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A NOVEL ALGORITHM FOR VERTICAL SOIL LAYERING BY UTILIZING THE CPT DATA

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Abstract

Determination of the relevant soil stratigraphy is of the paramount importance for any geotechnical analysis. The cone penetration test (CPT) is the cost-effective, rapid, continuous, and reliable testing method for assessing soil layering and estimating in-situ mechanical properties of soil, and as such is especially useful for subsoil investigations along linear infrastructure networks, such as roads, highways, or railways. The design soil profile can be effectively determined using the CPT-based soil behaviour type (SBT) classification system. However, the soil profile consists of layers of various thickness and some layers can be only a few centimetres thick. Because the cone needs to penetrate to a certain depth to develop the cone resistance and to identify the presence of another layer, thin layers of soil cannot be properly detected. The soil layering algorithm, presented in this paper, merges these thin layers into the adjacent layers and thus overcomes the unreliable determination of the thin layers. The implementation of the proposed algorithm is demonstrated using a CPT carried out on the embankment test-site in north Croatia.

Keywords: CPT, soil layering, vertical variability, SBT soil classification

1 Introduction

Obtaining reliable information on the soil stratigraphy and corresponding soil parameters is critical for any type of geotechnical analysis. Traditionally, the geotechnical investigation works overrely on the soil drilling, sampling, and laboratory testing. As an alternative, cone penetration test (CPT), Fig 1, provides continuous and reliable information along the investigation depth. Considering its repeatability and reliability, especially the major advances in speed of use, the method can overcome the commonly encountered delay issues of drilling and laboratory testing on construction projects or emergency interventions (such as unstable slopes). This especially comes to fore when investigating the soil below linear infrastructure such as road, highway, railway networks, where the necessity for the optimization of investigation works is often highlighted. As such, CPT is increasingly incorporated into the portfolio of investigation methods of geotechnical engineers.

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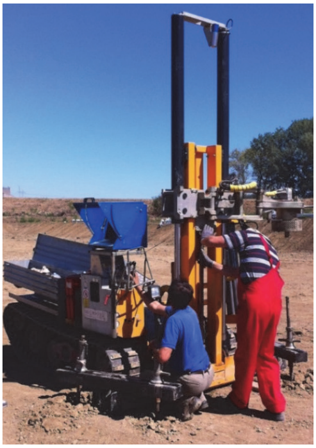

Figure 1 Cone penetration test (CPT) investigation

The method relies on pushing a specially designed cone (probe) into the soil, at relatively fast rate (20 mm/s), enabling continuous record of the cone tip resistance (q_c) and sleeve resistance (f_s), with the aim to delineate soil stratigraphy and to provide estimates of its in-situ physical and mechanical properties. The flexibility and applicability of testing can be aided by equipping the probe with the additional sensors. The method can also provide additional information on the groundwater pore pressure (CPTU), in-situ shear wave velocities (SCPT), liquefaction risk estimates, etc. Hence, as [1] notes, CPT can provide up to seven independent measurements in one cost-effective test, where a soil classification system should include all these measurements to be fully effective.
The well-known heterogeneity of most soils, along with many difficulties in obtaining not only undisturbed samples but also samples that can be considered as representative of soil mass [1], requires proper procedures of dealing with the inherent variability in both horizontal and vertical direction. The design soil profile, determined by the CPT procedures, usually consists of several layers of various thickness, where some identified layers can be only a few centimetres thick. However, since the CPT probe needs to penetrate to a certain depth to develop the cone resistance and to sense the presence of another layer, thin layers of soil cannot be properly detected. This paper offers the procedure to overcome the unreliable determination of these thin layers, within the framework of the CPT-based soil behaviour type (SBT) classification system.

2 The soil behaviour type (SBT) classification system

CPT-based classification of complex natural soil behaviour is convenient since the CPT can offer multiple, repeatable, independent in-situ measurements. As an alternative to the traditional soil classification schemes such as Unified Soil Classification System (USCS), which relies on laboratory classification tests, Robertson [2, 3] proposed a soil classification based on the CPT recorded data. This classification utilizes CPT-based charts, Fig 2a, to predict the Soil Behaviour Type (SBT), whereas author stress that the cone responds to the in-situ mechanical behaviour of the soil and not directly to soil classification criteria based on grain-size distribution and soil plasticity. However, as Molle [4] noted, there is reasonably good correlation between the soil in-situ mechanical behaviour and soil classification criteria, even though there are several exceptions [5] Originally, Robertson [2] proposed 12 SBT zones, and this was later reduced to 9 SBT zones [3], as shown in Table 1. To avoid further elaboration on the reasons for the reduction of the zone number, as well the differences between these SBT classifications, the reader is referred to the appropriate literature [5].

