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CHARACTERIZING THE CPT RESPONSE AND PARTICLE SIZE DISTRIBUTION OF FLUVIALLY DEPOSITED PLEISTOCENE SAND IN THE NETHERLANDS

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Abstract

Understanding the geological and geotechnical characteristics of the shallow subsurface is crucial for engineering decisions in densely populated regions like the Netherlands. Urban areas are for a large part built on a complex stack of sand, clay, silt, gravel and organics that were deposited over the last hundreds of thousands of years under gradually subsiding tectonic conditions. One of these units, a fluvially deposited sand known as the Kreftenheye Formation, is widespread across the western part of the country and is vital for foundation design and groundwater dynamics. The Kreftenheye Formation is therefore well described by geotechnical and geological tests, yet integrating both types of data has rarely been done on a nationwide scale. This paper focuses on 76 pairs of Cone Penetration Tests and boreholes that include Kreftenheye, out of a full database of nearly 200 pairs from TNO - Geological Survey of the Netherlands, generally reaching depths up to 40 meters. The study reveals significant spatial variations and depositional patterns within the Kreftenheye Formation, illustrating how overlying or interlayered flood plain or soft channel lag sediments influences the response of the CPT. Furthermore, CPT response and borehole samples have helped with making geological distinctions between the upper, Weichselian part of the Kreftenheye Formation and the lower Saalian part, showing how integrating both datasets can give both geological and geotechnical insights.

Key words

CPT, soil variability, granular soil, particle size distribution, Late Pleistocene, fluvial sand

1 Introduction

In the Netherlands, a fluvially deposited Middle and Late Pleistocene sand, known as the Kreftenheye Formation, is widespread across the country and the Dutch North Sea Sector (Busschers et al., 2007; TNO-GSN, 2024). In the heavily populated coastal and river areas of the Netherlands, the formation is typically overlain by clay and peat of Holocene age (Ngan-Tillard et al., 2010; Koster et al., 2018). Consequently, most infrastructure and buildings are founded on piles. These foundation piles are driven through the overlying soft sediment, transferring most of the load to the stiff sands of the Kreftenheye Formation.

Nevertheless, the formation poses some engineering challenges. The formation is generally dense to very dense, with Cone Penetration Test (CPT) tip resistances reaching more than 80 MPa in parts. Getting piles to their target depth whilst avoiding refusal and pile damage can therefore be challenging (de Gijt et al., 2019; Duffy et al., 2024). Furthermore, weak zones within this layer can bring unexpected changes in the pile installation resistance, as well as affecting the ultimate capacity of the pile.

Traditionally, many studies focus on the geological characterization of formations, often missing out on important patterns revealed by geotechnical data such as CPTs (Busschers et al., 2005; TNO-GSN, 2024). Conversely, CPT focused research and industry practices may disregard the geological origin of deposits and overlook essential insights into the formation's history and potential risks (Robertson, 2016;Mayne, 2017). By integrating both geological and geotechnical perspectives, a more comprehensive understanding of subsurface conditions can be achieved, leading to better-informed engineering decisions.

This research addresses this integration gap by analysis of a dataset of nearly 200 CPTs and borehole pairs from the TopIntegraal drilling and measurement program provided by TNO – Geological Survey of the Netherlands (Buma et al., 2024), generally penetrating the shallow subsurface up to depths of ~40 meters. This paper presents this analysis, showing the geological and geotechnical patterns and variations within the Kreftenheye Formation and how the integration of geological and geotechnical knowledge can lead to more effective engineering designs.

2 Depositional history of the Kreftenheye Formation

The Kreftenheye Formation was deposited by the river systems Rhine and Meuse in the Netherlands, commencing during the late Middle and Late Pleistocene, spanning approximately 160,000 to 12,000 years ago (Busschers, 2008; Peeters et al, 2015; Verbraeck, 1983; Weerts and Busschers, 2003). This timeframe encompasses the late Saalian (cold climate, glaciation), Eemian (warm climate), Weichselian (cold and temperate climate), and Holocene (warm climate) periods, each characterized by distinct climate conditions and sea levels (Figure 1).

