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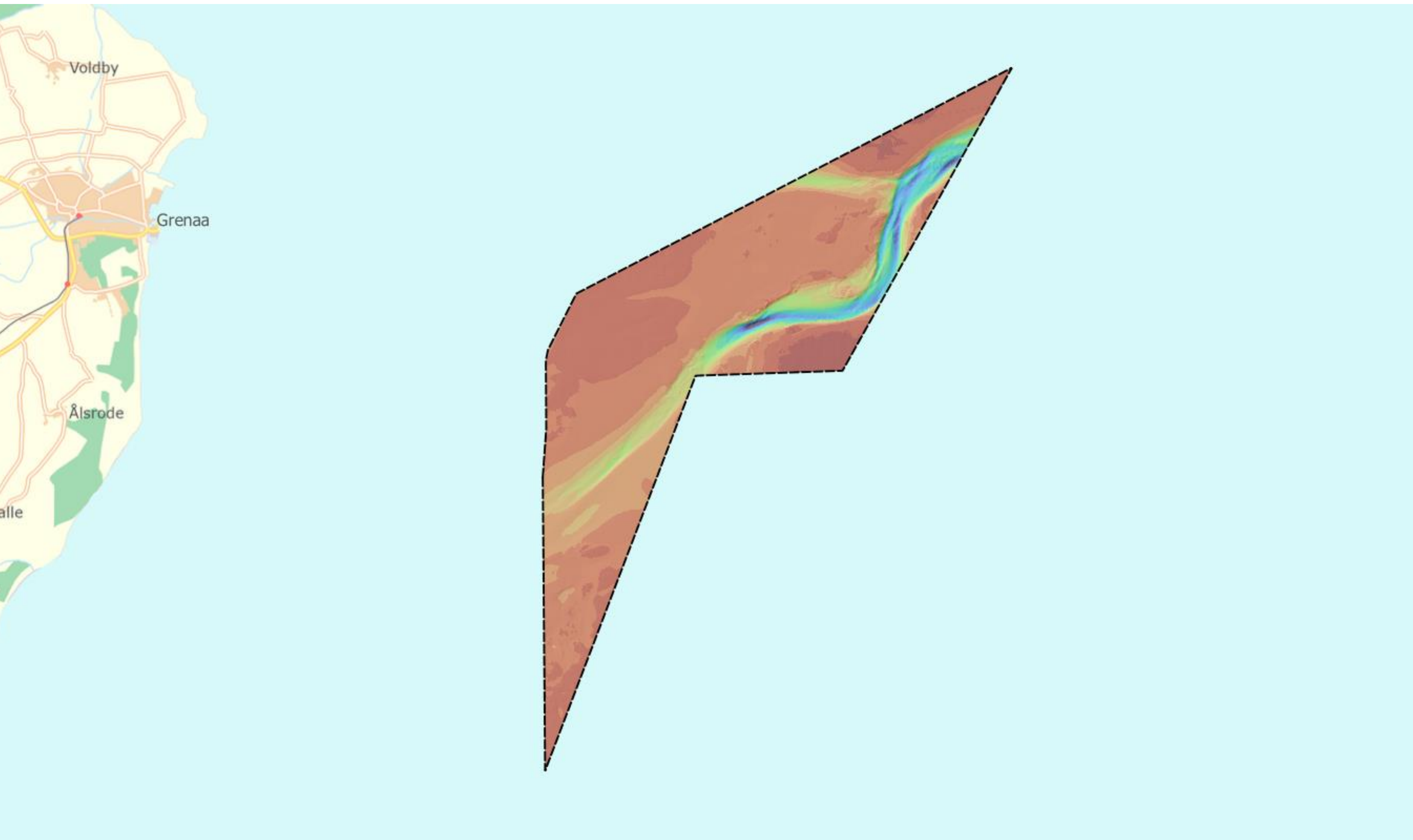
ENERGINET ELTRANSMISSION A/S

KATTEGAT – INTEGRATED 3D GEOMODEL

REPORT



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APPENDICES

1 Executive Summary

As part of Denmark’s plan for expansion of the energy supply from offshore wind farms (OWF) towards 2030, The Danish Energy Agency is preparing tenders for the Kattegat OWF area for design and installation of wind turbines. Energinet is developing the site with investigation in 2023 and subsequent reporting. The area of investigation covers 123 km² and is planned for a capacity of approx. 1 GW.

This report describes the work and outcome of the Integrated Geological Model (IGM) for the Kattegat OWF project site in the Danish Inner Seas (Kattegat). The 3D IGM covers the site down to a minimum depth of 100 m bsb (meters below seabed) and is based on integrated interpretation of geophysical and geotechnical data.

The geotechnical site investigations and reporting is performed by Gardline and geophysical investigations and reporting by GEOxyz, both investigations finalized in 2023. Seismic 2D UHRS data covers the site down to minimum 100 m bsb with a line spacing of approx. 250 m by 1000 m (2868 line-km in total) and SBP covers the top 10 m bsb with a line spacing of approx. 62.5 m by 1000m (650 line-km in total). The geotechnical data comprise offshore and onshore testing from six (6) individual borehole locations (4 re-tests), 18 CPT's (15 re-tests), and 13 dCPT’s (4 re-tests). Further, 2 SCPT’s, and 2 P-S logs have been included in the interpretations, together with several classification tests, advanced laboratory tests, and chemical tests.

The site investigation results are combined by integrated interpretation in the IGM containing detailed information on the spatial distribution of the soil units as well as the characteristic geotechnical parameters.

The IGM contains seven (7) integrated soil units consisting of Holocene, Pleistocene, and bedrock from Early Palaeocene, Cretaceous and Late Jurassic. A Conceptual Geological Model is also provided which visualizes the geological layers and their variation for the entire site in two conceptual profiles for the northern and southern part respectively.

The sediments generally comprise 0-8 m relative soft Holocene and Late Weichselian soils overlaying competent Pleistocene soils of a general thickness of more than 25 m. Bedrock is found deeper than 30 m over most of the site. Potential geohazards include a prominent seabed channel feature, evidence of limited areas with shallow gas, peat and boulders. Further, glacial deformation can create a larger variability in geotechnical properties of the Pleistocene soils whereas faulting is found to be confined to the bedrock layers.

The lateral distribution as well as the geotechnical properties are described for the seven soil units and variation range of soil parameters given for state properties as well as for strength and stiffness properties.

Based on the IGM a geotechnical zonation has been made outlining eight (8) different geotechnical zones with regards to ground conditions for WTG foundation design and installation. The zones have been defined based on selected criteria for thicknesses of soft sediments combined with depth to the pre-quaternary deposits.

Overall good soil conditions are found feasible for OWF foundation design. In the northern part of the site especially the geotechnical zonation shows large thickness of competent glacial material within foundation depth. In the southern part of the site pre-quaternary material is found more shallow resulting in a smaller thickness of competent glacial material.

The leg penetration risk has been assessed for each of the geotechnical locations for two generic vessels – an installation vessel and an O&M vessel – and a risk category has been assigned for each survey location. Also, a risk categorisation of the entire site has been made based on the integrated ground model. The results from the performed assessment show large variance of jack-up behaviour across the Kattegat OWF project site, which is also in accordance with expectations based on the results from the geotechnical zonation. The highest leg penetration risks are seen in the geotechnical zones with thickest layers of normally consolidated soft clays.

Enclosures provided with this report present the soil units as surface maps with respect to depth below seabed, elevation, thickness, and lateral extent. Furthermore, twelve (12) cross sections are provided showing the soil units, seismic data, and geotechnical data. Appendices include presentation of geotechnical data and interpretations, and the Conceptual Geological Model.

All enclosures and grids are provided digitally. The Integrated Geological Model is delivered as a digital 3D model in a Kingdom suite project.

2 Introduction

This report presents the Integrated Geological Model (IGM) from the Kattegat OWF project site. The IGM was made by COWI January-Juli 2024 and is based on the geophysical investigations (2023) and preliminary geotechnical investigations (2023) procured by Energinet Eltransmission A/S.

2.1 Area of investigation

The Kattegat OWF project site is situated approximately 15 km offshore the eastern coast of Jutland in the inner waters of Kattegat.

The Kattegat OWF project site covers 123 km² and is shown in Figure 2-1. The coordinates for the vertices of the area are listed in Table 2-1.

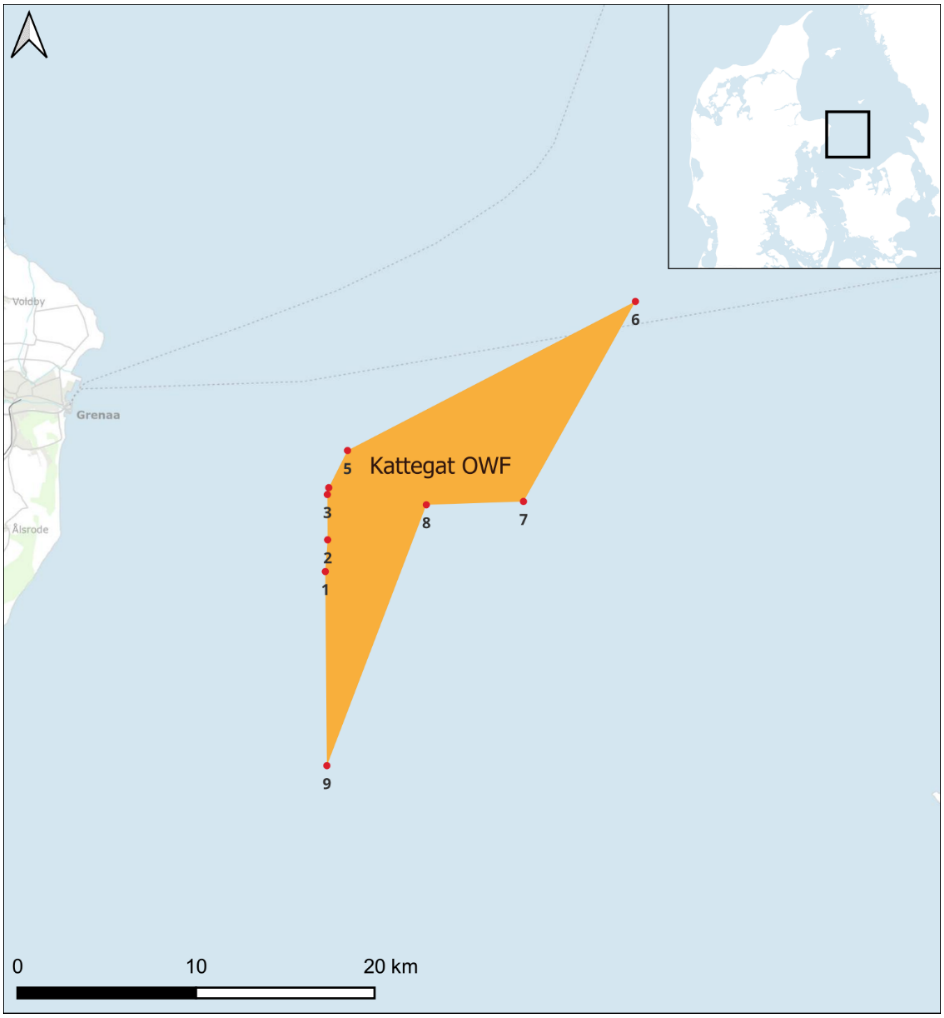


Figure 2-1 Kattegat OWF project site shown in orange. Numbered vertices for the area are shown as red dots, see Table 2-1 for coordinates.

Table 2-1 Coordinates for the 9 vertices of the Kattegat OWF project site.

Point ID	Easting EUREF89 Zone 32N [meter]	Northing EUREF89 Zone 32N [meter]	Longitude EUREF89	Latitude EUREF89
1	633170	6243935	11° 09.200' E	56° 19.284' N
2	633299	6245712	11° 09.379' E	56° 20.239' N
3	633285	6248250	11° 09.443' E	56° 21.607' N
4	633363	6248635	11° 09.530' E	56° 21.813' N
5	634414	6250716	11° 10.614' E	56° 22.916' N
6	650544	6259071	11° 26.561' E	56° 27.125' N
7	644273	6247861	11° 20.091' E	56° 21.204' N
8	638829	6247677	11° 14.804' E	56° 21.203' N
9	633257	6233058	11° 08.956' E	56° 13.424' N

2.2 Scope of Work

The results presented in this report will be part of the Kattegat OWF tender process, informing development tenderers about the local geology, associated geotechnical properties and potential geohazards as well as supporting subsequent development of the Kattegat OWF project site. A key objective of the present work is to ensure the applicability for sub-selection of a specific OWF site within the area of investigation.

The output of the assignment must be applied for

- Sub-selection of specific OWF area within the area of investigation.
- Initial determination of foundation concept and design.
- Assessment of the soil-related risks for installation of foundations.
- Initial planning of the layout for turbines.

These applications are relevant for both the license tender process and the subsequent development performed by the nominated developer.

The Integrated Geological Model comprises a Conceptual Geological Model, a digital, spatial geological model, and a geotechnical characterization of the soil units in the model.

Furthermore, a Geotechnical Zonation Map and a Leg Penetration Analysis are provided.

The digital deliverables include a Kingdom Suite 3D ground model and all soil unit interfaces as grids and shapefiles.

Please see section 12 for detailed information on the appendices, charts, and digital deliverables to this report.

3 Basis

Data packages have been received successively from Energinet. An overview of the data received from Energinet is listed below, divided into the geotechnical and geophysical data packages including reports.

Geotechnical data packages	
Datatype	Year
Danish Offshore Wind 2030 - Lot 1 – Kattegat II, Volume II: Measured and Derived Geotechnical Parameters and Final Results, Revision 2, Gardline. AGS data and Excel files providing results from offshore and onshore works of the geotechnical site investigation for Lot 1 documented in the report. Geotechnical Positions, 22	2024

Geophysical data packages	
Datatype	Year
GEOxyz: Kingdom Project with 2D Ultra High Resolution Seismic (2D UHRS) Line spacing 250*1000 m Sub Bottom profiler (SBP) Line spacing 62.5*1000 m SEG-Y data was also delivered separately from the Kingdom project	2024
GEOxyz: Geodatabase with Multi Beam Echo Sounder (MBES), 0.25 m x 0.25 m bin size / 16 x pings per 1.0 m x 1.0 m Side Scan Sonar (SSS) and Magnetometer (MAG) with 62.5 m line spacing. Tracklines, maps and results from geophysical surveys (MBES, SSS, MAG)	2024

Reports		
Author	Title	Year
GEUS	Screening of seabed geological conditions for the offshore wind farm area Kattegat and the adjacent cable corridor area	2023
GEOxyz	Geophysical and Geological Survey Report For Kattegat II	2023

3.1 Geotechnical basis

The geotechnical basis for the project can be divided into two categories:

- Offshore sampling and in-situ testing
- Laboratory testing and description

The Kattegat OWF site investigations have been performed by Gardline from March 2023 to August 2023. The campaign consisted of in-situ testing and laboratory testing. The in-situ works include borehole sampling (BH), different CPT types and wireline logging (P-S log). The laboratory works consist of soil description and classification testing as well as a comprehensive onshore laboratory test programme performed mainly by Gardline. Chemical testing and rock UCS was performed by GEOLABS and the advanced tests by GEO.

The geotechnical work has been summarised in a factual report Ref. /1/.

3.1.1 In-situ works

The offshore works consist of in-situ testing (seabed, downhole and seismic CPTs), P-S logging, and borehole drilling incl. sampling. The acquired samples are used for testing in the onshore laboratory programme.

An overview of the positions for CPT, including seabed (CPT), down-the-hole (dCPT) and seismic (SCPT), boreholes (with sampling), and P-S logs is shown in Table 3-1, Figure 3-1, and on Enclosure 1.02.

Several locations across the OWF project site have multiple CPTs due to premature CPT refusal, which means that the total number of unique locations surveyed is 22. Of these 22 locations, 6 locations have been surveyed with minimum one (1) CPT and one (1) borehole, while 16 have been surveyed with minimum one (1) CPT but no borehole.

For two (2) of the survey locations the CPTs have been performed as seismic cone penetration tests, i.e. including measurement of the shear wave velocity. Also, two (2) locations had wireline logging performed.

For boreholes a target depth of 70 m was considered. For CPTs a target depth of 55 m was considered. However, it is noted that most of the seabed CPTs have not reached the target depth due to stop criteria, like CPT refusal or rod deviation. Seven (7) locations had excessive sinkage of the seabed frame, which led to abortion of the CPT push and unprocessed CPT leading to bump-over locations were done.

The distances between CPTs and boreholes performed at the same location and the distances between extra repeated CPTs performed at the same location are maximum 16.5 m.

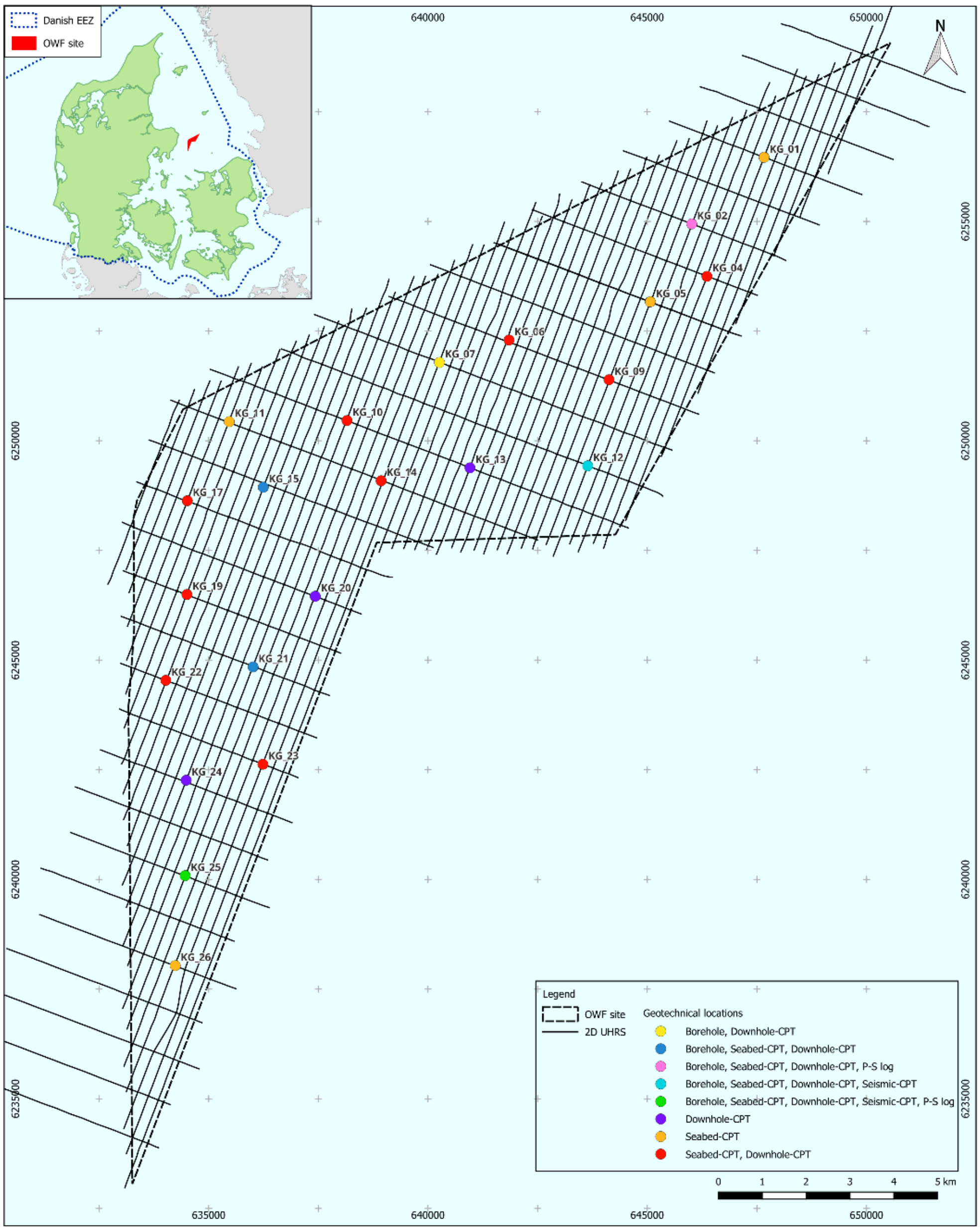


Figure 3-1 Overview map of the Kattegat OWF project site with locations for the 2D UHRS seismic lines and geotechnical data (borehole, CPT and P-S log).