Table 1 Proposed unification between 12 SBT zones [2] and 9 SBT zones [3]

SBT zones [2]	SBT zones [3]	Proposed SBT description
1	1	Sensitive fine-grained
2	2	Clay – organic soil
3	3	Clays: clay to silty clay
4 and 5	4	Silt mixtures: clayey silt & silty clay
6 and 7	5	Sand mixtures: silty sand to sandy silt
8	6	Sands: clean sands to silty sands
9 and 10	7	Dense sand to gravelly sand
12	8	Stiff sand to clayey sand (OC or cemented)
11	9	Stiff fine-grained (OC or cemented)

However, it was noted that the CPT-based SBT classification systems can cause some confusion in geotechnical practice, since they use textural-based descriptions, such as sand and clay. Therefore, a CPT-based SBT classification system with behaviour-based descriptions for each soil group was proposed, where Robertson [6] provided latest update to use behaviour-based descriptions, which includes a method to identify the existence of microstructure in soils and its influence on this CPT-based classification. Within this work, Robertson differentiates seven (7) soil behaviour types, shown on Fig 2b. These include: (1) CCS: Clay-like – Contractive – Sensitive; (2) CC: Clay-like – Contractive; (3) CD: Clay-like – Dilative; (4) TC: Transitional – Contractive; (5) TD: Transitional – Dilative; (4) SC: Sand-like – Contractive; (5) SD: Sand-like – Dilative. CPT-based charts from [2, 3, 6] use the Q_t, F_r and B_q as normalized parameters to determine the SBT, and these can be expressed with:

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \tag{1}$$

$$F_r = \left(\frac{f_s}{q_t - \sigma_{v0}}\right) \times 100\% \tag{2}$$

$$B_q = \left(\frac{u_2 - u_0}{q_t - \sigma_{v0}}\right) = \left(\frac{\Delta u}{q_t - \sigma_{v0}}\right) \tag{3}$$

where q_t is the cone resistance corrected for water effects defined as $q_t = q_c + u_2(1\text{-}a)$, with 'a' being the cone area radio, u_2 being penetration pore pressure and u_0 being current in-situ pore pressure; is the current in-situ total vertical stress; and is the current in-situ effective vertical stress. Furthermore, the contours (thick lines) on the Q_t - F_r chart represent the boundaries of respective SBT zones, which are, for original Robertson chart (Fig 2a), given by the equation:

$$I_c = \left[\left(3.47 - \log Q_t\right)^2 + \left(\log F_r + 1.22\right)^2\right]^{0.5} \tag{4}$$

where I_c is identified as the soil behaviour type index. The boundaries of updated version of Robertson chart (Fig 2b), which considers the behaviour based descriptions of materials, are given by the equations:

$$I_B = \frac{100\left(Q_{tn} + 10\right)}{70 + Q_{tn}F_r} \tag{5}$$

$$CD = \left(Q_{tn} - 11\right) \times \left(1 + 0.06F_r\right)^{17} \quad (6)$$

where I_B stands for modified soil behaviour type index and CD stands for contractive – dilative boundary.

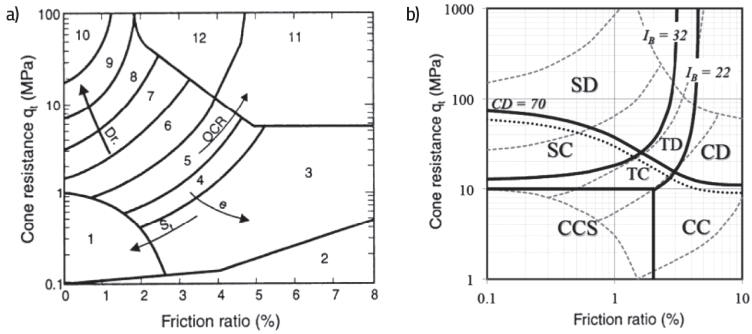

Figure 2 CPT-based charts: (a) from original Robertson [2] and (b) an updated version [6]

