Geotechnical Characterization of Shallow Foundation and Wide Area: the Case Study of Venice Airport (Italy)

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ABSTRACT: A new arrangement of Venice Airport (Italy) was planned in order to enlarge the airside areas, by means of taxiway and runway extensions and de-icing-area. In this respect, a significant geotechnical and geophysical campaign was carried out during 2013-2014 with the aim to characterize the shallow Lagoon deposits of the wide airport zone. The combination of punctual geotechnical tests and linear geophysical methods underlined the complementarities of these two approaches to define a detailed areal model of Venice airport subsoil. In particular, these results confirm the comprehensive geotechnical studies carried out in the last three decades to characterize the Lagoon soils, highly heterogeneous and characterized by a predominant silt fraction, combined with sand and/or clay, forming a chaotic interbedding of various sediments.

1 INTRODUCTION

The subsoil of the Venice lagoon and of the closest mainland has been intensively studied in the past.

The first relevant geotechnical investigations (dating back to the decades ’60-’70), were carried out to study the man-induced subsidence, particularly important between 1946 and 1970, and to design new large industrial structures on the mainland (Simonini et al. 2007). These investigations were mostly based on laboratory tests on samples drown up from shallow and deep boreholes.

In the late 1980s, comprehensive geotechnical investigations started to design and construct various engineered solutions aimed at reducing the frequency of flooding, including huge movable gates located at the three lagoon inlets. In this respect, two research sites, Malamocco (Cola & Simonini 2002, Simonini & Cola 2000, Ricceri et al. 2002) and Treporti (Simonini 2004, Gottardi & Tonni 2004, Marchetti et al. 2004, Mayne & McGillivray 2004, Monaco et al. 2014), were also selected to accurately characterize the mechanical behavior of Venice lagoon soils and to calibrate advanced site testing techniques, such as SCPTU, DMT, CHT, SBPT etc.

Besides the presentation of some geological features of the lagoon sediments, this paper discusses the main results concerning the characterization of the shallow Lagoon deposits of "Marco Polo" Venice Airport (Italy), where several investigations were performed from the early 1970 since today. In particular this study focused on the 2013-2014 campaign, planned to enlarge the airside areas, by means of taxiway and runway extensions and de-icing-area.

2 GEOLOGICAL SETTING

The Northern Italian lowlands, namely the Padana and Veneta plains, were formed through the fluvial transport of sediments coming from the erosion of the surrounding Alps and Apennines.

At the end of the Pliocene epoch, the sea level was much higher than today and the Padana and Veneta plains were submerged.

The Pleistocene epoch was characterized by several glaciation and interglaciation periods with alternating regression and transgression of the shoreline. At the apex of last Würmian (Wiscontsinian) glaciation, the shoreline was located around two hundred kilometres from the present position and, therefore, the Padana and Veneta plains together with a part of the Northern Adriatic Sea were emerged.

Then, a warmer period set in about 15,000 years ago and the sea level rose during the de-glaciation period, reaching, between 7000 and 5000 years ago, a value slightly higher than the present one. The origin of the Venice lagoon is traced around 6000 year ago, during the flandrian transgression, with the sea water diffusing into a pre-existing lacustrine basin.

In the Venetian lagoon, the upper hundred metres below mean sea level (MSL) are characterized by a complex system of sands, silts and silty clays chaotically accumulated during the Würmian glaciations (Favero et al. 1973). The Holocene epoch is responsible only for the shallowest lagoon deposits, up to 10-15 m below ground level.

The top layer of Würmian deposits is composed of a crust of highly overconsolidated very silty clay, commonly referred as to *caranto*, on which many historical Venetian buildings are founded through driven wooden piles. It was subject to a process of overconsolidation as a result of exsiccation during the 10,000 year emergence of the last Pleistocenic glaciation. Moving from the mainland towards the shoreline, the *caranto* layer lies at depths increasing from less then 5 m to about 16 m below MSL (Gatto & Previatello 1974).

3 GEOTECHNICAL AND GEOPHYSICAL INVESTIGATIONS

The "Marco Polo" Airport is an international airport located on the mainland 8 km north of Venice, Italy. The importance of this infrastructure (actually it is the 3rd airport in Italy) that needed some expansions, and the heterogeneity of Venetian soils, required different geotechnical and geophysical campaign during the last decades.