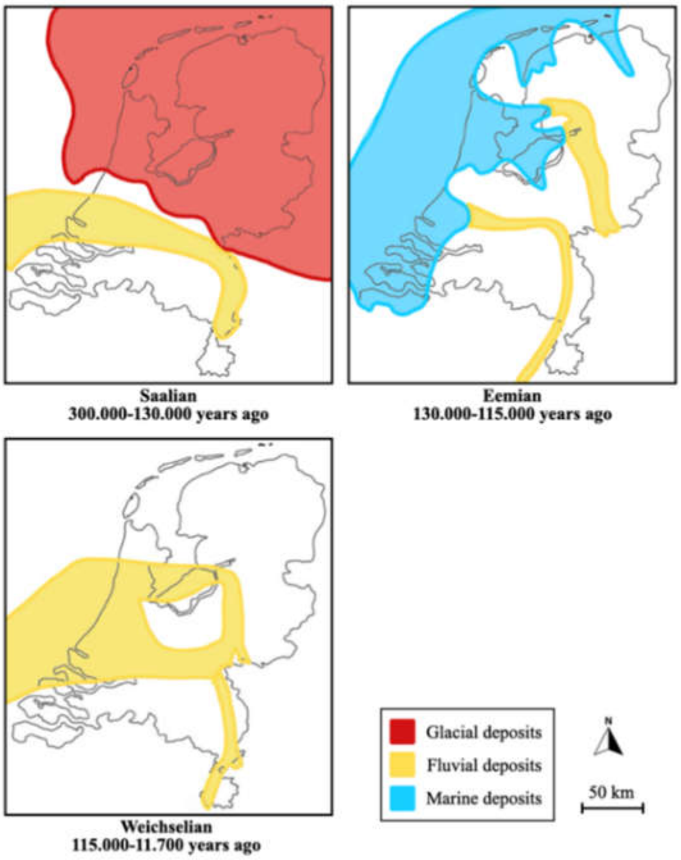

Figure 1. Simplified paleogeographical maps of the Netherlands during the late Saalian, Eemian, and Weichselian periods. Adapted from Busschers et al. (2007) and Wong (2007).

During the late Saalian glaciation, which occurred approximately 160.000 to 130.000 years ago, the northern region of the Netherlands experienced extensive glaciation with the ice sheet prograding into the Netherlands up-to the Haarlem – Utrecht – Nijmegen – Dusseldorf line. Along the ice front ice-pushed ridges were formed and fluvial sediments of the Rhine-Meuse were deposited in front, depositing the older part of the Kreftenheye Formation. During the late Saalian deglaciation the Rhine took a new course into the former glaciated area and the Meuse remained in a position south of the former ice line. During the Eemian (130.000 to 115.000 years ago), the climate warmed, tree vegetation developed and sea-level rose to elevations similar to or above present day values, hereby submerging major part of the Netherlands. The encroaching coastline reduced the energy of the river systems, with dominance of deposition in meandering rivers, estuaries and shallow marine environments (Peeters et al., 2016). In the subsequent Weichselian period (115.000 to 11.700 years ago), the Netherlands experienced a return to generally colder conditions with a strong drop in sea-level, formation of (temporal) permafrost and opening of the vegetation cover. Colder periods alternated with warmer climatic periods although especially the last 20.000 years of the Weichselian experienced most cold climatic conditions with large scale development of permafrost and supply of coarse-grained sediments into the Rhine-Meuse system, hereby depositing the upper part of the Kreftenheye formation. During the second half of the Weichselian, the branch of the Rhine through the northern Netherlands became entirely abandoned and the Rhine retook a course south of the former late Saalian ice line, merging with the Meuse.

To summarize, the diverse climatic and environmental conditions over this timescale resulted in fluvial deposits that include a wide range of sediment types. Consequently, the Kreftenheye Formation is characterized by fine to coarse-grained sand and gravel, interspersed with five characteristic Members and Beds (TNO-GSN, 2024), although we do note that most of the Kreftenheye Formation is not subdivided into Beds and/or Members:

- **Wijchen Bed**: Silty clay from meandering rivers and wind-blown fine grained sands, deposited during the late Weichselian .
- **Ockenburg Mb.**: Coarse sand with reworked marine fossils from the Eemian sea, deposited during the Weichselian.
- **Zutphen Mb.**: Clay, silt, peat and sand, deposited during the Eemian.
- **Twello Mb.**: Medium fine to coarse sand, and stiff clay, deposited during late Saalian and early Eemian.
- **Well Mb.**: Medium to coarse sand, deposited during the late Weichselian.