Table 3-1 Summary of in-situ geotechnical tests.

Test type	Quantity*
Seabed Cone Penetration Test (CPT)	33 (incl. 15 re-tests)
Composite Cone Penetration Test and sampling boreholes (BH)	10 (incl. 4 re-test)
Downhole Cone Penetration Test (dCPT)	17 (4 re-tests)
Seismic Cone Penetration Test (SCPT)	2
P-S logging	In 2 BHs

**Only counting locations with usable data.*

3.1.2 Laboratory works

The laboratory works consist of classification testing, advanced laboratory testing and chemical testing. The performed laboratory tests available are summarized in Table 3-2.

Laboratory works are performed using samples acquired from the geotechnical composite downhole CPT and boreholes.

Table 3-2 Summary of performed laboratory tests.

Test type	Quantity*
Water content	167
Bulk and dry density	136 bulk density, 96 dry density
Particle density	66
Atterberg limits	37
Particle size distribution	65
Maximum and minimum dry density	6
Carbonate content	11
Acid & Water-soluble Sulphate	15
Acid & Water-soluble Chloride	15
Loss on ignition (Organic content)	8
Thermal conductivity	3
Oedometer (incremental load)	8
Laboratory hand penetrometer	90
Laboratory torvane test	1
Unconsolidated Undrained (UU) triaxial test	12
Point load tests (PLT)	32 (excl. 52 invalid tests)
Unconfined compressive strength (UCS)	21 (incl. 10 with strain gauges)
Consolidated Isotropically Undrained (CIU) triaxial tests	14
Consolidated Isotropically Drained (CID) triaxial tests	7 (1 excluded due to missing in M&D report)
Consolidated Anisotropically Undrained (CAU) triaxial tests	4 (1 excluded due to soil type)
Cyclic Consolidated Anisotropically Undrained (CAUcyc) triaxial tests	3
Direct simple shear (DSS) tests	6
Direct simple shear cyclic (CSS) tests	9 (3 sets of 3)

**Numbers based on available quantity of test results in available AGS data file, and numbers therefor can differ when comparing to numbers presented in Factual Report, cf. Ref. /1/, due to discrepancies between the Factual Report and related AGS data file.*

3.2 Geophysical and hydrographical basis

The geophysical basis for this report is a geophysical survey including 2D UHRS and SBP, acquired in 2023 by GEOxyz. The outcome of the site investigations (SI's) has been documented in Ref. /10/.

3.2.1 Bathymetry

MBES data were acquired for the entire Kattegat OWF area with a line spacing of 62.5 m. The bathymetry grid was received in 0.25x0.25 m grid size.

The bathymetry is shown on enclosure 1.01. A small part of the OWF project site to the west is seen not to be covered.

The water depth in the main part of the site is varying from approx. 16 to 26 m whereas water depth down to 48 m can be found in channel features.

3.2.2 Subsurface data

The 2D UHRS data were acquired with NNE-SSW orientated lines with a line spacing of 250 m, and cross lines of WNW orientation with a line spacing of 1000m (see enclosure 1.02).

The SBP mainlines were also acquired with NNE-SSW orientated lines with a line spacing of 62.5 m, and cross lines of WNW orientation with a line spacing of 1000 m.

The quality of the seismic data and limitations and uncertainties in the data is discussed in section 9.3.

4 Geological Setting

In this section an overview of the geological setting for the Kattegat OWF project site is presented. A more detailed description can be found in Ref. /7/.

4.1 Pre-Quaternary Geology

The Kattegat OWF is located near the south-western boundary of the Baltic Shield between the southern part of Sweden, the Kattegat, and the central part of Jutland. The area is strongly influenced by the Sorgenfrei Tornquist zone, a South-East to North-West oriented fault system, where one of the major faults, the Grenå-Helsingborg fault transcends the northern part of the Kattegat OWF, see Figure 4-1.

In the late Cretaceous to early Paleogene, the previous subsiding depocenter became inverted, primarily along pre-existing faults, due to a change in the regional stress orientation dominated by compression associated with the Alpine Orogeny and the opening of the north Atlantic.

The bedrock of Kattegat is expected to consist of Danien limestone in the southern half of the site and Jurassic and Upper Cretaceous sandy mudstone in in the northern half, see Figure 4-1 (Ref. /7/).

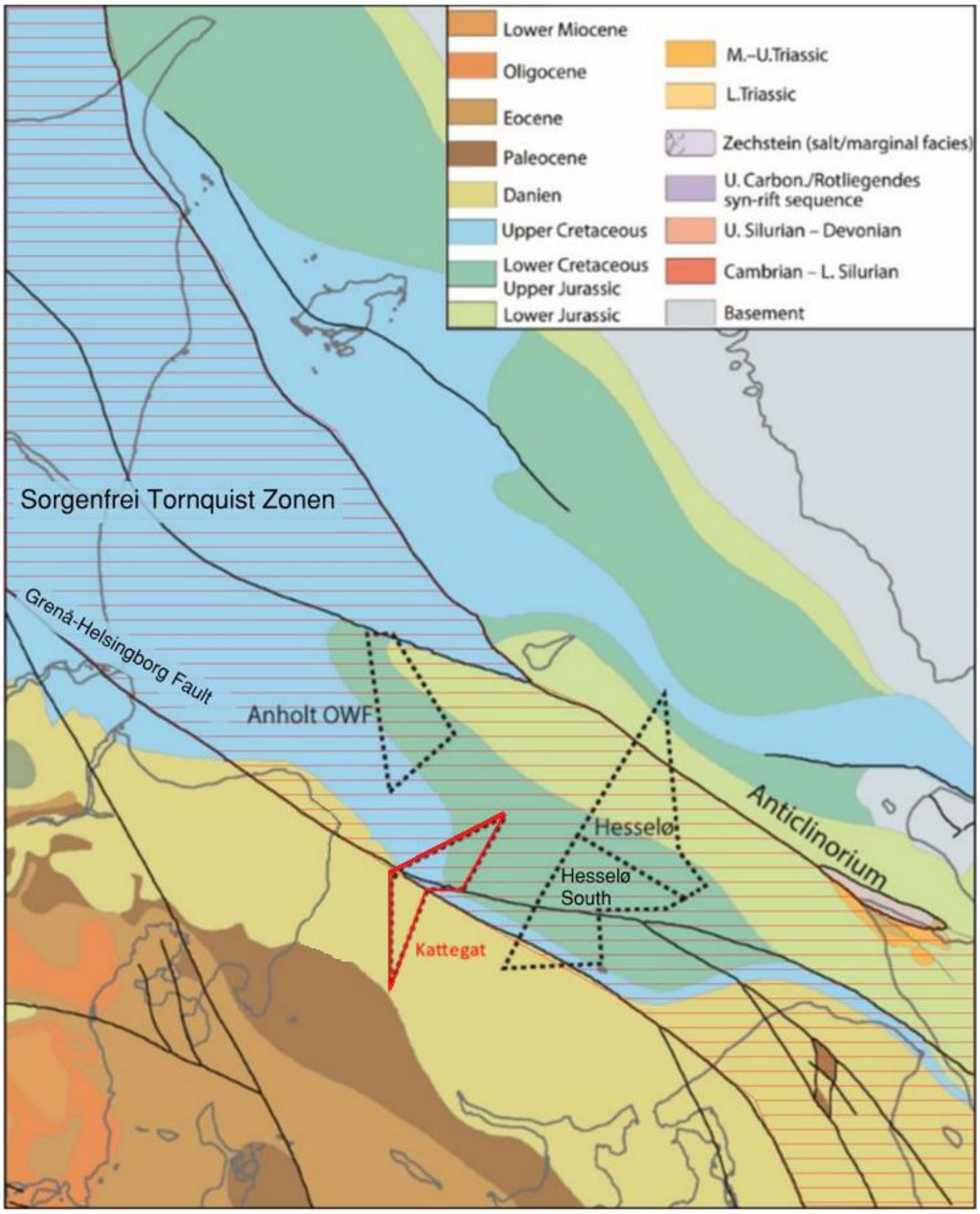


Figure 4-1 Map of the major faults and the Pre-Quaternary of Kattegat. The Kattegat OWF area is marked by a red line (Ref. /7/). The Grenå-Helsingborg fault is marked by a black line and the Sorgenfrei Tornquist fault zone is marked with vertical red lines. Anholt OWF and the Hesselø sites are also shown.

4.2 Quaternary Geology

During the Quaternary period several glacial events have been identified in the northern Danish area. The different glacial events are separated by interglacial or interstadial marine or glaciolacustrine conditions. In Figure 4-2 the extend of the 3 major ice advances, the Elsterian, the Saalian, and the Weichselian ice advance can be seen. During the full extent of all 3 advances the Kattegat OWF (marked by a star in the figure) has had a subglacial setting.

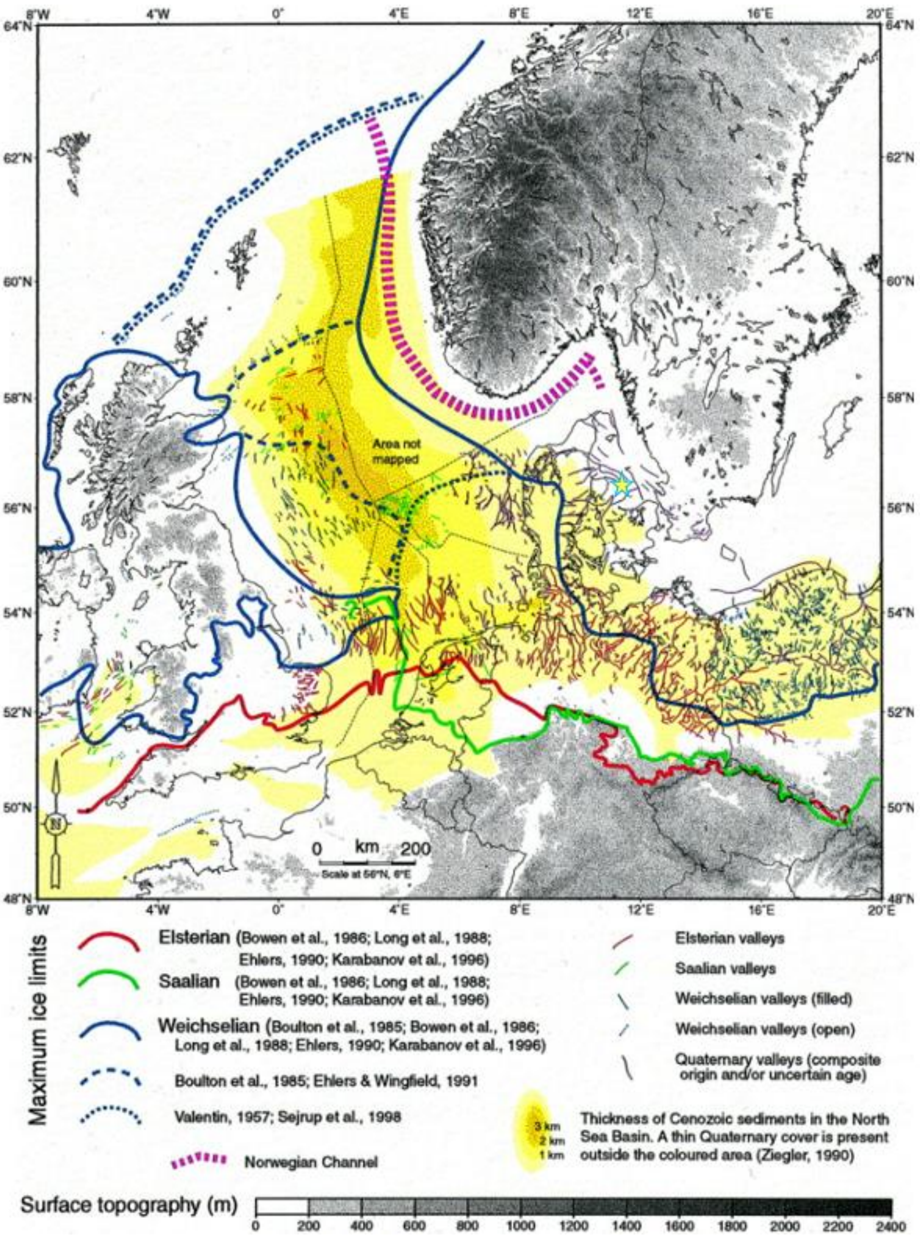


Figure 4-2 *The extend of the three major ice advances along with known associated tunnel valleys. Kattegat OWF is marked by a light-blue/yellow star (Ref. /9/).*

Till from Last Weichselian glaciation is found south of Anholt along with late glacial and post glacial deposits. The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22 ka BP followed by stepwise retreat. Around 18 ka BP the sea began to inundate northern Denmark which led to rapid deglaciation. At ca. 17 ka BP the ice margin had retreated to the Halland coastal moraines along the Swedish west coast (Ref. /7/) In the Danish area the ice cap steadily retreated, which caused the opening of the Kattegat depression and transgression of the area. A glaciomarine environment was established where the glacier was in direct contact to the sea. Therefore, discharge of meltwater-borne sediments could be dispersed from the glacier to the sea and drop-stones rafted by calving icebergs should be expected. Thick glaciomarine deposits related to the late glacial are reported from the area (Ref. /7/).

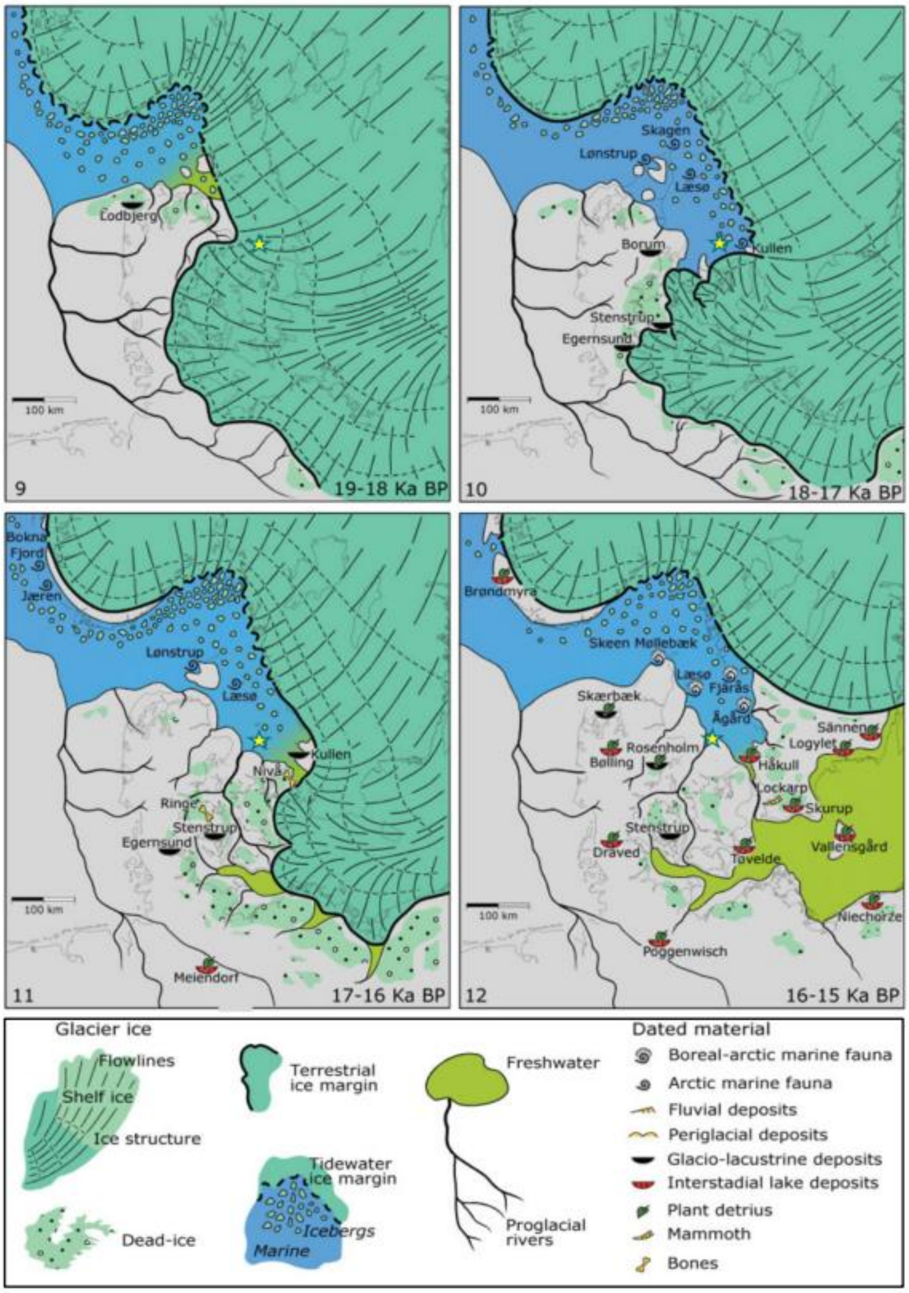


Figure 4-3 *Palaeogeographical reconstructions of the last deglaciation of southern Scandinavia (19-15 ka BP). The location of the Kattegat OWF is marked by a yellow star (Ref. /7/).*

The interplay between eustatic sea-level rise caused by global melting of ice caps and glacio-isostatic rebound (regional reaction to the relief of the glacier burden) caused the sea-level to fluctuate in late glacial and Holocene. In early Holocene the sea level dropped and may have caused the area to become terrestrial for a short time before a new transgression from which marine conditions continued through the rest of the Holocene, see Figure 4-3 (Ref. /7/).

5 Conceptual Geological Model

The Conceptual Geological Model is compiled as two (2) hand-drawn geological profiles that summarize the geology across the entire OWF project site. They are based on units from the Integrated Geological Model, geological cross sections, and layer thickness maps extracted from the 3D digital model. The Conceptual Geological Model can be seen in Figure 5-1 and Figure 5-2 and in better resolution in Appendix G.

