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CHALLENGES IN INTERPRETING CPT FOR RIVER LEVEE MATERIAL CHARACTERIZATION

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River levees are man-made earthen structures built to prevent flooding, and their failure can result in catastrophic loss of life and economic damage. Despite being artificial, the properties of aging levees are often unknown, especially those constructed decades ago without records of their materials and construction history. Proper geophysical and geotechnical investigations are crucial for characterizing these earthen embankments. The cone penetration test (CPT) is one of the most widely used in-situ techniques for evaluating soil stratigraphy and parameters due to its availability, cost-effectiveness, spatial resolution, and extensive experience base. However, interpreting CPT data for levees is challenging because most of the available procedures were developed for natural, saturated soil deposits rather than the compacted, unsaturated materials found in levees - an aspect frequently overlooked. This paper critically examines the applicability of CPT for characterizing river levees through real case studies in Italy. Its aim is to guide practitioners and levee managers in properly utilizing CPT for levee assessments to ensure more reliable predictions of embankment vulnerability.

Keywords: CPT, levee, soil characterization, flood defence, soil behaviour type, friction angle.

1 Introduction

River levees are manmade structures built up for flood protection; their failure can lead to disastrous consequences such as life loss and severe economic damages. Despite the fact that they are artificial structures, their properties are often unknown, especially if they were built many decades ago and there is no information about the age, history, and composition materials. For these reasons, the safety assessment of existing river levees requires appropriate geotechnical investigations to characterize the earth embankment. Among all the available methods, Cone Penetration Testing (CPT) is one of the most widely used in situ testing technique for evaluating soil stratigraphy and material parameters (Dezert et al., 2019). However, interpretation of CPT in levees is not straightforward because most of the available procedures has been developed for natural deposits in saturated conditions, see e.g. Lunne et al. (1997), Robertson (2016), Robertson & Cabal (2014), but levees are made of compacted materials characterized by unsaturated conditions and these aspects are often disregarded or the procedure to take this into account are complex and requires several soil parameters (Lo Presti et al., 2016; Miller et al., 2018).

Levees are typically mixtures of sand, silt and clay in different proportions, other types of materials are rare. For levee vulnerability assessment it is important to identify whether the clay fraction is present and significant to reduce seepage and erosion propensity or if the sand fraction is prevalent and therefore the levee could have a higher hydraulic conductivity and erodibility. In addition, estimates of friction angle, permeability and soil unit weight are necessary for stability analysis.

This paper reviews critically the applicability of CPT for river levee characterization considering real case studies in Italy. In particular, we consider 3 rivers in North Italy (Tagliamento, Grizzaga, and Panaro), where CPT and boreholes were carried out at a close distance (lower than 6m). In total, 14 CPTs were considered and the data are elaborated with particular reference to the levee body. A summary of the main features of the considered cases is given in Table 1. Note that these levees are prevalently a mixture of silt and sand, with no or low percentage of clay, thus the considerations of this study may not be valid for other types of materials.

This study aims to provide a support to practitioners and levee manager for a correct use of CPT for levee characterization, ensuring more reliable predictions of embankment vulnerability.

Table 1 Main features of the considered sites

River	Tagliamento	Grizzaga	Panaro
Levee average height (m)	6	5	5
Material composition	Mixture of silt and sand	Mixture of silt, sand and clay	Mixture of silt and sand
Number of CPT	8	4	2

2 Methodology

Material type can be identified from CPT data with different methods; in this paper we use the classification based on the soil behaviour type index (SBT) proposed by Robertson (2009), which divides 9 classes. The same classification is used for the material extracted from the borehole, although the classification is based on USCS system considering granulometric distribution and Atterberg limits. Table 2 shows the correspondence between USCS classification and SBT used in this paper, which agrees with other similar studies (Muhsin & Shakir, 2023). The CPT-based SBT may not always agree with traditional USCS-based soil types especially in the mixed soils region (i.e., sand mixtures and silt mixtures). This is because CPT offers a classification based on the mechanical response of soil to cone penetration, while USCS is based on granulometric fractions, thus mixtures of sand and silt or clay may fall in zone 3, 4 or 5 depending on the content and mineralogy of fines. CPT records measurements every 2cm, and a value of SBT is obtained at each measured depth; however, sometimes there might be outliers in the measurements or very thin layers, which however do not influence the overall identification of the soil type. In order to avoid this effect in the evaluation of accuracy of CPT, measurements have been grouped in 20cm-thick layers to which the most frequent SBT is assigned. The reference SBT is then compared with the USCS classification derived from the closest borehole, at the corresponding depth.

