Stress-Normalized CPT Layering Using Friction Ratio and Cone Resistance for Ground Modelling

Introduction

Understanding and modelling subsurface variability is essential for accurate geotechnical design, ground risk assessment, and planning of additional site investigation. Cone Penetration Test (CPT) plays a central role in modern site characterization by providing high resolution, continuous profiles if soil resistance parameters. However, its full potential is often limited by the way CPT data is interpreted-either through manual stratification or generic empirical correlations that may not reflect site-specific conditions or soil behavior under varying stress states (Lunne et al., 1997; Robertson and Cabal, 2015).

A key limitation in conventional CPT interpretation is the stress-dependence of cone resistance (qc), which increases with depth regardless of changes in soil type. Without normalization, deeper layers appear artificially stiff, complicating soil classification and modeling (Mayne and Peuchen, 2022). Additionally, layering decisions are frequently subjective and engineer-dependent, leading to the inconsistency across CPT's on the same site. This becomes particularly problematic when constructing 2D or 3D ground models where spatial consistency and reproducibility are crucial (Eurocode 7, 2024).

The work presents a method for automated, stress-normalized CPT layering based on two normalized parameters: friction ratio and normalized cone resistance. These are used to cluster data points into transparent, engineer-defined material classes. The method is fully automated yet customizable, allowing engineers to define classification boundaries and material properties. It is designed to enhance stratigraphic consistency, identify meaningful transitions, and support downstream modeling workflows such as settlement analysis, finite element simulations and uncertainty quantification.

This methodology has been applied to a real-world dataset from Wilhelmshaven, Germany where six CPT's were processed using this classification system. The resulting stratigraphy shows consistent and geologically plausible layering across the site, including the preservation of thin but interpretable transitions-an important step toward more reliable site wide ground modeling.

Methodology

The proposed methodology performs automated stratigraphic classification of CPT data by combining normalized cone resistance and friction ratio in a reproducible and site-adaptable manner. The process is configuration-driven, allowing engineers to define model material behaviour transparently and apply it consistently across a project site.

The input consists of raw CPT measurements in GEF (Geotechnical Exchange Format) which are parsed into the structured CSV files. For each depth record, cone resistance (q_c), and sleeve friction (f_s) are used to calculate the friction ratio $R_f = \frac{f_s}{q_c} \times 100\%$. As cone resistance is stress-dependent, normalization is applied using a formulation derived from the Hardening Soil model (Schanz et al., 1999), avoiding empirical overburden correction methods. The modelled resistance $q_{c\text{-model}}$ is computed as:

$$q_c model = q_{cref} \cdot \left(\frac{c.\cos\varphi + \sigma'_v .\sin\varphi}{c.cos\varphi + 100.sin\,\varphi} \right)^m$$

where, q_{cref} is the reference cone resistance at one hundred Kpa effective stress, σ'_v is the effective vertical stress at each depth increment, c, φ and m, are configuration-defined parameters representing cohesion, internal friction angle, and stress-dependency factor, respectively. This physically based normalization links stratigraphy to stiffness parameters used in geotechnical modelling.

Each CPT data point is then assigned to the nearest classification anchor in the normalized parameter space, defined by a unique combination of friction ratio and normalized cone resistance. Classification is repeated in a second loop following the update of unit weights and stress conditions. All model materials and thresholds are defined in external configuration files, ensuring adaptability and transparency.

To reduce classification noise and ensure geologically plausible layering, a minimum layer thickness is enforced. Layers thinner than this threshold are merged with adjacent layers using a weighted averaging of material properties. This parameter, like all others, is site-specific and defined based on geological conditions and modelling needs. At the Wilhelmshaven site, this setting proved effective for capturing transitions while eliminating spurious fragmentation.

The output is vertically sequenced stratigraphy per CPT, containing layer depths, material ID's, and associated parameters. These can be directly used in 2D/3D ground model construction, settlement analyses, or numerical simulations, with all classification steps being fully traceable.

Case Study: Wilhelmshaven Site Application

To demonstrate the practical performance of the proposed method, we applied it to a CPT dataset from the Wilhelmshaven area in northern Germany. The site contains 18 CPT soundings distributed across varying geological features (Figure 1). Six representative CPT's (CPT_15, 18, 22, 26, 27, and 28) were selected to evaluate classification stability and assess the consistency of interpreted soil layering.

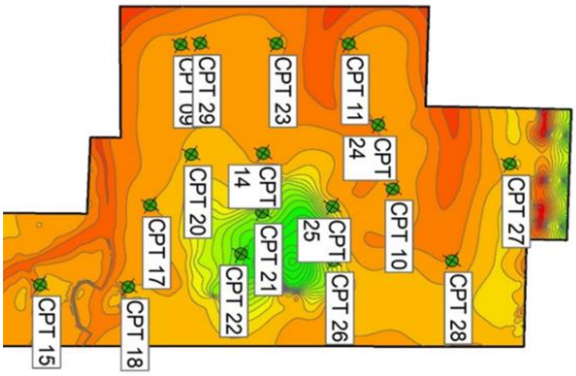

Figure 1 *CPT layout for the Wilhelmshaven site. The Six CPT's used in this study (CPT_15, 18, 22, 26, 27, 28) are highlighted.*

Each selected CPT was processed using the method described in the methodology section, based on a site-specific configuration file defining friction ratio and normalized cone resistance thresholds. Stress normalization was based on the Hardening Soil model (Schanz et al., 1999), using effective vertical stress profiles derived from groundwater conditions and material-specific unit weights. This allowed modelled cone resistance ($q_{c\text{-model}}$) to reflect stress dependency and material stiffness realistically, consistent with the classification framework. A minimum layer thickness of 0.3m was applied to reduce over-fragmentation of the stratigraphy while preserving key meaningful geological transitions.