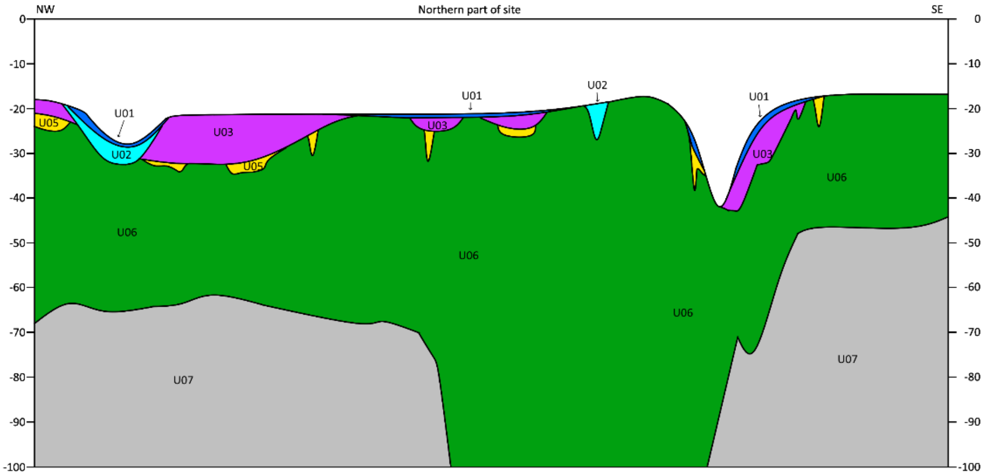


Figure 5-1 *Conceptual Geological Model cross section oriented from north-west to south-east through the northern part of the OWF project site. List of units constituting the model with assigned age and depositional environment can be found in Table 5-1.*

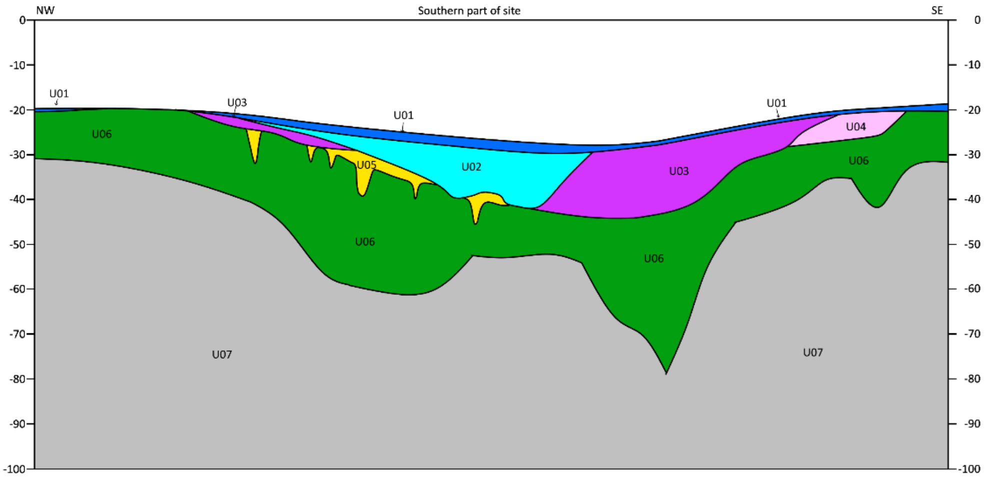


Figure 5-2 *Conceptual Geological Model cross section oriented from north-west to south-east through the southern part of the OWF project site. List of units constituting the model with assigned age and depositional environment can be found in Table 5-1*

The Conceptual Geological Model presents all the interpreted and integrated model units. Thickness, depth and location are only indicative for the individual units and represent the entire model rather than a specific location of the profiles. The model consists of the units presented in Table 5-1.

The colours used for the conceptual model was chosen so that the same shades of colours resemble a similar geological age or lithology. The colours differ from the ones used in the cross sections and the figures from interpretations in the Kingdom software. The colours in the Kingdom software were chosen to be differing as much as possible to ease interpretation.

Table 5-1 List of units constituting the Conceptual Geological Model with assigned age and depositional environment.

Unit	Age		Depositional environment	Lithology
U01		Holocene	Post glacial, marine	Clayey to silty and sandy clay
U02		Early Holocene	Post glacial, estuarine, deltaic	Clay to silty sand
U03		Late Weichselian	Late glacial, estuarine to fluvial	Sandy silty clay to clay
U04		Late Weichselian	Late glacial, estuarine to fluvial	-
U05		Late Weichselian	Late glacial, glaciofluvial	Sand, clayey to gravelly
U06		Weichselian and earlier Pleistocene	Mixed Glacial – Subglacial, Glaciofluvial, Glaciolacustrine and more	Clay and sand till. Mixed lithology
U07		Early Palaeocene, Cretaceous, Late Jurassic	Marine	Chalk and Limestone

The model can be divided into four primary stratigraphical groups. The Holocene, The Late Weichselian, the Weichselian and Early Pleistocene, and the Late Jurassic, Cretaceous and Early Palaeocene, see Table 9-4.

The Holocene comprises U01 and U02 and represents the post glacial deposits. U01 represents deposits from the Littorina transgression to present marine conditions. U02 represents the estuarine to shallow marine conditions in Early Holocene.

The Late Weichselian comprises U03, U04, and U05 and is related to the period of deglaciation (late glacial) where rivers led meltwater from the glacier front and later from the Baltic Ice Sea to Kattegat. U05 represents deposits which may be only little affected by the marine environment, but rather by glaciofluvial processes. U03 and U04 are deposited on the threshold to the glaciomarine environment in esturarine to fluvial settings. None of the Late Weichselian deposits seem to have been subject to glacial compaction and deformation.

The Holocene and the Late Weichselian together constitute a relatively shallow part of the model mainly consisting of weak deposits.

The Weichselian and Early Pleistocene unit U06 consists of glacial deposits which have been glacially overridden and compacted. U06 constitutes the main part of the model. U06 is a complex unit with internal layers of mixed depositional environments and lithologies. Parts of U06 may have been glacially overridden several times.

The Late Jurassic, Cretaceous and Early Palaeocene U07 consists of limestone and chalk as seen in borehole samples. In the northern part the layer is expected to consist of mudstone, siltstone or sandstone, though it has not been proven by borehole samples. Faulting has been observed within U07. Some of the faulting is most likely related to the Sorgenfrei-Tornquist Zone. None of the faults have been observed to be impacting the overlying Pleistocene units.

The integrated model units are described in detail in section 9.9.

6 Methodology for integration of geotechnical/geophysical data

The methodology used for the performed work with interface between geophysics and geotechnics is an iterative process, from which the geophysical and geotechnical findings support each other to obtain an Integrated Geological Model representing the site conditions.

The steps in the iterative work process between geophysics and geotechnics for the work covered in this report are the following:

1 The geophysical and geotechnical work is initially assessed in each discipline for establishing a basis to work from.

1a) A preliminary geophysical model was received for the Kattegat OWF project site. Initial work included understanding the interpreted seismic units, the stratigraphical model and helped identify where additional stratigraphic units need to be interpreted.

1b) The geotechnical basis is established by generating a stratigraphy for each available test location across the Kattegat OWF project site. In addition, classification parameters are determined to support this selection. The soil behaviour type index, I_c, (cf. section 7.2.1) with depth is shared with the geophysical team as basis for merging the two models and initial interpretation.

2 The geophysical and geotechnical disciplines share horizons and stratigraphy at the test locations across the Kattegat OWF project site.

3 Each discipline reviews the received information from the other discipline for re-evaluation and update the models for alignment. This is supported through meetings between the disciplines. The integrated ground model will mainly be influenced by geotechnical relevance, hence the selection of relevant horizons to interpret is driven by the geotechnical relevant boundaries.

4 Steps 2 and 3 are repeated until an alignment between the geophysical and geotechnical interpretation is made. When the work for updating the model is finalised, the documentation and post processing of the result is completed within each discipline.

5 In parallel with the individual work for each discipline, the zonation is ongoing between the disciplines, where input from both parties is considered.

The iterative process used for the project is visualised by a flowchart in Figure 6-1.

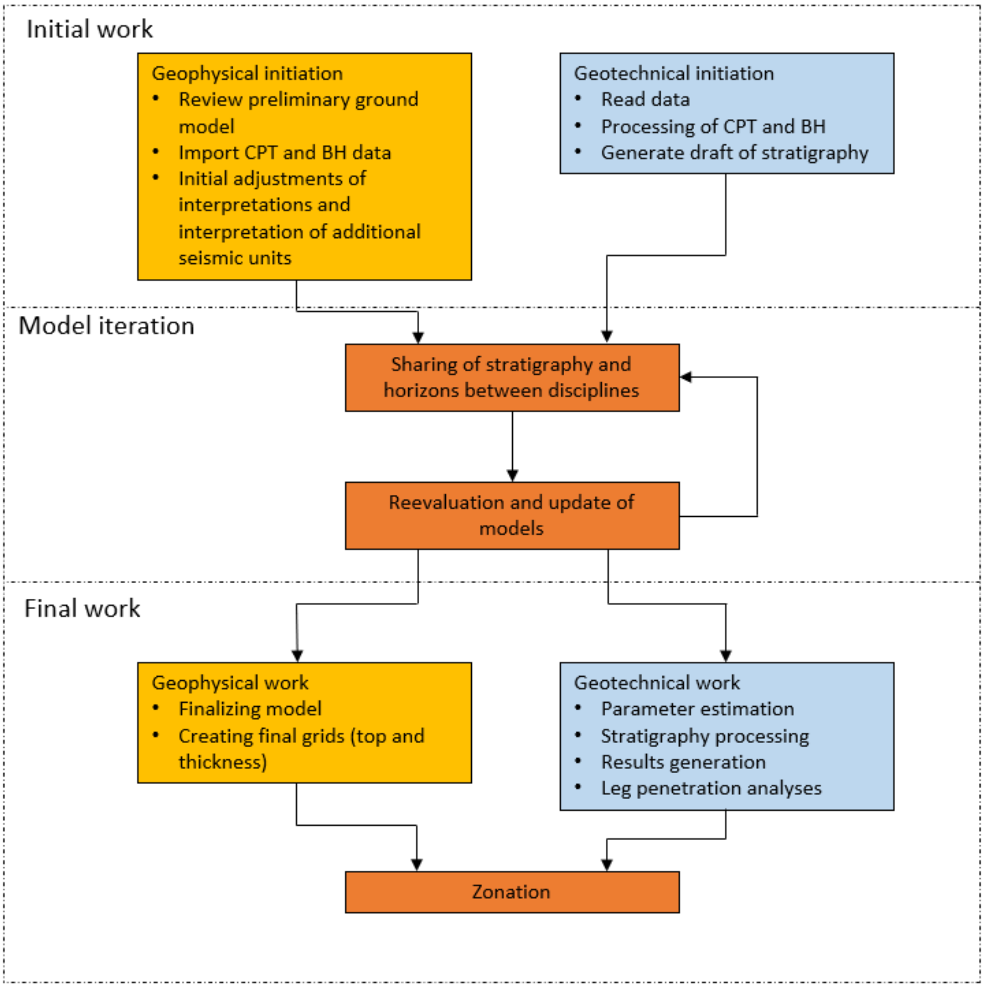


Figure 6-1 Flowchart for visualising the work iteration between disciplines.

7 Geotechnical interpretation

In this section it is described how the geotechnical data have been evaluated to characterize the model units in the IGM and the layering of geotechnical units at each geotechnical survey location. The layering and soil characterization interpreted at survey locations has served as input to the Integrated Geological Model, cf. section 9.

For each geotechnical survey location, a geotechnical interpretation of the stratigraphy has been carried out. This interpretation has considered input from borehole logs, CPT logs (using CPT correlations as presented in section 7.2) and geophysical data (to link geotechnical units across the Kattegat OWF project site). One geotechnical interpretation of the stratigraphy has been prepared for each geotechnical survey location. This also implies that at geotechnical survey locations where borehole and CPT data are available, or CPT data from multiple tests are available, the information from these tests has been combined into one interpreted stratigraphy. A total of 22 unique geotechnical interpretations of stratigraphy have been developed, cf. Appendix A, where geophysical data has been included for the stratigraphy estimation. All these interpretations have been applied as input to the Integrated Geological Model.

The following sections describe the procedure for the geotechnical stratigraphic interpretation in further detail.

7.1 Geotechnical unit overview

The development of the soil stratigraphy can generally be divided into two parts:

- based on borehole log descriptions,
- based on CPT classification and correlation.

The work documented in Ref. /1/ can be considered the basis. The soil descriptions provided in the borehole logs provide descriptions of soil type/class as well as estimates of soil age and depositional environment. In addition, the seismic horizons interpreted from the geophysical data also serves as input into the definition of geotechnical units.

An overview of the defined geotechnical units is presented in Table 7-1 based on the defined units in the integrated ground model. Additionally, the table presents the amount of available CPT data for each geotechnical unit. The integrated model unit ID refers to the presented integrated model units in section 9.9. Figures for verifying a similar behaviour for the established geotechnical units are presented in Appendix B.1. This is done by gathering all available CPT data from the site in the same figure for each unit to verify that the layers categorised as the same unit have the same behaviour from measured properties.

The following is noted with regards to the defined units:

- U01 split between sand and clay at seabed, with clay as the dominant material. The clay is interpreted as a very weak clay. The unit is mainly found within the first meters below seabed with few exceptions of deeper occurrences. The unit is a marine Holocene deposit.

- U02 is a very weak clay unit and from the geotechnical locations the unit found within a few meters depth and being up to approximately 10 m thick. The unit is a late glacial estuarine/deltaic deposit.

- U03 is a weak clay unit. From the geotechnical locations the unit is mainly found within the first meters below seabed with few exceptions of deeper occurrences. The unit is a late glacial fluvial to estuarine deposit.

- U04 is from the geophysical data interpreted as a weak clay. No geotechnical information is available for this unit as no geotechnical tests at the site is performed in the unit. It is noted the unit only covers a limited area of the site. The unit is a late glacial fluvial to estuarine deposit.

- U05 is a sand-dominated unit normally seen with a few meters thickness. The unit is found from a meter below seabed until approximately 10 m below seabed. The unit is a late glacial glaciofluvial deposit.

- U06 consists of both glacial sand and clay. The material is over-consolidated and based on geotechnical locations the unit is found from seabed at some locations, and down to end of the geotechnical tests, which in some cases is deeper than 70 m below seabed. The unit is a Weichselian to Early Pleistocene mixed glacial deposit.

- U07 is a unit consisting of pre-quaternary deposits. All geotechnical boreholes performed within the unit describes the material as slightly to strongly indurated, unfractured to slightly fractured chalk with one location having a short interval of unlithified chalk which is found from 22 m below seabed. However, as seen from section 4.1, the material within the unit is potentially switching between chalk, limestone, mudstone, etc. across the site, hence caution should be taken when reading information of the material from the few available geotechnical tests. The unit is a Jurassic to Early Palaeocene (Danien) marine deposit.

Table 7-1 Overview of identified integrated model units and considered geotechnical units.

Geophysical unit	Geotechnical unit	Geotechnical material	Total length of CPT measurement [m]	Percent of total CPT length in geophysical unit [%]
U01	UC01	Clay	28.0	70.9
	US01	Sand	11.5	29.1
U02	UC02	Clay	15.3	100.0
U03	UC03	Clay	30.8	95.4
	US03(1)	Sand	1.5	4.6
U04	(2)	Clay	0.0	-
U05	UC05(1)	Clay	1.6	18.8
	US05	Sand	6.9	81.2
U06	UC06	Clay	144.4	37.9
	US06	Sand	236.2	62.1
U07	UC07	Chalk	0.9	100.0

(1) Geotechnical unit established to group measurements of sub-material.

(2) No geotechnical data available for geophysical unit.

7.2 Stratigraphic interpretation based on CPT

The process of determining the stratigraphy for all survey locations based on the CPT data is described in the following steps:

1. Load raw CPT data from AGS-file.
2. Calculate additional parameters for soil interpretation and classification.
3. Calculate soil behaviour type for each depth with available CPT data.
4. Select stratigraphy based on calculated parameters and soil behaviour type related to depth.
5. Define geotechnical unit for all defined layers.

Initially, the raw CPT data is loaded into a script designed to classify the soils (Step 1). Some postprocessing of the raw data are performed to derive additional parameters required for classifying the soil using the Robertson-method (Step 2). These parameters are shown below, cf. Ref. /2/.

Corrected cone resistance: $q_t = q_c + u_2 \cdot (1 - a)$

Friction ratio: $R_f = \frac{f_s}{q_t}$

Normalised cone resistance: $Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{P_a}\right) \cdot \left(\frac{P_a}{\sigma'_{v0}}\right)^n$

Stress exponent: $n = 0.381 I_c + 0.05\left(\frac{\sigma'_{v0}}{P_a}\right) - 0.15 \leq 1.0$

Normalised pore pressure ratio: $B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}}$

Normalised friction ratio: $F_r = \left(\frac{f_s}{q_t - \sigma_{v0}}\right) \cdot 100$

Soil behaviour type index: $I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$

Where:

f_s is the measured CPT sleeve friction,

q_c is the measured CPT cone tip resistance,

u_2 is the measured pore pressure immediately behind cone tip,

u_0 is the hydrostatic pore pressure,

σ_{v0} is the total vertical in-situ stress,

σ'_{v0} is the effective vertical in-situ stress,

a is the area ratio of the adopted CPT cone,

P_a is the atmospheric pressure.

From the available parameters, an initial estimation of the soil behaviour type for each layer is made based on different classification methods (Step 3). Three different classification methods are used for evaluating the variation in the soil behaviour type (SBT):

- Using soil behaviour type index.
- Using normalised cone resistance and friction ratio.
- Using normalised cone resistance and pore pressure ratio.

The three considered classification methods are described in sections 7.2.1, 7.2.2 and 7.2.3, respectively.

Based on the measurements in the CPT (cone resistance, sleeve friction and pore pressure) and the estimated SBT, the soil layering can be determined, and the geotechnical units can be defined (Step 4 and 5).

Once the soil stratigraphy and the associated geotechnical units have been defined, layer specific information can be determined in the postprocessing. For each soil layer, the associated CPT data can be used to estimate the strength and stiffness parameters for that specific soil layer. The methods adopted for defining strength and stiffness properties can be found in section 8.3.

7.2.1 Soil behaviour type index

The estimation of the SBT is based on the soil behaviour type index I_c value using Table 7-2 as seen below. Table 7-2 shows that the correlation between the soil behaviour type index and SBT only applies for SBT zones 2-7, i.e., zones 1, 8 and 9 are not considered here.

This method considers both the normalised cone resistance and the normalised friction ratio, whilst pore pressure is not accounted for.

Table 7-2 Soil behaviour types (SBT) based on I_c, cf. Ref. /2/.

Zone	Soil Behaviour type	I_c
1	Sensitive, fine grained	N/A
2	Organic soils – clay	> 3.6
3	Clays – silty clay to clay	2.95 - 3.6
4	Silt mixtures – clayey silt to silty clay	2.6 - 2.95
5	Sand mixtures – silty sand to sandy silt	2.05 - 2.60
6	Sands – clean sand to silty sand	1.31 - 2.05
7	Gravelly sand to dense sand	< 1.31
8	Very stiff sand to clayey sand	N/A
9	Very stiff, fine grained	N/A

7.2.2 Normalised cone resistance and friction ratio

SBT is estimated based on Ref. /2/ where normalised cone penetration resistance, Q_{tn}, and normalised friction ratio, F_r, are used as basis, cf. Figure 7-1.

As seen from Figure 7-1, information about OCR/age and sensitivity can also be deduced from the plot. However, this type of information shall be treated with some caution, and it has not been used actively to establish geological age or degree of pre-consolidation for the soils.

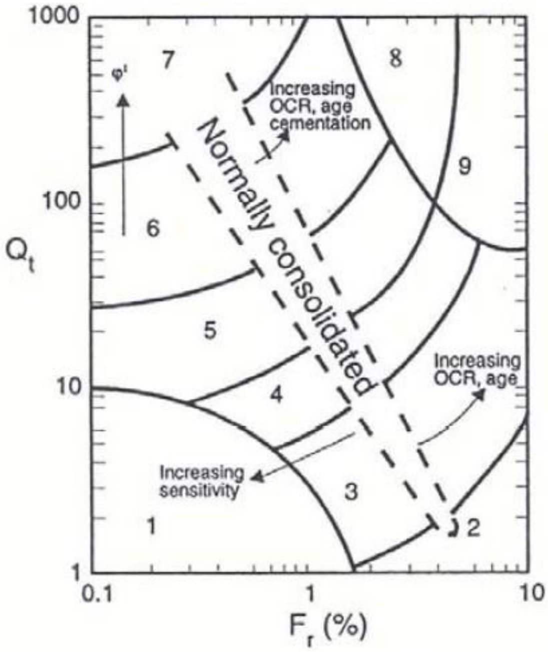


Figure 7-1 *Robertson Q_t – F_r classification chart for soil behaviour type, cf. Ref. /2/. As recommended in Ref. /2/ the normalised cone resistance (Q_{tn}) is considered instead of Q_t when evaluating the soil behaviour type.*

7.2.3 Normalised cone resistance and pore pressure ratio

SBT is estimated based on Ref. /2/ were normalised cone penetration resistance, Q_{tn}, and normalised pore pressure ratio, B_q, are used as basis, cf. Figure 7-2.

