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GEOTECHANICAL CHARACTERIZATION OF THE LEVEES OF TAGLIAMENTO RIVER (ITALY): INSIGHTS AND IMPLICATIONS FOR LEVEE VULNERABILITY

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Recent flooding events in the Po Plain have once again highlighted the critical importance of river embankments in protecting against hydrogeological risk. The current characterization methodology relies on localized investigations (penetrometric tests and boreholes), combined with geophysical surveys. However, spatial variability and the presence of local heterogeneities of diverse origins can promote various forms of instability and, in the worst-case scenario, lead to breaching. Their analysis necessitates novel investigation methods and data analysis techniques.

This study presents the characterization of the lower Tagliamento River embankments, conducted through two investigation campaigns encompassing 120 CPTs (Cone Penetration Tests), 20 boreholes, and several ERT (Electrical Resistivity Tomography) surveys, covering a length of 40 km. Additionally, 15 CPTs were performed in closely spaced vertical profiles, at intervals of only 6 meters.

The results were analysed to assess the vertical and longitudinal spatial variability of specific soil characteristics at various scales, with the aim of enhancing the reliability of embankment safety evaluations.

Keywords: Embankments; Levee; Site investigation; Spatial variability; closely spaced CPT.

1. Introduction

River embankments are critical infrastructural components designed to protect surrounding areas from flooding. These embankments are longitudinal structures, constructed using local soils and materials, characterized by limited cross-sections and extensive lengths. Their current configuration is often the result of reinforcements and enlargements implemented over time using various methods, and local repairs executed with diverse materials, frequently under emergency conditions. Consequently, despite being an artificially constructed embankment, the levee body may be characterized by significant spatial variability, with heterogeneities primarily linked to human activities occurred over centuries, information about which is lost over time: materials used, construction and compaction methods, maintenance practices, or repair works of local breaches (Demer et al. 2019).

Spatial variability and the presence of local heterogeneities of diverse origins, in terms of material composition or compaction, can cause localized zones of lesser resistance, local variability in hydraulic conductivity, or preferential seepage paths. These are potential triggers for the most common embankment failure mechanisms such as internal erosion or slope instability, which can lead to the opening of a new breach (Vanmarcke 2011; De Gast et al. 2021; van Beek et al. 2011; Kool et al., 2022). Although crucial for assessing the stability and safety level of the infrastructure, detailed knowledge of the embankment's composition and characterization of material properties along its entire length is generally lacking due to the length of these structures, subsequent modifications, and the difficulty of conducting and interpreting large-scale investigations.

Typically, geotechnical characterization of river embankments is performed through in-situ investigations, such as boreholes and CPT tests: these can provide direct or indirect measurements of soil properties, but are limited to characteristic sections of the analyzed stretch. The possibility of extending the acquired information remains difficult to define: even small-scale variations in strength parameters, such as cohesion and friction angle, can lead to substantial differences in the calculated safety factor in stability analyses. Generally, geotechnical investigations are associated with geophysical surveys, such as ERT geoelectrical tests, which can provide continuous spatial data on soils properties, supporting the identification of heterogeneities, but require point-wise calibration to be correctly interpreted (Dezert et al. 2019).

Despite significant advances in understanding the spatial variability of levee soils, several challenges remain, particularly in bridging the gap between small-scale and large-scale levee soil variability characterization. This paper presents an attempt to evaluate spatial variability using a comprehensive on-site investigation dataset acquired along the Tagliamento River levees in northeastern Italy. The study integrates characterization data obtained at different spatial resolutions through a multi-scale comparison.

2. Dataset description and applied methodology

The Tagliamento River is considered the last natural river in the Alps, maintaining intact characteristics along its course. The river has a torrential nature, with a basin of approximately 2,916.86 km² and a total length of 178 km. In its upper and middle course, it flows freely with a braided channel morphology, variable discharge, and significant interaction with phreatic aquifers, facilitated by the presence of highly permeable gravel deposits. Beyond the spring line, the river flows over an alluvial plain composed of silty-clayey flood deposits and sandy channel bodies, characterized by extreme variability both horizontally and vertically. Spaliviero (2003) reports interesting information on the history of the embankments reporting their evolution and historical cartography with the localization of major flood events. By 1833 a significant portion of the current embankments were already present, with their completion occurring shortly after 1850. From 1850 onwards, an increase in river levels was recorded, consequently increasing episodes of breaches or overtopping, causing consequent reconstruction or reinforcement operations of the embankments. In 1889, following the devastating flood of 1882, all embankments were reinforced and remained so until 1966 when, after another significant flood event, all embankments were raised by approximately 2m. Finally, other reinforcement interventions were implemented (bank revetments, jet-grouting diaphragms, raises, and thickening).

