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CPT-Based classification with 3D overlay for special soils

Arny H.J. Lengkeek[1*], and *Friso* F.L.E. Meijer[1]

[1] Witteveen+Bos, Deventer, The Netherlands

Abstract. Current CPT/CPTU-based Soil Behaviour Type (SBT) classifications predominantly rely on two-dimensional charts that use normalized cone resistance and friction ratio. These 2D approaches have limited capability to discriminate certain special soils. This paper introduces a three-dimensional classification framework that incorporates a normalized pore-pressure parameter alongside normalized cone resistance and friction ratio. Using an extended database developed by the author, six special-soil classes are represented as statistical ellipsoids in 3D CPTU parameter space. Each ellipsoid denotes the mean and variability of a soil type; the 95% confidence volume defines the class boundary. The 3D ellipsoidal overlay improves discrimination of special soils relative to classical 2D SBT charts and yields a statistically robust, interpretable tool for site characterization in challenging deposits.

1 Introduction

The cone penetration test (CPT/CPTU) is an essential instrument for geotechnical site investigation. Classification methods have evolved from direct parameter inspection (qt, fs, u_2) to the widespread use of two-dimensional Soil Behaviour Type (SBT) charts based on normalized parameters [1, 2]. Additional CPTU measurements, most notably pore pressure (u_2) measured at the cone shoulder, can be normalized and plotted in separate 2D charts. However, using separate charts may yield conflicting classifications for the same measurement interval.

Previous modifications to 2D charts [3] showed improved classification of organic soils when normalized pore pressure is included; nevertheless, the potential of a combined multi-parameter classification has not been fully exploited. Incorporating normalized pore pressure as a third coordinate reduces ambiguity for many special soils. Accordingly, this paper proposes a 3D classification model in which distinct special-soil types are represented by statistical ellipsoids in a normalized CPTU parameter space.

2 Database

2.1 Database of special soils

The database used here builds on the extensive dataset compiled in [3]. It includes CPTU soundings linked to borehole logs and laboratory test results for ground-truthing. The current dataset has been extended with special soils selected for their engineering relevance in the Netherlands: Gyttja, Boom Clay, Pot Clay, Clay Till, Glauconitic Sand, and Glauconite silty Sand. Fig. 1 shows the geographical distribution of these soils in the upper 40 m of the Dutch subsurface. Table 1 lists the number of CPT–borehole pairs and the average CPT parameters for each soil type. Tables 2, 3 and 4 summarize respectively the minimum, maximum observed CPT parameter values and standard deviation.

Table 1. Average CPT parameters of special soils database.

Units	# [-]	q_t [kPa]	R_f [%]	u_2 [kPa]	σ'_{v0} [kPa]
Boom Clay	327	4416	3.44	627	315
Clay Till	235	2694	1.94	566	139
Glauconite silty Sand	487	11087	4.42	186	342
Glauconitic Sand	161	24916	1.07	113	389
Gyttja	134	256	4.68	48	16
Pot Clay	181	2256	5.52	20	129
Grand Total	1525				

Table 2. Minimum values CPT parameters.

Units	depth [m]	q_t [kPa]	R_f [%]	u_2 [kPa]	σ'_{v0} [kPa]
Boom Clay	20.8	3091	1.83	-100	175
Clay Till	1.7	569	0.40	-80	21
Glauconite silty Sand	15.4	4529	1.58	-100	144
Glauconitic Sand	11.4	7823	0.45	-100	103
Gyttja	1.4	83	2.84	-24	4
Pot Clay	2.1	699	3.24	-49	26

Table 3. Maximum values CPT parameters.

Units	depth [m]	q_t [kPa]	R_f [%]	u_2 [kPa]	σ'_{v0} [kPa]
Boom Clay	43.4	6605	6.00	1662	434
Clay Till	36.9	12558	5.53	2229	344
Glauconite silty Sand	58.3	19190	8.48	2013	553
Glauconitic Sand	56.8	65572	2.54	497	551
Gyttja	9.6	909	8.65	285	87
Pot Clay	28.9	4412	7.12	171	281

* Corresponding author: arny.lengkeek@witteveenbos.com

Table 4. Standard deviations of CPT parameters.