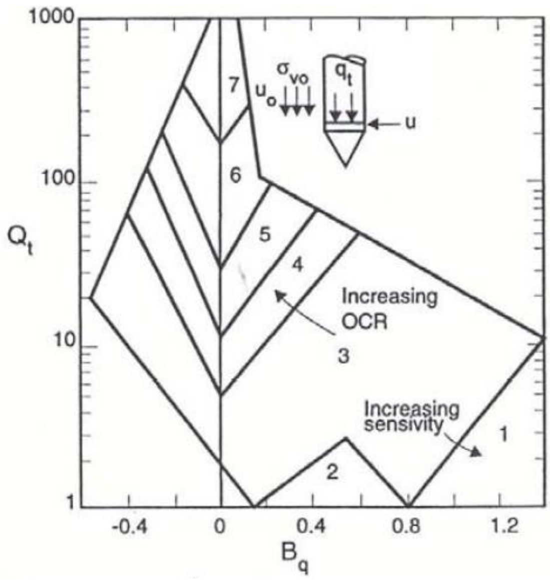


Figure 7-2 *Robertson Q_t – B_q classification chart for soil behaviour type, cf. Ref. /2/. As recommended in Ref. /2/ the normalised cone resistance (Q_{tn}) is considered instead of Q_t when evaluating the soil behaviour type.*

7.3 Classification of soils using CPT, borehole logs and geophysical horizons

For the classification of soils used for the definition of the stratigraphy and the geotechnical units, the following is noted:

- In the borehole logs, the soil types given are evaluated based on classification tests (particle size distribution, Atterberg limits, etc.) and based on geological evaluation.
- Classification based on CPT interpretation, cf. section 7.2, generally takes into consideration the mechanical behaviour of the soil.

Hence, the source of the interpreted stratigraphy from borehole log and CPT is different and each geotechnical investigation type is valuable for a detailed understanding of the soil characteristics and behaviour.

At the survey locations the maximum distance between the performed tests is found as 16.5 m. Some lateral variation of the stratigraphy may be present between the locations for borehole and CPT. However, given the short distance between borehole and CPT, such lateral variation is expected to be insignificant.

The variation in soil behaviour type (based on normalised cone resistance together with normalised friction ratio or normalised pore pressure, cf. section 7.2.2 and 7.2.3) interpreted from CPT of selected geotechnical units are presented in Figure 7-3 to Figure 7-6 as an example for the geotechnical units US06 for a sand and UC03 as a clay. The scatter of CPT data is presented with a colour scale to indicate where a high density of the data is located within the chart. It is observed that UC03 mainly plot at the boundary between soil behaviour type zone 3 and 4 representing "Clay – silty clay to clay" and "Silt mixtures – clayey silt to silty clay", respectively, cf. Figure 7-3 and Figure 7-4. Additionally, it is noted from the normalised friction ratio plot that the soil behaviour type shows a tendency to have experienced some over-consolidation.

Geotechnical unit US06 is considered for the example of sand, and generally fall within the soil behaviour zone 6 representing "Sands – clean sand to silty sand", cf. Figure 7-5 and Figure 7-6. Further, it is noted from the normalised friction ratio plot that the soil behaviour type shows a tendency to have experienced some over-consolidation. The concentrated area in the soil behaviour type plot covered by the sand unit highlights the similarity in behaviour of this unit across the OWF site.

The same Robertson charts for all other geotechnical units are presented in Appendix B.2.

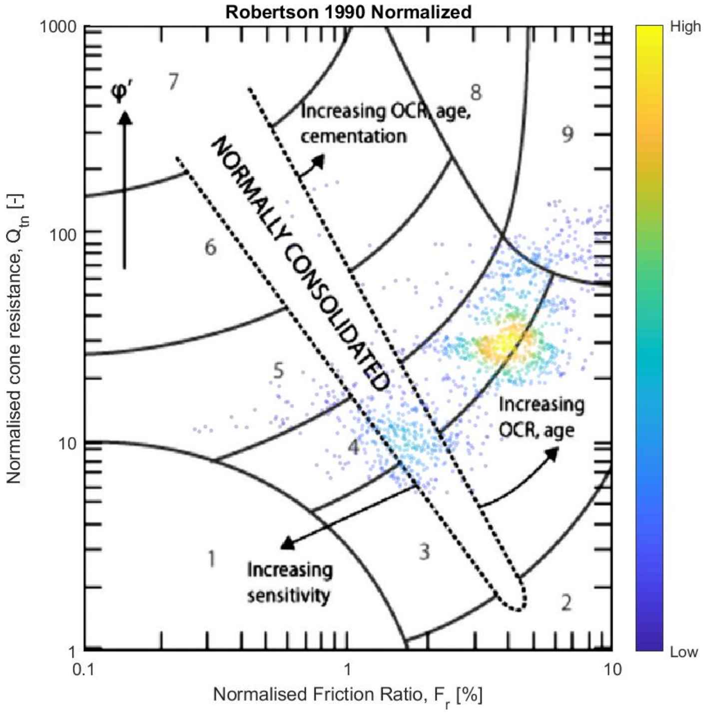


Figure 7-3 *Robertson Q_{tn} – F_r classification chart for soil behaviour type plotted for all CPT survey locations for the geotechnical unit UC03.*

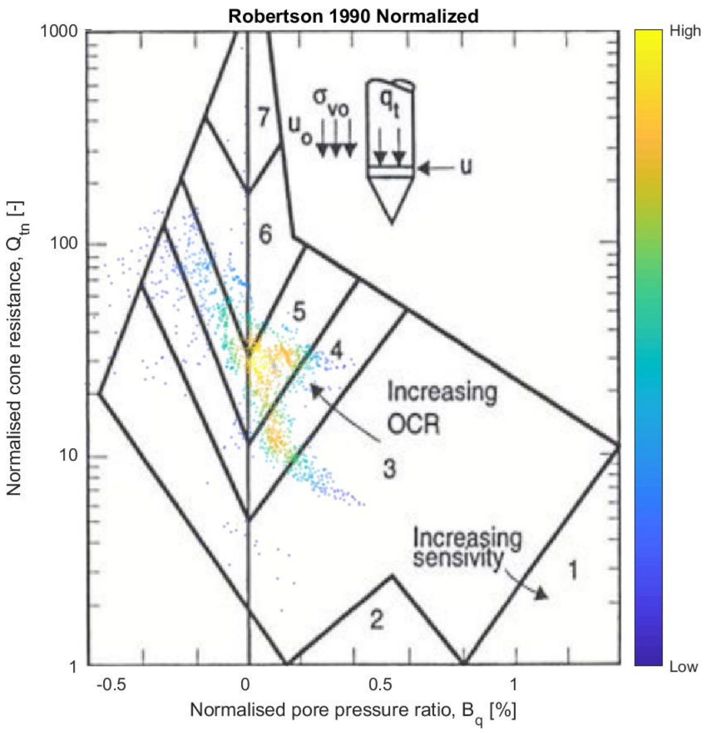


Figure 7-4 *Robertson Q_{tn} – B_q classification chart for soil behaviour type plotted for all CPT survey locations for the geotechnical unit UC03.*

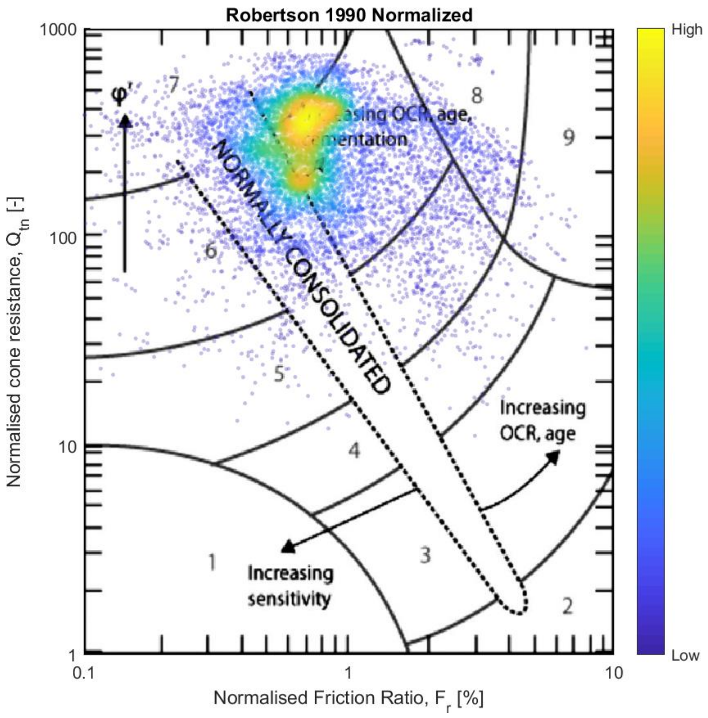


Figure 7-5 *Robertson Q_{tn} – F_r classification chart for soil behaviour type plotted for all CPT survey locations for the geotechnical unit US06.*

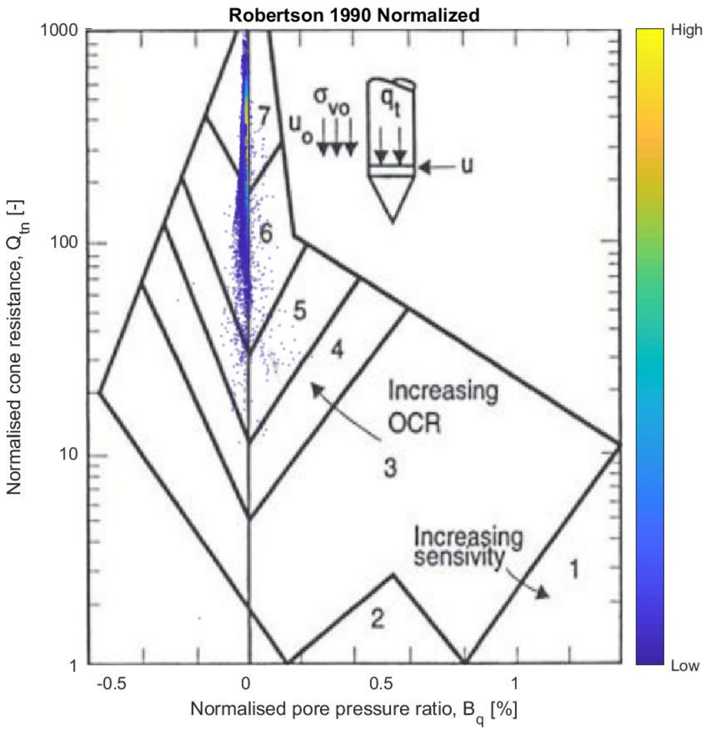


Figure 7-6 *Robertson Q_{tn} – B_q classification chart for soil behaviour type plotted for all CPT survey locations for the geotechnical unit US06.*

8 Geotechnical properties and variation

Following the definition of soil layers and stratigraphy based on CPT and borehole data outlined in section 7.3, this section addresses the methodologies considered for determination of geotechnical properties and associated variation including the assignment of these properties to the geotechnical units. The results for all geotechnical units are presented in Appendix D.

The determination of geotechnical properties is based on both selected CPT correlations and the available laboratory test data from the performed campaign, cf. Ref. /1/. For the CPT data, the geotechnical properties are determined based on selected correlations, while the properties derived on the basis of onshore laboratory testing are generally taken as-is from the outcome of the testing. The only performed processing of the data are:

- For triaxial tests and DSS tests a re-evaluation of the peak value is performed if the peak is located after 10% strain level for triaxial test or 15% for DSS test or UU test.

- The undrained shear strength from UU tests and DSS tests have been calibrated by multiplying with a factor of 1.2, cf. Ref. /3/. The lack of consolidation of the sample before shear result in lack of radial stresses which exist in the in-situ conditions. This means it will most likely show a false low strength as the sample is not brought to the actual in-situ condition, hence the applied factor is used for considering this and having comparable strength values between the different types of tests.

- The friction angle determined from the laboratory campaign has been reevaluated for the effective cohesion to be zero.

- The G_{max} results from the seismic CPTs have been determined from below correlation to the measured shear wave velocity and soil density:

$$G_{max} = \rho V_s^2$$

Beside the above points, no additional interpretation has been imposed on the laboratory testing.

The use of CPT correlations to derive soil parameters is an efficient way of assessing the soil characteristics reducing the need for soil sampling and subsequent onshore laboratory testing. It must, however, be emphasized that these correlations shall ideally be benchmarked using additional results from testing of soil specimens under controlled laboratory conditions. The assessed soil properties based on the CPT correlations are shown for all CPT survey locations in Appendix C.

The relevant geotechnical properties assessed in the following are divided into three categories:

- State properties,

- Strength properties,
- Stiffness properties.

Table 8-1 provides an overview of the parameters that will be determined including the data sources considered for each of these. The abbreviations presented in the brackets represent the naming in the plots. The focus is to provide estimates for traditional soil parameters including the expected ranges of variation for the different geotechnical units. These parameters provide an estimate of the soils' ability to withstand loads and a general understanding of the deformation characteristics of the soil. Results from the CPT correlations are made with a 90% transparent scatter for being able to determine the concentrated areas in the plots.

In addition, an overview of the ranges of classification, strength, and stiffness properties per geotechnical unit is presented in section 8.4.

Table 8-1 Overview of data sources adopted for assessing geotechnical properties.

Category	Soil property	Data source
State	Over-consolidation ratio	CPT correlation
	Relative density	CPT correlation
Strength	Undrained shear strength	CPT correlation Triaxial testing (CAU, CIU, UU) Direct simple shear (DSS) Unconfined compressive strength (UCS) Point load tests (PLT) Pocket penetrometer (PP) Laboratory vane test (Vane)
	Friction angle	CPT correlation Triaxial testing (CIDU)
Stiffness	Small-strain shear modulus	CPT correlation Seismic CPT (SCPT) P-S logging (PS)

8.1 Presentation of CPT properties

As outlined in section 8, the soil parameters are derived partly using CPT correlations and partly using results from the laboratory testing when available.

This section presents the data from the CPTs across the Kattegat OWF project site. The results are presented per geotechnical unit.

Figure 8-1 shows an example of range of basic CPT measurements for geotechnical unit US06 which include soil behaviour type index, cone tip resistance, cone shaft resistance, friction ratio and pore water pressure. The presented example shows that the CPT measurements in this layer generally plots within a consistent trend.

In Appendix B.1 the variation of measured CPT parameters is presented for the considered geotechnical units.

Figure 8-1 Range of CPT parameters for geotechnical unit US06.

8.2 Presentation of state properties

As outlined above in section 8, state parameters such as over-consolidation ratio (for cohesive soils) and relative density (for non-cohesive soils) have been determined from CPT correlations.

The assessment of these parameters serves as input to the overall understanding of the in-situ soil state, which is crucial for assessing the general soil behaviour. This section presents the methods adopted for the analyses of these parameters as well as the outcome.

8.2.1 Over-consolidation ratio

The over-consolidation ratio, OCR, is determined by a CPT correlation commonly used in the industry. The method considered for the parameter estimation is the Mayne (2019) methodology which is representative for both sand, clay, and mixed soil conditions due to the correction from the m' exponent.

The Mayne methodology adopts the following formula, cf. Ref. /5/:

$$OCR = k\left(\frac{(q_t - \sigma_{v0})^{m'} * \left(\frac{p_a}{100}\right)^{1-m'}}{\sigma'_{v0}}\right)$$

where q_t is the corrected cone resistance, σ_{v0} is the total in-situ vertical stress, σ'_{v0} is the effective in-situ vertical stress, p_a is the atmospheric pressure, k is a dimensionless constant which is set to 0.33, and m' is an exponent which can be calculated from below formula, where I_c is the soil behaviour type index, cf. Ref. /5/.

$$m' = 1 - \frac{0.28}{1 + (I_c/2.65)^{25}}$$

Figure 8-2 presents the variation of OCR (interpreted based on CPT) with depth for the geotechnical unit UC06. It is observed the OCR value for the clay generally indicate slightly over-consolidated state with higher values near the top. It should be kept in mind the OCR value is less reliable in the depths near seabed due to the low overburden pressure.

In Appendix D.1, the variation of OCR with depth is presented for the individual geotechnical units.

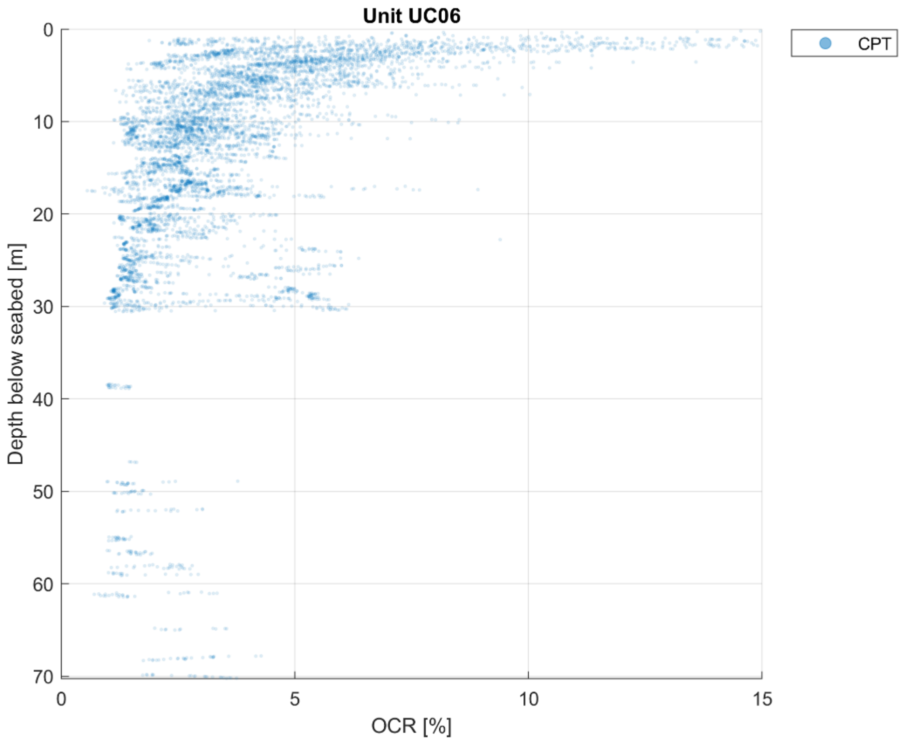


Figure 8-2 Range of OCR for geotechnical unit UC06.

8.2.2 Relative density

The relative density, I_D, is determined for the non-cohesive soils by the Jamiolkowski (2003) CPT correlation which is commonly used in the industry, as no laboratory testing is used for calibration of the parameter.

The Jamiolkowski (2003) correlation is determined from the below formulas, cf. Ref. /6/:

$$I_{D,sat} = I_{D,dry} * \frac{-1.87 + 2.32 \ln\left(\frac{q_t}{(p_a * \sigma'_{v0})^{0.5}}\right)}{100} + I_{D,dry}$$

$$I_{D,dry} = \frac{100}{2.96} \ln\left(\frac{q_t/p_a}{24.94\,(\sigma'_m/p_a)^{0.46}}\right)$$

where q_t is the corrected cone resistance, σ'_m is the in-situ mean effective stress, σ'_{v0} is the effective in-situ vertical stress and p_a is the atmospheric pressure. By assuming a value for K_0 of 1.0, which means the material is considered as slightly over-consolidated, the in-situ mean effective stress σ'_m is set equal to the effective in-situ vertical stress σ'_{v0}.

In Figure 8-3, an example of the variation of relative density (interpreted based on CPT) with depth is presented for the geotechnical unit US06. It is observed that the relative density of the geotechnical unit varies within the range 50% to 130% with the highest concentration of scatter located around 90%. It should be noted the values above 100% is due to the formula from the CPT correlation. In Appendix D.2, the variation of relative density with depth is presented for all geotechnical sand units. For a number of locations some shallow intervals give a calculated relative density of less than 30–40%, which is deemed not being realistic for an offshore sediment subjected to wave action. Correlations exists, that can consider the shallow pressure conditions on the CPT, but these correlations are not incorporated here as they are only relevant for the shallow depths.