3 Methods

The dataset used in this research is provided by TNO – Geological Survey of the Netherlands and is collected as part of the drilling and measurement program TopIntegraal (e.g. Buma et al 2024, Harting et al., 2023; Bosch et al 2014; Vernes et al., 2010). The dataset serves as a resource for characterizing subsurface conditions up to a depth of 30–50 meters in the Netherlands.

The objective of the TopIntegraal program is to provide detailed insights into subsurface characteristics to support for instance geological mapping, hydraulic assessments, and infrastructure planning. This is achieved through the integration of lithological, geochemical, geotechnical, and hydraulic data obtained from borehole trajectories and CPTs in the Netherlands. The dataset targets all the lithostratigraphic units defined in the shallow subsurface of the Netherlands and is running since 2006.

Figure 2. Map of the Netherlands showing the locations of the CPT and borehole pairs, including a subset of locations within the Kreftenheye Formation used in this study.

Figure 2 shows an overview of the data locations in the Netherlands and the area of deposition of the Kreftenheye Formation. Each data point comprises two main components: a CPT sounding and a borehole. The CPT includes measurements of cone resistance, sleeve friction, and excess pore water pressure. The boreholes are sampled at different frequencies and intervals to capture the formation and its members. Data points are limited in the central eastern region of the Netherlands, as not all areas have been targeted yet in the ongoing TopIntegraal program. The acquisition and - in time - release of this data by TNO is expected in the future. The distance between the CPT and the borehole is intended to be limited as the CPT is performed first as an exploratory CPT before the drilling is performed. Three-quarters of the data points have the two main components lying within a 10-meter distance of each other. The bar chart in Figure 3 displays the number of data points (CPT and borehole pairs) for the Kreftenheye Formation, indicating the number datapoints for the members. Additionally, the chart highlights in green the number of grain size measurements available within the formation and its individual members. CPT data for the formation and its members were selected based on the lithostratigraphic interpretations of the associated boreholes by TNO.

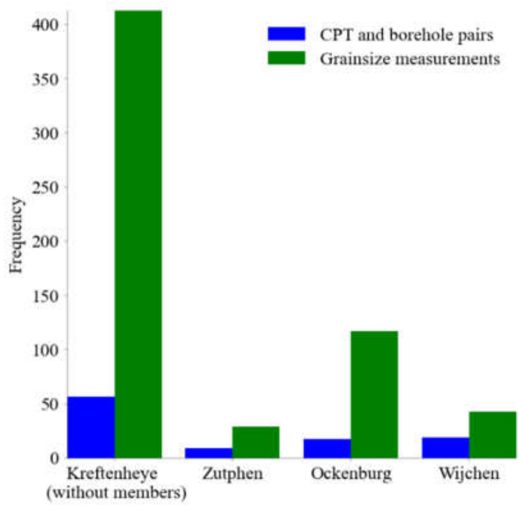

Figure 3. Overview of the dataset of the Kreftenheye Formation used in this study.

4 Results

4.1 CPT and borehole integration

Laboratory research (Ahmadi and Robertson 2005; de Lange 2018; Tehrani et al. 2018) as well as numerical research (van den Berg 1994) has shown that the CPT tip resistance is affected by soil not just at the CPT tip, but in a zone several diameters above and below the CPT tip. Figure 4 shows this effect in a field measurement context: in this case, the Wijchen Bed of approximately 25 cm thickness overlying the Kreftenheye Formation. The transition zone is indicated in the borehole picture by a red circle. First, the CPT data identifies the presence of the Wijchen Bed. Following this, the transition to the underlying layer, characterized by the higher cone resistance of the Kreftenheye Formation sand, extends over a considerable depth of more than a quarter of a meter. This suggests that the influence of the overlying soil on the CPT tip resistance affects a significant vertical range. This extended transition is unlikely to represent a gradual mixing of clay and sand over such a distance within the Wijchen Bed, given its distinct depositional environment compared to the undifferentiated Kreftenheye Formation sand. This observation suggests that the CPT cone is likely influenced by the Wijchen Bed, even after it has physically passed the boundary due to its sensing distance. Consequently, this result indicates that caution is needed when interpreting CPT data for the first interval of the Kreftenheye Formation because of the sensing distance.

