district, 3D geological and engineering geological models were realized by *RockWorks* modeling software (RockWare Inc.). According to Eurocode 1997, a statistical characterization of geotechnical properties of engineering geological units was carried out based on results of field and laboratory tests.

Given the complex geometry of the pyroclastic-alluvial deposits of the investigated area and their spatially variable geotechnical properties, comprising very poor conditions of peat lenses, the challenging purpose of this work is to propose a reference approach for the geotechnical design of civil engineering works in complex ground conditions to be consistent with the current technical rules for geotechnical design.

The study area description

Geological and geomorphological features of the Nola plain

The Nola plain is in the northeastern sector of the Campania Plain, about 16 km northward of the Somma-Vesuvius volcano, to the north of Cancello mountains and to the east of Avella ones (Fig. 1). The geological-structural setting of the study area is a consequence of the genetic mechanisms of the Campanian Plain which were controlled by the strong
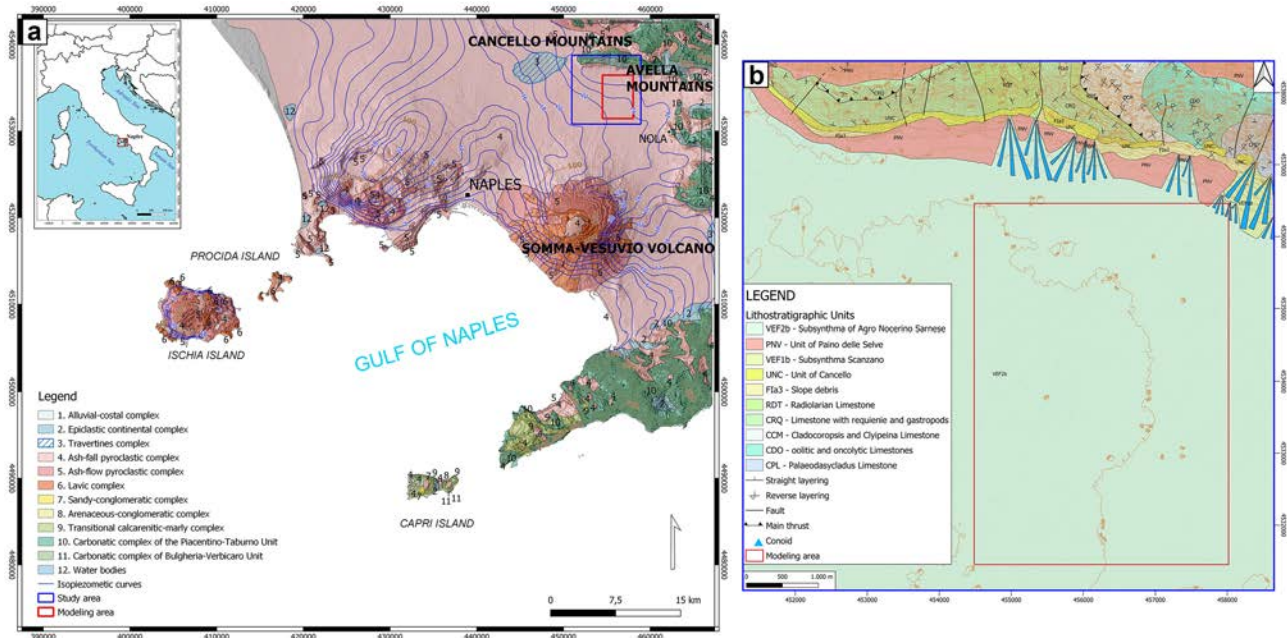
Fig. 1 **a** Excerpt from the hydrogeological map of Southern Italy (1:250.000 scale; De Vita et al. 2018, modified); **b** excerpt from the geological map of Italy at 1:50.000 scale (from ISPRA, modified), Ercolano sheet (N. 488)

interactions between volcanic, tectonic, and sedimentary phenomena occurred during the Quaternary (Ippolito et al. 1973; Ortolani and Aprile 1985; Brancaccio et al. 1995; Romano et al. 1994; Aprile et al. 2004).

The Campanian Plain is a wide semi-graben structure (Milia and Torrente 1999), formed by NE-SW, NW–SE and E-W normal fault systems, occurred from the Late Pliocene (Ippolito et al. 1973) to the Early Pleistocene (Cinque et al. 1987), which sunk the Apennine Chain along the Tyrrhenian side. The analysis of the thick stratigraphic series of alluvial and pyroclastic deposits filling the geological structure, based on campaigns of deep boreholes, allowed to attribute their formation from the Mid-Late Pleistocene to the Holocene (D'Erasmo 1931; Ippolito et al. 1973; Aprile and Ortolani 1978; Brancaccio et al. 1991, 1995; Torrente et al. 2010).

By a geomorphological point of view, the study area is located in the upper part of the Regi Lagni valley, which is characterized generally by an artificial drainage network, constructed between 1610 and 1616 for the reclamation of the area and the control of floods of the Clanio river. The valley is surrounded by mountainous ranges formed by Meso-Cenozoic carbonate rocks (Pescatore and Ortolani 1973; Pescatore and Sgrosso 1973). The topographic gradient is overall very low, thus characterizing it as a sub-flat with slopes of less than 2% degrading south-westward.

Due to the flat morphology and the limited drainage, the area was characterized by a marshy environment which allowed the formation of organic deposits, such as peat and paleosols intercalating with the alluvial and pyroclastic deposits, erupted in the last 10 k-years by the Phlegraean Fields and Somma-Vesuvius volcanoes (Di Vito et al. 1999; Santacroce et al. 2008). In addition, other studies (Di Vito et al. 2013) indicated that the occurrences of lahar, debris flow, and repeated flooding events favored the formation of marshy environments.

The fundamental geological features of the area can be grouped in two. The first group comprises the bedrock Meso-zoic lithostratigraphic units of the carbonate platform series, forming the Cancello and Avella mountains that border the study area to the north and east. The second includes the Quaternary deposits formed by marine-transitional facies, related to positive glacio-eustatic fluctuations that occurred during the Middle-Upper Pleistocene, and ash-fall/ash-flow pyroclastic deposits (Putignano et al. 2007; Santangelo et al. 2010), erupted by the intense volcanic activity dating back to 116 k-yrs (Campania Grey Tuff; De Vivo et al. 2001) and 15 k-yrs (Neapolitan Yellow Tuff; Deino et al. 2004). In the study area, these deposits include the detrital-colluvial unit (PNV) of *Piano delle Selve* and the detrital unit of *Ghiaie Carbonatiche di Tufino* (VEF2b2). The first is a pyroclastic-alluvial complex formed by sandy-loam gravels. By a geo-technical point of view, these deposits are generally characterized by a low value of voids ratio, which results in a relevant settlement under an increase of vertical load.

Instead, the second unit consists of alluvial calcareous gravels and pebbles with a polygenic sandy matrix. Based on

their physical–mechanical properties, these deposits can be characterized as variously saturated soils with a significant value of the elastic module (Carrara et al. 1973).

Engineering geological issues of the study area

At the end of 1970, a sector of the Nola plain was identified as the site for the construction of a logistic and commercial district formed by three structures with different and complementary functions, the *Centro Ingrosso Sviluppo* (*C.I.S*), a leading B2B trade distribution center in Europe, the *Interporto Campano*, an international logistics platform connected with the world's top hubs, and *Vulcano Buono*, a multifunctional center for shopping, entertainment, and accommodation. Specifically, the Interporto Campano (https://www.interportocampano.it) is one of the most important logistic platforms in Europe offering a transport system integrated with rail, road, and sea lines to provide services for storage, management and distribution of goods. It is an intermodal structure organized in different sites

(Fig. 2) including several services for the entire Interporto area (buildings, warehouses, viaducts, railway station, and various infrastructures). Many geological and geotechnical studies were executed for its design and construction allowing the recognition of a complex stratigraphic and lithological nature as well as the physical and mechanical characteristics of soils directly and/or indirectly involved in the constructions. The analysis of the stratigraphic logs obtained by continuous core drillings showed that the first 4 m of subsoil consist of an alternation of sandy silts and silty sands, belonging to the ML group (low-plasticity silts) of USCS classification. Instead, the deepest part of the stratigraphic setting is constituted of lithoid and pseudo-lithoid tuff.