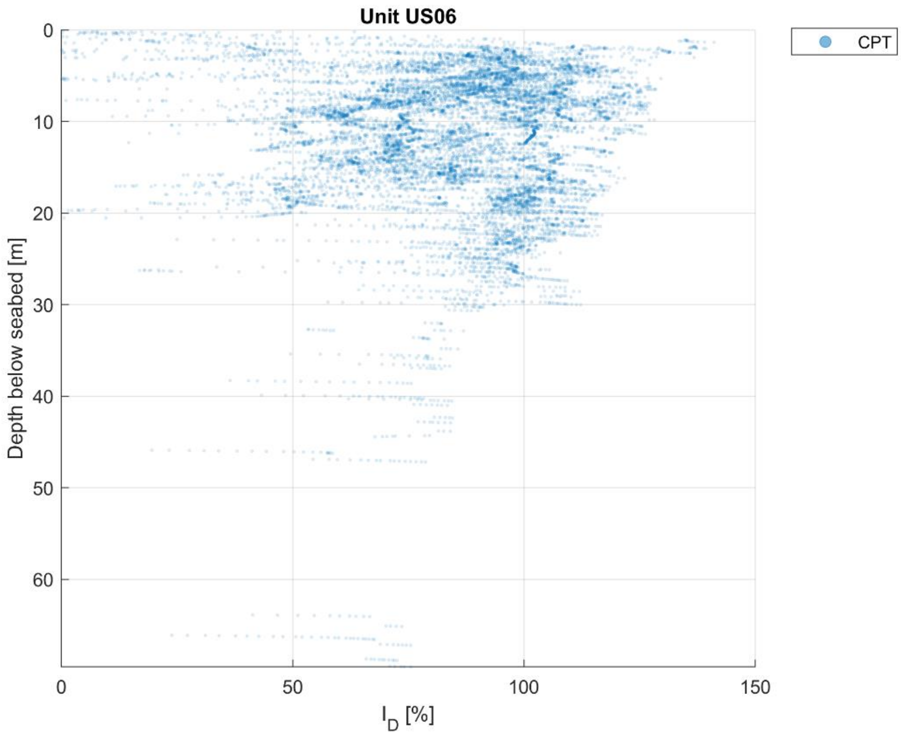


Figure 8-3 Range of estimated I_D using CPT correlations for geotechnical unit US06.

8.3 Presentation of strength and stiffness properties

Following the state parameters described in section 8.2, strength and stiffness parameters such as undrained shear strength (for cohesive soils), friction angle (for non-cohesive soils) and small-strain shear modulus (all soils) have been determined from CPT correlations, supplemented by laboratory testing, cf. Ref. /1/. In addition, the small-strain shear modulus has also been evaluated based on SCPT and P-S logging. The CPT correlations have been selected based on which of the considered literature correlations match the laboratory testing best.

The assessment of these parameters serves as input to the overall understanding of the soil behaviour during loading, e.g., in relation to placement of wind turbine foundations or jack-up operations on the Kattegat OWF project site. This section presents the method adopted for the analyses of these parameters as well as the outcome.

To determine just one representative value (soil strength/stiffness) per geotechnical unit per survey location, the average value for each geotechnical unit is determined. When deriving the average value for the sand and clay layers, the peaks and troughs in the CPT trace (usually found close to the layer boundaries) are removed to reduce the impact of this data on the average value, i.e., to obtain the most representative value.

8.3.1 Friction angle

The peak friction angle, φ'_p, is calculated for non-cohesive soils according to the method of Schmertmann (1978) assuming that the sand is "Uniform medium sand" to "Well-graded fine sand", cf. Ref. /4/. The Schmertmann correlation have been selected as representative for the Kattegat OWF project site based on visual inspections of the comparison between CPT correlated values and the laboratory test results from the same positions and depths.

$$\varphi'_p = 31.5 + 0.12\, I_D$$

where I_D is the relative density determined from the Jamiolkowski (2003), which was presented in section 8.2.

As the relative density calculated from CPT correlation for few layers are found above 100%, and values larger than 100% are considered for the correlation, a line representing the friction angle for a relative density of 100% is added to the figures.

Further to the CPT correlation, the friction angle is obtained through triaxial testing, CIDU. The CIDU triaxial tests have been reassessed for assuming no effective cohesion in the derivation of the strength parameter by considering the following equations:

$$M = \frac{q}{p'}$$

$$\varphi'_p = \text{asin}\left(\frac{3M}{6+M}\right)$$

where q is the deviatoric stress at failure and p' is the effective mean stress at failure. Hereby it is assumed that the effective cohesion is zero.

Using CPT data for all survey locations as well as the available laboratory test data, the range of friction angle for geotechnical unit US06 is shown in Figure 8-4. It is observed that the friction angle interpreted based on CPT generally fit well with result from the CIDU tests available for the unit with few exceptions of laboratory tests providing low friction angle values. Also, when the laboratory result is matched against the local CPT measurement a general good match is found.

In Appendix D.3, the variation of friction angle with depth is presented for all geotechnical sand units.

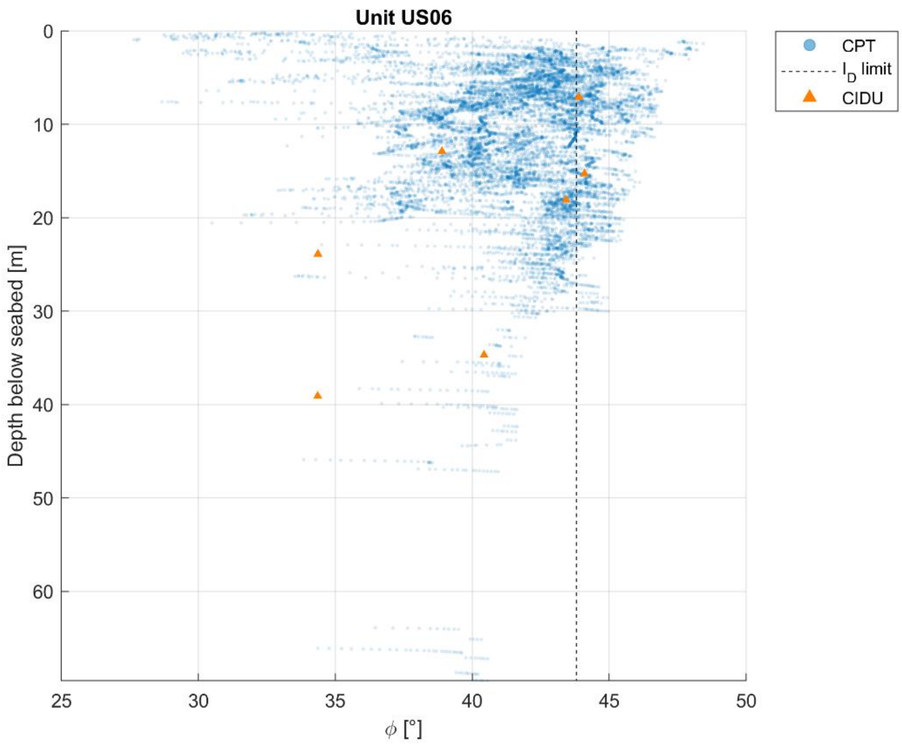


Figure 8-4 Range of φ' for geotechnical unit US06.

8.3.2 Undrained shear strength

The undrained shear strength, c_u, is determined for cohesive soils according to Ref. /2/ as:

$$c_u = \frac{q_t - \sigma'_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}}$$

For determination of undrained shear strength in fine grained materials, a cone factor has been determined for each unit containing laboratory data. These values are determined from visual inspections of CPT vs laboratory data, and they are found to ensure a proper match between the undrained shear strength determined based on CPT, and the undrained shear strength from the consolidated undrained triaxial tests (CIU and CAU). In addition to the consolidated undrained triaxial tests, the correlations have also been established partly from the unconsolidated undrained triaxial tests (UU) and direct simple shear tests (DSS), where a multiplication factor of 1.2 have been used on the UU tests, cf. section 8. From the visual inspection, a constant cone factor, N_{kt}, is determined to be 20 for clay layers of unit UC06. The same factor is assumed for other clay units at the site, as no laboratory tests considered for calibration of the factor is available within these units and the value is found reasonable. It should be noted the factor is based on a high-level assessment with limited/no data available in some geotechnical units, hence a more detailed assessment should be performed for future foundation design. The selection of cone factor is presented in Appendix E.

Further, the simpler laboratory tests, Vane and Pocket Penetrometer (PP) tests, are available for determination of undrained shear strength. These have not been considered when estimating the cone factor but are included in the figures presenting the data per geotechnical unit.

Using CPT data for all survey locations as well as the available laboratory test data, the range of undrained shear strength is shown in Figure 8-5 for the geotechnical clay unit UC06. It is observed that the unit generally shows increasing strength with depth but with strength variations being present at most depths which is following the expectations as the unit is a glacial unit consisting of both sand and clay dominated intervals. Further, it is observed that the CPT predicted strength matches generally well with the strength derived from advanced laboratory tests. In contrast, pocket penetrometer tests and unconsolidated undrained triaxial tests generally have larger spread of the results. In this regard it is emphasized that consolidated triaxial tests and DSS tests are considerably more reliable than the other laboratory tests.

In Appendix D.4, the variation of undrained shear strength with depth is presented for each of the individual geotechnical clay units.

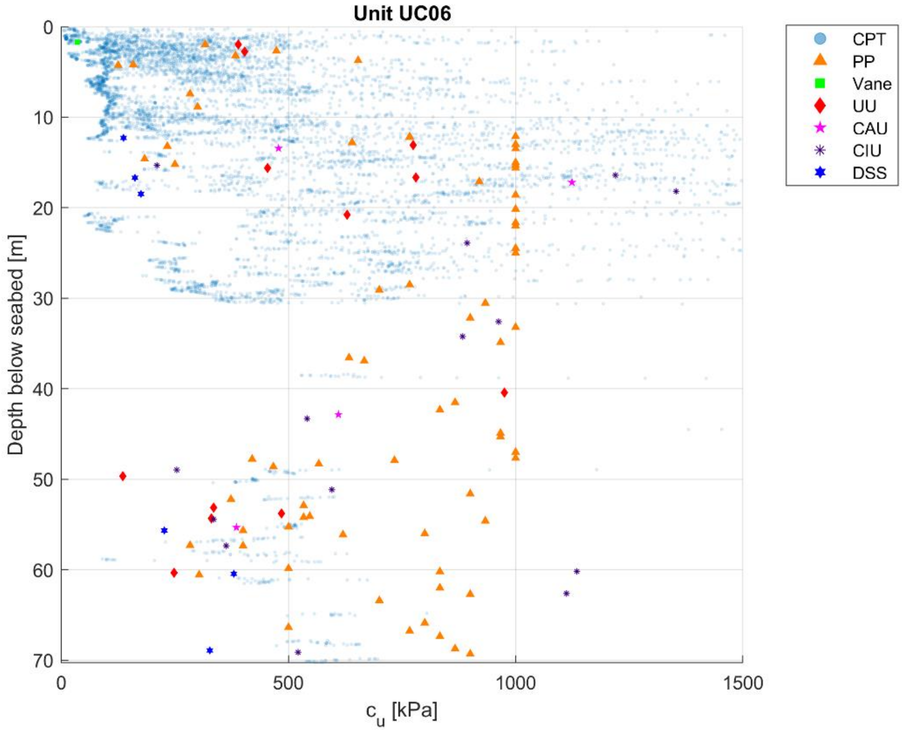


Figure 8-5 *Range of c_u for the geotechnical clay unit UC06 using CPT correlation (blue dots) and laboratory test results.*

8.3.3 Small-strain shear modulus

The small-strain shear modulus, G_{max}, is determined in all soils from below expression derived for elastic theory, cf. Ref. /2/:

$$G_{max} = \rho \, V_s^2$$

where ρ is the bulk density of the material and V_s is the shear wave velocity.

The shear wave-velocity, V_s, is for non-cohesive soils estimated from CPT using the following equation, cf. Ref. /2/:

$$V_s = 277 \, q_c^{0.13} \, {\sigma'_{v0}}^{0.27}$$

where q_c is the measured CPT cone tip resistance and σ'_{v0} is the effective in situ vertical stress.

For cohesive soils, the shear wave velocity, V_s, is estimated from CPT using the following equation, cf. Ref. /2/:

$$V_s = (10.1 \log q_c - 11.4)^{1.67} \left(\frac{f_s}{q_c}\right)^{0.3}$$

where q_c is the measured CPT cone tip resistance, and f_s is the measured CPT sleeve friction.

Further to the CPT correlation, the small-strain shear modulus is obtained through seismic CPT (SCPT) and P-S logging.

Using CPT data for all survey locations as well as the available P-S logging data, the range of small-strain shear modulus for the geotechnical unit US06 is shown in Figure 8-6. It is noted that the small-strain shear modulus from P-S logging and SCPT differs but generally fits well with the values interpreted from the CPT correlation with few exceptions of large discrepancies between tests and CPT correlation. No explanation of the discrepancies between correlation and some test results are found when comparing tests from different locations or looking into the data quality of the test results. In Appendix D.5, the variation of small-strain shear modulus with depth is presented for all the individual geotechnical units.

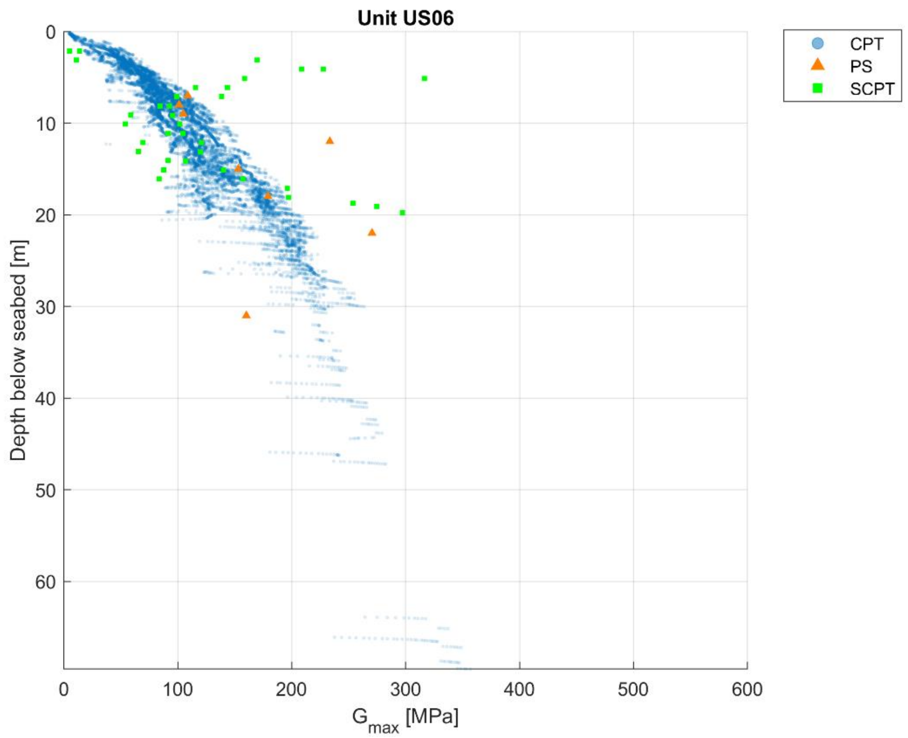


Figure 8-6 Range of G_{max} for the geotechnical unit US06.

8.4 Range of soil parameters per geotechnical unit

In Appendix F the range, average and standard deviation values from the laboratory results of classification, strength and stiffness parameters are presented for the geotechnical units.

9 Integrated Geological Model

In this section it is described how the Integrated Geological Model has been developed. The interpretations are based on the geotechnical results from Gardline (Ref. /1/) and geophysical results from GEOxyz (Ref. /10/).

9.1 Datum, coordinate system and software

The model is set up with datum ETRS89 (EPSG:25832) and the GRS80 Spheroid. The coordinate system used is the UTM projection in Zone 32 N. Units are in meters. Vertical reference is MSL, height model DTU21 MSL.

The software used for interpretations is the S&P Global Kingdom suite 2023. Seismic data was delivered in two data packages: 2D-UHRS and SBP data. The 2D UHRS was delivered in time and depth. No velocity model accompanied the 2D-UHRS data, only a description of used interval velocities. The SBP data was delivered in time and depth as well. No velocity model accompanied the SBP, but a unity velocity of 1600 m/s has been applied.

9.2 Assessment of existing geophysical models

The received geophysical model (Ref. /10/) was based on two seismic datasets, 2D-UHRS and SBP data. One horizon, H05, interpreted in the SBP data was transposed to the 2D-UHRS data. On the 2D-UHRS data the intermediate and deep units have been interpreted. In Table 9-1 a list of the initially identified horizons from GEOxyz can be seen.

Table 9-1 List of unit boundaries and the data where they were picked.

Data type	Unit name	Unit boundary (Horizons) Top	Base
SBP	I, H, Holocene	Seabed	H05
2D-UHRS	II, LG, late Glacial	Seabed, H05	H20
	III, GL, Glacial	H05, H20	H30
	IV, BR, Bedrock	H30	-

The interpreted unit boundaries in the existing SBP and 2D-UHRS-based geophysical model, were generally interpreted along some of the most clear and continuous reflectors identified in the seismic dataset. Across the entire site, a need for either updating or adding horizons has been identified. In the post glacial and late glacial deposits 3 units have been found relevant to add to the IGM based on geotechnical data and seismic facies.

In Table 9-2 list of the changes and new horizons can be seen.

Table 9-2 List of the original units and new units and the updates applied.

Primary Previous Units	Previous horizons (base of unit)	Updated integrated model units	Base of unit	Chrono-stratigraphic group	Changes
I	H05	U01	B01	Holocene	Only minor changes to H05
II	H20	U02	B02	Early Holocene	New horizon
		U03	B03	Late Weichselian	New horizon
		U04	B04	Late Weichselian	New horizon
		U05	B05	Late Weichselian	Updated horizon
III	H30	U06	B06	Pleistocene	Updated horizon
IV	-	U07	-	Early Palaeocene / Cretaceous / Early Jurassic	Updated Top

9.3 Limitations and uncertainties in the data

The data quality of the 2D-UHRS data is generally good, but there are elements of limitations and uncertainties found. Shallow gas is found in areas across the site, which disturbs the seismic signal and increases the uncertainty of the interpretations made. A further discussion on shallow gas and the consequences to data quality can be found in section 9.8.1.

Other significant limiting factors are seabed multiples and attenuation of the seismic signal. In Figure 9-1 an example of a seismic line can be seen. Three seabed multiples are found obscuring the seismic data in this example, and even though they have been removed quite effectively, they still create a blanking effect and heighten the uncertainty of the interpretations.

In Figure 9-1 it can be seen that the signal is diminishing quite substantially with depth. This should be expected, but it is important to note that the weak signal increases uncertainty of the interpretation of the deeper reflectors, for example the transitions from the Pleistocene unit to the underlying bedrock. The reflector marking the top of the bedrock in this profile has been pointed out with a red arrow, and it is seen as very faint especially in the left part of the profile. This makes it difficult to distinguish between the top of the bedrock and internal reflections leading to a more uncertain interpretation.