Units	q_t [kPa]	R_f [%]	u_2 [kPa]
Boom Clay	652	0.88	510
Clay Till	1552	0.86	477
Glauconite silty Sand	3266	1.34	410
Glauconitic Sand	9274	0.56	158
Gyttja	162	1.02	41
Pot Clay	657	0.82	50

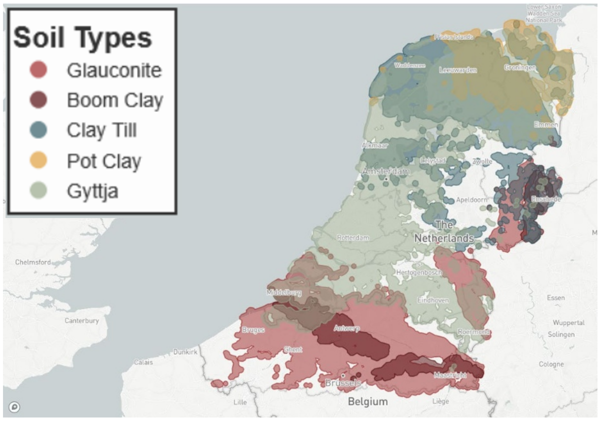

Fig. 1. Geographical distribution of special soils in the upper 40m in The Netherlands.

A brief geological description of the special soils is presented in below.

2.2 Gyttja

Gyttja is a typical soft soil encountered in The Netherlands, such as organic clay or peat. It is an organic-rich mud composed of partially decomposed plant and animal remains mixed with mineral detritus, typically imparting a near-black color to fine-grained sediments. It occurs where organic material accumulates in stagnant freshwater basins and decomposes under anaerobic conditions. In Dutch stratigraphy, Gyttja is recorded in several formations (e.g., Koewacht, Kreekrak, Boxtel, Singraven, Tilligte, and Nieuwkoop). Gyttja deposits in the Netherlands commonly form shallow, thin layers (0.1 – 2 m) and are frequent in western provinces and Flevoland.

2.3 Clay Till (Boulder Clay)

Clay Till, or boulder clay (Keileem), is a heterogeneous matrix of clay, silt, sand, gravel, and occasional Scandinavian boulders, deposited and compacted by glacial action. In the Netherlands it is primarily assigned to the Drente Formation (Gieten Member), formed during late Middle Pleistocene glaciations. Clay Till occurs in the northern provinces and commonly appears at or near the surface in layers up to about 10 m thick.

2.4 Pot Clay

Pot Clay (Potklei) is an organic-rich, very stiff clay historically used in pottery due to its hardness when dry. It is classified within the Peelo Formation (Nieuwolda Member) and formed in glacio-lacustrine settings during the Middle Pleistocene. Pot Clay is found mainly in northern Netherlands and within tunnel-valley deposits, ranging from near-surface occurrences to depths exceeding 100 m.

2.5 Boom Clay

Boom Clay is a very stiff, overconsolidated, low-permeability marine clay enriched in pyrite and exhibits grey to bluish-grey colors. It is part of the Rupel Formation (Boom Member), deposited in the early Oligocene (Rupelian). Boom Clay is thick (tens to hundreds of meters) in the subsurface and, in the Netherlands, typically occurs at depths increasing inland, with near-surface exposures in limited coastal regions.

2.6 Glauconitic (Glauconite) Sands

Glauconitic sands contain variable amounts of glauconite, a greenish iron-potassium phyllosilicate formed in slow sedimentation marine environments. In Dutch stratigraphy, glauconitic sediments occur in various formations spanning Cretaceous to Pliocene–Pleistocene units. Glauconitic sands can be problematic during pile installation because glauconite grains are friable and prone to crushing at relatively low stresses [4]. For classification purposes the database separates glauconitic sands into two clusters: "Glauconitic Sands" (estimated <40% glauconite) and "Glauconite silty Sand" (estimated >40% glauconite), based on literature estimates [5].