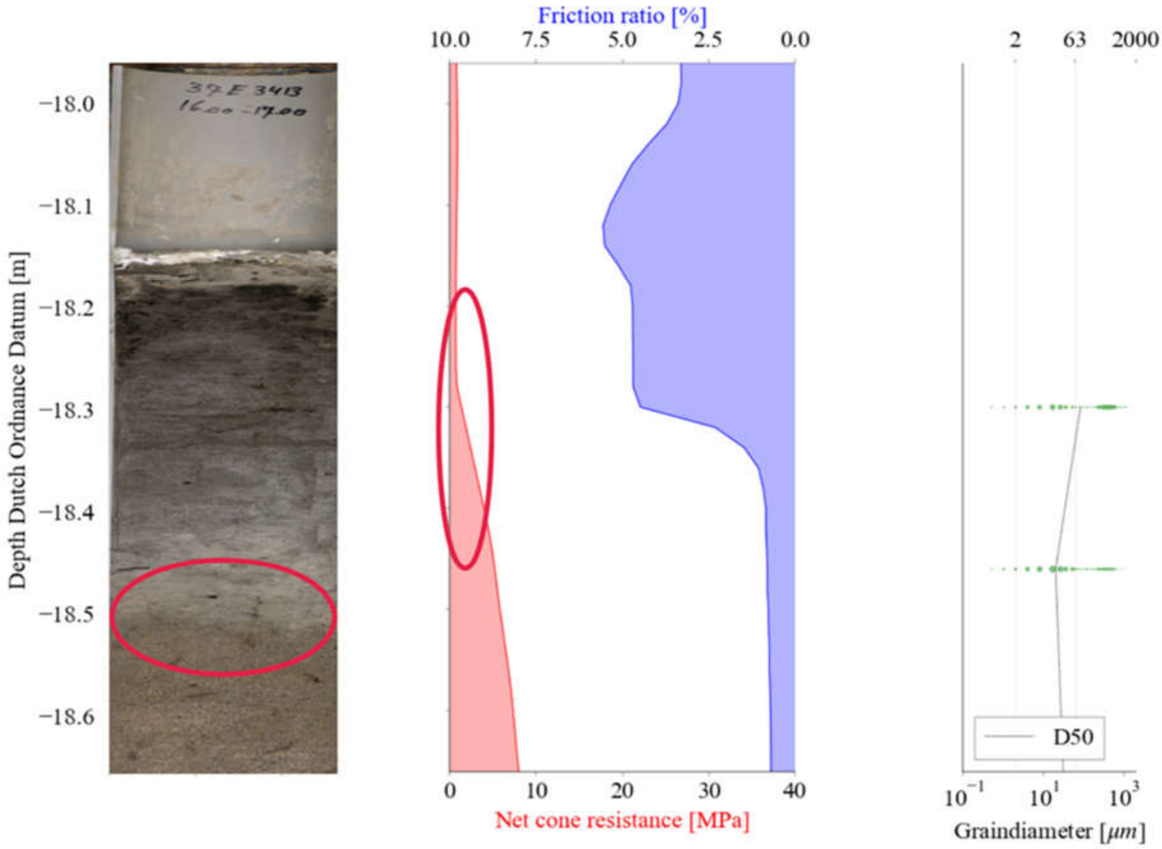

Figure 4. Influence of sensing distance on the Wijchen Bed. Left pane: photo taken from the borehole (B37E3413), central panel: CPT of the same interval (CPT000000012746), right panel: grainsize measurements for the interval.

Interlayered floodplain or soft channel lag deposits occur within the undifferentiated fluvial Kreftenheye Formation and can significantly affect the response of foundation piles, as studied by Chai et al. (2022). Their research underscores the importance of identifying weak zones and understanding their extent. Figure 5 illustrates an example of an intermediate weak zone in the CPT response within the undifferentiated Kreftenheye Formation, indicated by a red circle. However, the borehole picture shows no clear weak zone that can be linked to the CPT response. In other borehole pictures, small clay pebbles are visible, indicating that channel lag deposits described by Busschers (2008) may be present, and it is possible the CPT cone encountered one. This example demonstrates the importance of understanding the geological context when interpreting a CPT profile, as it can provide additional information on the spatial variability of weak zones.