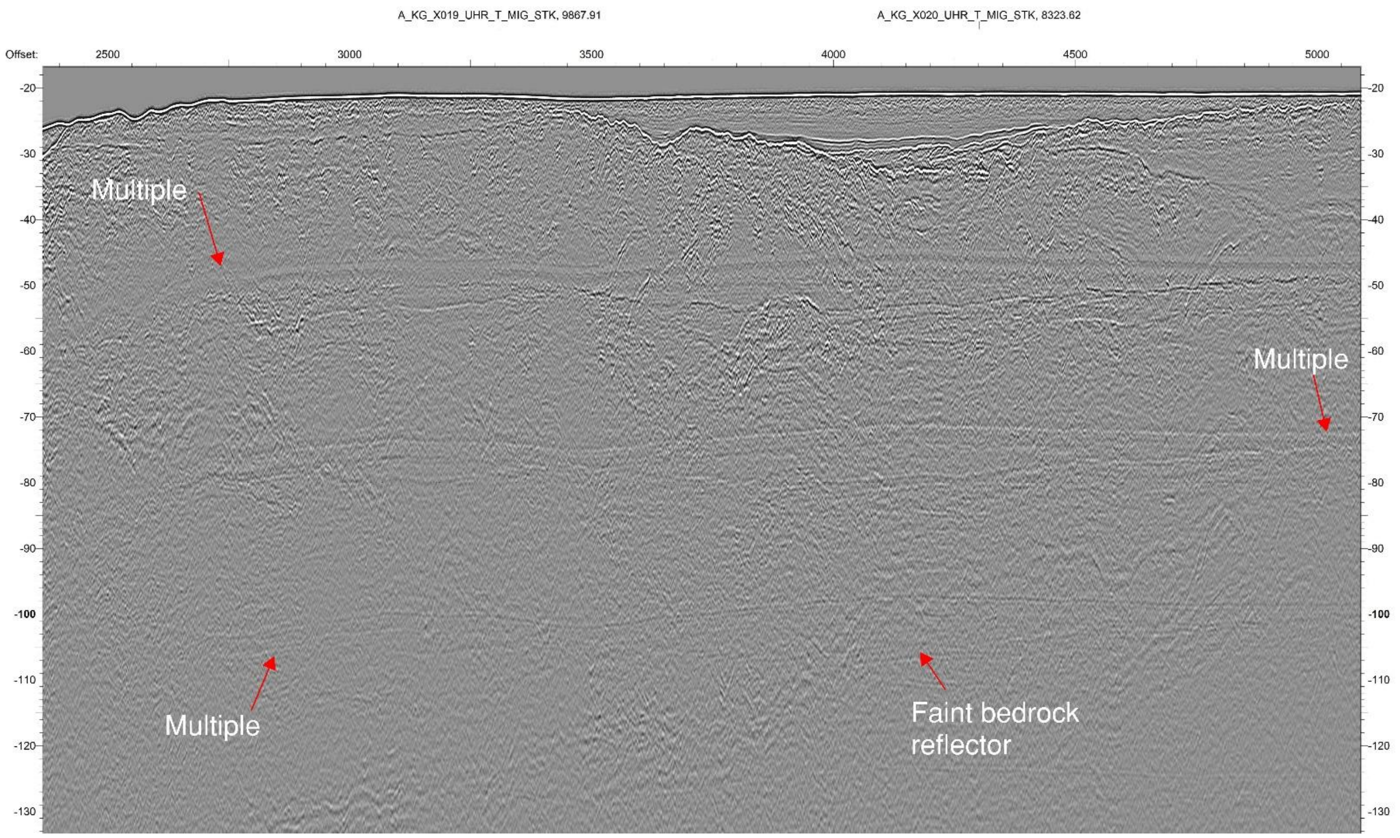


Figure 9-1 *Seismic line A_KG_L026A_UHR_T_MIG_STK. Example of the seismic quality showing 3 seabed multiples. Notice the low amplitude of the deeper reflectors which has lost energy due to attenuation.*

9.4 Setup of the Integrated Geological Model

A Kingdom project has been set up using the 2D UHRS seismic data. Horizons from the initial interpretation provided by GEOxyz have been imported and used as a basis for the integrated interpretation. The horizon interpreted on the SBP data was transposed and integrated into the 2D-UHRS data. Geotechnical data and borehole information have been imported into the Kingdom project from the delivered AGS files and incorporated into the integrated model.

Based on the geotechnical information, existing horizons have been modified and new horizons have been interpreted along clear reflectors in the seismic data (se section 9.4 for details).

The preliminary interpretation of H05 (GEOxyz), which was the only horizon interpreted in the SBP data, was transposed onto the 2D-UHRS data, in order to view it with the rest of the model.

The additional interpreted horizons (COWI) are mainly based on their geotechnical significance but have only been interpreted if it is possible to identify a clear seismic reflector or a unique seismic facies, to make a continuous interpretation over a wide extent (see Table 9-4 for a description of the seismic facies for each unit).

There were several reflectors present in the Pleistocene deposits, where interpretations were attempted, but due to the high level of deformation in the area, it was not possible to create convincing units which were not differing in seismic facies and lithology laterally. Instead of having divided the Pleistocene layers in the several subunits which would have been questionably defined because of the deformation, an attempt to describe the behaviour of the general Pleistocene unit is included.

Results have been exported as grids from the final model. The grids include layer boundaries as well as grid calculations of depth below seabed and vertical thickness (isochore) of the layers.

9.5 Interpolation and adjustment of surfaces

Geotechnical data (Ref. /1/) were imported into Kingdom and an integrated interpretation was performed, establishing a correlation between seismic reflectors and the stratigraphy based on the CPT and borehole logs, (section 7). The geotechnical data were imported in depth and converted to TWT (in ms) using a time-depth ratio calculation.

An overview of the resulting units in the Integrated Geological Model and its relation to the previous model is presented in Table 9-2.

9.6 Uncertainty in the grids

Grids for top of units (elevation relative to MSL and depth below seabed) and thickness (isochore) of units are delivered. For grids to be continuous across gaps between survey lines, interpolation was needed. An interpolation/extrapolation distance of 130 m which is a little larger than half of the survey line spacing (250 m) has been chosen. After gridding the results have been adjusted against each other to avoid crossing layer surfaces in the final model.

A grid cell size of 5x5 m has been chosen to make the grids compatible to the bathymetry grid. The small cell size accommodates the accuracy and lateral resolution of the seismic data along the seismic lines where the uncertainty is low.

In areas away from the seismic lines (maximum distance is up to approximately 125 meters) the cell size is small and may indicate a higher certainty than the actual seismic data density provides. The uncertainty becomes larger as the distance to the seismic lines increases independent of cell size and it is therefore important to note the location of the seismic lines when evaluating the uncertainty in the grids.

9.7 Depth conversion

The 2D-UHRS and SBP data were delivered both in the time and depth domain, however no velocity model was received. All interpretations carried out on the data after the delivery, was performed in the time domain and later converted to the depth domain. This was done to ensure that interpretations were available both in the time and depth domain, should any further work be needed.
To convert the reinterpreted and the new horizons from time to depth a velocity model was created for the 2D-UHRS data. No velocity model was created for the SBP data since the horizon, H05 (now B01), was transposed in TWT to the 2D-UHRS data.

The velocity model was created using the Dynamic Depth Conversion (DDC) tool in the Kingdom software. The model is a simple two-layer model, using the velocities 1600 m/s and 1800 m/s. The seafloor was corrected against the delivered bathymetry, which was extended to cover all 2D-UHRS seismic lines.

From the extended math calculator, a collective base of the units bounded by Seabed to B05 was created using the Merge-Max function. These units were given a velocity of 1600 m/s, and the underlying units were given a velocity of 1800 m/s. This velocity model corresponds to the one described in Ref. /10/, where the boundary between 1600 and 1800 m/s was set at H20, the horizon corresponding closely to B05. The sample size for the velocity model was set to 0.05 m. Using this velocity model a seismic volume in depth was created and the interpreted horizons were converted from time to depth using the model values.

9.8 Potential geohazards

The potential geohazards are presented based on the findings in the seismic data along with the geotechnical data (Ref. /1/). A summation can be found in Table 9-3.

Table 9-3 Table of identified geohazards in the Kattegat OWF project site.

Interpretation	Description	Associated units	Geohazard potential
Seabed slopes	Channel features at the seabed and associated steep slopes.	Primarily U01 to U04	The steeper slopes are a hazard for WTG installation due to potential lack of stability. Moreover, seabed current dynamics can influence the sediments and position of the channels over time

Interpretation	Description	Associated units	Geohazard potential
Shallow gas	Shallow gas is seen as a bright reflector which in many cases blanks the underlying seismic signal.	Found in U02 and U03 and affecting underlying units	Higher uncertainty of the thickness of masked layers. Primary units affected are U02, U03, U05 and U06
Peat	Strong soft-kick reflections at lower boundary of U01 is associated with organic content and a potential peat layer at KG_25_SCPT. Might be found other places at Holocene base.	U01 (U05)	Strong soft-kick. Low thermal conductivity, e.g. risk for cables.
Faults	Expected faulting in Pre-Quaternary related to the Grenå-Helsingborg fault.	U07 (Pre-Quaternary)	Since the faulting is confined to the bedrock no indication of hazard for installation have been identified
Boulders, cobbles, and patches of gravel	Few diffractions seen in 2D-UHRS from potential boulders. Possible boulders in till.	U02, U03, U06	No potential hazard from the cobbles and gravel. Possible boulders in U06 pose a potential geohazard for installation of WTG foundation.
Glacial deformation	Deformation of the sub glacial Pleistocene deposits.	U06	Some unpredictability in soil characterization. Units may vary in strength in different areas due to mixing.

9.8.1 Seabed channels and steep slopes

A 750 – 1650 m wide seabed channel crosses much of the site, approximately delineated by the 23.0 m MSL contours as described in Ref. /10/, see also enclosure 1.01.

The seabed channel has a depth off up to 48.6 m. Steep side slopes, with localised slope gradients of between 5.0° and 20.0° (Ref. /10/), are present along the northern and southern slopes of the channel feature. As visualized by the Conceptual Geological Model (Section 5) the slopes of the channel feature are generally found with relative thick layers of Holocene and Late Weichselian sediments. This combination of steep slopes and soft sediments constitute a risk of potential lack of stability at the slopes of the channel feature.

9.8.2 Shallow gas

Gas in the sediment can be seen as a disturbance and blanking of the below seismic signal. Only smaller areas of gas disturbance and blanking have been mapped in the data and the extend of this can be seen in Figure 9-2. The depth below seabed of the gas blanking is shown on enclosure 5.01.

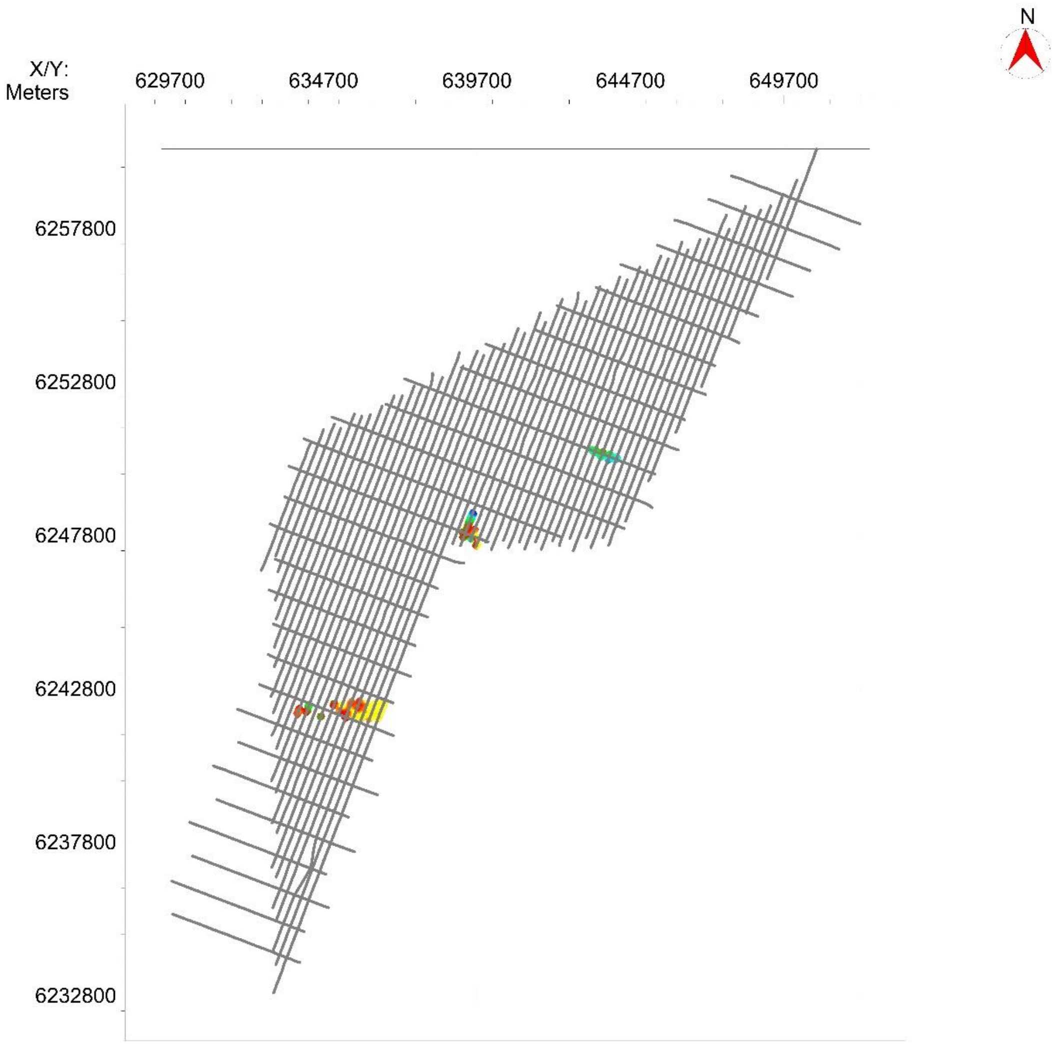


Figure 9-2 Extend of shallow gas found in Kattegat OWF area.

In Figure 9-3 an example of a gas horizon can be seen marked by a red line. The gas is found either in U02 or U03 and is seen masking the seismic data below, which is due to attenuation of the seismic signal. In Figure 9-3 a multiple of the gas horizon is also marked and it is important to note that this is not a reflector from a geological feature.

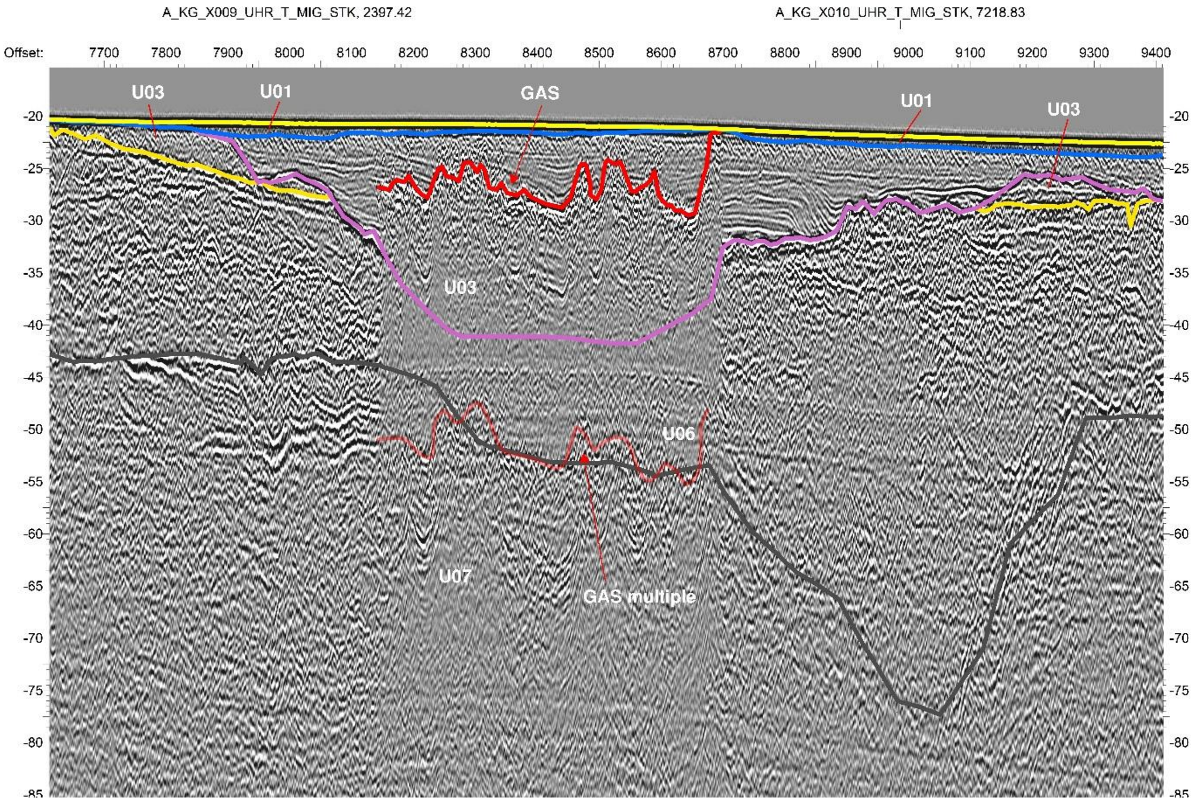


Figure 9-3 *Seismic line A_KG_L020_UHR_T_MIG_STK: Example of shallow gas (red) in U03, which is both seen to create a zone of seismic masking below as well as a gas multiple.*

9.8.3 Peat

Peat has been described in the geotechnical data (Ref. /1/) for KG_25_SCPT and was found at approximately depths 0.6 to 0.9 m bsb and at approximately 1.1 to 1.5 m bsb. An example can be seen in Figure 9-4 where the SCPT and the seismic response are shown. The peat can be seen as bright, high amplitude reflectors present in the top of U05, but it is assumed to be a transition layer into U01 as a part of the Holocene transgression into a marine environment.

The peat is not found extensively and can be found at the base of the Holocene unit U01.

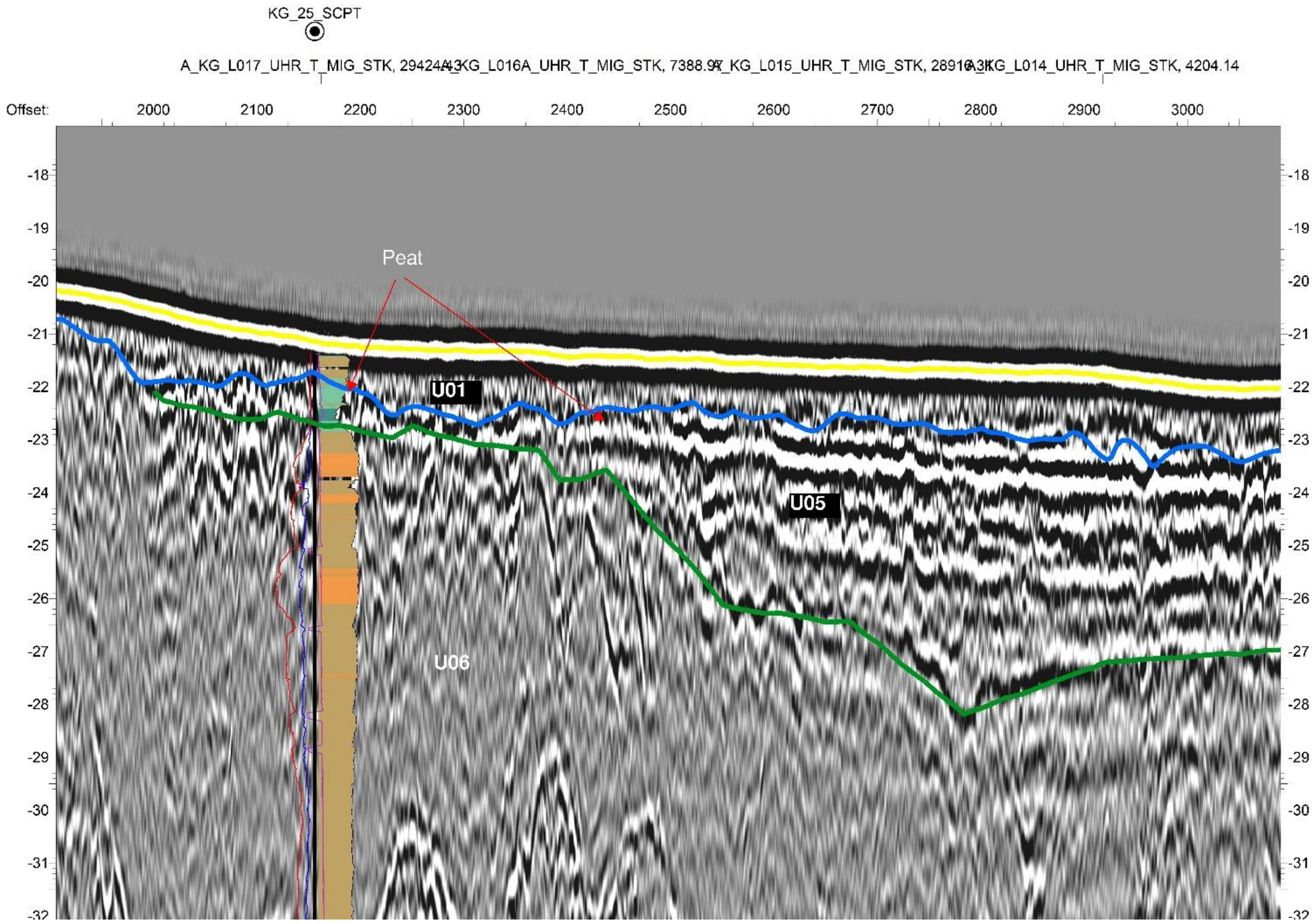


Figure 9-4 Seismic line A_KG_X007_UHR_T_MIG_STK. Example of KG_25_SCPT where peat was found in layers in the upper 1.5 m. In the seismic profile the peat is seen as a layer of high amplitude reflections and is interpreted as marking the Holocene transgression into a marine environment.