Figure 2 presents two representative CPT profiles, showing measured and modelled cone resistance (q_c, $q_{c\text{-model}}$) and friction ratio (R_f, $R_{f\text{-model}}$) are plotted against depth. Distinct soil units, such as stiff clays, medium-dense sands, and soft silts, are consistently identified. The classification output aligns visually and mechanically, demonstrating a reduction in interpretive subjectivity and supporting reproducible stratigraphic modelling.

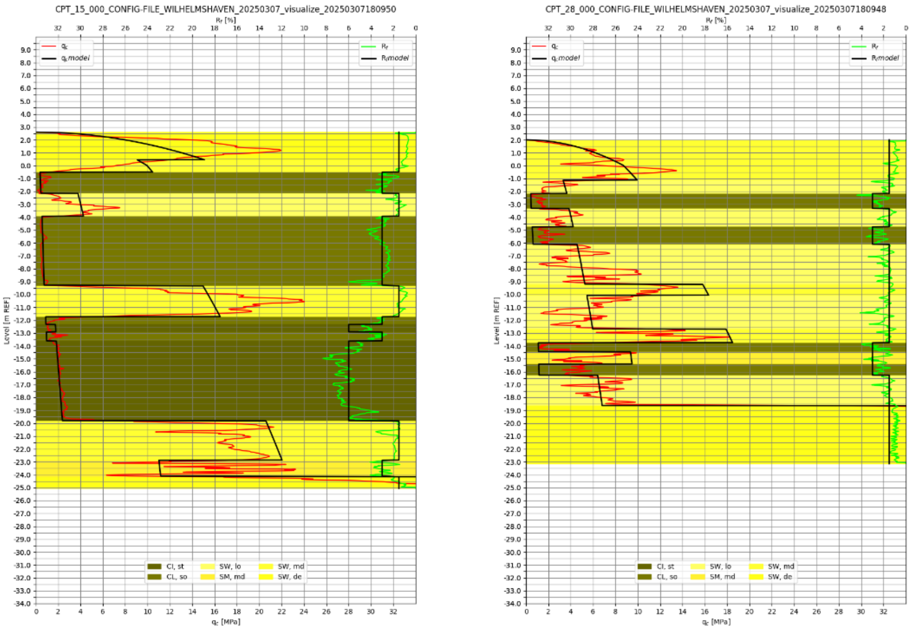

__Figure 2__ Classification results for CPT_15 and CPT_28 from Wilhelmshaven. Measured and modelled cone resistance and friction ratio are shown alongside interpreted model materials.

In addition, Figure 3 provides a 3D visualization of the stratigraphic columns across all six CPT locations. This rendering highlights the lateral consistency of identified model layers and reveals areas of vertical and horizontal variability. Such representations are valuable for early-stage geotechnical decision-making, enabling efficient planning of targeted additional investigation.

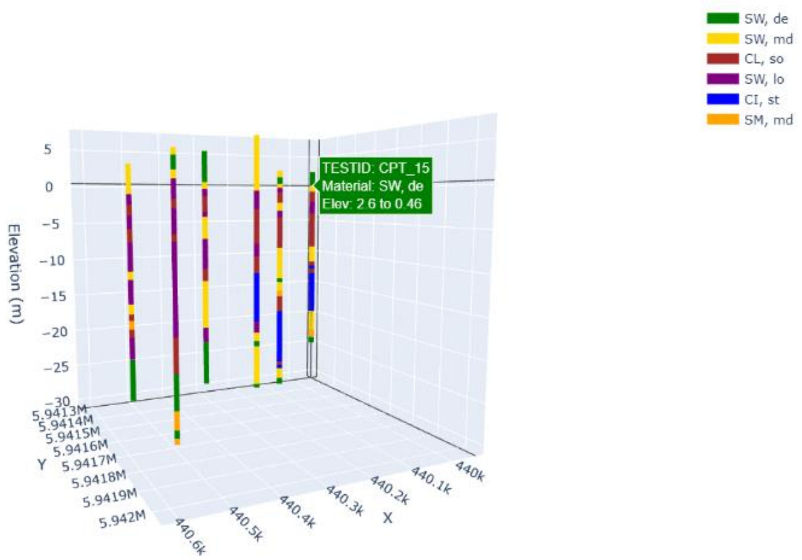

__Figure 3__ 3D view of the interpreted stratigraphy for six CPT's.

Conclusions

This study presents a method of automated, stress-normalized stratigraphic classification of CPT data using friction ratio and normalized cone resistance as primary clustering parameters. The approach allows geotechnical engineers to define material behaviour transparently through configuration files and applies these definitions consistently across all CPT's within a project site. Unlike traditional methods that rely on subjective interpretation or site-wide empirical assumptions, this method offers a reproducible, configurable framework that aligns with both engineering needs and soil behaviour principles.

The methodology was successfully applied to six CPT's from the Wilhelmshaven site in northern Germany. The results demonstrated consistent identification of model layers across locations, while preserving key transitions in material type and soil state. The enforcement of a minimum layer thickness of 0.3m improved model usability by filtering out noise without compromising geological detail. A 3D visualization of the output confirmed the stratigraphic coherence and spatial variability, making the approach well-suited for integration into early-stage geotechnical design and risk assessment workflows.

This work highlights the potential for improving ground modelling practices through transparent automation, stress correction, and material-aware classification logic. Future work will focus on integrating uncertainty quantification and extending the method to 2D/3D grid-based model generation.

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