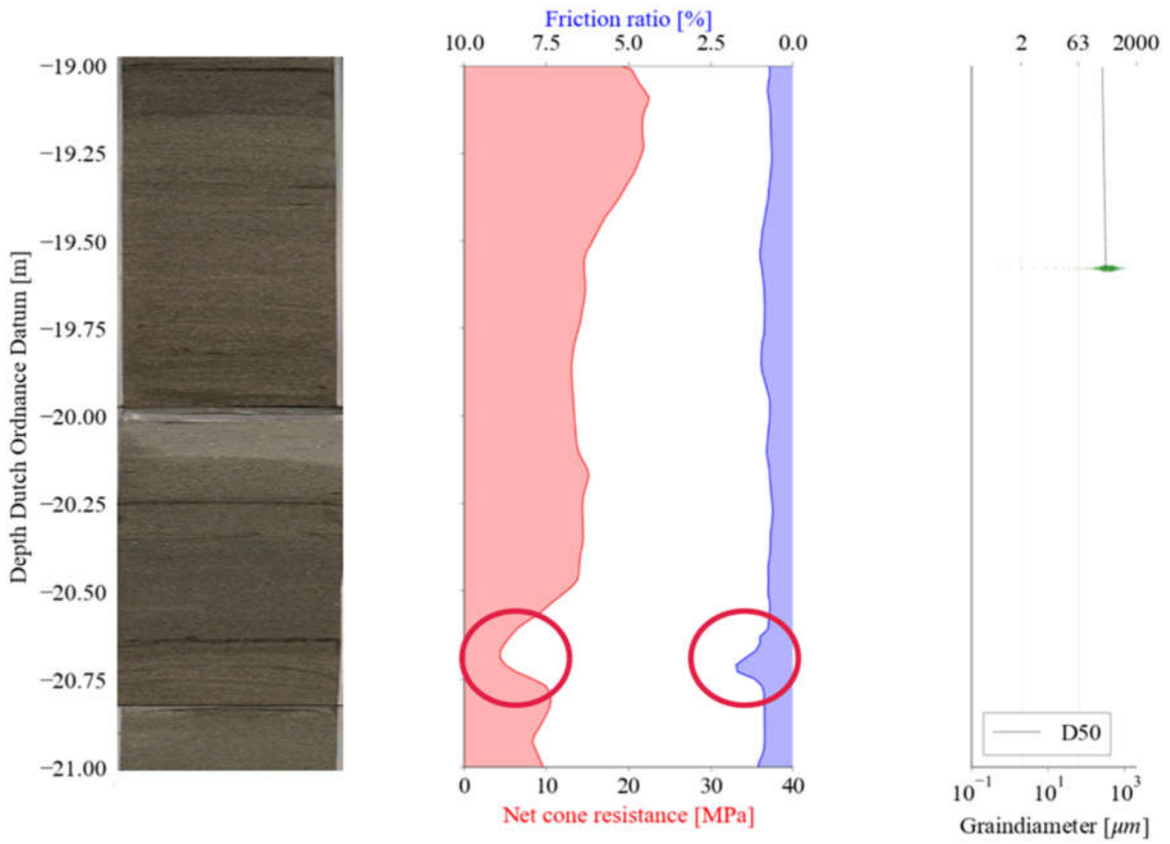

Figure 5. Intermediate soft layer within the Kreftenheye Formation. Left pane: photo taken from the borehole (B14E0952), central panel: CPT of the same interval (CPT000000043211), right panel: grainsize measurements for the interval.

4.2 Kreftenheye Area A and B

The second result presented in this article is the identification of differences between two regions within the Kreftenheye Formation. Busschers (2008) distinguished two areas within the Kreftenheye Formation based on the region and age: Area A, the upper/northern branch of the river system, deposited during the Weichselian and Eemian periods, and Area B, the lower/southern branch of the river system, deposited during the Saalian and Weichselian glacial period (see Figure 1). Busschers (2008) described the differences between these areas based on continuous core samples; however, a detailed analysis based on CPT measurements has not yet been conducted.