Geotechnical campaigns carried out in the area and laboratory tests allowed the undisturbed sampling and the characterization of geotechnical properties. Moreover, the execution of a series of Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) revealed a very complex geotechnical setting. The occurrence of highly compressible organic soils and their irregular spatial distributions,
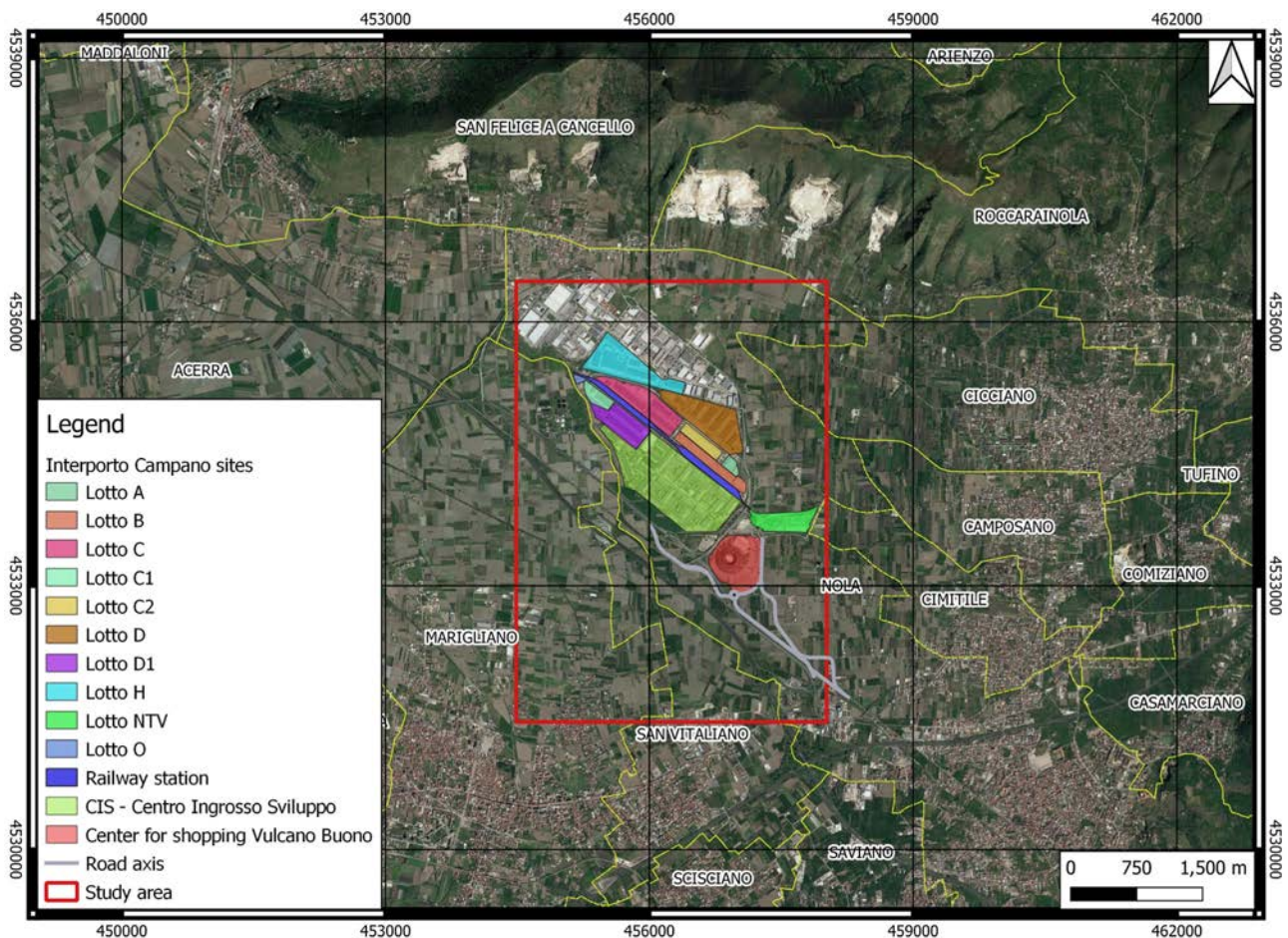

Fig. 2 Map of the Interporto Campano logistic plant with indication of specific subareas in which it has been subdivided according to the logistic activities

characterized by lenticular geometry, were recognized the major geotechnical problem because potentially controlling differential settlements of structures. For this reason, geotechnical studies were carried out in specific sites (NTV, O, and C; Fig. 2) and aimed at favoring the consolidation of these soils by an artificial earth fill load, equal to that of the structures to be constructed. This practice caused settlements varying from 0.7 to 15.9 cm.

Data and method

Construction of the 3D engineering geological models

In the case study presented, a quantitative representation of the subsoil through geological and geotechnical investigations, characterized by a high detail in the estimation of the lithological and geotechnical properties, was carried out (Fig. 3). Due to scale of analysis, the engineering geological units recognized are at the maximum level of detail (scale > 1: 5.000) being considered *engineering geological types* (UNESCO/IAEG 1976). Engineering geological properties were characterized by laboratory tests and field measurements as well as analyzed by a statistical approach, in accordance to recommendations of Eurocode 1997. Specifically, the geological and engineering geological model of the investigated area were reconstructed by *RockWork* modeling

software. The software is able to manage data of different nature (lithological, stratigraphic, geophysical, geochemical, hydrogeological, and geotechnical data) and to apply different interpolation methods to create 3D models, consisting in the reconstruction of overlapping regular mesh surfaces (grid model) or voxel matrices (solid model).

Organization of the collected data and creation of a database

The geological model of the area was reconstructed by stratigraphic and geotechnical data (Fig. 4). The datasets comprise:

  41 continuous core drillings;
  107 Standard Penetration Tests (SPT);
  93 Cone Penetration Tests (CPT);
  Laboratory tests carried out on 73 undisturbed soil samples taken during the survey.

