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Application of integrated Game Theory-optimization subground stratification (-IGTOSS) model to Venetian Lagoon deposits

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ABSTRACT: The geographical and geological spatial variabilities raise challenges for geotechnicians to devise globally applicable subground stratification models working based on cone penetration testing (CPT). Recently, a novel CPT-based stratification and classification model was proposed in Tampere University, Finland. It combines the soil behavior type (SBT) classification chart proposed by Robertson (1990) with a novel integrated Game Theory-optimization subground stratification model (denoted herein as RIGTOSS). The model has already been verified based on few test sites results from Taiwan and the U.S. Therefore, in this paper, the RIGTOSS model is developed further, and it is evaluated based on the stratification profiles provided by CPT experts for the Venetian Lagoon deposits. The test site has been selected because of high variability of CPT measurements and the thin transient soil layers in the area. The results indicated comparable stratification profiles from the developed model(s) and the profiles by experts, derived based on field and laboratory tests.

1 INTRODUCTION

Stratifying and classifying the soil behavior type (SBT) based on loads of sampling and laboratory testing can be currently in conflict with the sustainable design of a project. Furthermore, it may not finally lead to a desirable stratification-classification profile due to the probable discontinuities and soil disturbances in sampling. This problem is more challenging in highly variable and stratified soils. Then the thin transient layers may not be determined accurately. A solution can be sought in the advantageous continuous measurements of cone penetration test (CPT). Although, there are already challenges in the interpretation of the CPT measurements, and consequently in stratifying soils based on them.

In the past, much investigation has triggered the SBT classification and stratifying soils based on the CPT measurements. Several SBT classification charts have been successfully proposed based on data sets from around the world (Douglas 1981, Robertson 1990, Schneider et al. 2012, Eslami et al. 2017); although, in several studies, their applicability has been criticized for several soil types and geographical regions (Ricceri et al. 2002, Gylland et al. 2017). Besides, stratification models have been recently appealed to researchers, and several models have been proposed (Wang et al. 2013, Ching et al. 2015, Wang et al. 2019). They often recognize strata based on computing a consistency factor among the succeeding CPT measurements in depth. A probable problem of this approach has been with the recognition of thin strata. There have been recent improvements, though. On the other hand, several methods are proposed which seek the change points in the succeeding CPT measurements, as the boundaries of strata. They may discover the thin strata better, compared to the former approach. Following the latter approach, a novel model is proposed in Tampere University, Finland, named herein integrated Game Theory-optimization subground stratification (-IGTOSS) model (Farhadi & Länsivaara 2021).

The -IGTOSS model has been previously combined with the classification chart proposed by Robertson (1990), so called RIGTOSS. In this study, it is developed further, and applied to the CPTu ('-u' indicates the pore water pressure measured in CPT) measurements at the highly nonhomogeneous deposits of the Venetian lagoon, Italy. Herein, the modified model is explained briefly, and the resulting stratification profiles of the site are compared with the ones suggested by experts.

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2 STRATIFICATION MODEL

The basics of the utilized stratification model are described in (Farhadi & Länsivaara, 2021). In general, the proposed model consists of the following steps:

1. Importing and interpreting CPTu measurements
2. Denoising interpreted measurements
3. Stratifying and classifying soils based on integrated Game Theory-soil classification charts
4. Illustrating stratification profile

In the Game Theory model, the previously optimized parameters are utilized herein as well. The steps 1 and 3 are briefly explained below.

2.1 *Classification charts and data interpretation*

The previously published model contained only the F_r-Q_t Robertson SBT classification chart (1990). It is developed in this study, and currently, three other CPTu-based classification charts are implemented in the model. Hence, the modified model consists of:

a. $\text{RIGTOSS}_{\text{Fr-Qt}}$ (sub)model: stratification based on the F_r-Q_t classification chart, proposed by Robertson (1990).
b. $\text{RIGTOSS}_{\text{Bq-Qt}}$ (sub)model: stratification based on the B_q-Q_t classification chart, proposed by Robertson (1990).
c. $\text{SIGTOSS}_{\text{Fr-Qt}}$ (sub)model: stratification based on the F_r-Q_t classification chart, proposed by Schneider et al. (2012).
d. $\text{SIGTOSS}_{(\Delta\text{u2}/\sigma'\text{v0})\text{-Qt}}$ (sub)model: stratification based on the $(\Delta u_2/\sigma'_{v0})$-$Q_t$ classification chart, proposed by Schneider et al. (2012).