Table 2 Correspondence between SBT classification and USCS classification

SBT classification	USCS classification	SBT classification	USCS classification
1 – sensitive fine grained	CH	5 – silty sand and sandy silt	SC, SC-SM, SW-SM, SW-SC
2 - organic soils and peats	OH, PT	6 – clean sand and silty sand	SM, SW, SP
3 – clay and silty clay	CL, CH	7 – dense sand and gravelly sand	SW, SP
4 – clayey silt and silty clay	ML, CL-ML, MH	8 & 9 – stiff soils	all

Several equations have been presented in the literature to estimate soil friction angle from CPT. In this study we apply and compare the empirical equations proposed by Robertson et al. (1986) (Eq. 1), and Kulhawy & Mayne (1990) (Eq. 2), where q_t =corrected tip resistance, σ'_{v0} = in-situ vertical effective stress and p_a = atmospheric pressure. Only sands and silty sands are considered because Eq. 1 and 2 should not be applied to fine grained soils.

$$\varphi = \arctan(0.1 + 0.38 \log \frac{q_t}{\sigma'_{v0}}) \tag{1}$$

$$\varphi = 17.6 + 11.0 \log \frac{q_t}{\sqrt{\sigma'_{v0} p_a}} \tag{2}$$

The peak friction angle used for comparison is obtained in laboratory test (triaxial cell, TxCIU and TxCID, or direct shear) carried out at a confining stress similar to the in-situ vertical effective stress and assuming zero cohesion. For some samples, ring shear test was performed on disturbed samples.

Hydraulic conductivity (k) is estimated as a function of the soil behaviour type index I_c, with the equations proposed by Robertson (2010) (Eq. 3 and 4). Since I_c is representative of the mechanical behaviour of the soil and depend on many soil variables, the suggested relationship between k and I_c is approximate.

$$k = 10^{0.952-3.04 I_c} \left[\frac{m}{s}\right] \text{ when } 1.0<I_c<3.27 \tag{3}$$

$$k = 10^{-4.52-1.37 I_c} \left[\frac{m}{s}\right] \text{ when } 3.27<I_c<4 \tag{4}$$

The material permeability was measured in laboratory with different techniques: constant head or variable head in triaxial or oedometric cell, with the constant head permeameter, or derived from the Soil Water Retention Curve (SWRC).

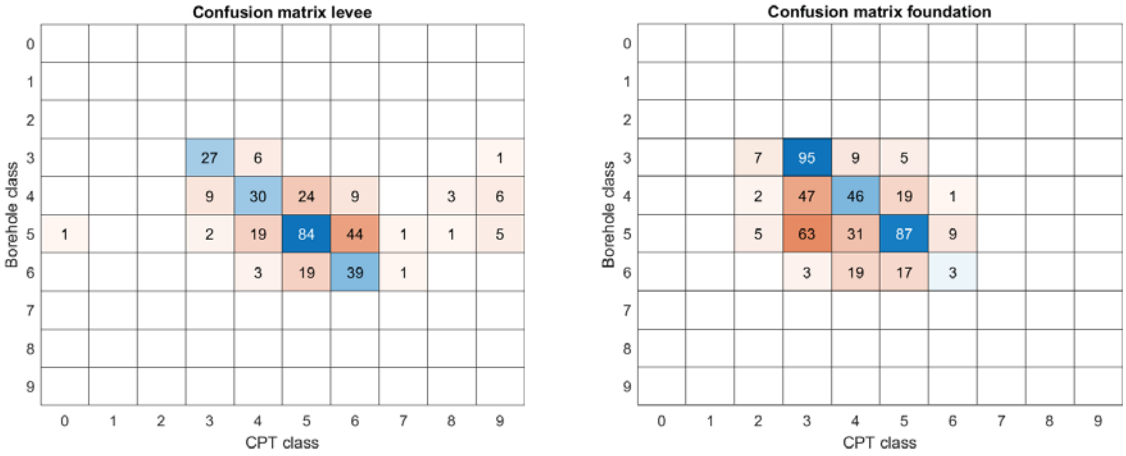
Soil unit weight is estimated with the equation proposed by Robertson & Cabal (2010) (Eq. 5), where R_f =friction ratio, G_s=specific weight of solid grains.

$$\frac{\gamma}{\gamma_w} = \left(0.27 \log(R_f) + 0.36 \log\left(\frac{q_t}{p_a}\right) + 1.236\right) \frac{G_s}{2.65} \tag{5}$$

In laboratory, soil unit weight is measured on undisturbed samples.