The first operation consisted in the geospatial location of boreholes and CPT (UTM WGS84), whose elevation value was obtained by a LiDAR Digital Terrain Model (DTM) available by the geodatabase of the Città Metropolitana di Napoli (http://sit.cittametropolitana.na.it/lidar.html).
Secondly, two datasets were created, respectively, related to stratigraphic and geotechnical data, arising from the CPT tests. Based on the variety of data available, three different
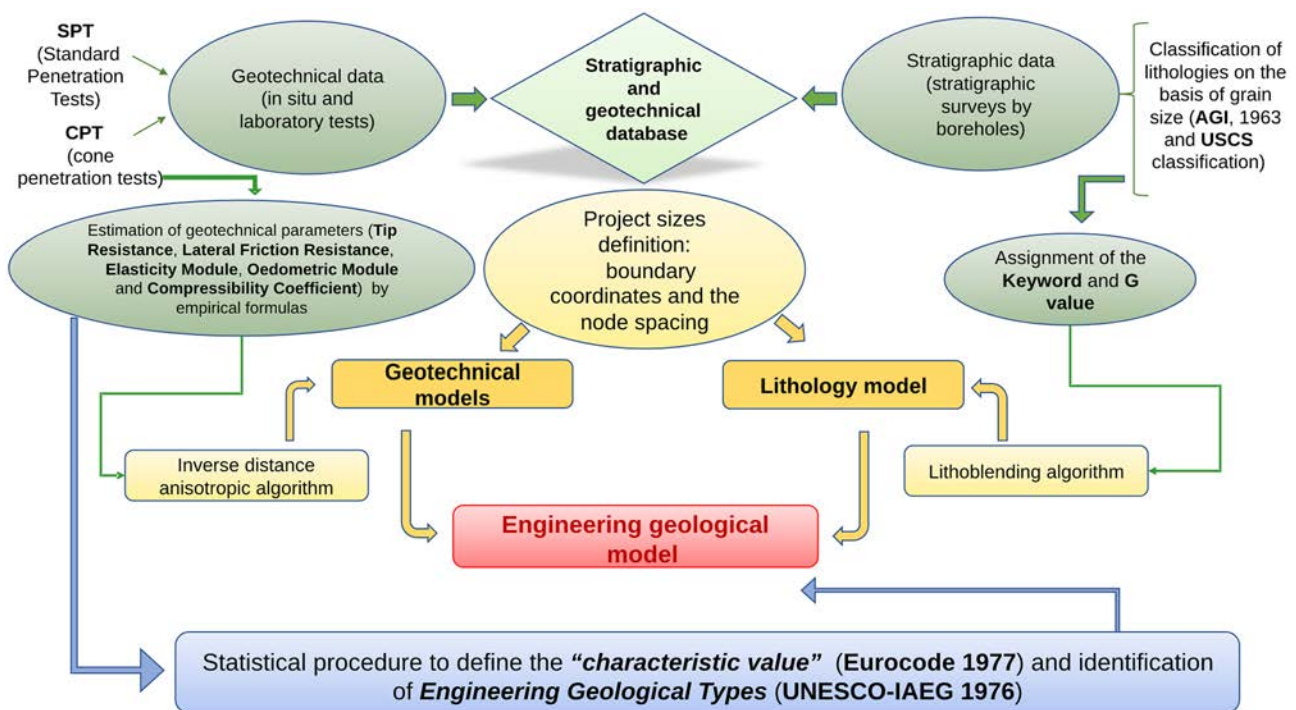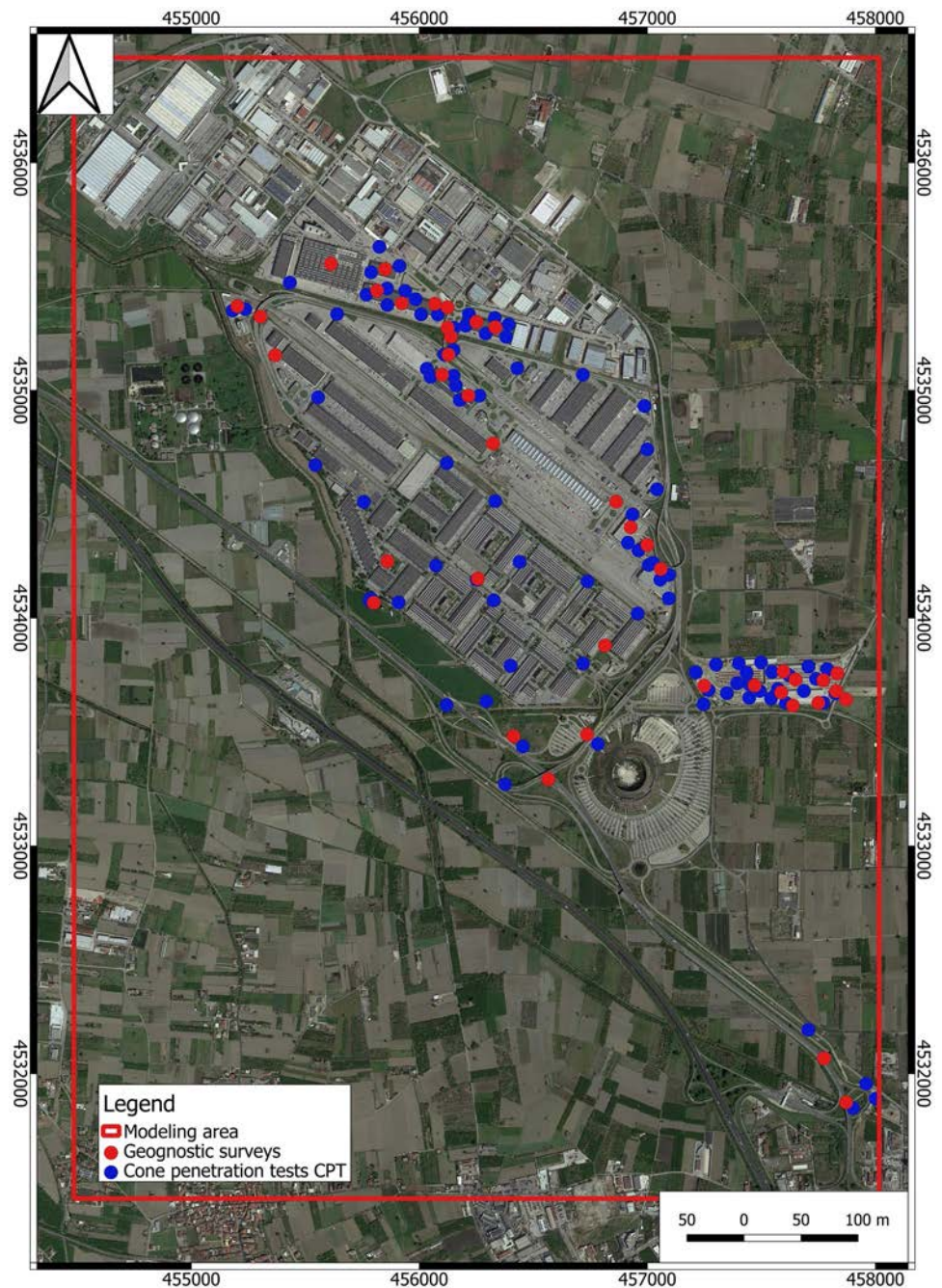

Fig. 3 Flowchart of the methodological approach

Fig. 4 Modeling area (red polygon) and locations of boreholes and CPT tests

types of subsoil 3D models of the subsoil were created: lithological, geotechnical, and engineering geological. The lithological model was realized with lithology data directly observed by stratigraphic surveys executed by a borehole campaign. These data were imported and managed in the *borehole data manager* of the software by the *lithology* tool which is connected to the *lithology type*, a table defining a representative *keyword* and a *G value* for each lithology observed. The *keyword* is a synthetic unambiguous name that is attributed to the lithology through a revision of the classification terms. As the first step, the classification name based on grain size fractions (AGI 1963) was used to estimate grain size fractions themselves. Subsequently, the application of USCS classification allowed to assign a name, a symbol, and a pattern to each lithology. The G-value, appearing in the *lithology type*, is an integer numeric value used to represent the lithologies in the interpolated lithological models.

The results of the site and laboratory geotechnical tests were applied to estimate the compressibility parameters

which were used to create the geotechnical models. At this scope, several empirical formulas known by the geotechnical scientific literature were considered to estimate these parameters. Those used for this study are based on results of the Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT), which were tested on sands and silts, thus being equivalent to soils investigated. Therefore, in order to create engineering geological models with high resolution, the continuous characterization along the vertical obtained by CPT tests was used. For this reason, geotechnical parameters deriving from the Standard Penetration Tests (SPT) were not used for the reconstruction of the engineering geological model even if they were used for validating values derived from CPT tests. Thus, the parameters stored with *P-Data* instrument and used for the creation of geotechnical models of the subsoil, estimated every 0.2 m of depth, were: tip resistance and lateral friction resistance. Moreover, elasticity module, oedometric module, and compression index were obtained by empirical formulas.

The *elasticity module E* was estimated as the average of results obtained by the following empirical formulas.

The De Beer (1965) formula, based on the correlation of the elasticity module (E) to the tip resistance (q_c) by means of an empirical coefficient α, whose value is assigned based on the nature of soil tested (Canadian Geotechnical Society 1992):

$$E = \alpha \cdot q_c \text{ (MPa)} \tag{1}$$

The Schmertmann (1970, 1978) formula, which correlates the value of the module with the tip resistance directly through a constant equal to 2.5:

$$E = 2.5 \cdot q_c \text{ (kg/cm}^2) \tag{2}$$

The Fellenius (2006) formula:

$$E = \alpha \cdot q_t \cdot C_m \text{ (kPa)} \tag{3}$$

where:
q_t is the corrected tip resistance [$q_t = q_c + u_2 – (1—a)$];
q_c is the measured tip resistance;
u_2 is the interstitial pressure measured at the base of the cone;
a is the ratio of the base area of the cone to internal area of the cone;
α is the empirical coefficient assigned by the Canadian Foundation Engineering Manual (Canadian Geotechnical Society 1992).

The oedometric module (M) was estimated by the Sanglerat (1972) equation applicable for silts and silty sands:

$$M \text{ (MPa)} = q_c \cdot{}^\alpha m \tag{4}$$

The constant α_m depends on the type of lithology and it is assigned through the USCS classification.

Finally, Urmi and Ansary (2019) proposed an original solution to derive the compression index (Cc) value according to the following correlations:

$$C_c = 0.24e^{-0.19qcl} \tag{5}$$

$$C_c = 0.2336 − 0.0333q_{cl} \tag{6}$$

where, q_{cl} represents the *tip resistance*.