On the levee of the Tagliamento River, in 2019 and 2023, two extensive geotechnical campaigns were conducted on the river embankments in the plain stretch, for a total length of 40 km up to the outlet into the Adriatic Sea. The campaigns included more than 110 penetration tests (CPTUs, CPTs, SCPTUs, and DPSHs), 20 boreholes with collection of undisturbed samples for laboratory testing, and about 10 DMTs, combined with several cross-sections and longitudinal ERT surveys. Additionally, 15 CPTs were performed at 6m intervals along the right levee axis, to analyze the horizontal spatial variability in an84m long stretch.The results were analyzed to assess the vertical and horizontal spatial variability of soil properties at different scales: this paper describes the CPT and CPTUs data, comparing the results obtained by the 15 closely spaced CPTs with the ones obtained by the CPTU performed along the whole 40 km stretch.

In the verticals investigated by the CPT, cone tip resistance q_c and sleeve friction f_s were measured at vertical intervals of 2cm. The Robertson's Soil Behavior Type Index $I_c$was evaluated from the data at each depth, to identify the stratigraphic profile in each investigation point (Robertson 2009). To quantify the horizontal variability captured by the closed space CPTUs in the stretch, descriptive second-moment sample statistics were calculated depth-wise for $q_{c,}$ f_s and I_c..For the$I_c$dataset, characterized by a normal distribution, the mean value (μ), standard deviation (Ã) and coefficient of variation (COV = ¼Ã) are computed over the horizontal direction for each investigated depth (Ceccato et al. 2021). Unlike, the datasets of q_c and f_s have a log-normal distribution, thus for them the dataset distribution limits have been calculated through the "back-transformed" values $\mu* = e^{\mu}$, $\tilde{A}* = e^{\tilde{A}}$. As indicated by Limpert et al. (2001), both the inferior and superior limits corresponding to the probability of 68.3% (calculated as $[\mu*/\tilde{A}*, \mu*\cdot\tilde{A}*]$) and the probability of 95.5% (calculated as $[\mu*/(\tilde{A}*)^2, \mu*\cdot(\tilde{A}*)^2]$) have been evaluated and represented in Fig.1. After checking the material homogeneity along the entire river embankment (40km), the described statistical approach has been extended to the entire penetration tests dataset.

3. Results

The closed spaced tests reached a maximum depth of 6m, where the levee body is almost 5.20m high. The depth-wise profiles are represented in Fig.1 a-c. In thegraphs, the gray shaded areas represent the values within one sample standard deviation from the sample mean. Three different stratigraphic units are identified by the $I_c$average vertical profile; a first sandy superficial layer down to about the depth of 1.2m (the 1960s reinforcement), a second layer classifiable as a mixture of sand and silts down to the depth of 2.8-3m, and a last layer of silt mixtures, from clayey silts to silty clays. Although the closely spaced CPTs were conducted at intervals of only 6m, Figures 1a-b demonstrate significant horizontal variation in the strength properties (q_c, f_s) measured at the same depth. As expected, the cone tip resistance exhibits greater variability near the interfaces between different homogeneous stratigraphic units (around 1.2m, around 2.8m, and in the deeper part of the embankment body). The COV of tip resistance and sleeve friction is highly variable, always greater than 0.3. This indicates that the horizontal variability of the deposit is relatively high, according to the limits indicated in literature (Ceccato et al.2021). Conversely, the I_c appears almost consistent showing low horizontal variability, with the COV always lower than 0.15, except in the lower part (Fig. 1d). In Fig. 1a-c, the blue and red vertical profiles represent the data acquired in two control CPTUs in the North and in the South, at a distance of about 300m from the closed space CPTUs.

Fig. 2a presents the contour plot of the I_c index derived from spatially interpolating the values obtained from all penetrometer tests (CPTU, CPT, SCPTU) performed on the right bank embankment, over a stretch of approximately 40km, as a function of distance from the river mouth. The various investigation points are shown at the top to provide an idea of the spatial distribution. A substantial uniformity in the stratigraphic sequence emerges along the entire embankment: the presence of the sandy material (I_c<2.05) implemented after the 1966 flood to rise the levees height is observed throughout its length. Beneath this, the majority of the embankment body is composed of sand mixtures, except for the central part where sand extends to 3-4m depth, possibly due to historical repairs. Only at CPTU31, approximately 10km from the mouth, the soil appears finer, classified as clayey.