3 Results

Levees are typically mixtures of sand, silt and clay in different proportions; thus, the expected SBT class ranges from 2 to 6, points falling in other classes could be anomalies or measurements errors and should be further investigated. Figure 1a is the confusion matrix illustrating the performance of CPT in classifying soil types, highlighting correct predictions along the diagonal and misclassifications in the off-diagonal elements. The overall accuracy can be measured as the ratio between the sum of diagonal elements and the total number of elements, and it is equal to 58%. Having in mind the differences between the two types of classifications, this can be considered a fair result and it is similar or even higher than the accuracy that the same test has for the foundation soils (43%, see Fig. 1b). Most of the off-diagonal elements falls in the adjacent class, which is absolutely reasonable. In addition, it should be considered that the CPT classification, which is based on the mechanical behaviour of soil could be even more informative than the classification based on USCS for the purpose of safety assessment. This is because, depending on the particle size distribution and mineralogy, similar mixtures of sand, silt and clay belonging to the same USCS type, may have a different mechanical behaviour, which could be more similar to sand or to clay.



Borehole class (levee)	0	1	2	3	4	5	6	7	8	9
0										
1										
2										
3				27	6					1
4				9	30	24	9		3	6
5	1			2	19	84	44	1	1	5
6					3	19	39	1		
7										
8										
9										

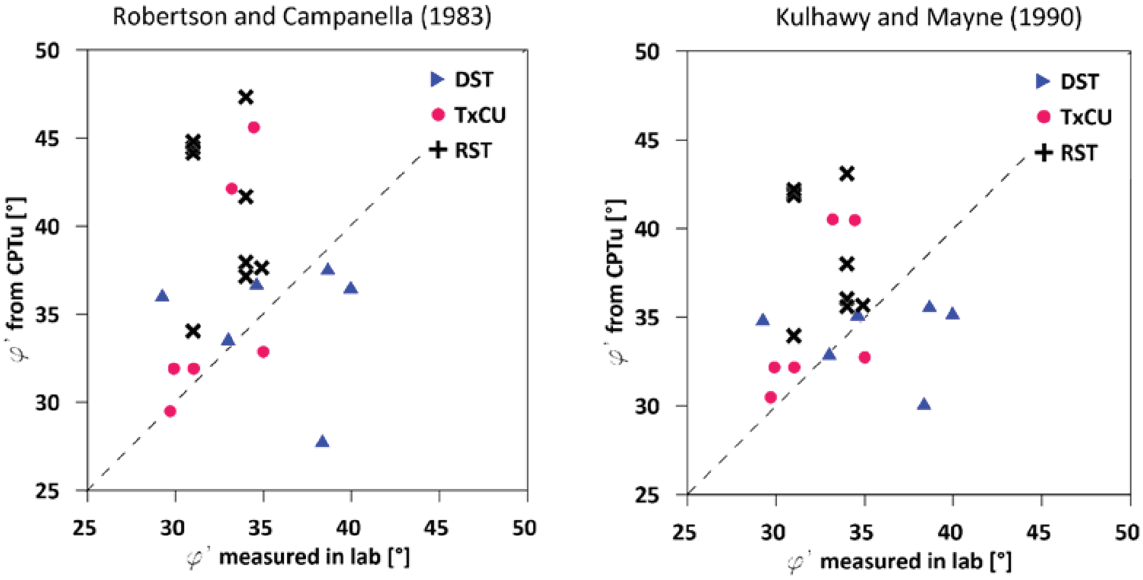
Borehole class (foundation)	0	1	2	3	4	5	6	7	8	9
0										
1										
2										
3			7	95	9	5				
4			2	47	46	19	1			
5			5	63	31	87	9			
6				3	19	17	3			
7										
8										
9										

(a) (b)

Fig. 1 Confusion matrix for the levee (a) and foundation (b) soil

Figure 2 compares the friction angle measured in the lab with the estimates of CPT using Eq. 1 (Fig. 2a) and Eq. 2 (Fig. 2b). Laboratory peak friction angles ranges between 29° and 40°, with an average of 33°. To note that shear strength angles from Ring Shear Test (RST) are related to critical state condition, being therefore at the lower bound of strength range, whereas ones from Direct Shear Test (DTS) lie at the upper bound. Friction angles estimated from CPT tends to be overestimated and this maybe due to higher site density and stiffness of compacted soil as well as to partial saturation in levees that increases the effective stress providing additional strength. Overall, Eq. 2 performs better than Eq. 1.