The initial R/S letters of the mentioned (sub)models names represent either of the employed charts proposed by Robertson (1990) or Schneider et al. (2012).

In the classification charts, several normalized parameters are used, which are interpreted from the CPTu measurements as:

- Normalized cone tip resistance, Q_t:

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

- Friction ratio, F_r:

$$F_r = \frac{f_s}{q_n} \times 100 = \frac{f_s}{q_t - \sigma_{v0}} \times 100 \tag{2}$$

- Pore pressure ratio, B_q:

$$B_q = \frac{\Delta u_2}{q_n} = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \tag{3}$$

- Normalized excess pore pressure, $\Delta u_2/\sigma'_{v0}$, which equals B_qQ_t;

where, q_n is the net corrected cone tip resistance, σ'_{v0} is effective vertical stress, q_t is total corrected cone tip resistance, σ_{v0} is total vertical stress, f_s is sleeve friction, u_2 is pore pressure measured at the cone shoulder, u_0 is the in-situ pore pressure prior to cone penetration, and Δu_2 is the excess pore pressure measured at the cone shoulder in penetration. As generally utilized, q_t is the corrected measured cone tip resistance, q_c, based on water content and unequal end effect of the piezometer: $q_t = q_c + u_2(1\text{-}a)$, where, a is the cone area ratio.

For computation of the in-situ vertical effective stress, σ'_{v0}, unit weight of soil, γ, is computed based on the equation by Robertson & Cabal (2010), which provides a continuous profile in depth:

$$\frac{\gamma}{\gamma_w} = 0.27\left[\log R_f\right] + 0.36\left[\log\left(\frac{q_t}{p_a}\right)\right] + 1.236 \tag{4}$$

where, friction ratio, R_f, equals $(f_s/q_t)\times 100$, γ_w is the unit weight of water in same unit as γ, and p_a is the atmospheric pressure in the same unit as for q_t.

2.2 *Digitized classification charts*

In order to implement the charts in computations, different equations have been fitted to the boundary lines of each classification chart. The fitted equations for the F_r-Q_t chart of Robertson (1990) is previously published in Farhadi & Länsivaara (2021). The fitted equations for the other used charts are presented in Figures 1-3.

In Figure 1, the SBT zones in the B_q-Q_t chart of Robertson (1990) are defined as:

1. Sensitive, fine-grained soils
2. Organic soils and peat
3. Clays (clay to silty clay)
4. Silt mixtures (silty clay to clayey silt)
5. Sand mixtures (sandy silt to silty sand) or cemented soil
6. Sand (silty sand to clean sand)
7. Sand to gravelly sand
8. Sand (clayey sand to 'very stiff' sand)
9. Very stiff, fine-grained, overconsolidated

Note that the SBTs of 8 and 9 only exist in the F_r-Q_t chart, not in the B_q-Q_t chart.

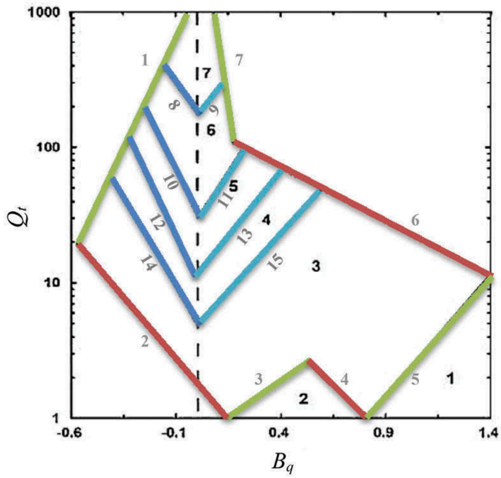
Figures 2-3 illustrate the classification charts proposed by Schneider et al. (2012) and the fitted equations to the boundary lines. In these two charts, the SBTs are defined as:

1a. Low-I_R clays (I_R=G/S_u; where, I_R, G and S_u represent rigidity index, shear modulus, and undrained strength, respectively)
1b. Clays
1c. Sensitive clays
3. Silts and transitional soils

2. Essentially drained sands and sand mixtures

3 TEST SITE

The data of the CPTu measurements are derived from a long-lasting project in the Venetian lagoon basin, Treporti test site, Italy. The importance of studying the Treporti site originated from the regional land subsidence in 1970s, and designing submersible gates to protect Venice from recurrent flooding in 1990s. There exist predominantly Pleistocene silty sediments of the Venetian lagoon basin with a high variability of strata (Tonni & Gottardi 2019), which can be a challenging soil condition to stratify.