The contour plot does not reveal any material variation dependent on proximity to the river mouth, as might have been expected. This substantial homogeneity allows for the extension of the statistical approach previously used to analyze the group of 15 closely spaced CPTs to the set of tests performed along the entire stretch. The profiles of q_c, f_s, and I_c derived from the 28 tests as a function of depth are represented in Fig. 1e-h. As already observed, for the entire analyzed plain stretch, the I_c values are highly homogeneous (Fig. 1g); the mean value trace is even more vertical than that representative of the 90m stretch, and the interval amplitude is extremely limited, as highlighted also by the COV value (Fig. 1h).

Despite this uniformity in the stratigraphic sequence, the cone tip resistance qc shows a wide variability, as shown in Fig.2b, slightly wider than the one observed in the previous dataset, as expected given the extent of the examined stretch (Fig. 1a and 1e), while the profile of the mean fs value (Fig.1f) and the interval amplitude can be considered comparable to those observed in the short stretch (Fig.1b).

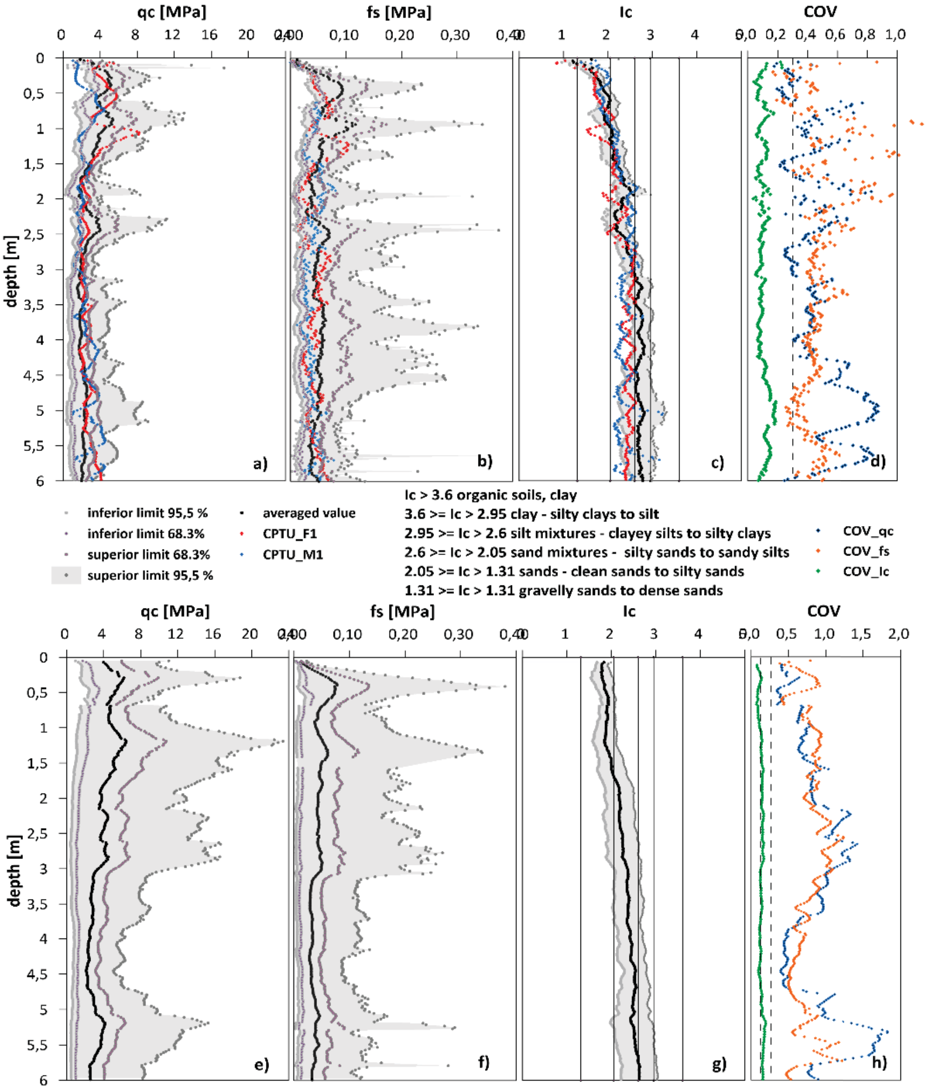


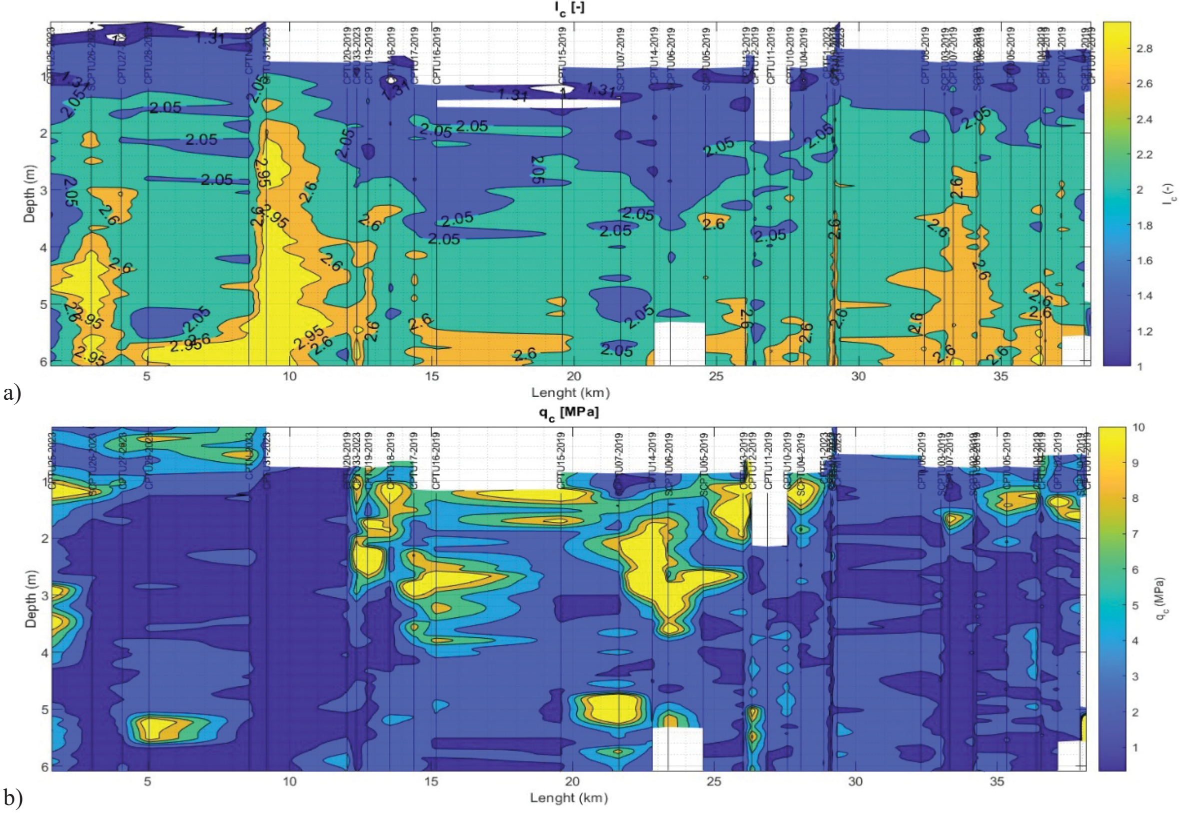
Fig. 1.(a-d) Vertical profiles of the main parameters measured in the 15 spatially adjacent CPT: a) q_c, b) f_s and c) Robertson's behaviour Index I_c. d) COV in horizontal direction of q_c, f_s and I_c. (e-h) Vertical profiles of the same parameters measured for the 28 CPTUs performed along the 40 km long river embankment.

5. Conclusions

Using a multiscale approach, this study analyzes the spatial variability of material constituting a lowland embankment, primarily composed of sand and silt-sand mixtures along a 40km stretch, integrating characterization data obtained at medium and large scales.

At the medium to large scale, stratigraphic sequences (vertical variability) and resistance behavior characteristics (horizontal) provided by both a dataset derived from 15 closely spaced CPTs covering 90m and the set of all penetrometer tests performed over 40km in length were compared. The comparison reveals a substantial uniformity in the type of soil constituting the embankment throughout the examined length, which is, however, associated with a wide variability in resistance (Fig.2b): given that the material is the same, this non-uniformity can be attributed to local inhomogeneities in compaction conditions or saturation state during test execution. The CPT thus appears capable of capturing this non-uniformity in terms of resistance.

The definition of local heterogeneities remains an open challenge, although it is crucial for assessing the stability and safety level of the infrastructure. Possible developments include quantitative assessment of horizontal soil variability, which could be useful for probabilistic levee safety assessment and extension of this analysis to other types of tests such as DMT.



a)

b)

Fig. 2. a) I_c contour plot and b) q_c[MPa] contour plot along the whole 40 km embankment. The white spaces are due to pre-drilling holes or lack of data.

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