For the reconstruction and characterization of the engineering geological units, specifically engineering geological types (UNESCO-IAEG 1976), the integration and interpretation of lithological and geotechnical data was carried out.

Project size

The project size was preliminarily set by considering the boundary coordinates and the node spacing which controls the density of the models, namely their detail and the time needed for data processing. The modeling area was estimated extending over about 17.5×10^6 m² (Fig. 4).

To find the correct balance between model resolution and processing time, the spacing along *x* and *y* axes were set equal to ½ of the average distance between the boreholes, while the spacing along *z* axis was related to that of the sampling intervals as recommended by Rockworks manual (https://www.rockware.com). In this study, a spacing of 500 m was initially set for all models considered as derived by the average distance of the survey boreholes, estimated in about 1000 m. However, a reduction of this spacing value down to 100 m was carried out to improve the spatial resolution. This was considered an acceptable compromise between resolution and processing time, which resulted three times greater than that occurred for the 500 m resolution. Instead for the elevation (*z* axis), different values of extension and spacing were tested. Specifically, choices to obtain a greater resolution for the elevation were conditioned by the following factors:

a) Different depths of boreholes, which are deeper than the CPT tests;
b) Spacing along the *z* axis of 0.1 m, which is lower than the measure frequency of CPT tests (0.2 m).

Depending on these settings, the volume of the lithological model obtained by processing the survey data is equal to about 745.7×10^6 m³. Instead, the volume of the geotechnical models built by the results of the CPT tests is about 420.0×10^6 m³.

3D models creation

Different interpolation algorithms were used for the 3D modeling of the subsurface. The choice of the most appropriate interpolation method was based on the type of model to be realized and the reasonableness of results obtained.

The lithological model was created by using the lithology data directly observed by borehole surveys and the lithoblending interpolation algorithm which is the only available method for the lithological modeling of lateral lithological transitions, such as heteropic facies and geological bodies with lenticular geometries. Lithoblending is an algorithm that extrapolates lithology types from the borehole data into a solid block model. It reconstructs lithozones around each borehole which can end suddenly when a lithological zone from a near borehole is encountered. More specifically, this algorithm works as a nearest neighbor geospatial methodology, exclusively designed for lithological modeling. After the reconstruction of the 3D model, the software allowed the extraction of cross-sections and fence diagrams, using the respective *lithology section* and *lithology fence diag*ram tools.

Values of geotechnical parameters of tip resistance, lateral friction resistance, derived by CPT tests, elastic module, oedometric module, and compression index, derived by empirical formulas, were also used to create 3D models. For the reconstruction of the 3D models of geotechnical parameters, the inverse distance anisotropic interpolation method was considered the most suitable among the other available for solid modeling (triangulation and kriging), as it was assessed by an expert judgment. It is based on a directional search which can improve the interpolation of voxel values that lie between data point clusters and can be useful for modeling borehole data in stratiform deposits.

Finally, for the reconstruction of boundary surfaces separating overlapping engineering geological units, the kriging algorithm was applied.

By the combined interpretation of lithological and geotechnical models, an engineering geological model was finally created. It represents a synthetic subdivision of the subsoil into layers corresponding to specific engineering geological types (UNESCO-IAEG 1976).

Statistical characterization of geotechnical properties

According to Eurocode 1997, geotechnical properties of engineering geological units are characterized by "*characteristic values*" which are representative of statistical variability and can be considered applicable to the design of civil works involving the ground (characteristic design geotechnical value; Fig. 3).

In terms of shear strength or compressibility, a "characteristic value" is characterized by a reasonably high exceedance probability which implies a low probability of not exceedance and therefore the acceptance of a low level of risk. Before the introduction of the Eurocode 1997, there were no guidelines providing information on how identifying characteristic values of geotechnical parameters to be used for the design stage. To this regard, different authors discussed the correct approach, such as Simpson et al. (1981) who highlighted the difficulty in recognizing a univocal method to determine characteristic values, since the degree of uncertainty of a specific geotechnical parameter varies significantly depending on local geological conditions. They concluded that the mean value is not adequate as a characteristic value and recommended to consider the worst conditions that could occur, although this approach could be extremely conservative. In 1981, also, the Danish Code of Practice for Foundation Engineering (Danish Geotechnical Institute 1978) stated that the characteristic values of the parameters of strength and deformation of the soil had to be established by a conservative estimate based on the results of the relevant measurements, giving to the designer the choice of the level of conservativeness this estimate should have.

Finally, Eurocode 7 provided guidelines for planning geotechnical investigations and using results establishing that the characteristic value of geotechnical parameters can be determined through statistical methods applied to the results of laboratory and field tests. Furthermore, the choice of the representative value is not based on just a pure statistical analysis of results but involves the judgment of the designer about the engineering problem to be solved.

For this study, a statistical procedure was adopted to define representative values of five geotechnical parameters which were identified for characterizing engineering geological types: tip resistance, lateral friction resistance, derived by CPT tests, elastic module, oedometric module, and compression index, derived by empirical formulas applied to results of CPT tests.

This approach was based on the frequency analysis, whose results were represented by percentile values of 25%, 50% (median), and 75% frequencies, showed by means of box plots.

Results and discussion

In this paragraph, results of the modeling process are shown and discussed. 3D models, as well as the 2D representations, were shown with a vertical exaggeration of 100 to improve the visualization of thin soil horizons.

The lithological model

The 3D lithological model (Fig. 5) shows the distribution of the lithology types directly observed by boreholes, highlighting lateral transitions due to heteropic facies and the occurrence of geological bodies with lenticular shapes. The investigated area is characterized for the most part by alternations of low-plasticity silts (ML) and silty sands (SM), with intercalations of peats lenses (Pt) and rare levels of coarse soils (GP, GW, SP, and SW). In the deeper zone, a tuff formation occurs with lateral and vertical discontinuities which determine interfingering with loose pyroclastic sandy deposit (SM and SP).

A series of 2D representations of the investigated subsoil were derived from the 3D lithological model. In particular, Fig. 6 shows a cross section along the trace A-A' starting from the survey S_4, at SE of the examined area, and ending in the survey S_{41}.

In addition, a series of *fence diagrams* relating to the entire volume of the investigated area were reconstructed. The diagrams orientation can be selected manually or by means of default tools that allowed different 3D models. The following figure shows the fence diagram reproduced by one of these tools (Fig. 7).

Geotechnical models

Five geotechnical models were reconstructed representing the spatial variability of tip resistance and lateral friction resistance, measured by CPT, and geotechnical parameters derived by empirical formulas, such as elasticity module, oedometric module, and compression index. For each of these parameters, a 3D model was reconstructed and their values were graphically represented with color scales varying from "hot" colors (tending to red), as representative of higher values, to "cold" colors (tending to purple), as representative of lower values (Fig. 8).

The P-data logs, added to the basic model, are formed by a series of overlapping colored disks that occur according to the sampling step (in this specific case of 0.2 m), whose dimension (diameter) and color represent the value of the parameter.