Between 1972-1973 in situ and laboratory tests were performed for the extension of the runway (blue area, Fig. 1). The test depth reached 14 m to characterize the sandy layer detected roughly at 7 m depth. Instead, a supplementary campaign was realized for the fire and finance police stations in 2009. Additional investigations, including California bearing ratio (CBR) and plate load tests, were carried out along the existing runway (violet polygon, Fig. 1) in 2012, and then in 2013 in order to renovate the pavement. Finally, during 2013-2014 a new arrangement of Venice Airport was planned to enlarge the airside areas, by means of taxiway and runway extensions and de-icing-area. In this respect, a significant geotechnical and geophysical campaign was carried out in the “TWT TN” taxiway extension (red rectangular, Fig. 1), “04L22R” runway extension (blue polygon, Fig. 1) and de-icing areas (yellow rectangular, Fig. 1), beside other tests in the *resa* and *barena* (green area) and the existing runway. The investigation was aimed to analyze the airside subgrade and the shallow Lagoon deposits of the wide airport zone, and it included 5 boreholes and 10 trenches, 2-15 m depth; 14 seismic dilatometer (SDMT) tests, 10 m depth; 65 piezocone (CPTu) tests, 5-20 m depth; oedometric, triaxial and direct shear tests from 11 indisturbed samples; 15 electric resistivity tomography (ERT) and 14 multichannel analysis of surface waves (MASW) surveys. Due to the huge amount of data, Fig. 2 plots only the SDMT tests that were performed mainly in the “TWT TN” taxiway extension (SDMT3 to SDMT6), and “04L22R” runway extension (SDMT7 to SDMT9, SDMT11 to SDMT13) areas, while the de-icing area included three verticals (SDMT1, SDMT2, SDMT10) and the *resa* and *barena* area only SDMT14. Addition details are available in SOGEN s.r.l. (2014).

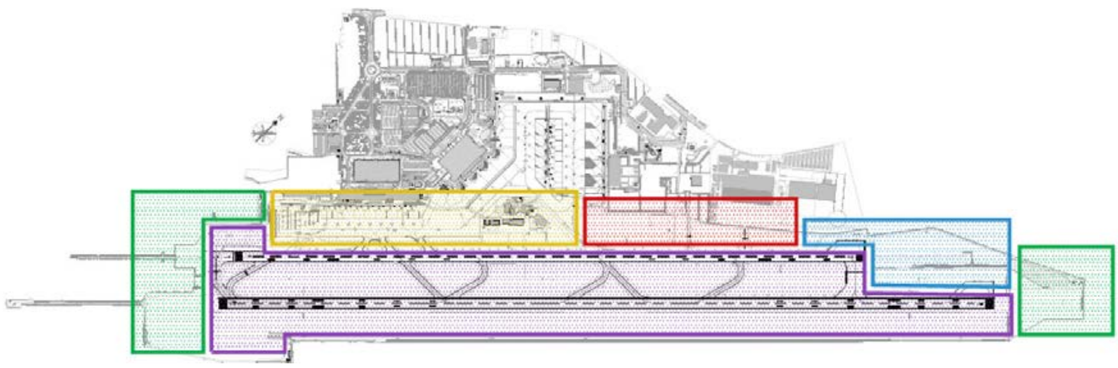

Fig. 1. Infrastructures of “Marco Polo” Venice Airport (Italy).