3 Methodology

3.1 3D classification space

The proposed 3D classification augments the standard normalized CPT parameters with a normalized pore-pressure parameter. The approach is applied in both the dimensionless framework [1] and the stress-normalized framework [2]. All parameters are transformed by base-10 logarithm to reduce skewness. For the dimensionless [1] framework the axes are:

- Dimensionless cone resistance: $log(q_t/p_a\,)$
- Friction ratio: log(R_f), with $R_f\; = f_s\,/q_t\; \cdot\; 100\%$
- Dimensionless pore-pressure parameter: $\log\left(1 + B_{qt}\right)$, with $B_{qt}\; = (u_2\; -\; u_0)\;/\;q_t$
- The additive 1 in the third axis $log(1\; +\; B_{qt})$ avoids negative arguments for the logarithm; drained soils (zero pore-pressure response) therefore plot near the plane intersecting the third axis at $log(1)\; =\; 0$.

The same 3D classification can be applied for the stress-normalized (2016) framework where the axes are:

- Normalized cone resistance: $log(Q_{tn})$, with $Q_{tn}\; = (q_t\; -\; \sigma_v)\;/\;p_a\; \cdot\; C_n$ and C_n = min [2, $(p_a\;/\;\sigma'_v)^n$].
- Normalized friction ratio: log(F_r), with $F_r\; = f_s\;/\;(q_t\; -\; \sigma_v)\; \cdot\; 100\%$
- Normalized pore-pressure parameter: $log(1\; +\; B_q)$, with $B_q\; =\; (u_2\; -\; u_0)\;/\;(q_t\; -\; \sigma_v)$

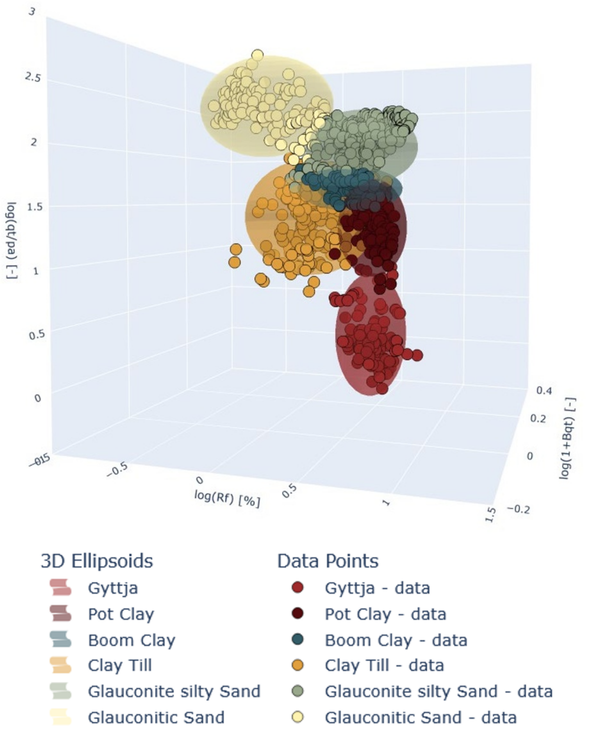

Fig. 2. 3D ellipsoids with pairs in the dimensionless framework [1].

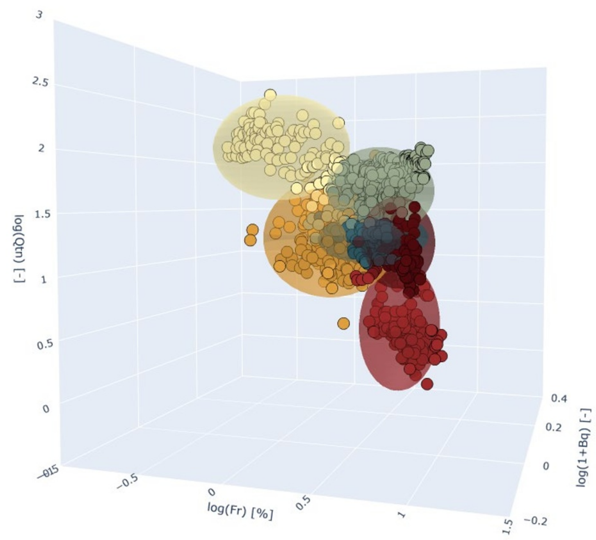

Fig. 3. 3D ellipsoids with pairs in the stress-normalized framework [2].