3 A novel algorithm for vertical soil layering

Several studies used the data from an individual CPT to generate a stratigraphic profile based on Soil Behaviour Type (SBT) chart. Ganju et al. [7] developed an algorithm to handle the occurrence of thin soil layers within a stratigraphic profile. The CPT identification of these layers in not reliable since the standard CPT cone cannot accurately sense layers with thickness below a certain limit. This can confuse a geotechnical practitioner who relies on the CPT-based soil stratigraphy for the various geotechnical analysis. Ganju et al. [7] used three different approaches to absorb thin CPT layers into thick adjacent layers, and these include:

1. SBT chart band approach: consolidation of thin layers into adjacent layers considering secondary soil type(s) classification;
2. Soil group approach: consolidation of thin layers into adjacent layers of the same soil group;
3. Average qc approach: consolidation of thin layers into adjacent layers with similar average q_c.

This paper will not elaborate each approach in detail, since their comprehensive description is given in the literature [7]. The algorithm presented in this paper is a novel protocol of merging thin layers with the adjacent thick layers, and as such being most similar to the above-mentioned 'soil group approach'. The algorithm is reliable for the everyday geotechnical practice which utilizes CPT for defining soil stratigraphy. The algorithm consists of two main phases. The first phase deals with the generation of initial soil profile, while the second phase merges thin layers into adjacent thick layers, by grouping soil behaviour types into soil groups of similar behaviour.

The initial soil profile generation phase consists of three steps. First step provides a CPT input on depth of each data (d_i), measured values of cone tip resistance (q_{ci}), and sleeve resistance (f_{si}), penetration (u_{2i}) and in-situ pore water (u_{0i}) pressures, as well an information on pre-drilling depth and the corresponding unit weight of the soil above the drilling depth. All these provide an input for step two, which calculates Q_{tni}, F_{ri}, CD_i i IB_i using the equations (1), (2), (5) and (6). To calculate the unit weight of the soil, a correlation proposed by Kovačević et al. [8] is used. Finally, in a third step of initial soil profile generation, SBT_{ni} value is calculated, thus enabling the classification of soil in one of the soil-behaviour types.

The second phase of grouping layers consists of two steps. First step requires the input on the distance (d_z) between two adjacent CPT results, which was determined prior the CPT execution. By providing a required input on the minimum soil thickness ($Thick_{min}$) a calculation of the number of adjacent CPT results (n_t), corresponding to the minimum layer thickness, follows. Finally, a code for merging thin layers into the adjacent thick layer is given, based on the comparison of behaviour types of thin layer of calculated thickness with the behaviour types of thick layers. A full algorithm, which can be implemented for any SBT chart available in literature, is given in Table 2.