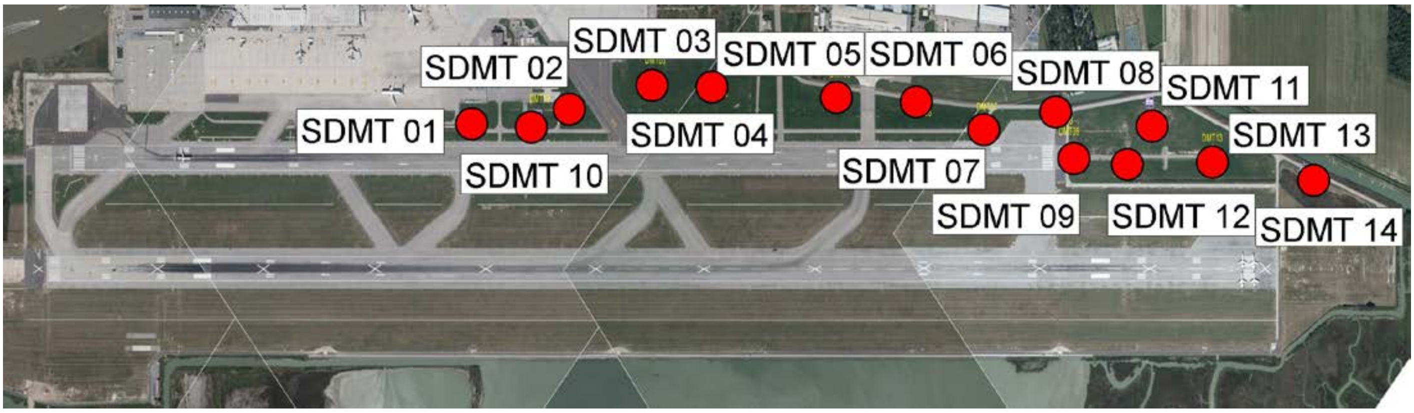

Fig. 2. Location of seismic dilatometer tests at “Marco Polo” Venice Airport (Italy).

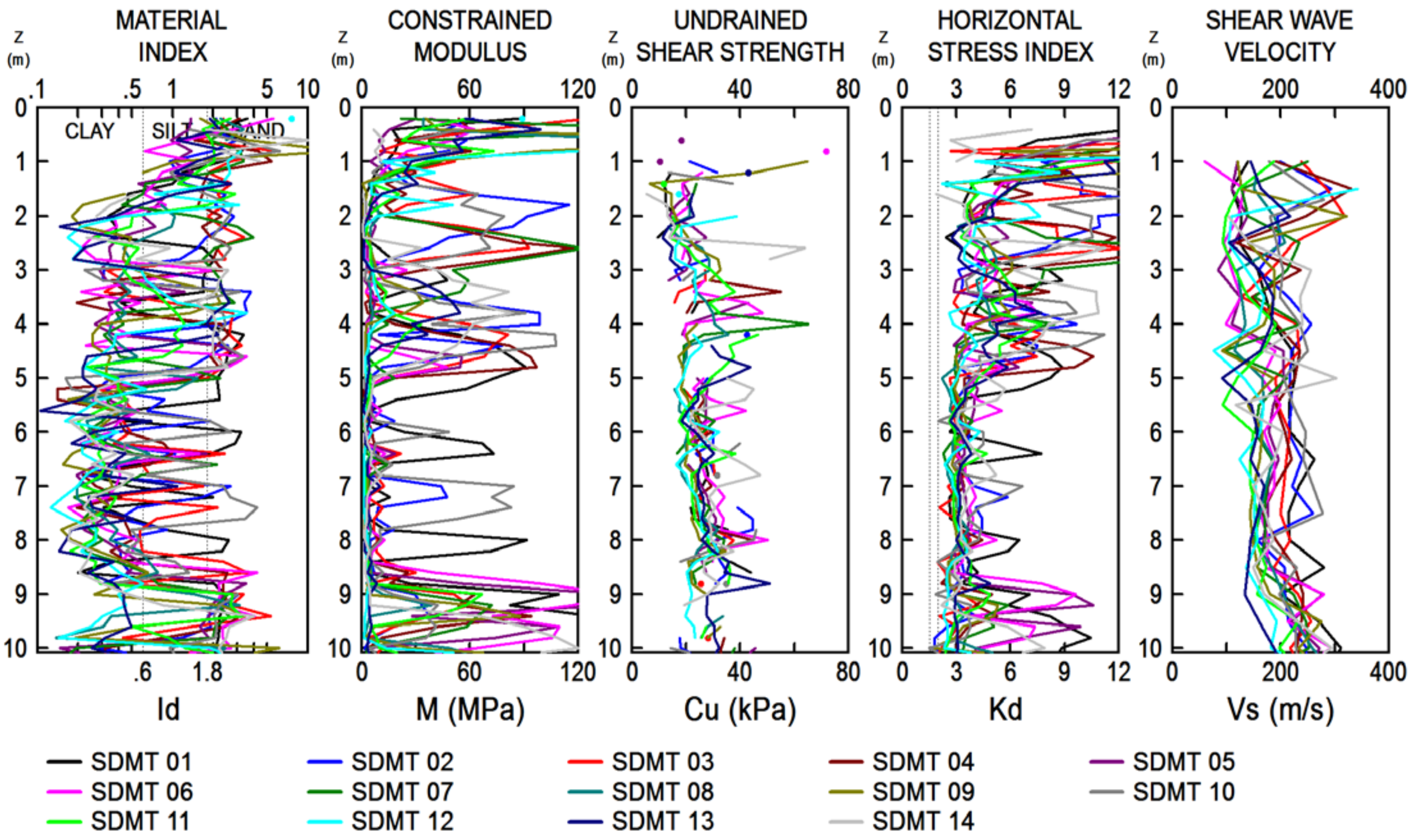

Fig. 3. SDMT test results at “Marco Polo” Venice Airport (Italy).