From the analysis of 3D models of the tip resistance, elasticity module, and oedometric module, soils down to a depth of 4–5 m were recognized with significant values of geotechnical properties. Instead, at greater depths, there is a general decay of geotechnical properties due to the alternation of soil horizons with poor values. Finally, the models
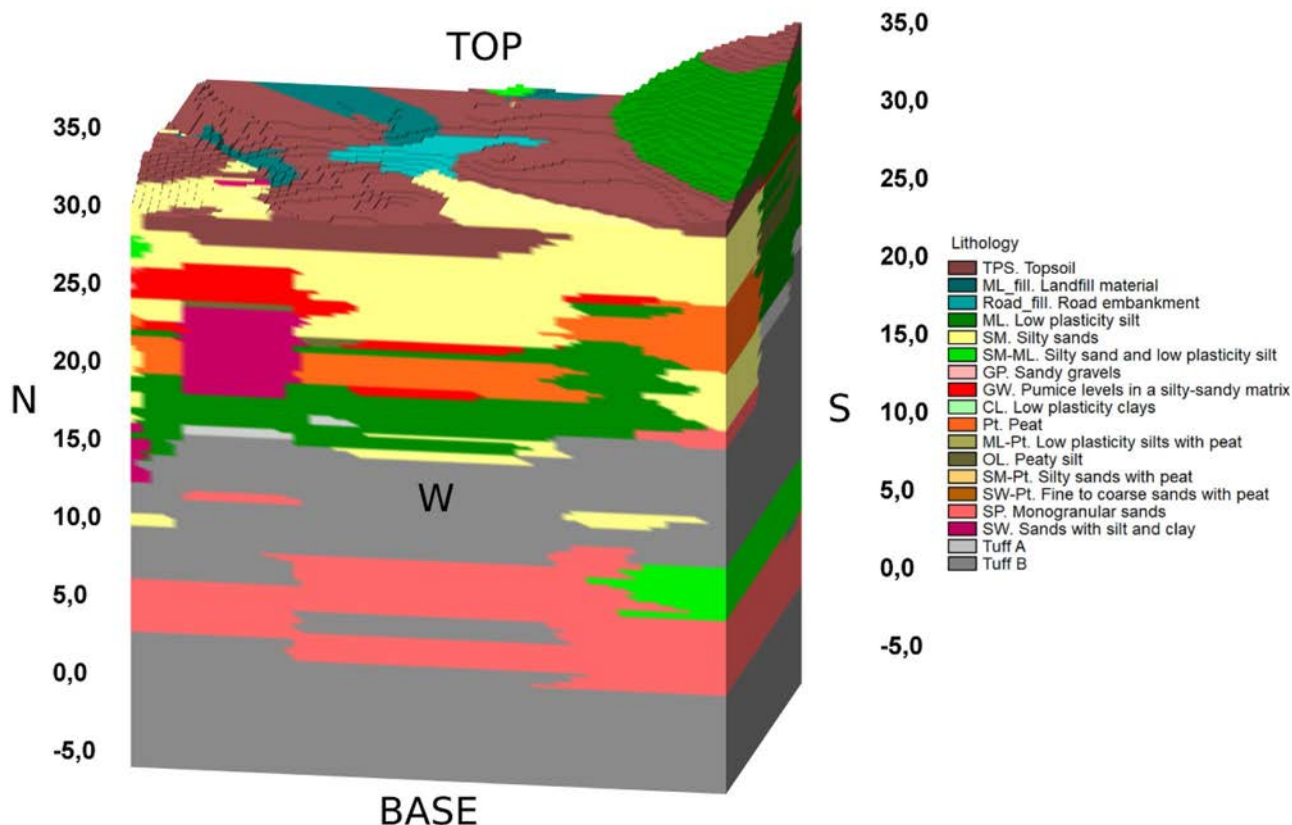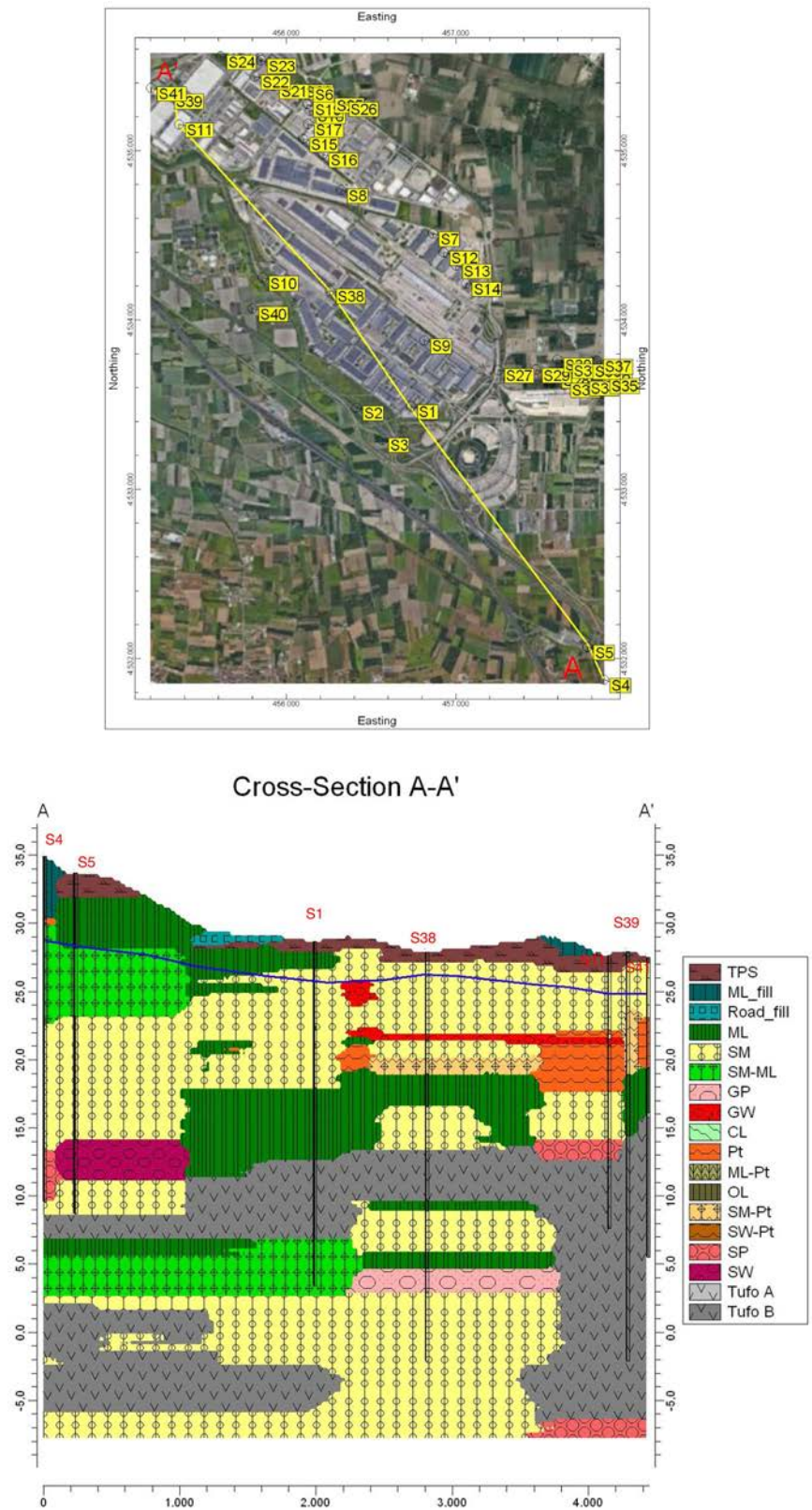

Fig. 5 Lithological model with indication of USGS classification

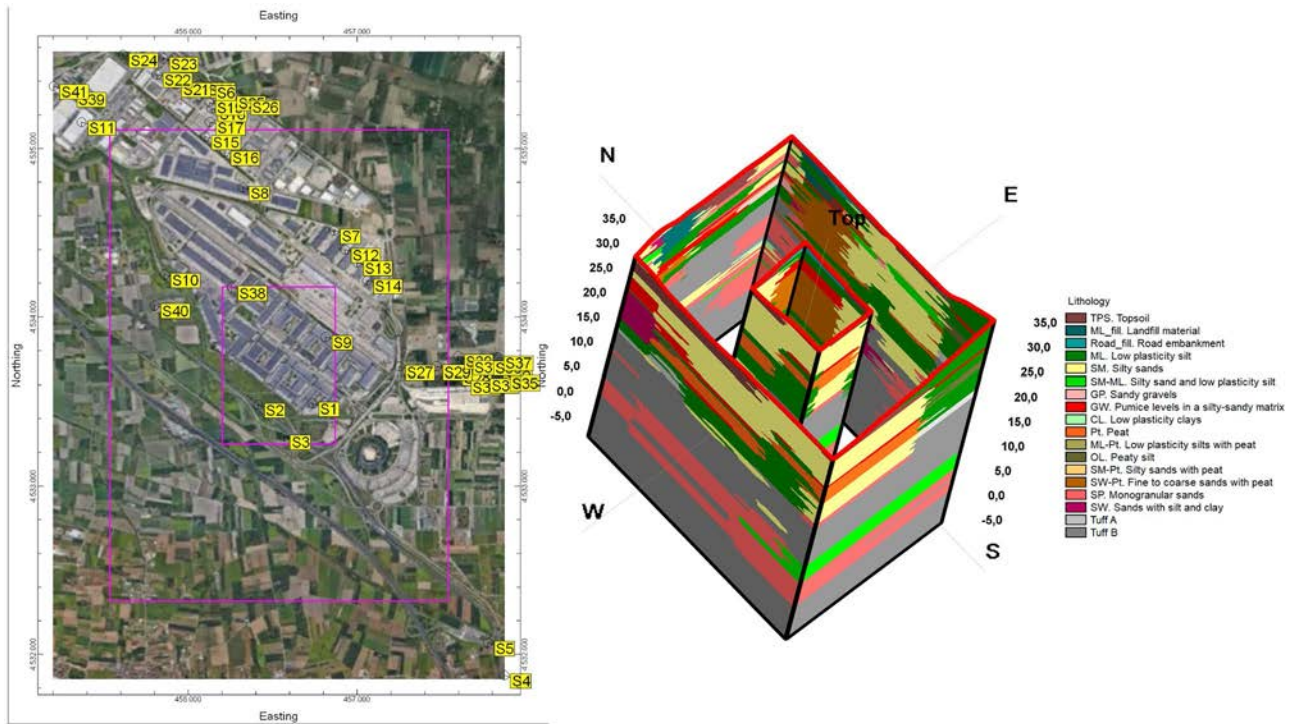**Fig. 6** Cross section A-A' and location on the map