9.8.4 Faulting

Faulting is assumed to be abundant in the bedrock due to the Sorgenfrei-Thornquist zone with the Grenå-Helsingborg fault running through the middle of the Kattegat OWF area, see section 4.1. It is however difficult to see the faults in the seismic data, due to the attenuation of the seismic signal, but in Figure 9-5 an example of a fault found in the northern part of the Kattegat OWF area can be seen. In the area signs of tectonic activity from folding can be seen, and in Figure 9-15 an example of an angular unconformity is given. No faults have been identified in the Pleistocene deposits, and faulting is therefore not evaluated to be a significant geohazard in the Kattegat OWF area.

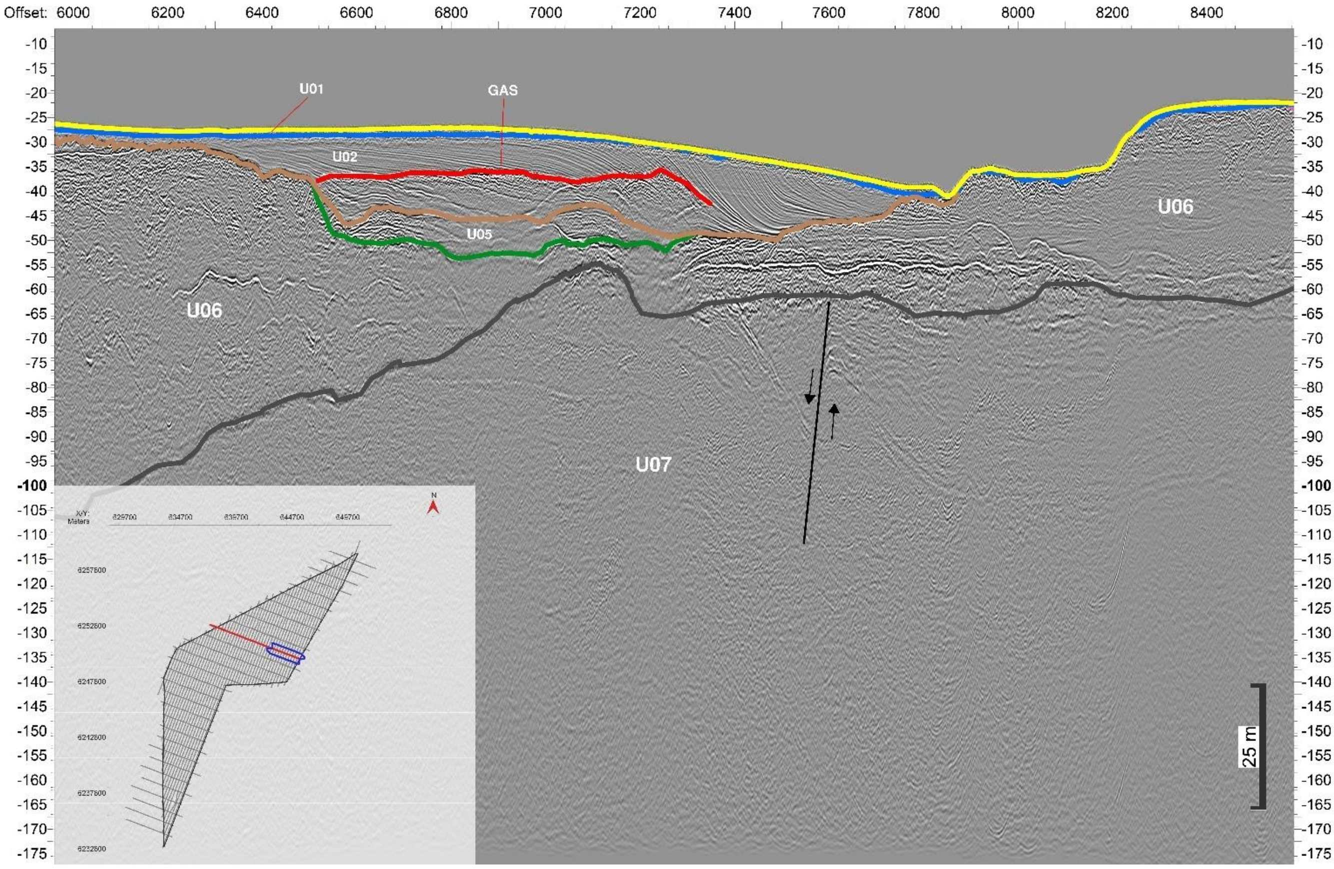


Figure 9-5 Seismic line A_KG_X020_UHR_T_MIG_STK. Example of a fault identified in U07.

9.8.5 Boulders, cobbles, and patches of gravel

An example of a possible boulder can be seen in Figure 9-6, where a hard kick with high amplitude is seen in the low amplitude U03. The potential boulders in the late glacial deposits are few and are not evaluated to be a significant geohazard in the Kattegat OWF site. The seismic data has, however, not been systematically scanned for possible singular boulders.

In the Pleistocene till unit, U06, larger boulders and pieces of Chalk from subglacial erosion can be expected throughout the area. Refusal have been encountered in the CPT's which could be possible boulders. A description of the locations can be found in section 9.9.3. Only few signs of boulders were identified in the 2D-UHRS data.

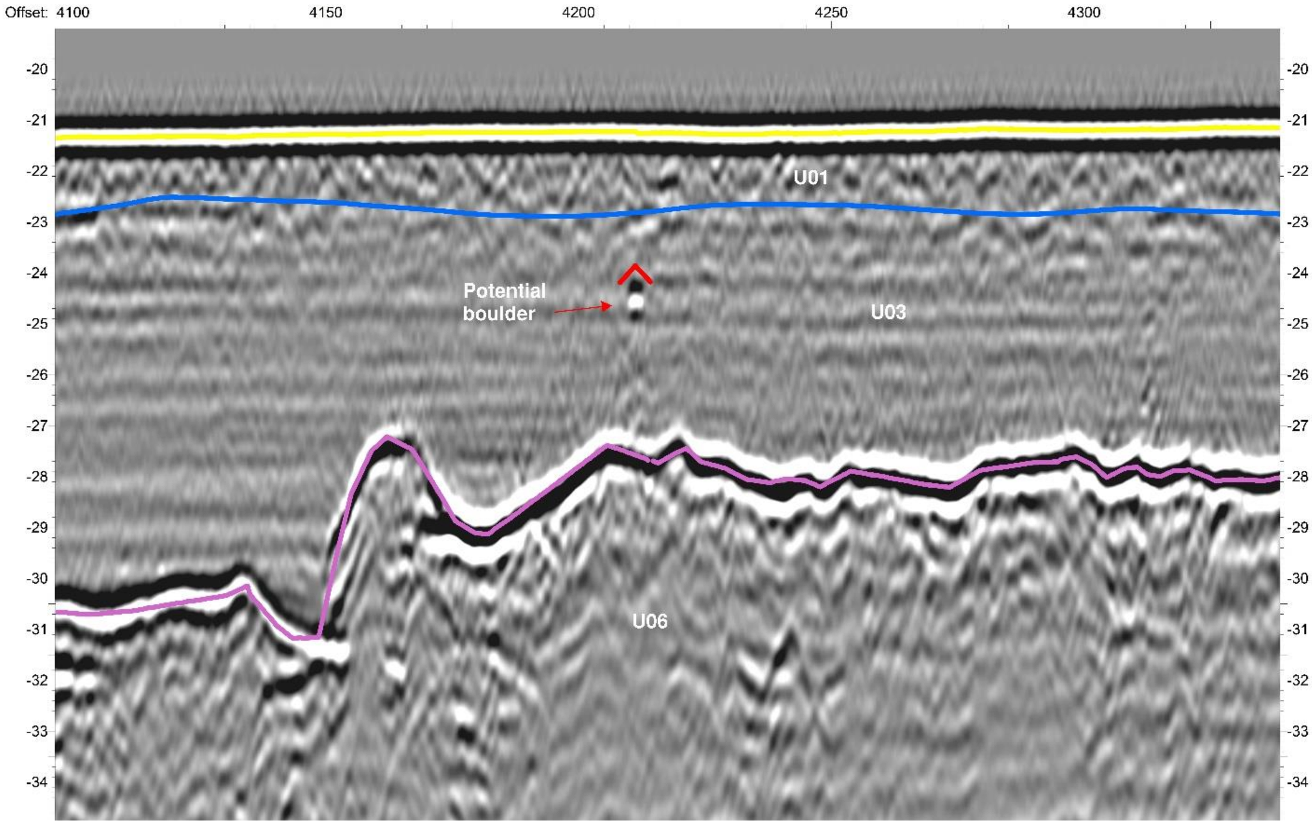


Figure 9-6 Seismic line A_KG_X010_UHR_T_MIG_STK. Example of a hard kick in U03 interpreted as a potential boulder.

9.8.6 Glacial deformation

Deformation of units covered by ice is observed in unit U06, which has been interpreted as a subglacial unit, see section 5. An example of glacial deformation can be seen in Figure 9-7. In the right side of the figure, partially deformed reflectors can be found, where the depositional structures are still visible despite being slightly altered. Moving towards the left side, more heavily deformed materials are seen, where the sub-parallel/wavy facies is completely erased. Different generations of deformation can be seen in Figure 9-7, where a clear deformation surface has been marked with older deformed material below it. This indicates that U06 has been deformed by different ice advances throughout the Pleistocene.

Generally, unit U06 is found to be competent. However, the deformation in U06 of different types of materials poses a potential hazard. The heterogenetic nature of the unit, where lithologies of different depositions are mixed, can create a variability in geotechnical properties across the extend of the unit.

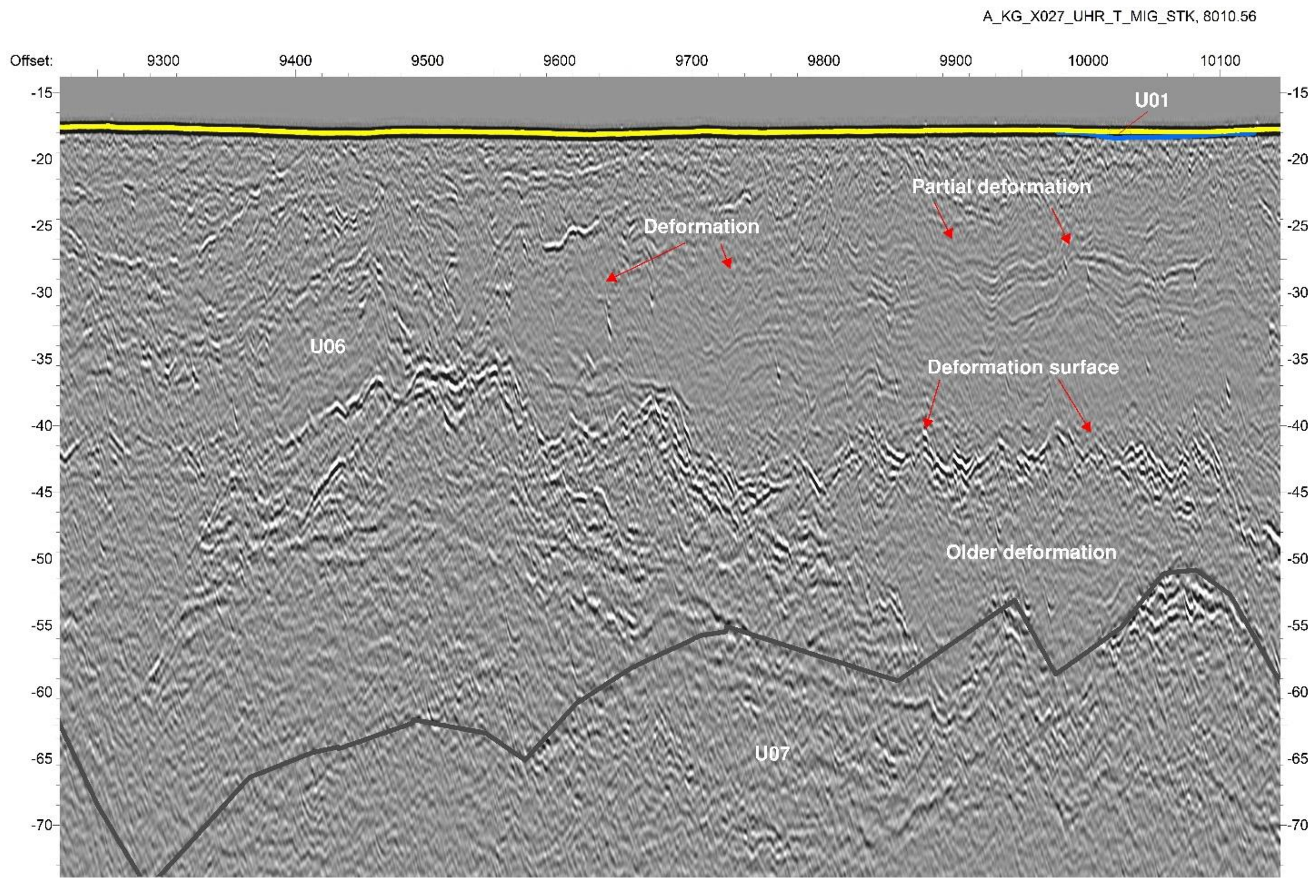


Figure 9-7 *Seismic line A_KG_L037_UHR_T_MIG_STK. Example of a profile showing U06 where different grades and generations of glacial deformation are seen.*

9.9 Model stratigraphy

The stratigraphy of the Kattegat OWF site has been divided into 7 units. A summarized description of the different units can be found in Table 9-4, see also section 5 and Table 5-1.

Cross sections through the model are presented in enclosures 6.01-6.12. In total 12 representative cross sections have been made to illustrate the stratigraphy and the variation of the units across the site. The 12 cross sections have been distributed over the entire site and have at the same time been placed along 2D UHRS seismic lines and where geotechnical positions are present. An overview of the position of the cross sections can be seen on enclosure 1.02.

The stratigraphy interpreted in the data collected for the Kattegat OWF has been guided by scientific papers and reports, amongst others from the desktop study conducted by GEUS (Ref. /7/). The ages of the units have been interpreted based on the seismic characteristics, the lithology, and the geotechnical behaviour of the units.

The 7 units has been divided into four (4) chronostratigraphic groups as follows: Holocene, Late Weichselian, Weichselian and Earlier Pleistocene, and Late Jurassic to Early Palaeocene (pre-quaternary). The four groups have been given four different colours in Table 9-4.

The Weichselian and Earlier Pleistocene group have been created for the soils covered by ice sheets after deposition. The unit U6, assigned to Weichselian and Earlier Pleistocene, is heavily deformed and cannot be separated further into either the Weichselian, the Saalian, or the Elsterian glaciations.

None of the units found in the Kattegat OWF project site have been interpreted as belonging to the interglacial periods Eem or Holstein. However, there is a possibility that deposits from these periods are present within the Kattegat OWF project site and have been mixed with the glacial deposits during the glacial deformation in the area.

Deformation has been identified in U06, see section 9.8.6. The deformation creates a mixture within the unit, and older material might occur on top of younger deposits.

Table 9-4 Summary of units in the Integrated Geological Model for Kattegat OWF including description of seismic facies.

Unit	Base Horizon	Seismic facies	Depositional Environment	Soil Type according to the borehole descriptions. (Ordered by frequency)	Chronostrati-graphic group
U01	B01	Acoustically semi-transparent in the thicker parts and chaotic in the top.	Marine	CLAY, Silty SAND, Sandy CLAY, Silty CLAY, Clayey SAND, Gravelly SAND	Holocene
U02	B02	Sigmoidal reflectors with onlapping and toplapping	Estuarine/ deltaic	CLAY, Silty CLAY, Silty SAND	Early Holocene
U03	B03	Parallel to sub-parallel reflectors. Occasionally undulating.	Fluvial to estuarine	Sandy CLAY. Silty CLAY, CLAY, Silty Sandy CLAY, Gravelly CLAY	Late Weichselian
U04	B04	Low amplitude semi-parallel reflectors and transparent facies.	Fluvial to estuarine	-	
U05	B05	Sub-parallel to chaotic nature with occasional transparent facies	Glaciofluvial	SAND, Clayey SAND, Gravelly SAND	
U06	B06	Chaotic facies. Occasionally areas with sub-parallel reflectors.	Mixed Glacial	CLAY TILL, SAND TILL, SAND, Silty SAND, Sandy CLAY, GRAVEL, Gravelly SAND, Clayey Sandy Gravelly SILT, Sandy Gravelly CLAY, Silty Sandy CLAY, GRAVEL, Silty Gravelly CLAY, Silty Gravelly SAND, Silty CLAY, Sandy CLAY	Weichselian and Earlier Pleistocene
U07	-		Marine	CHALK, LIMESTONE	Jurassic to Early Palaeocene (Danien)

9.9.1 Holocene

The units assigned to the chronostratigraphic group Holocene represent an environmental transition from terrestrial to marine. The Holocene group consists of U01 which is present across most of the Kattegat OWF site and U02 which is mostly associated with a valley crossing the site.

Enclosure 2.01 shows the depth below seabed of the top of U01, enclosure 3.01 shows the elevation, and enclosure 4.01 shows the thickness (isochore) of U01.

U01 – Post glacial marine

U01 represents the latest unit deposited in the model and is a recent Holocene marine deposit. The unit is identified on the SBP data and has been transposed to the 2D-UHRS afterwards. The seismic facies is mostly transparent in the UHRS data. Towards the top unit is generally affected by seabed artefacts. An example of this can be seen in Figure 9-8.

The geotechnical data indicate the unit to be predominantly CLAY with sandy and silty variations containing larger parts of silty SAND. More sandy and silty CLAY variations is often found in the top of the unit. Areas of silty sand are found (KG_02_BH) as well as a thinner layer of clean sand (KG_01_CPT) seen in the north. Generally, the unit is geotechnically considered as a weak CLAY.

U01 is generally identified a weak layer in the geotechnical data and correlates well with geophysical data. However, where U01 overlies the weak layers of U02 or U03 it's difficult to identify a boundary in the geotechnical data. It was however easily distinguishable when overlying the SAND unit U05.