The 2016 framework requires estimates of effective vertical stress (σ'_v), hence the unit weight and groundwater level for normalization. For deltaic areas like the Netherlands one has to account for soft organic soils and peats with very low unit weights [6]. The 2010 framework requires no effective stress correction. This works out fine for relative low effective stresses (<100 kPa) and reduces the uncertainty related to the stress estimation and correction. The disadvantage is that it requires slightly deviation parameters like the B_{qt} instead of B_q.

3.2 Ellipsoidal model

For each special-soil class, the statistical mean and covariance are computed in the selected 3D parameter space. An ellipsoid is defined with its center at the class mean and principal axes aligned with the covariance eigenvectors. The ellipsoid boundary is chosen as the 95% confidence volume of the multivariate normal approximation. The distance of a measurement point to an ellipsoid center, scaled by the ellipsoid covariance (i.e., Mahalanobis distance), provides a probabilistic indicator of class membership.

Ellipsoids may overlap; in overlapping regions the class assignment is made based on the relative Mahalanobis distance (the smallest normalized distance indicates the most likely class). Points lying outside all ellipsoids revert to the classical 2D SBT assignment.

3.3 3D classification charts

Figs. 2 and 3 display the 3D classification charts for the dimensionless and stress-normalized frameworks, respectively. The charts show the dataset pairs and semi-transparent ellipsoids representing the five special-soil classes. These visualizations facilitate qualitative assessment of the separation between special soils and conventional SBT clusters.

4 Examples

This section presents representative examples that compare the classical 2D SBT classification with the new 3D ellipsoidal overlay. Figs. 4, 7, 10, and 13 present CPT stratigraphy and SBT classification (following [3], which includes organic soils). For each example the raw CPT parameters (qt, Rf, u_2) are plotted; groundwater level (u_0) is estimated from open-source groundwater data. Figs. 5, 8, 11, and 14 show the classical 2D SBT charts; Figs. 6, 9, 12, and 15 show the new 3D classifications with ellipsoids.

4.1 Gyttja example

Site: central Netherlands (Flevoland). Gyttja occurs near the surface (approximately −5 to −7 m NAP) as confirmed by local boreholes and the stratification in Fig. 4. The low cone resistance indicates that Gyttja is a very soft soil. Given the low cone resistance and low effective stress, it is preferred to use the dimensionless framework [2] with the L25R10-3D overlay. Most CPT points plot within the Gyttja ellipsoid (Fig. 6). In the classical 2D chart (Fig. 5) these points largely overlap the Organic Clay SBT and are classified as undrained. The third axis $log(1 + B_{qt})$ is diagnostic because Gyttja typically exhibits moderate positive u_2 responses; however, organic clays and Gyttja have significant overlap and are not always separable using this dataset alone.

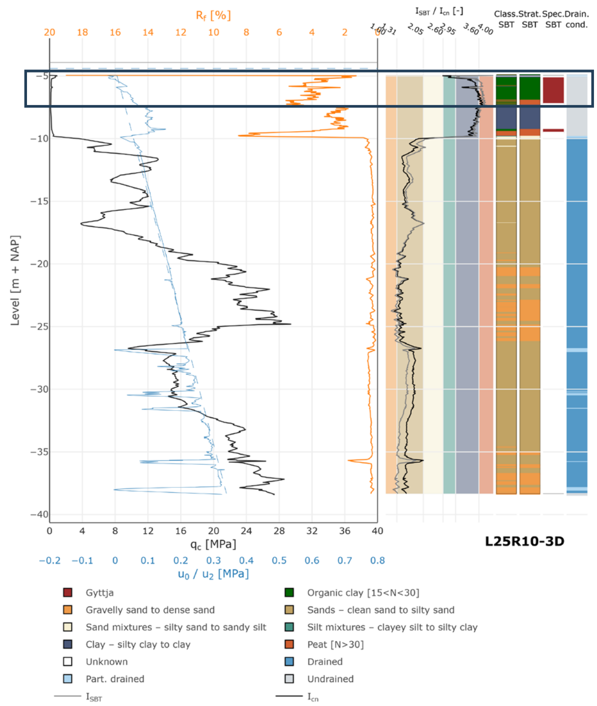

Fig. 4. Example CPT profile with Gyttja.