It should be considered that in stability analyse of levees, since the failure surface is superficial, the presence of cohesion can significantly increase the factor of safety. It is reasonable to assume that this contribution is always present in levees because of partial saturation effects, and mineralogy of fines. However, it is extremely hard to estimate both cohesion and friction angle from CPT; in addition, apparent cohesion due to suction may vary seasonally.

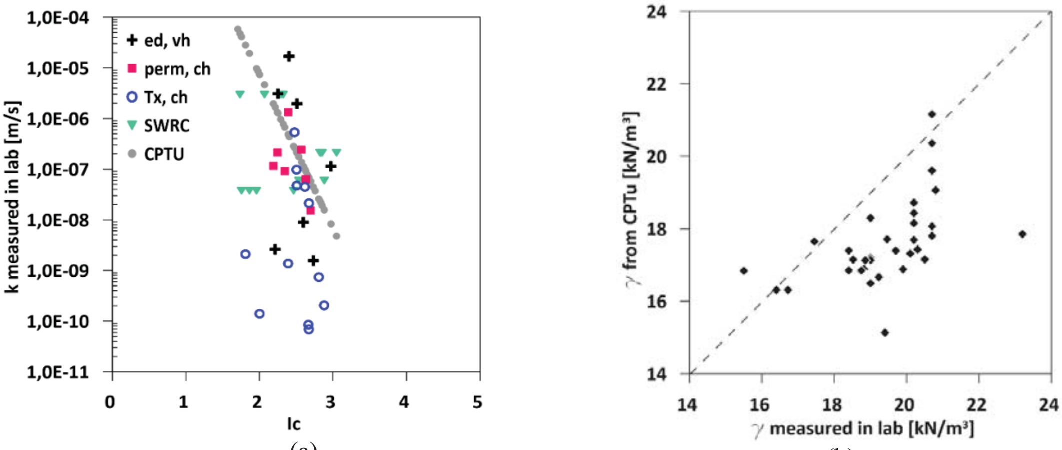


(a) (b)

Fig. 2 Comparison between friction angle measured in laboratory and estimated with Eq. 1 (a) and Eq. 2 (b)

Figure 3a shows the hydraulic conductivity measured in laboratory as a function of the SBT Index (I_c). The grey points are calculated with Eq. 3, and represents the CPT estimate. There is a significant scatter on the laboratory data, mainly due to the type of test, but it can be observed that CPT is in good agreement with the measurement of constant head permeameter, while constant head triaxial test tends to underestimate the hydraulic conductivity. Overall, considering all the uncertainties, CPT may offer an additional support to estimate this parameter.

Figure 3b compares the soil unit weight measured in the lab, with the CPT estimation, and it shows a tendency of CPT to underestimate this value. This is reasonable because levees are compacted materials and, excluding a few of low values, most of the unit weight measurements varies in a relatively small range, that is between 18.56kN/m^3 and 20.8kN/m^3, with an average of 19.6kN/m^3.



(a) (b)

Fig. 3 (a) Estimates of coefficient of permeability as function of material index and comparison with laboratory test (*ed, vh*=oedometric cell with variable head, *perm ch*=constant head permeameter, *Tx, ch*=constant head test in traxial cell, *SWRC*=extrapolated from soil water retention test, *CPTU*=estimates of Eq. 3). (b) comparison between soil unit weight measured in laboratory and estimated with Eq. 5

4 Conclusions

This study investigates critically the interpretation of CPT to obtain data for assessing the safety of river levees considering 3 rivers in North Italy. The results demonstrate that CPT can provide reasonable estimates of soil type, and hydraulic conductivity for levees composed primarily of silt-sand mixtures. In contrast, the friction angle and soil unit weight are slightly underestimated. In addition, the value of cohesion, which significantly impacts stability, cannot be reliably obtained from CPT alone. This study is limited to levees prevalently made of mixtures of silt and sand with very low clay fractions. The findings may not be applicable to levees composed of other material types. Future studies should investigate levees with higher clay contents and consider the effects of partial saturation on the CPT interpretations.

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