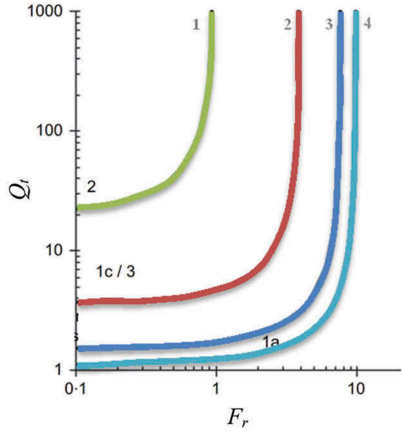


Line	Equation
1	$y = 3.2658\,x + 3.1106$
2	$y = -1.8182\,x + 0.2643$
3	$y = 1.0551\,x + 0.1487$
4	$y = -1.6003\,x + 1.2965$
5	$y = 1.7339\,x - 1.4019$
6	$y = -0.8139\,x + 2.1723$
7	$y = -10.361\,x + 3.8844$
8	$y = -2.2189\,x + 2.2501$
9	$y = 2.0043\,x + 2.2281$
10	$y = -3.3930\,x + 1.4843$
11	$y = 2.3345\,x + 1.4666$
12	$y = -3.3298\,x + 1.0567$
13	$y = 1.8446\,x + 1.0468$
14	$y = -2.7551\,x + 0.6999$
15	$y = 1.6359\,x + 0.6958$

* y and x stand for $\log(Q_t)$ and B_q, respectively.

Figure 1. The equations fitted to the boundary lines of the B_q-Q_t classification chart proposed by Robertson (1990). The boundary lines numbers are shown in grey.

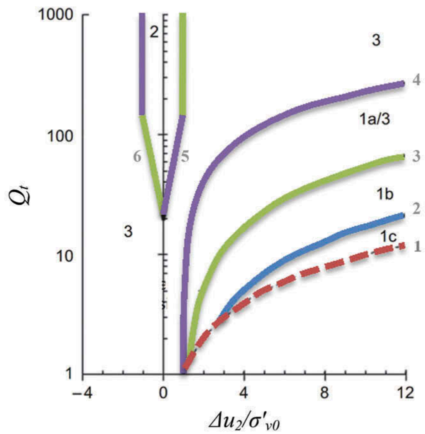
A sandy loading bank was constructed for studying the compressibility behavior of silty deposits at the site. For details of the Treporti site refer to Tonni & Gottardi (2011). Several CPTu tests were performed before and after construction of the loading



Line	Equation
1	$y = (-2.599x + 0.0003) / (x^4 + 2.418x^3 + 2.189x^2 - 1.176x - 0.0124)$
2	$y = (-327.7x^3 + 6481x^2 - 9851x + 3617) / (x^3 + 13580x^2 - 17150x + 5389)$
3	$y = (-7.102x + 6.555) / (x^4 + 8.338x^3 + 10.15x^2 - 46.84x + 27.2)$
4	$y = (-524.4x^2 - 237.6x + 848.7) / (x^4 + 814.3x^3 + 4563x^2 - 13510x + 8155)$

* y and x stand for $\log(Q_t)$ and F_r, respectively.

Figure 2. The equations fitted to the boundary lines of the F_r-Q_t classification chart proposed by Schneider et al. (2012). The boundary lines numbers are shown in grey.



Line	Equation
1	$y = (7861x^2 + 29940x - 44390) / (x^4 - 33.84x^3 + 2694x^2 + 73050x - 4572)$
2	$y = (1296x - 2062) / (x^3 - 33.7x^2 + 1041x + 769)$
3	$y = (601.3x - 739.8) / (x^3 - 26.6x^2 + 493.9x - 255.2)$
4	$y = (598.1x - 578.3) / (x^3 - 22.55x^2 + 382.3x - 299.3)$
5	$y = -0.7734x + 1.364$
6	$y = 0.8438x + 1.312$

* y and x stand for $\log(Q_t)$ and $\Delta u_2/\sigma'_{v0}$, respectively.