Fig. 7 Concentric fence diagram with indication of USGS classification

show a marked improvement of geotechnical properties in the deepest zone, approximately down the altitude of 15 m a.s.l., as showed by the highest values of tip resistance (about 70 MPa), elasticity module (about 140 MPa), and oedometric module (about 122 MPa).

By the 3D models of tip resistance, lateral friction, and compression index, a lower spatial variability and a progressive increase of values down to the altitude of 20–25 m a.s.l. is recognized. Instead, a high value of compression index is recognized at different altitudes depending on the

Fig. 8 3D model of tip resistance by CPT tests
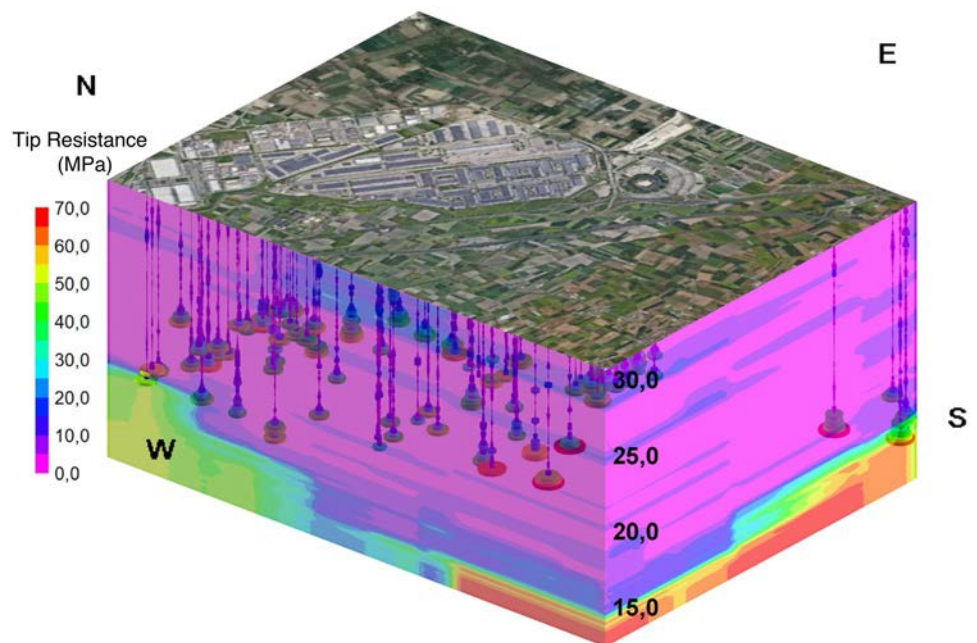
occurrence of highly compressible organic soil horizons (Fig. 9).

Engineering geological model

The jointed interpretation of the 3D geotechnical models with the lithological one allowed the recognition of engineering geological units belonging to the rank of engineering geological types (UNESCO-IAEG 1976) and therefore the reconstruction of the engineering geological model (Fig. 10).

The engineering geological types recognized for the study area are described in the following.

Engineering geological type A — low compressible silts (ML)

Formed by low compressible silts which can be classified in the ML group (USCS). In general, these soils are normally consolidated (NC) and only subordinately over-consolidated (OC). Their pozzolanic nature favors an intergranular cohesion due to low-grade crystallization processes such as zeolitization. The analysis of geotechnical properties indicated for this unit a general good condition for foundations with low settlement.

Engineering geological type B — high compressible silts and peat (MH — peat)

This units comprises poorly to normally consolidated (NC) silt and peat which are characterized by a relevant variability in physic and geotechnical conditions.

The peculiar characteristic of this unit is the presence of peaty lenticular deposits that enhances the compressibility of the whole unit, thus characterizing it with a poor geotechnical quality due to scarce value for foundations and relevant settlement.

Engineering geological type C — semi-lithoid tuff

Consisting of fine-grained ash-tuff, from semi-lithoid to lithoid with spatially variable thickness and welding. The tuff basal horizon is always preceded by the weathered term called "cappellaccio" and its low degree of compressibility is showed by high values of the tip resistance, elasticity module, and oedometric module. The top of the tuff horizon is identified by the refusal depth of CPT. Due to its geotechnical features, it represents a bedrock reference for eventual deep foundations with negligible settlement expected.

The good geotechnical properties of the shallower engineering geological unit are probably determined by an over-consolidation degree induced by the lowering of groundwater table. This lowering may have resulted either from a reclamation process of the area or from over-exploitation of the groundwater for agricultural use. The groundwater level is mostly coincident with the bottom of the engineering geological type A. Another essential factor that distinguishes the different geotechnical behavior of the two units is the intercalation of highly compressible peat deposits in the soils that characterizes the engineering geological type B. From the lithological 2D and 3D models shown above, peat deposits result with a very