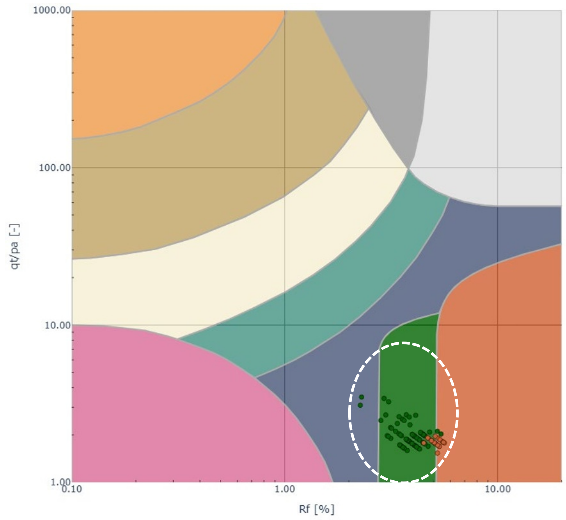

Fig. 5. Classical 2D SBT chart with 3D Gyttja measurements.

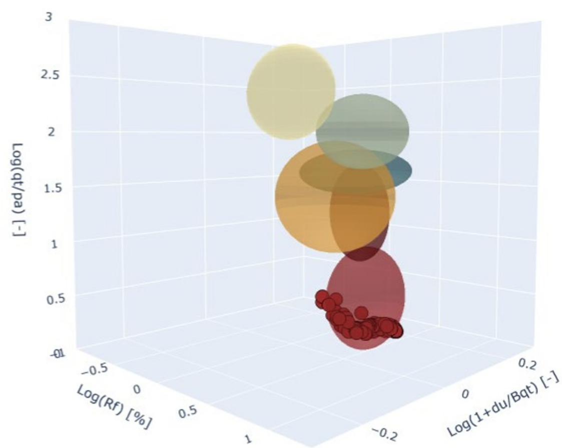

Fig. 6. New 3D framework with Gyttja measurements and ellipsoids.

4.2 Clay Till example

Site: northern Netherlands (Friesland). Clay Till occurs between roughly −6 and −15 m NAP, interbedded with sandy layers (Fig. 7). The stress-normalized framework [2] with L25R16-3D overlay shows most points clustering within the Clay Till ellipsoid (Fig. 9). In classical 2D charts (Fig. 8) Clay Till spans several SBTs, including Transitional Dilative (TD), Transitional Contractive (TC), Sand Dilative (SD), and Sand Contractive (SC), and drainage is typically intermediate. Clay Till displays a wide range of positive u_2 values; higher u_2 values assist in distinguishing Clay Till from other transitional soils.

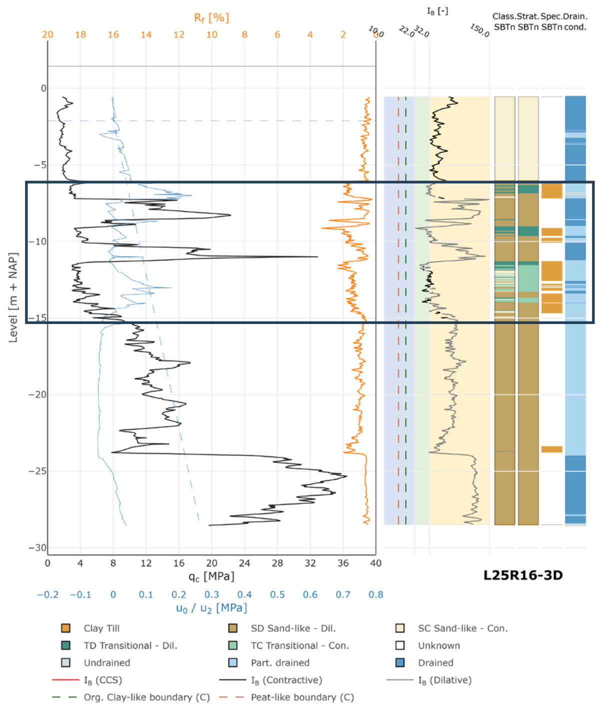

Fig. 7. Example CPT profile with Clay Till.