Table 2 A novel algorithm for the vertical layering from CPT data

Phase	Step	Code
1 - initial soil profile generation	1.1 input data	d_i, qc_i, fs_i, $u2_i$ i $u0_i$ (i=1, 2, . . ., n), predrill_depth, gamma_predrill
	1.2 Calculating the Qtn_i, Fr_i, CD_i IB_i from: d_i, qc_i, fs_i, $u2_i$ and $u0_i$ (i=1, 2, . . ., n)	qt[i] = qc[i] + 0.001 * u2[i] * (1-0.8) Rf[i]=100*fs[i]/(qt[i]*1000) gama[i]=11.849+0.109*log(z[i])+2.595*log(fs[i])+0.561*log(qt[i]) sigv0[i]= sigv0[i-1] + gama[i]*(z[i]- z[i-1]) + predrill_depth * gamma_predrill sigv0c[i]=sigv0[i]-u0[i] Fr[i]=(fs[i]/(qt[i]*1000-sigv0[i]))*100 Qtn[i]=0.01*(qt[i]*1000-sigv0[i])*(100/sigv0c[i]) ^n[i] Ic[i]=sqrt((3.47-log(Qtn[i])) ^2 + (log(Fr[i])+1.22) ^2) n[i]=0.381*Ic[i]+0.05*(sigv0c[i]/100)-0.15 IB[i]=100*(Qtn[i]+10)/(Qtn[i]*Fr[i]+70) CD[i]=(Qtn[i]-11)*(1+0.06*Fr[i]) ^17
	1.3 Determining the $SBTn_i$ from: Qtn_i, Fr_i, CD_i and IB_i (i=1, 2, . . ., n)	if Qtn[i] <= 10. and Fr[i] <= 2.: SBTn[i] = 1 if Fr[i] > 2. and IB[i] <= 22. and CD[i] <= 70.: SBTn[i] = 2 if IB[i] <= 22. and CD[i] > 70.: SBTn[i] = 3 if Qtn[i] > 10. and IB[i] > 22. and IB[i] <= 32. and CD[i] <= 70.: SBTn[i] = 4 if IB[i] > 22. and IB[i] <= 32. and CD[i] > 70.: SBTn[i] = 5 if IB[i] > 32. and CD[i] <= 70.: SBTn[i] = 6 if IB[i] > 32. and CD[i] > 70.: SBTn[i] = 7 SBTn = 1: CCS - Clay-like - Contractive - Sensitive SBTn = 2: CC - Clay-like - Contractive SBTn = 3: CD - Clay-like - Dilative SBTn = 4: TC - Transitional - Contractive SBTn = 5: TD - Transitional - Dilative SBTn = 6: SC - Sand-like - Contractive SBTn = 7: SD - Sand-like – Dilative
2 - grouping of thin layers with the thick layers	2.1 Defining minimum soil thickness $Thick_{min}$	dz – the distance between two adjacent CPT results nt – the number of adjacent CPT results corresponding to the minimum layer thickness $Thick_{min}$ nt = int($Thick_{min}$/dz)+1
	2.2 Merging the thin layers within the adjecent thick layers	For j=1, 2, . . . , nt: For i=1, 2, . . . , n: Determining the number of adjacent CPT results nl_i, which have the same $SBTn_i$. Determining the average values of Frav and Qtnav for the nl_i adjacent CPT results. For k=j, j+1, . . . , n–j: If nl_k = j: Calculating the distance between the average (Frav,Qtnav) result and the last previous result n1 for which it is nl_k > j: ds1= sqrt((log(Fr[k])-log(Fr[n1]))^2 + (log(Qtn[k])-log(Qtn[n1])) ^2). Calculating the distance between the average (Frav,Qtnav) result and the first next result n2 for which it is nl_k > j: ds2= sqrt((log(Fr[k])-log(Fr[n2]))^2 + (log(Qtn[k])-log(Qtn[n2])) ^2). If ds1 <= ds2: The current result merges with the previous adjacent results for which it is nl_k > j: SBTn[k]= SBTn[n1] If ds1 > ds2: The current result merges with the next adjacent results for which it is nl_k > j: SBTn[k]= SBTn[n1] For k=1, 2, . . ., j: The first j results merge with the j+1 result: SBTn[k] = SBTn[j+1] For k= n-j+1, . . ., n: The last j results merge with the n-j result: SBTn[k] = SBTn[n-j]

4 An example of a CPT sounding from north Croatia

To demonstrate the effectiveness of the proposed algorithm in determination of soil stratigraphy, a single CPT record is selected from the test-site location of an embankment in north Croatia. The analysed CPT has the investigation depth up to 15 m, with the predrilling depth of 0.5 m. The continuous raw acquisition data, Fig 3, contains the probe tip resistance (q_c) and probe skin friction (f_s).

The input data was used to calculate the normalized values of cone resistance (Q_{tn}) and friction ratio (F_r). The recordings for each depth are plotted on the CPT-chart, proposed by Robertson [6], in order to get an insight into dispersion of the Q_{tn} - F_r plots in regards to the one of the seven soil behavior types, see Fig 4.