Figure 3. The equations fitted to the boundary lines of the $(\Delta u_2/\sigma'_{v0})$-$Q_t$ classification chart proposed by Schneider et al. (2012). The boundary lines numbers are shown in grey.

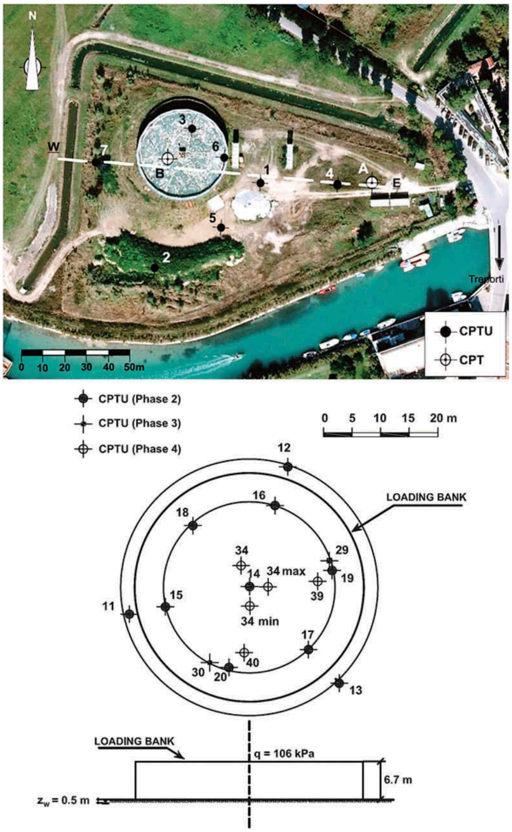


Figure 4. Location of CPTu tests at Treporti test site (TTS), from Tonni & Gottardi (2011). The diameter of the loading bank is 40 m.

bank. In this study, the CPTu measurements before the bank construction are utilized, which are indicated as 'Phase 2' in Figure 4.

4 RESULTS AND DISCUSSION

4.1 *Stratification profiles*

The (R/S)IGTOSS models were applied to nine CPTu measurements: CPTu 11-CPTu 19.

In the first step, data were imported into the model and were interpreted.

In the second step, the interpreted data were denoised using the locally estimated scattered smoothing (LOESS) method. The results of the smoothing for the four interpreted parameters of test CPTu14 (performed at the center of the loading bank) are presented in Figures 5a-5d. As can be observed, the benefit of the smoothing has been denoising the outliers (for instance, the abrupt large fluctuations at depths of 10-17 m), such that the general trends of variations would be preserved.

The solid lines in Figures 5f-5i show the identified SBT versus depth after using directly the classification charts of F_r-Q_t and B_q-Q_t by Robertson (1990) and F_r-Q and $(\Delta u_2/\sigma'_{v0})$-$Q$ by Schneider et al. (2012), respectively. It can be observed that the succeeding data points are highly variable on the charts and too many SBTs/strata are identified. Thus, it may be really challenging for a geotechnician to decide on the number of strata and their boundary depths in highly heterogeneous soils, such as in the Venetian lagoon. In this regard, (R/S)IGTOSS models facilitate the stratification procedure. Their resulting stratification profiles (illustrated with colored contours) for the test CPTu14 can be compared with the profiles resulting from direct use of classification charts in Figures 5f-5i. In the colored stratification profiles, the tone of colors varies from blue to yellow; where yellow means the highest probable SBT, and vice versa. Then, it is observed that after applying the (R/S)IGTOSS models, less strata can be detected generally.

Figure 5j illustrates the distribution of all CPTu measurements points on the used classification charts. As observed, especially in the F_r-Q classification chart of Schneider et al. (2012), numerous points are located out of the boundary lines of the chart, indicated by SBT='f' in Figure 5h. They may result from different factors, such as uncertainties in measurements, interpretation methods and parameters, or incompatibility of the chart with the soils at the Treporti site. However, Figures 5f-5i unveil that after application of (R/S)IGTOSS models, a large number of the data points close to the boundary lines have been regarded within the zones. It evidences that the model considers the proximity of the succeeding points in detecting strata.