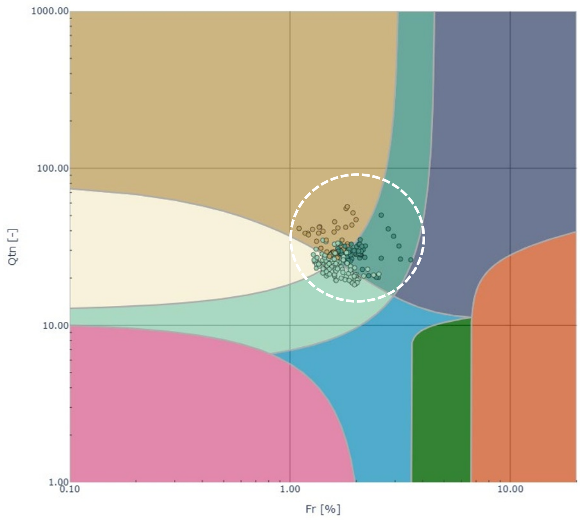

Fig. 8. Classical 2D SBT chart with 3D Clay Till measurements.

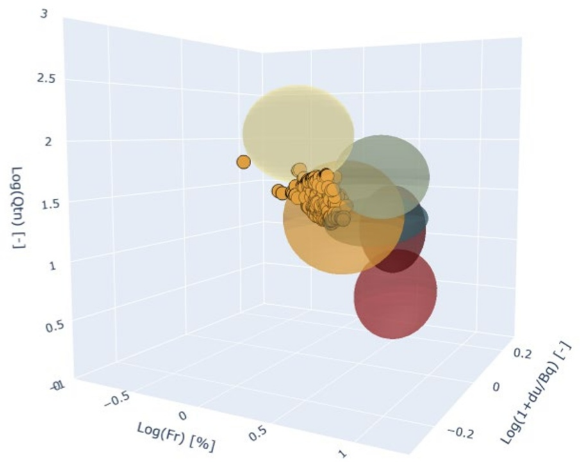

Fig. 9. New 3D framework with Clay Till measurements and ellipsoids.

4.3 Pot Clay example

Site: northern Netherlands (Groningen). Pot Clay extends between approximately −10 and −30 m NAP (Fig. 10) and generally aligns with the Clay Dilative (CD) SBT in 2D charts (Fig. 11). In the 3D overlay (Fig. 12) most points fall within the Pot Clay ellipsoid. Pot Clay tends to exhibit slightly negative u_2 values; these negative pore-pressure responses help to distinguish Pot Clay from other clays.

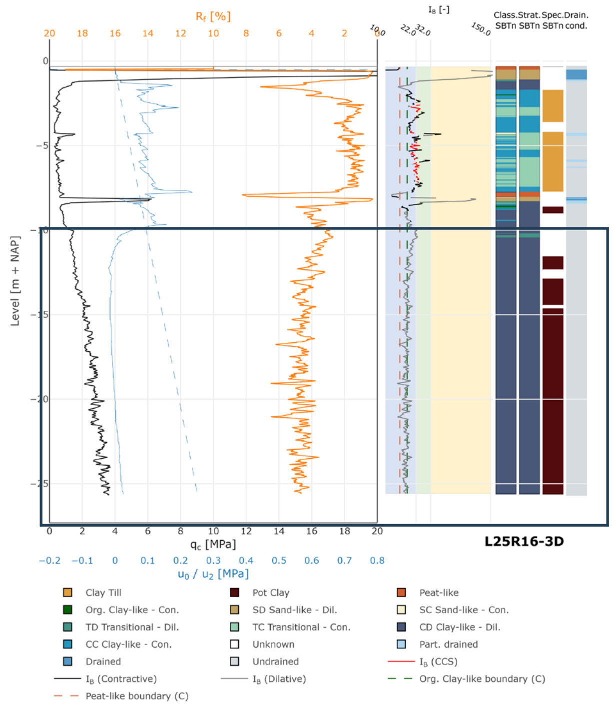

Fig. 10. Example CPT profile with Pot clay.