Fig. 3 summarizes the profiles with depth of the SDMT parameters, in terms of material index I_D (indicating soil type), constrained modulus M, undrained shear strenght c_u, and horizontal stress index K_D (related to stress history/OCR), obtained using common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001), as well as shear wave velocity V_S (Marchetti et al. 2008).

The ground water level was detected between 0.5 m depth (“TWT TN” taxiway extension area) and 1.80 m depth (“04L22R” runway extension area) by means of the C-readings (see Marchetti et al. 2001), additional DMT measurements which were acquired only in sandy layers. This result was also verified by piezometers and piezocone tests, and a historical documentation that provided the water table fluctuations too.

SDMT profiles, together with CPTus, confirmed the heterogeneity of the lagoon deposits since I_D moves from sand-like to silty-like to clay-like behaviour, and the soil resistance and deformability are highly variable. In this respect, different subsoil models were identified for each area of the "Marco Polo" Airport. The following paragraphs are going to introduce the geotechnical units detected for a section of “TWT TN” taxiway extension area and of “04L22R” runway extension area, combining punctual geotechnical tests and linear geophysical methods.

3.1 *"TWT TN" taxiway extension area*

A sample section was considered at "TWT TN" taxiway extension area to detect the subsoil model. In particular, ERT05 and ERT06 were used together with MASWT2 tests, as linear geophysical methods, while SDMT04, 5mCPTU15, 5mCPTU16 and 15mCPTU17 in situ tests, and 15mS03 borehole with samples were identified for punctual geotechnical tests.

Both the ERT surveys were performed using a linear array of 48 electrodes (equally spaced of 2 m) organized in Wenner-Schlumberger and dipole-dipole configurations. The 2D resistivity model, as shown in Fig. 4, is quite homogeneous across the section. On average the resistivity values are equal to 10 Ω within 1 m depth, while they are smaller than 2.5 Ω m between 1 m and 10 m and over 2.5 Ω m at higher depth.

The active seismic survey was acquired close to the same line by using 24 vertical geophones (with eigenfrequency of 4.5 Hz), spaced at first 0.5 m, and then 2.0 m, and a manual hammer (5 kg), connected to an integrated trigger system. More than six shots were performed in different source positions, and dispersion curves were reconstructed considering a frequency of 12-24 Hz, showed apparent surface waves phase velocities ranging between 160 and 170 m/s. V_S profile from MASWT2 is lower than the one from SDMT04, that ranges between 150 m/s and 250 m/s (Fig. 4).

CPTu and SDMT profiles, and borehole log were coupled with linear data to provide a detailed 2D subsoil model. Table 1 summarizes the average parameters obtained for each geotechnical unit: unit weight γ (from in situ and laboratory tests), corrected cone resistance q_t, constrained modulus M_{DMT}, horizontal stress index K_D, overconsolidation ratio *OCR* (from SDMT and CPTu), undrained and drained shear strength parameters in terms of c_u, c', φ'(from in situ and laboratory tests), and shear wave velocity V_S (from SDMT).

M_{DMT} was assumed as oedometric modulus, representing a reasonable estimate of the "operative" or drained *working strain* modulus (i.e. the modulus that, when introduced into the linear elasticity formulae, provides realistic estimates of the settlement of a shallow foundation under working loads). This assumption is supported by the good agreement observed in a large number of well documented comparisons between measured and DMT-predicted settlements or moduli (see Monaco et al. 2006, Marchetti et al. 2008), such as Treporti test site (Marchetti et al. 2004, Monaco et al. 2014).

OCR was evaluated from DMT interpretation formulae (Marchetti 1980) for undrained soils, while from SDMT and CPTu for sands according to Monaco et al. (2014) formulation, calibrated for Treporti site.