4.2 *Spatial variability of sediments*

Figure 6 illustrates the highly horizontal variability of deposits in the Venetian lagoon for tests CPTu11, CPTu12 and CPTu13, located around the perimeter of the loading bank. Although the (R/S)IGTOSS models have identified the strata based on each CPTu (Figures 6b-6m), it is still challenging to find similar layers with almost the same boundary depths at the test site. This is due to the highly spatial variability of soils at the Treporti site.

4.3 *Comparison of classification charts*

Despite the spatial variability of deposits at the Treporti site, and highly alternation of different grain-sized sediments, Gottardi & Tonni (2005) reported the following strata (as illustrated in Figures 5e and 6a):

- very soft silty clay, from ground level to 2 m in depth,

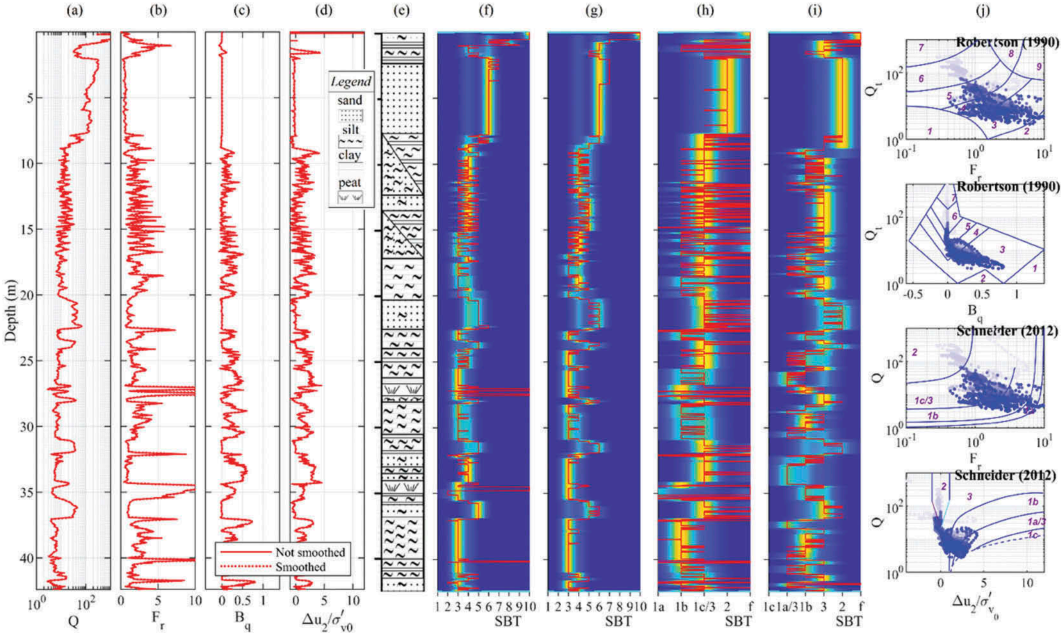


Figure 5. Illustration of CPTu measurements, experts stratification profile, RIGTOSS and SIGTOSS stratification profiles, and distribution of CPTu measurements on classification charts, for test CPTu14: a-d) smoothed versus unsmoothed interpreted CPTu parameters, e) expert-based stratification reported for Treporti site (Tonni & Gottardi 2011), f-i) directly chart-based stratification profile, presented by solid line, versus the profiles by the $\text{RIGTOSS}_{\text{Fr-Qt}}$, $\text{RIGTOSS}_{\text{Bq-Qt}}$, $\text{SIGTOSS}_{\text{Fr-Q}}$ and $\text{SIGTOSS}_{(\Delta u2/\sigma'v0)\text{-Q}}$ models, respectively, and, j) distribution of measurements points on the classification charts (the color of data points gets darker with depth). In (R/S)IGTOSS stratification profiles, SBTs of '10′ and 'f' mean that the data points located out of the boundaries of the classification charts.