Figure 6 illustrates all the CPT data for the undifferentiated Kreftenheye Formation without the members, categorized into Areas A and B, plotted on a Robertson (1990) classification chart for translating CPT sounding into soil types. The CPT data is selected based on the borehole descriptions. The plot reveals a significant difference between the regions: Area A exhibits a wider range of cone resistances and friction ratios compared to Area B, with Area A having a higher proportion of low cone resistance soils. Additionally, the grain size distribution plot for Areas A and B shows a similar pattern, with Area B comprising more uniform and coarser material compared to the more variable and fine grained material in Area A.

The coarser and more uniform sediments in Area B can possibly be explained by the colder climate and low vegetation of the Saalian glacial period compared to the more variable Weichselian period (Peeters et al 2015). These conditions contribute to a more energetic river system, which deposits coarser and more uniform sediements.

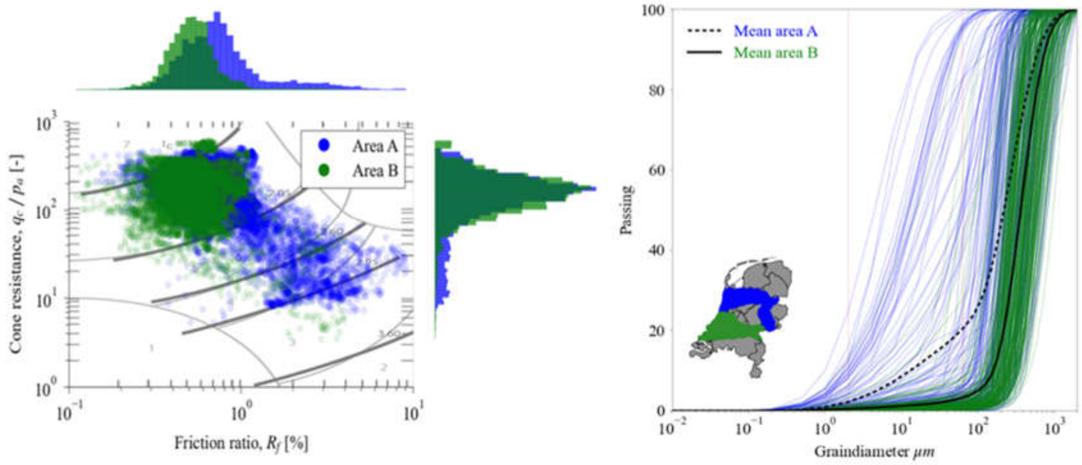

Figure 6. Robertson (1990) soil classification chart and the cumulative grain size distribution for Areas A and B of the undifferentiated Kreftenheye Formation. 27 CPTs and 157 grain size distributions for Area A, 26 CPTs and 256 grain size distributions for Area B.

4.3 Ockenburg Member

The Ockenburg Member is characterized by the presence of reworked marine fossils from Eemian tidal and coastal deposits by the Rhine-Meuse river during the Weichselian (Busschers et al., 2005; 2007; Peeters et al., 2016). The dataset of this study is used to find other distinguishing features within the Ockenburg Member to differentiate it from the Kreftenheye Formation, motivated by its mixed characteristics and location underneath major cities such as Rotterdam.

Figure 7 provides an overview of the CPT data and grain size measurements for both the Ockenburg Member and the Kreftenheye Formation. The CPT data shows a more centred distribution of data points compared to the Kreftenheye Formation. A region for the Ockenburg Member is visible (indicated by a red circle), consisting of two outlier data points from locations near the present-day coastline. The grain size data indicates that the Ockenburg Member is slightly more uniform and coarser on average compared to the Kreftenheye Formation.