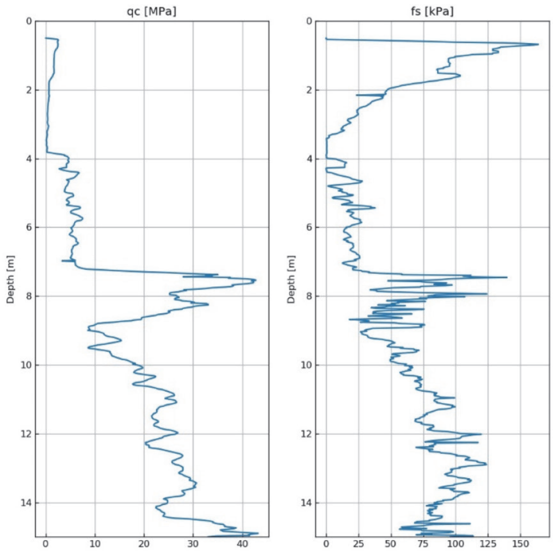

Figure 3 Analysed CPT raw recorded data: q_c and f_s

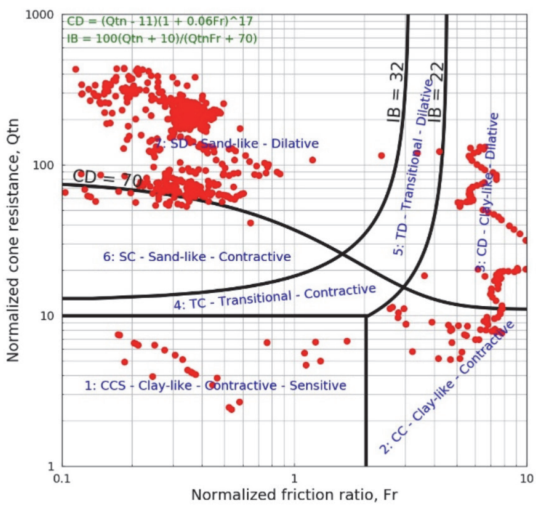

Figure 4 CPT results plotted on the Robertson [6] Q_{tn} - F_r chart

The determined soil stratigraphy, using the various input of minimum layer thickness, is shown on Fig 5. The selected minimum thickness are 15 cm, as suggested by [7] to be a minimum which can be properly detected by the standard CPT cone to avoid ambiguity in the assignment of soil type to such layers, 50 cm and 100 cm. The increase of the minimum thickness of the layer merges thin layers with the adjacent thick layers, leading to the reduction of the number of layers as well the number of SBT group types in the overall stratigraphic soil profile.

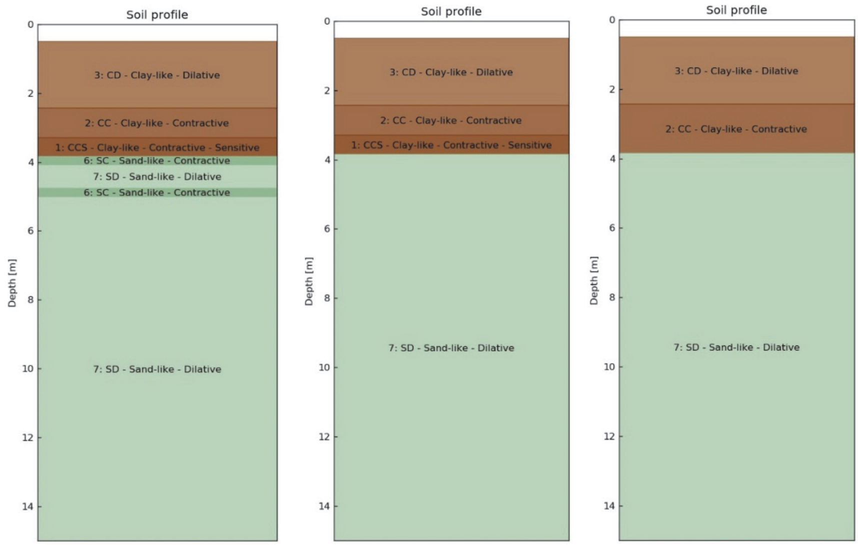

Figure 5 Obtained stratigraphy profile for minimum thickness of: 15 cm (left), 50 cm (middle) and 100 cm (right)

5 Conclusions

This paper presents the soil layering algorithm for the development of a design soil profile, determined using the CPT-based soil behaviour type (SBT) classification system. The algorithm merges thin soil layers into the adjacent layers and thus overcomes the unreliable determination of the thin layers. It consists of two main phases, where the first phase deals with the generation of initial soil profile, while the second phase merges thin layers into adjacent thick layers, by grouping soil behaviour types into soil groups of similar behaviour. Having in mind that the CPT is increasingly incorporated into the portfolio of investigation methods of geotechnical engineers, especially those dealing with construction and remediation of linear infrastructure such as road, highway or railway networks, the algorithm is sufficiently reliable for the everyday practice.

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