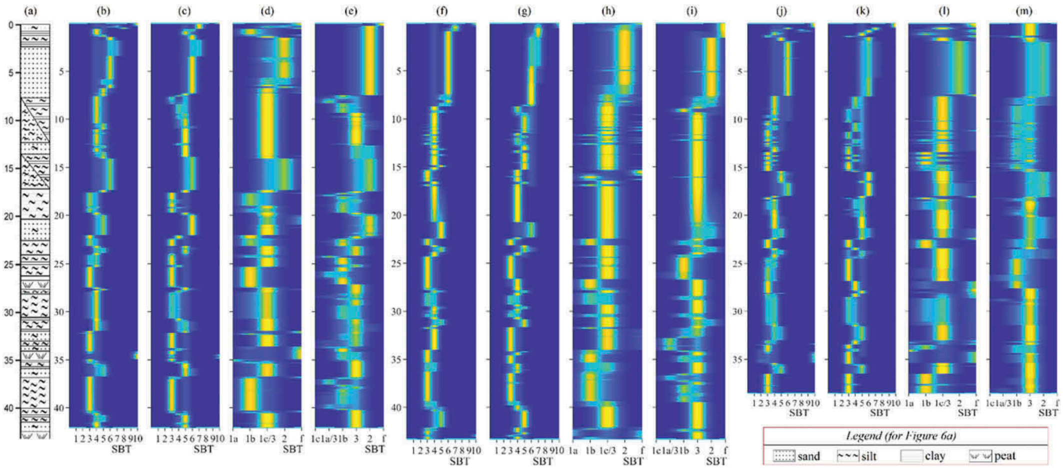


Figure 6. The expert-based stratification profile (a) by Tonni & Gottardi (2011) compared with the profiles from RIGTOSS and SIGTOSS models for tests: b-e) CPTu11, f-i) CPTu12, and, j-m) CPTu13. Every four profiles, i.e. a-e, f-i, and j-m, are derived from $\text{RIGTOSS}_{\text{Fr-Qt}}$, $\text{RIGTOSS}_{\text{Bq-Qt}}$, $\text{SIGTOSS}_{\text{Fr-Q}}$ and $\text{SIGTOSS}_{(\Delta u2/\sigma'v0)\text{-Q}}$, respectively.

- medium-fine sand (to approximately 8 m in depth),
- silt with thin layers of sandy to clayey silt, from 8 to 20 m in depth,
- dense clean sand (interbedded within the silty unit, though not everywhere),
- silty sand,
- alternate layers of silty sand, sandy silt, and clayey silt, with occasional presence of peat, at depths greater than 24 m.

Figures 5-6 indicate highly variable behaviour of soil at depths less than 2 m. However, they are mostly silt, or silty clays, which is almost similar to the observation of Gottardi & Tonni (2005).

At the depth range of approximately 2-8 m, an almost homogeneous layer is identified with SBT of 6, that means sand (silty sand to clean sand) according to the Robertson chart, and based on the Schneider et al. chart, SBT is 2, that means essentially drained sands and sand mixtures. Although the SBT from two charts are almost similar, the thickness of the layer based on each chart is a little different. For example, Figure 6h shows SBT of 2 from surface to approximately 7.5 m deep, while Figure 6f indicates SBT of 6 for 1-8.5 m deep.

From 8 to 40 m in depth, highly variable deposits are identified. Their SBTs based on the Robertson charts are 3 or 4 and at some depths it is 5. Generally, they range from clay/silty clays to sandy silts/silty sands. On the other hand, the chart by Schneider et al. (2012) indicates almost all SBT classes from *1b* to *3*, which means from clays and sensitive clays to drained sands and sand mixtures. Therefore, using each chart leads to different profiles of stratigraphy. Such observations may lead to the necessity of a site-specific classification chart, such as the B_q-F_r chart by Ricceri et al. (2002).

5 CONCLUSIONS

In this study, a stratification-classification model is modified and employed for the highly variable deposits of Venetian lagoon, Treporti site, Italy. The model classified soil behavior based on four classification charts. It was observed that the model was capable of stratifying highly variable deposits. Generally, the obtained stratification profiles have been comparable with the profile provided by experts, which have been not only based on CPTu tests, but also based on the field and experimental tests.

The differences between the model and experts stratification profiles originate from numerous factors, such as the incompatibility of the classification charts with the testing site condition, uncertainties in measurements, or different criteria in classifying soils in contrast to those of the available classification charts.

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