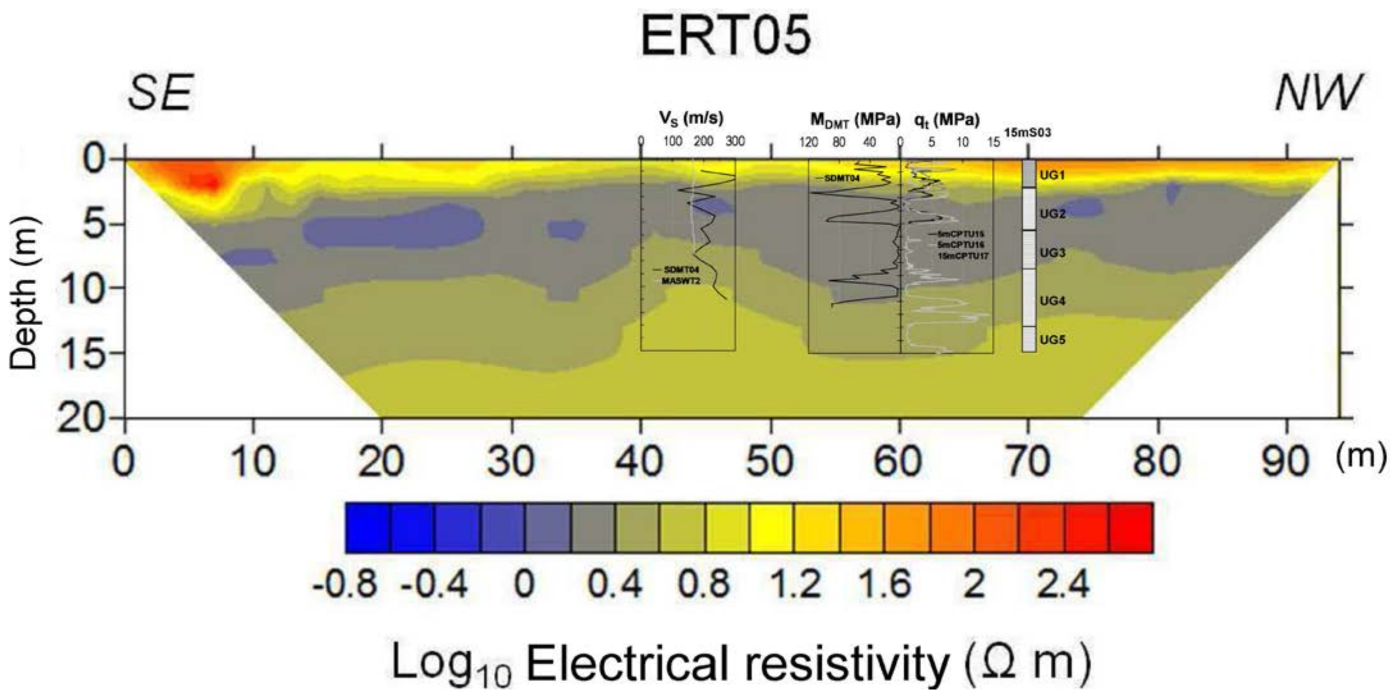

Fig. 4. Geotechnical and geophysical investigation for a section of "TWT TN" taxiway extension area.

Table 1. Geotechnical units for ERT05 section.

Geotechnical unit	Depth (m)	γ (kN/m^3)	q_t (MPa)	M_{DMT} (MPa)	K_D	OCR	c_u (kPa)	c' (kPa)	φ' (°)	V_S (m/s)
UG1-Fill material	0.0-2.0	17.0	2.4	31.5	12.9	1.0	-	0	44	256
UG2-Silty sand with clay	2.0-5.0	17.8	4.5	50.7	7.9	2.0	-	0	41	193
UG3-Silty clay with mud	5.0-8.4	18.6	1.2	4.5	3.3	2.2	27.3	5	27	194
UG4-Silty sand with clay	8.4-12.6	20.2	5.7	43.5	4.1	1.1	-	0	37.5	243
UG5-Silty clay with sand	12.6-15.0	19.2	2.8	-	-	-	60.7	5	27	-

Friction angle φ' estimation relies on CPTu (Durgunoglu & Mitchell 1975, Simonini et al. 2007) and laboratory data, while undrained shear strength coupled DMT results with lab tests since flat dilatometer test is an undrained test.

Atterberg limits are characterized by average values of liquid limit LL = 36±9% and of plasticity index PI = 14±7%, as already found by Simonini et al. (2007) at Malamocco site.