Fig. 9 3D model of compressibility coefficient. Horizons with high compressibility are circled in red
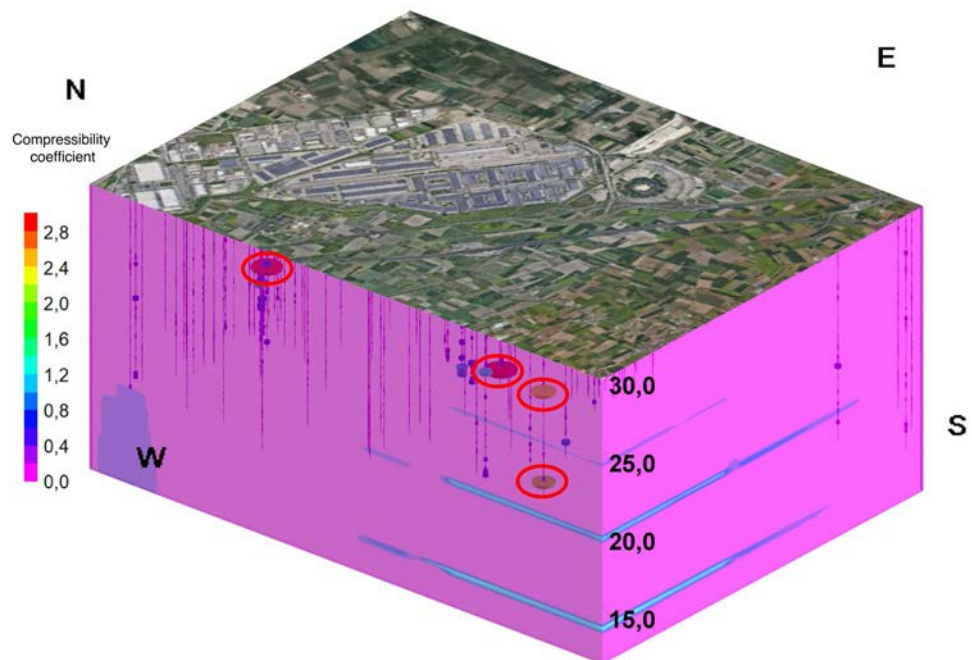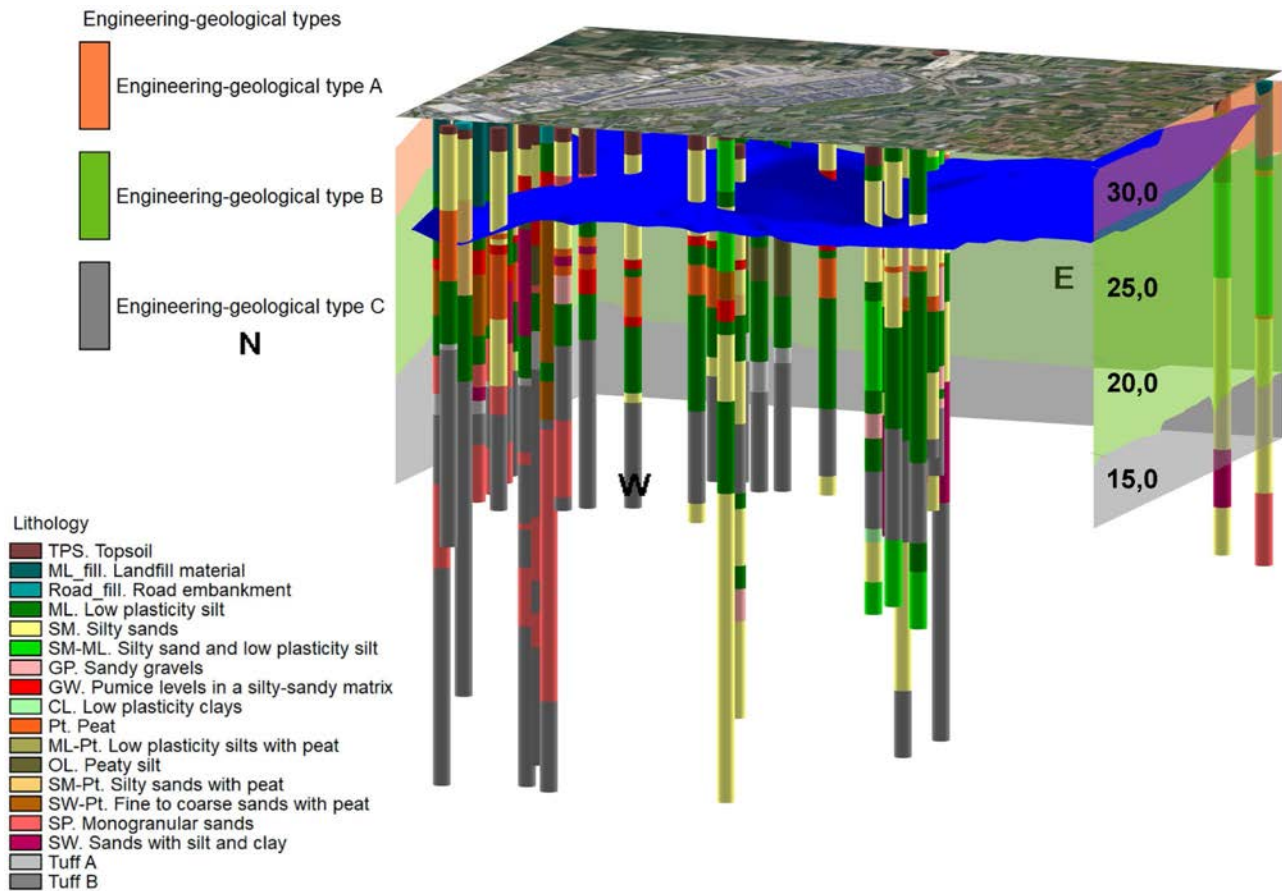
Fig. 10 Engineering geological units and lithology logs with indication of USCS classification

variable thickness. Their uneven occurrence could originate significant differential settlements, as demonstrated by other cases experienced in the area by these materials when subjected to overloads.

The very good match between the spatial variation of the geotechnical parameters and the engineering geological model of the subsoil is shown in the following figures (Fig. 11a, b, c, d, and e) in which the engineering geological model was combined with each geotechnical model. Therefore, considering the mean values of geotechnical properties, it is possible the following characterization:

The engineering geological type A — low compressible silts (ML) — is characterized by medium–high values of tip resistance (8 MPa), elasticity module (19.8 MPa), and oedometric module (14 MPa) and by a low value of compression index (0.1);

The engineering geological type B — high compressible silts and peat (MH — peat) — has very variable values of tip resistance (3.2 MPa), elasticity module (6.7 MPa), oedometric module (5.9 MPa), and compres-

sion index (0.12); the unit consists of high compressibility levels also probably due to peaty lenses;

The engineering geological type C — semi-lithoid tuff — shows the highest values of tip resistance (30 MPa), elasticity module (62.3 MPa), oedometric module (52.5 MPa), and lateral friction resistance (0.65 MPa) confirmed also by the low compression index values (0.07).

Statistical characterization of the geotechnical properties

The geotechnical characterization of engineering geological units was carried out by a statistical analysis of principal properties which was accomplished by a box plot analysis. For each engineering geological unit, a box plot was calculated for each geotechnical property and mutually compared (Fig. 12a, b, c, d, and e), finding coherence with what previously described about their values. The C type is the only engineering geological unit that has higher values
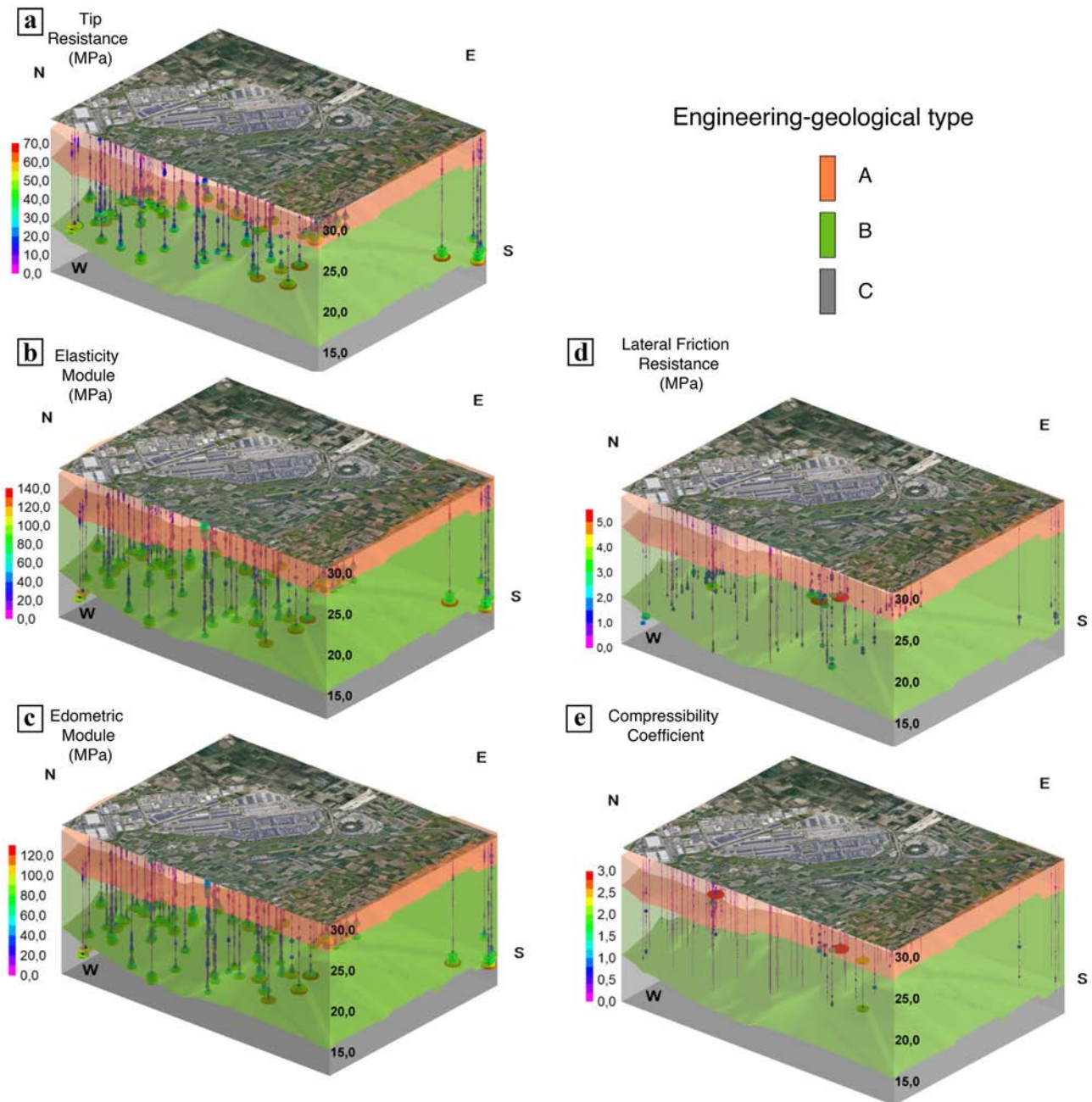
Fig. 11 Engineering geological model combined with tip resistance (**a**), elasticity module (**b**), oedometric module (**c**), lateral friction resistance (**d**), and compression index (**e**) geotechnical models

of geotechnical properties, since the tip resistance, resistance to lateral friction, elasticity module, and oedometric module values reach the highest values, instead those of the compression index reach the lowest ones. On the contrary, the B type is the engineering geological unit which is characterized by the poorest values of geotechnical properties, since the first four parameters tend to be distributed towards the lowest values, while the compression index towards the

highest, according to the higher compressibility of these soils.