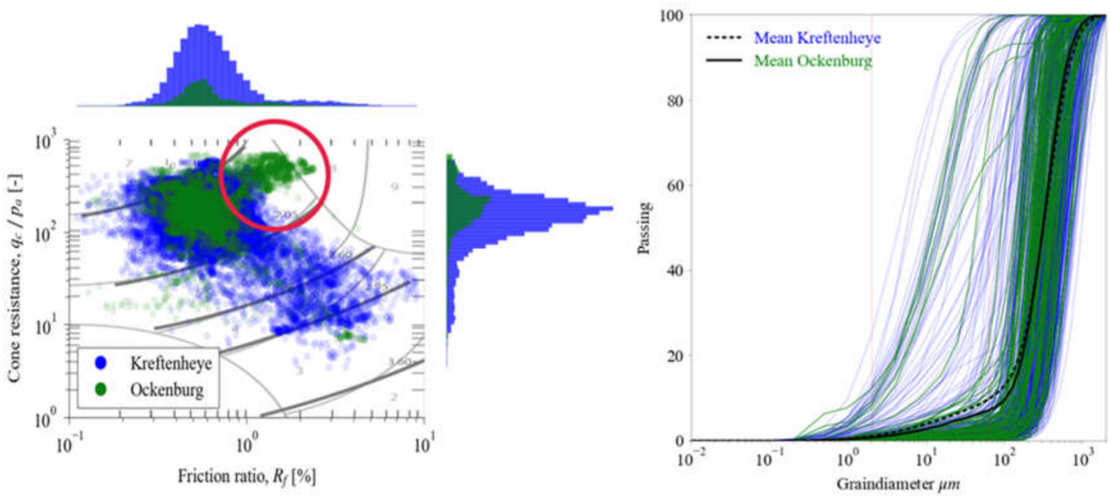

Figure 7. Robertson (1990) soil classification chart and the cumulative grain size distribution for the undifferentiated Kreftenheye Formation and the Ockenburg Member. 53 CPTs and 413 grain size distributions for the Kreftenheye Formation, 18 CPTs and 117 grain size distributions for the Ockenburg Member.

5 Implications for geotechnical engineering

The findings of this study have several signification implications for geotechnical engineering practices, particularly in the context of ground modelling and probabilistic analysis.

From a geotechnical perspective, the stratigraphic changes within the Kreftenheye Formation can affect how the formation is modelled at both a site-specific and regional level. CPT-based ground models are used to infer the soil properties between investigation points and—in the context of deep sand formations—are used for both stochastic and probabilistic modelling of deep excavations (Roubos 2019), as well as for offshore and onshore piled foundations (Peuchen et al. 2022; Vanneste et al. 2022). Ground models can be qualitative or quantitative and are developed using various methods, including geostatistical methods (Vanneste et al. 2022; Vessia et al. 2020) and machine learning methods (Peuchen et al. 2022; Vanneste et al. 2022; Xie et al. 2022). Ground models should accurately reflect the stratigraphical and lithological variation within each formation. A thorough understanding of the depositional processes and the resulting stratigraphical and lithological differences, is crucial for this purpose.

Lithological heterogeneity, such as the thin zones embedded within the Kreftenheye Formation, significantly affects how piles respond based on their location, relative strength, and thickness (Boulanger and DeJong, 2018; de Lange, 2018; Tehrani et al., 2018). Recognizing the likelihood of encountering these thin zones can help designers anticipate unexpected changes in a pile's installation response or performance under loading. This understanding enables more accurate predictions and adjustments during the design and construction phases, ultimately enhancing the reliability and safety of geotechnical structures.

6 Conclusion

A combined dataset was used of nearly 200 CPTs and borehole pairs provided by TNO – Geological Survey of the Netherlands, penetrating the shallow subsurface up to depths of ~40 meters, was used to study the Kreftenheye Formation. This formation is vital for geotechnical engineering applications such as foundation design and groundwater dynamics.

The data analysis revealed the influence of a weak layer in the formation on the CPT response, highlighting the importance of understanding the sensing and development distance from a CPT cone, as well as the geological context, when interpreting CPT measurements within this formation. Additionally, the dataset has improved the distinction between a northern and southern geographical area within the undifferentiated Kreftenheye, demonstrating coarser and more uniform sediment in the southern area compared to the northern area. Finally, the research has shown the challenge of identifying the Ockenburg Member from the undifferentiated Kreftenheye data using only CPT data, as both exhibit resemblance and overlap. However, the Ockenburg Member exhibited an additional cluster that did not overlap with the undifferentiated Kreftenheye. Additional research is recommended to further understand this cluster.

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