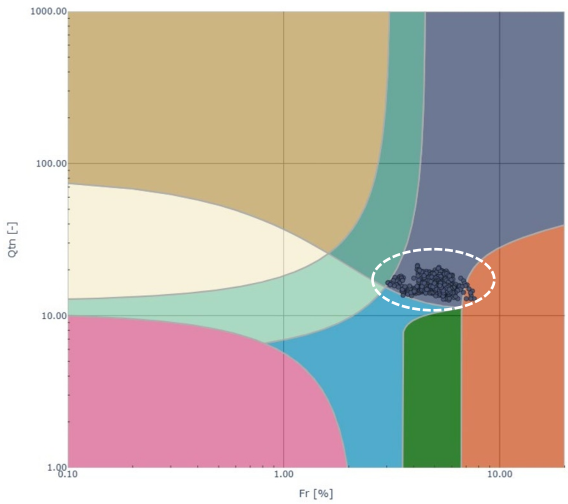

Fig. 11. Classical 2D SBT chart with 3D Pot clay measurements.

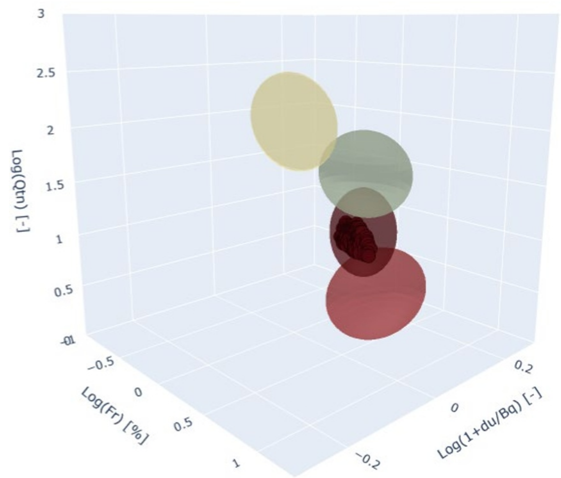

Fig. 12. New 3D framework with Pot clay measurements and ellipsoids.

4.4 Boom Clay and Glauconitic Sands example

Site: southern Netherlands (Zeeland). The profile contains Boom Clay (−21 to −38 m NAP), Glauconite silty Sand (−38 to −42 m NAP), and Glauconitic Sand (below −42 m NAP) (Fig. 13). In 2D charts (Fig. 14) Boom Clay overlaps with Clay Dilative (CD), whereas Glauconitic Sand aligns with Sand Dilative (SD) and Glauconite silty Sand overlaps transitional and clay-dilative SBTs. The 3D overlay (Fig. 15) places most measurements within the corresponding ellipsoids for Boom Clay and the two glauconitic sand clusters.

Boom Clay shows a broad u_2 range from negative to positive values; its narrower ranges in qt and Rf are more useful discriminators. Glauconite silty Sand often shows relatively large positive u_2 for sands, which helps distinguish it from Glauconitic Sands and from mineral sand/silt mixtures. Glauconitic Sand typically presents small negative u_2 anomalies; these responses, albeit subtle, assist in differentiating it from mineral sands with hydrostatic pore pressures.

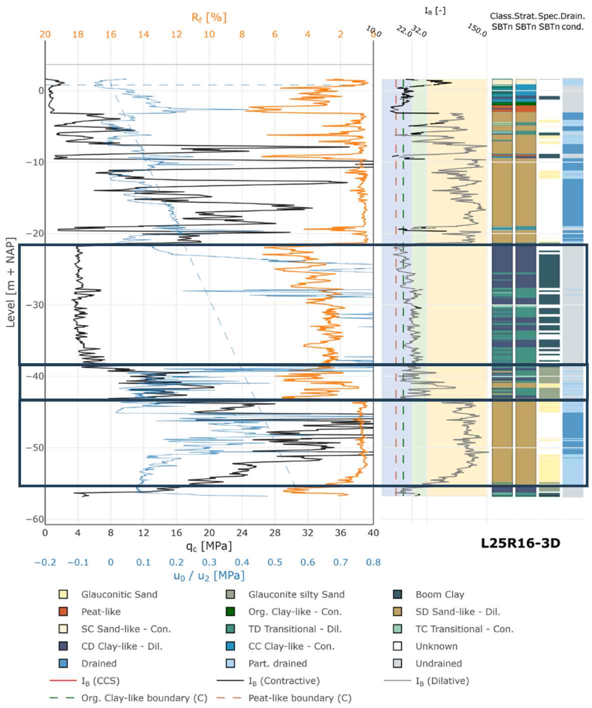

Fig. 13. Example CPT profile with Boom Clay and Glauconite Sands.