OCR values suggests, in the upper 10 m, light overconsolidation, possibly as a result of erosion that occurred during the Pleistocene, combined with the effects of waves/tides, aging, and desiccation (Monaco et al. 2006).

3.2 *"04L22R" runway extension area*

A cross section was considered also at "04L22R" runway extension area to define the geotechnical model. In particular, ERT13 and ERT14 were used together with MASWT4 tests, as linear geophysical methods, while SDMT13, 5mCPTU33 and 15mCPTU13 in situ tests, and 15mS05 borehole with samples were identified for puntual geotechnical tests.

ERT surveys and MASW test followed the same procedures used for "TWT TN" taxiway extension area. The 2D resistivity model, as shown in Fig. 5, is quite homogeneous across the section. On average the resistivity values are equal to 10 Ω within 1 m depth, while they are smaller than 2.5 Ω m between 1 m and 10 m and over 2.5 Ω m at higher depth. Dispersion curves were reconstructed considering a frequency of 6-22 Hz, showed apparent surface waves phase velocities of about 150 m/s. V_S profile from MASWT2 was not provided, hence Fig. 5 plots only the one from SDMT1, that ranges between 100 m/s and 200 m/s.

CPTu and SDMT profiles, and borehole log were coupled with linear data to provide a detailed 2D subsoil model, and the results are summarize in Table 2.

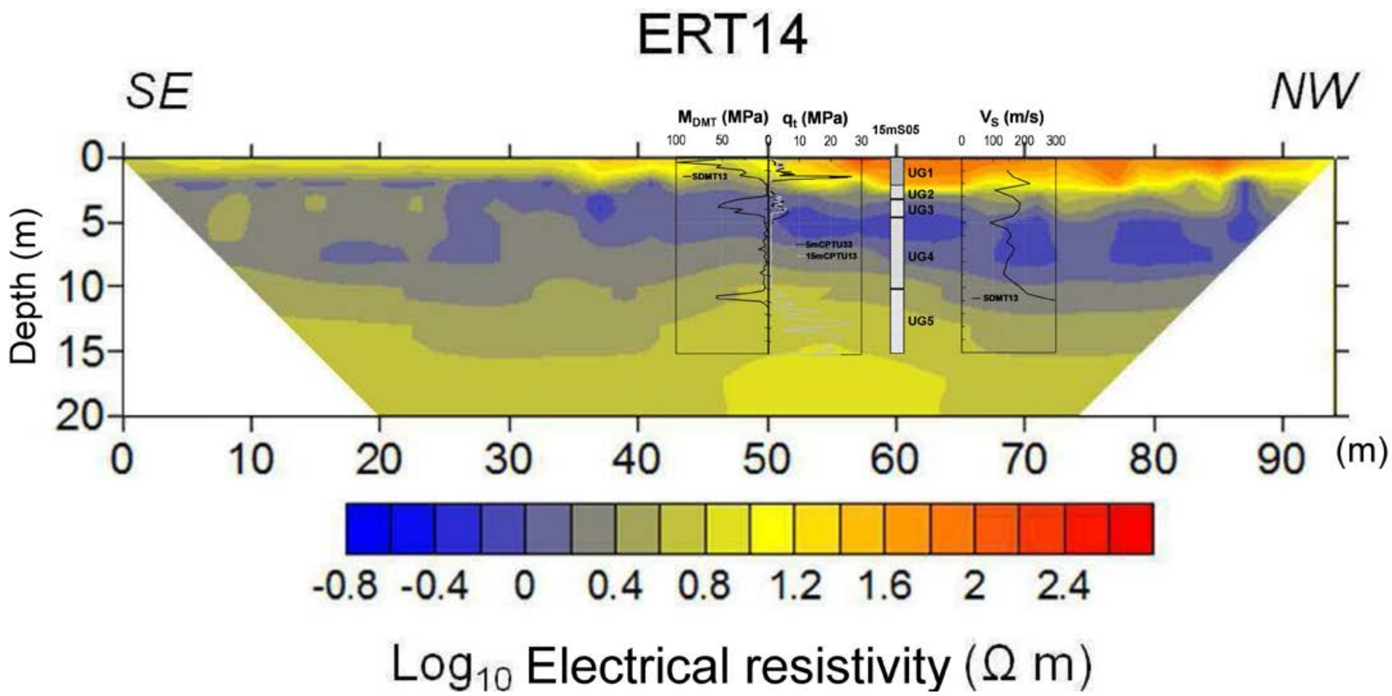

Fig. 5. Geotechnical and geophysical investigation for a section of "04L22R" runway extension area.