The statistical analysis of geotechnical properties for each engineering geological unit was based on the calculation of 5%, 25%, 50%, 75%, and 95% percentiles (Table 1). As known from the practice of geotechnical design, the choice of percentiles to be used depends on the problem to be solved and the volume of soil involved in the artificially induced
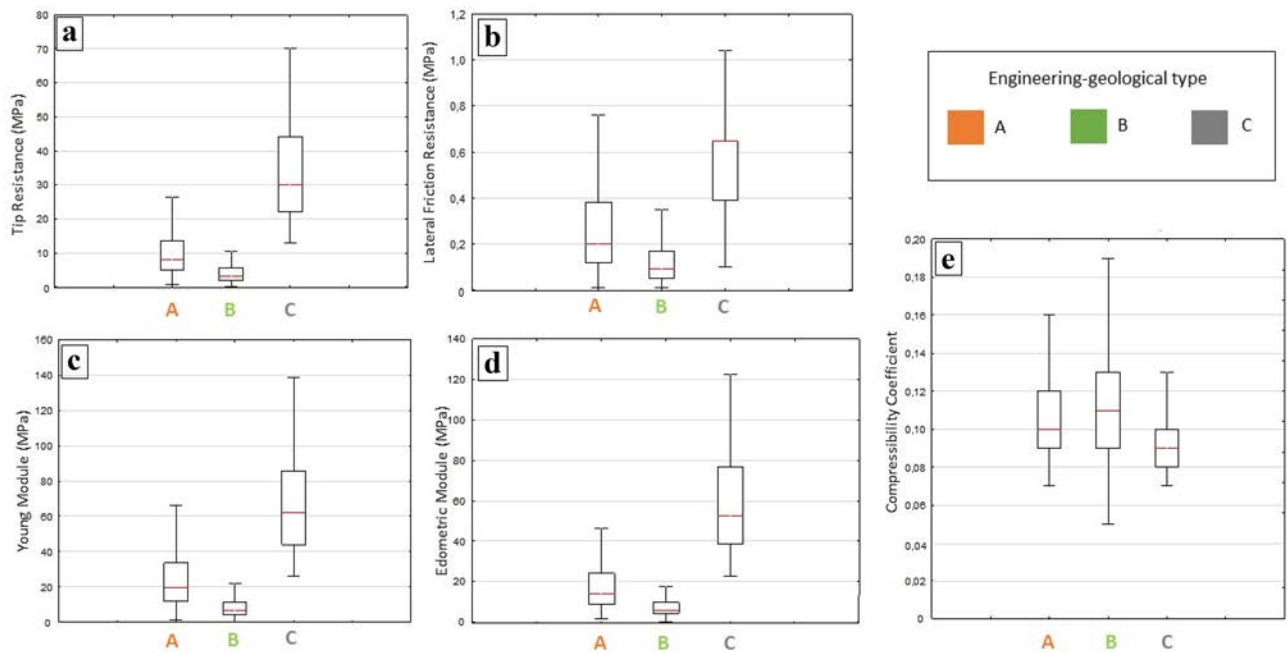
Fig. 12 Tip resistance (**a**), elasticity module (**b**), oedometric module (**c**), lateral friction resistance (**d**), and compression index (**e**) box plots of the three engineering geological units

Table 1 Percentile values of geotechnical properties, estimated for the three engineering geological units

Percentile	Tip resistance (MPa)			Lateral friction resistance (MPa)			Elasticity module (MPa)			Oedometric module (MPa)			Compressibility coefficient		
	Unit A	Unit B	Unit C	Unit A	Unit B	Unit C	Unit A	Unit B	Unit C	Unit A	Unit B	Unit C	Unit A	Unit B	Unit C
5%	2.09	1.02	14.1	0.06	0.05	0.2	4.5	2.4	31.1	4.3	2.7	24.9	0.08	0.09	0.07
25%	5	2	22	0.12	0.06	0.39	11.8	4.1	44	8.8	4.2	35.5	0.09	0.09	0.08
50%	8	3.2	30	0.2	0.09	0.65	19.8	6.7	62.3	14	5.9	52.5	0.1	0.11	0.09
75%	13.7	5.5	44	0.38	0.17	0.65	33.6	11.3	85.6	24	9.6	77	0.12	0.13	0.1
90%	27.8	21.5	59.8	1.3	2.6	3.2	67.4	41.12	116.6	48	34.6	104.3	0.3	1.9	0.3

deformation. The representative value of the geotechnical parameters can be estimated in a reasoned and precautionary way considering a value varying from the lower values (5th percentile), in the case of a small volume of soils involved in deformation, to the median value (50th percentile), in the case of a large volume of soils involved.

Conclusions

Methods applied and results obtained in this research are intended to propose a comprehensive methodological approach for 3D engineering modeling and geotechnical characterization of design and construction sites formed by complex stratigraphic settings and heteropic sedimentary deposits. The approach has been conceived to be consistent with both concepts of engineering geological modeling and mapping and current technical rules in geotechnical design, Eurocode 7, as well as the national regulations which have followed it, such as Italian "Norme Tecniche per le Costruzioni." In such a direction, the Nola plain represents an emblematic case study regarding how a complex stratigraphic setting, characterized by heterogeneous and heteropic deposits, determines difficult ground conditions and can influence the geotechnical design, thus requiring proper engineering geological modeling and characterization approaches.

From 3D representations of the lithological, stratigraphic, and geotechnical characters, shown in this paper, it emerges that the pyroclastic-alluvial deposits forming

the subsoil of the Nola's area are mostly made of alternations of sandy silt and silty sands with lenses of intercalated peat. The occurrence of organic soils, which are characterized by high compressibility, joined with their very variable spatial distribution, represents a critical factor to be considered for the design of foundations, to avoid differential settlements. The very complex stratigraphic architecture and variable geotechnical properties of deposits allowed the identification of different engineering geological units at the highest level of detail allowed by existing data (engineering geological types).

In such a framework, the reconstruction of 3D models can be conceived as an essential approach to advance the engineering geological site characterization to be used for highlighting design issues related to soils with poor geotechnical behavior.

The analysis and interpretation of the lithological and geotechnical features of the study area have allowed the development of an engineering geological model resulted in the recognition of three engineering geological types at a detailed scale ($> 1:5,000$), which were distinguished by different geotechnical behavior. Specifically, the engineering geological type B is the one that, from a geotechnical point of view, is more problematic due to the presence of highly compressible organic material classified as organic soils (OL) or peat (Pt), according to the USCS classification. The difficult predictability of the spatial occurrence of these materials is related to their lenticular-shaped geometry with variable thickness and depth. The occurrence of these soils can generate differential settlements as it has been already experienced in previous civil works carried out in the area. Besides, the accurate assessment of spatial geometry of these deposits, another important point is the assignment of characteristic values of geotechnical parameters for each engineering geological unit, to be used for the design stage.

Finally, the approach proposed is not intended to be a simple application of a 3D modeling software to stratigraphic and geotechnical data because it has been consistently included in the conceptual framework of engineering geological modeling and mapping based on the definition of engineering geological units (IAEG-UNESCO 1976). In such a sense, the manuscript potentially represents a guideline for the application of technical rules for geotechnical design bridging between geology and geotechnics.

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