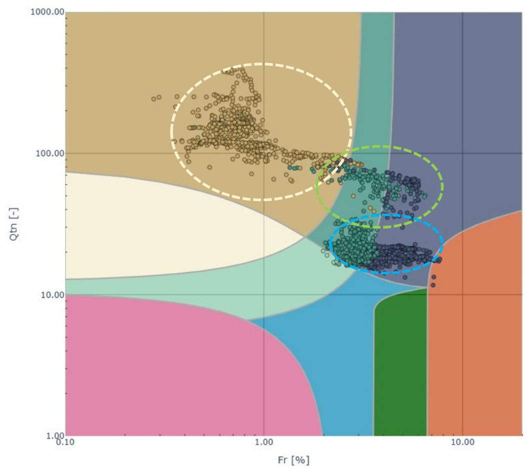

Fig. 14. Classical 2D SBT chart with 3D Glauconite sands and Boom Clay measurements.

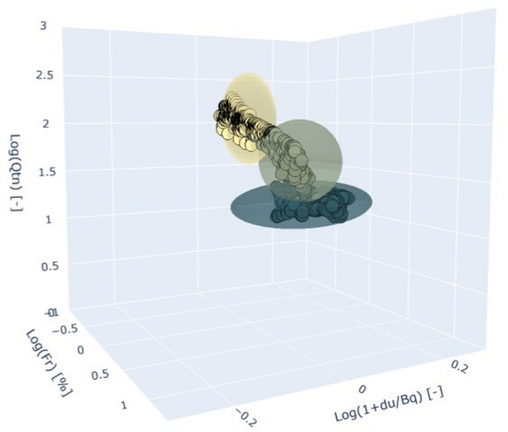

Fig. 15. New 3D framework with Glauconite Sands and Boom Clay measurements and ellipsoids.

5 Application and discussion

The examples demonstrate that, given a large and high-quality database, special soils can be more effectively identified using a 3D overlay of statistical ellipsoids than with classical 2D SBT charts. Incorporating the pore-pressure response (u_2), via the parameter Bq, yields better-defined classes and reduces conflicts that arise when separate 2D charts are used independently.

The ellipsoidal overlay is simple to compute, interpretable, and readily visualized with standard software, facilitating manual verification and use by practitioners. The approach is easily adaptable: ellipsoid parameters can be updated for site-specific datasets or extended to additional soil classes. As an overlay, the model complements rather than replaces existing 2D SBT frameworks; points that lie outside defined ellipsoids default to classical SBT assignment.

5.1 Limitations

- Overlap and scatter: Some classes (notably Classes 3 and 4 in the original taxonomy) exhibit considerable scatter and were excluded from the special-soil database because their ellipsoids would be overly large and uninformative.
- Mixed units: If the database contains mixed soil assemblages within a nominal class, the resulting ellipsoid may span multiple lithologies and lose practical discriminatory power.
- Data quality and depth effects: Site-specific calibrations are sensitive to CPT quality, particularly the accuracy of fs and u_2 measurements. Long, multi-layer CPTU soundings may record complex responses (e.g., drainage or boundary effects) that are not reproducible in small-scale laboratory conditions.
- Generalizability: Site-specific ellipsoids are not necessarily transferable to other regions without careful validation and local calibration.
- The 3D ellipsoidal overlay provides an interpretable intermediate step between classical SBT charts and fully automated machine-learning classifiers. While machine learning may ultimately provide more comprehensive classification models, the ellipsoidal approach offers transparency, statistical grounding, and ease of implementation.

6 Conclusions

Including normalized pore-pressure measurements (via Bq) directly in CPTU classification significantly improves the discrimination of several special soils relative to classical 2D SBT charts. The ellipsoidal 3D overlay:

- Defines soil classes statistically by mean and covariance in 3D CPTU space.
- Reduces ambiguous or conflicting 2D classifications by providing an additional diagnostic axis.

- Is straightforward to visualize and validate with standard geotechnical software.
- Is adaptable to site-specific data and extendable to additional classes given sufficient high-quality data.

Future work should include a systematic comparison between this visually interpretable 3D method and supervised machine-learning classifiers, and extensions of the ellipsoidal database to broader SBT clusters and other regions.

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