Table 2. Geotechnical units for ERT14 section.

Geotechnical unit	Depth (m)	γ (kN/m^3)	q_t (MPa)	M_{DMT} (MPa)	K_D	OCR	c_u (kPa)	c' (kPa)	φ' (°)	V_S (m/s)
UG1-Fill material	0.0-1.4	17.7	2.6	49.4	26.8	1.0	-	0	45	154
UG2-Silty clay with mud	1.4-3.0	15.5	0.8	3.7	4.0	3.0	17.3	5	27	161
UG3-Silty sand with clay	3.0-4.2	18.3	3.6	40.5	6.0	2.0	-	0	39	185
UG4-Silty clay	4.2-10.4	16.6	1.0	4.0	3.5	2.4	29.1	5	27	149
UG5-Silty sand with clay	10.4-15.0	17.9	13.7	50.1	4.3	1.2	-	0	41	231

4 COMPARISONS OF THE RESULTS

The combination of punctual geotechnical tests and linear geophysical methods underlined the complementarities of these two approaches to define a detailed areal model of Venice airport subsoil.

Geophysical methods can support to define a "first order" 2D subsoil model, detecting the main lateral variations and thickness of the deposits found in a wide area. Instead, in situ testing can refine the details of this preliminary model, identifying critical points that need to be investigate in order to have a thorough knowledge of the whole site.

At "Marco Polo" airport the collected data confirm the comprehensive geotechnical studies carried out in the last three decades to characterize the Lagoon soils, highly heterogeneous and characterized by a predominant silt fraction, combined with sand and/or clay, forming a chaotic interbedding of various sediments.

"TWT TN" taxiway extension and "04L22R" runway extension areas provides significant variations of the stress level within the first 10-15 m depth, as shown by DMT and CPTu profiles, by means of the corrected cone resistance q_t and the constrained modulus M_{DMT} (Figs. 4, 5). This aspect can be also noted introducing Janbu's relationship (Eq. 1) that considers the dependence of the Young modulus E on the stress level:

$$E = K_E p_a \left(\sigma_v^{'} / p_a\right)^n \qquad (1)$$

where K_E is the modulus number; p_a is the reference atmospheric pressure (100 kPa); σ_v' is the current vertical effective stress; and n is the exponent, generally varying between 0.5 and 1; here, assumed equal to 0.5 in accordance with Cola & Simonini (2002). The variation of the modulus number K_E corresponding to E derived from M_{DMT}, assuming a Poisson's ratio of $\nu = 0.15$ (hence for the theory of elasticity, E = 0.95 M_{DMT}) is represented in Fig. 6, and it confirms the deviation of CPT and DMT parameters at low and high stress level.

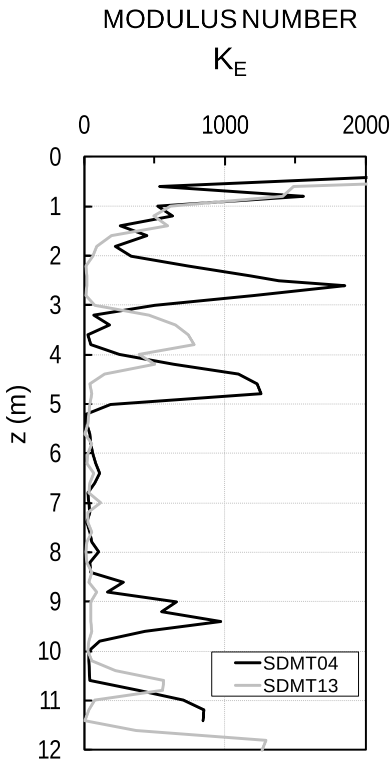

Fig. 6. Modulus number profiles at "TWT TN" taxiway extension and "04L22R" runway extension areas.

5 CONCLUSIONS

The extensive investigations carried out to enlarge the airside areas, by means of taxiway and runway extensions and de-icing-area, allowed to collect a huge amount of geotechnical data gathered since the 70's.

The combination of punctual and linear tests underlined the complementarity of these two approaches to define a detailed areal model of the subsoil.

Further studies are suitable to be prepared in order to increase the value of the available information considering the research interest on Venice lagoon deposits.

6 ACKNOWLEDGEMENTS

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