U01 has an erosive boundary when it is directly overlying units older than U02. When it is overlying U02 a change from a transparent facies to a toplapping sigmoidal facies is seen.

The thickness of the unit is generally below 3 meters across the site except for a SW-NE oriented channel infilled with U01. Here the thickness is found to be up to approximately 10 m. The channel can be seen on the bathymetry as well and is also easily visible on the depth map of the underlying U2 (enclosure 2.02) and the isochore map for U01 (enclosure 4.01).

The unit is interpreted as being a Holocene marine unit, marking the change from a glaciofluvial environment through transgression to a marine environment. Due to the sandier material found in the northern part of the unit, which is also described by GEUS (Ref. /7/), the input to the area is interpreted to come from the north. As described in section 9.8.3, peat is occasionally found below horizon B01 and marks the change from a fluvial to marine environment. The peat is not directly a part of U01 but is a sign of the transgression which occurred during the Holocene.

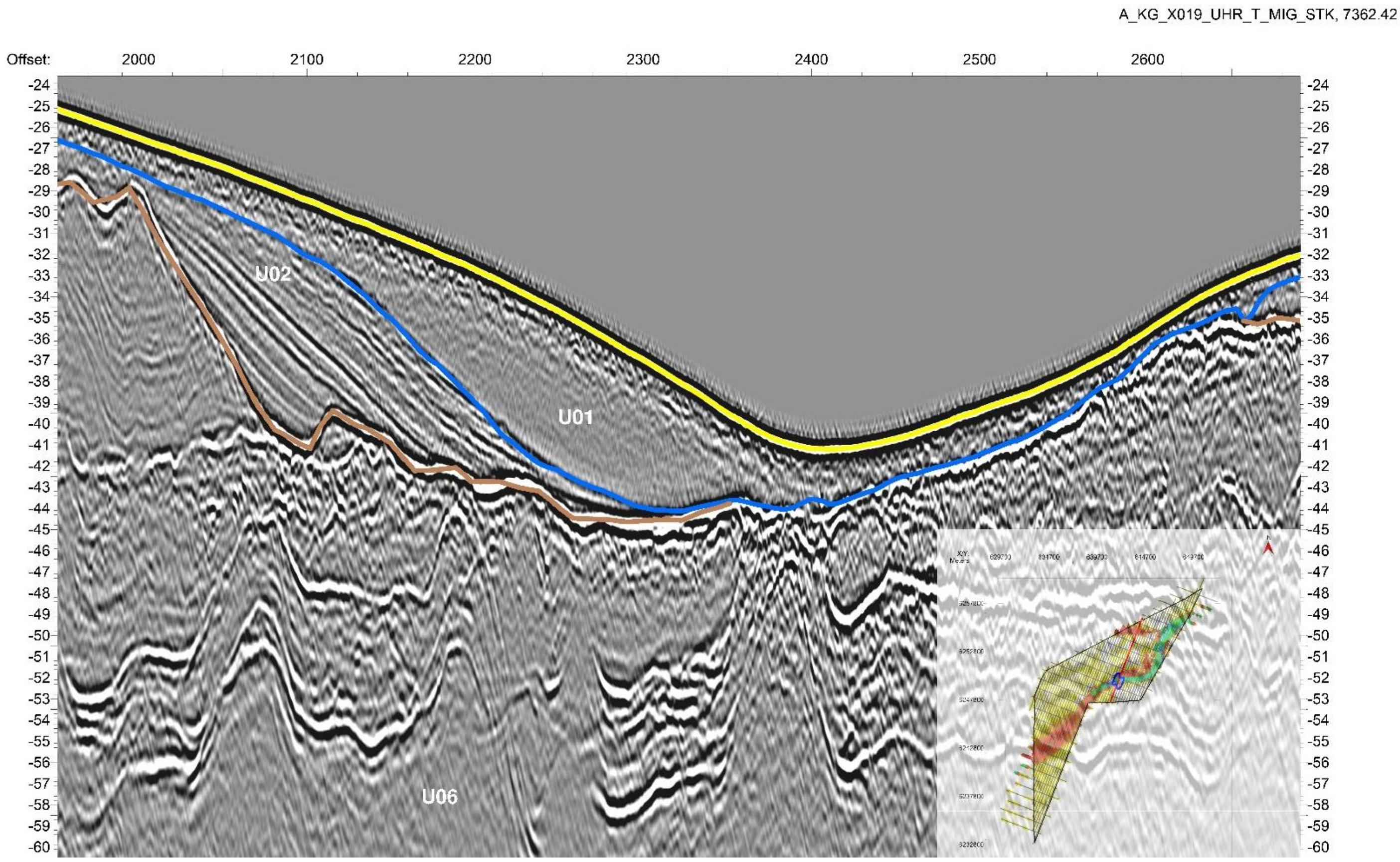


Figure 9-8 Seismic line A_KG_L031_UHR_T_MIG_STK. Example of U01, in this example seen bounded by B01 (Blue) at the base and the Seafloor (yellow) to the top. The seismic facies is mostly identified as being transparent with a disturbed upper part caused by seabed artefacts. The overview map in the lower right corner shows the position of the profile (red line), the displayed section (blue area), and the elevation of top of U01 (see also enclosure 3.01).

U02

The unit is found in the same channel incision and seabed depression as the deepest deposits of U01 were found in, which is a SW-NE running channel incision. There is a disconnect between the southern and northern part of the unit, where the channel thickness is decreasing. No erosive boundary between U01 and U02 is identified, the change is seen as a change from chaotic and transparent seismic facies to more structured facies. The change from U01 to U02 can be hard to distinguish in the 2D-UHRS data but is well defined in the SBP with a higher vertical resolution. Enclosure 2.02 shows the depth below seabed of the top of U02, enclosure 3.02 shows the elevation, and enclosure 4.02 shows the thickness (isochore) of U02.

As seen in Figure 9-9 the seismic facies of U02 are sigmoidal reflectors of medium to low amplitude, and they are seen toplapping B01 and onlapping B02 at the sides of the channel. The base of U02 has a clear erosive boundary against the underlying units.

The geotechnical position KG_13_DCPT_A is penetrating U02 and a lithology of silty CLAY is interpreted with no clear lithological difference between U01 and U02 established. That is the general case across the site and the two units are therefore differentiated on their seismic facies and from the difference that U01 is well defined in the SBP data and not the 2D-UHRS while U02 is well defined in the 2D-UHRS data and not in the SBP data. The unit is also found as clean CLAY and as clayey silty cobbly SAND. Generally, the unit is considered geotechnically as a weak CLAY.

U02 is well correlated between geophysical and geotechnical data. The unit is often underlain by the TILL of U06 which creates a visible boundary towards the CLAY of U02. When overlain by U01 it can be hard to distinguish between the two CLAY deposits.

The thickness of U02 is found to be below 6 m on the side of the channel and up to 27 m in the middle of the channel incision but is generally below 20 m thick.

The unit is interpreted as an estuarine/deltaic deposit and is found having its input of sediment coming from a northern direction, due to the inclusion of coarser sediment in geotechnical positions KG_13_DCPT_A and KG_02_BH (Silty CLAY and SAND). The unit has been deposited in a periglacial setting during a late ice advance into the Kattegat OWF area. Gas can be found in the unit, disturbing the underlying seismic data, for more information see section 9.8.1.

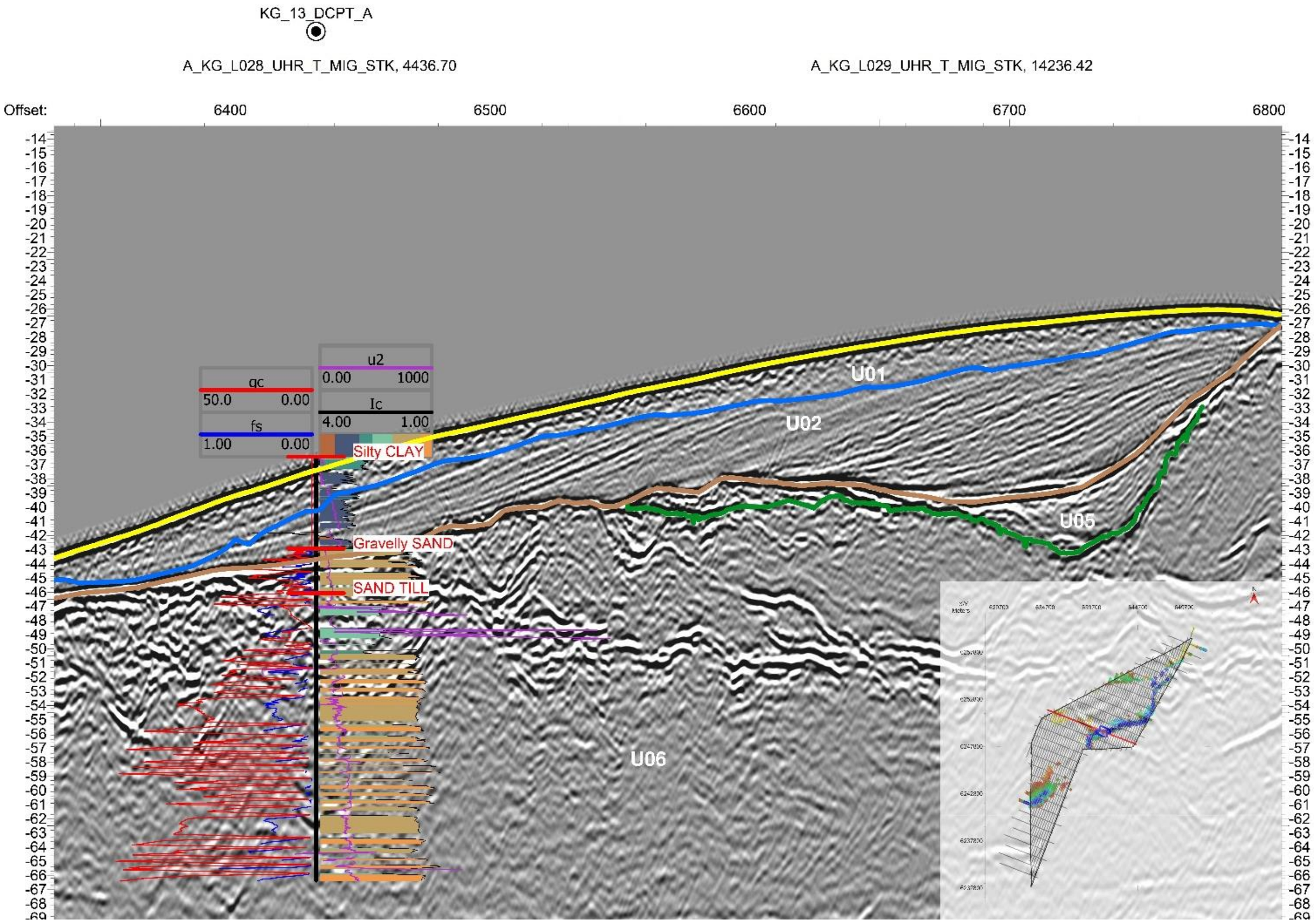


Figure 9-9 *Seismic line A_KG_X018_UHR_T_MIG_STK. Example of U02, in this example seen bounded to the top by B01(Blue) and at the bottom by B02 (Brown). The seismic facies is seen as medium to low amplitude sigmoidal reflectors which are toplapping onto B01 and onlapping onto B02. Geotechnical position KG_13_DCPT_A is penetrating the unit and shows a lithology of silty CLAY. The overview map in the lower right corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U02 (see also enclosure 3.02).*

9.9.2 Late Weichselian

The units assigned to the chronostratigraphic group; Late Weichselian, are related to last glacial maximum, which occurred in last phase of the Weichselian around 20,000 years ago. Late Weichselian includes deposits from the latest glacial readvances during general glacial retreat. The units U03, U04 and U05 are identified as belonging to the late glacial. U03 and U04 are predominantly clay while U05 is sandy. U03 and U04 are both interpreted to be estuarine to fluvial origin while U05 is interpreted to be mainly glaciofluvial origin. All the units have been deposited during a retreat of the ice sheet from the area in a proglacial to periglacial setting.

U03

The unit is found in channel incisions running SW-NS but is mostly independent from the younger channel systems comprising of U01 and U02. U03 is mainly seen west of U02. Enclosure 2.03 shows the depth below seabed of the top of

U03, enclosure 3.03 shows the elevation, and enclosure 4.03 shows the thickness (isochore) of U03.

U03 has an erosive surface B03 as base and is also bounded in the top by erosive surfaces. The surface between U02 and U03 is a strong reflector marking the erosion of U02 into U03, while the boundary between U01 and U03 has a clear but weaker reflector between them marking an erosive surface. This slight erosive surface between U01 and U03 has been used in some instances to differentiate between U02 and U03, as no erosive surface between U01 and U02 has been identified.

In Figure 9-10 an example of the seismic facies of U03 can be seen, also illustrating gas blanking in the left side of the figure. The facies is often seen as parallel to sub-parallel reflectors but can also be slightly undulating as seen in Figure 9-10. In some instances, the facies shows acoustic transparency as well. The unit is found to consist mainly of Sandy CLAY, as can be seen in the figure, but is also found consisting of silty CLAY, CLAY and in geotechnical position KG_05_CPT also gravelly CLAY. Generally, the unit is considered geotechnically as a weak CLAY.

The correlation between the geophysical and the geotechnical data is generally good at the base of the unit where a change from CLAY to SAND and TILL can be found when found above U06. When overlying U05 a clear change from CLAY to SAND is found which makes correlation easy. When the unit is below U02 and U01 it can be difficult to see the boundary in the geotechnical data, since the three units mostly consist of CLAY where overly each other.

The thickness of the unit is generally below 7 m but can be found locally up to 12 m in the north. In the northern WSW-ENE running incision the unit is found reach a thickness of 29 m in the middle of the incision. In this area the base of the unit is however masked by gas blanking which creates a higher uncertainty around the found depths.

U03 is interpreted as being deposited in a fluvial to estuarine environment, in a low energy area due to its clay lithology. The unit is expected to contain organic material, which could be the source of the gas findings in the unit. The extent of gas found in the area can be seen in Figure 9-2, and is found to disturb the signal of the underlying unit as well as mask the horizon B03 as seen in Figure 9-10. This makes the interpretation of B03 more uncertain here. The unit is found to be deposited in a periglacial setting, during a late Weichselian ice advance.

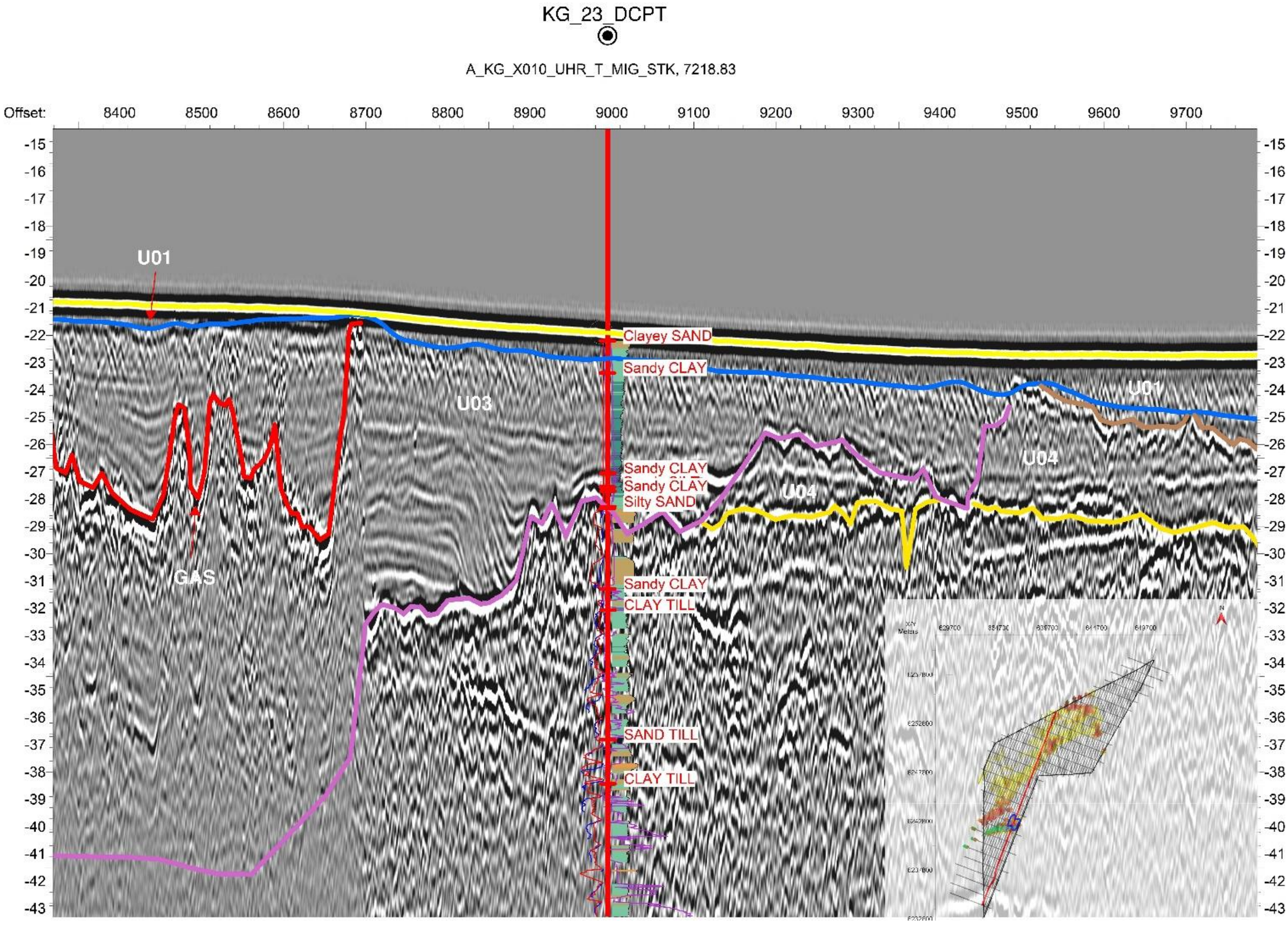


Figure 9-10 *Seismic line A_KG_L020_UHR_T_MIG_STK. Example of U03, here bounded by B01 (Blue) to the top and B03 (Purple) at the base. Top of gas is seen to the left (red). The seismic facies is seen as subparallel to semi-chaotic reflectors with a slight transparency towards the top. Geotechnical position KG_23_DCPT is penetrating the unit and shows a Sandy CLAY lithology. The overview map in the lower right corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U03 (see also enclosure 3.03).*

U04

The unit is only found very locally in the Kattegat OWF site located in the western part of the southern half of the site. There is a small disconnect between the northernmost and the southernmost part of the unit. U04 has an erosive base and has been eroded to the top as well by U01-U03. It can be assumed that the extent of U04 has been greater at one point, but that the erosion from the younger units has limited it to the small area it now inhibits. In Figure 9-11 an example of the seismic facies of U04 can be seen. In the example it is seen as having low amplitude semi-parallel reflectors towards the left side, and a more transparent facies in the rest of the unit. This is also the case for the remaining unit, where the majority of the facies is seen as acoustically transparent, with areas, especially towards the top of the unit, with a more structured facies. Enclosure 2.04 shows the depth below seabed of the top of U04, enclosure 3.04 shows the elevation, and enclosure 4.04 shows the thickness (isochore) of U04.

No geotechnical positions penetrate this unit, so the lithology of U04 is based solely on its seismic behaviour, and the description should be assumed to be of lower certainty. Due to its resemblance in seismic facies with both U01, and in some areas U03, it is expected that U04 is also a fine-grained deposit and is put together with U01-U03 in the category of weak soils.

The unit is found having thicknesses of up to 9 m but is generally found with up to 7 m of sediment. The unit is thickest in the northernmost extent.
U04 is interpreted as being an estuarine to fluvial deposit which potentially has had a greater extent in the area but has since been eroded by younger units.

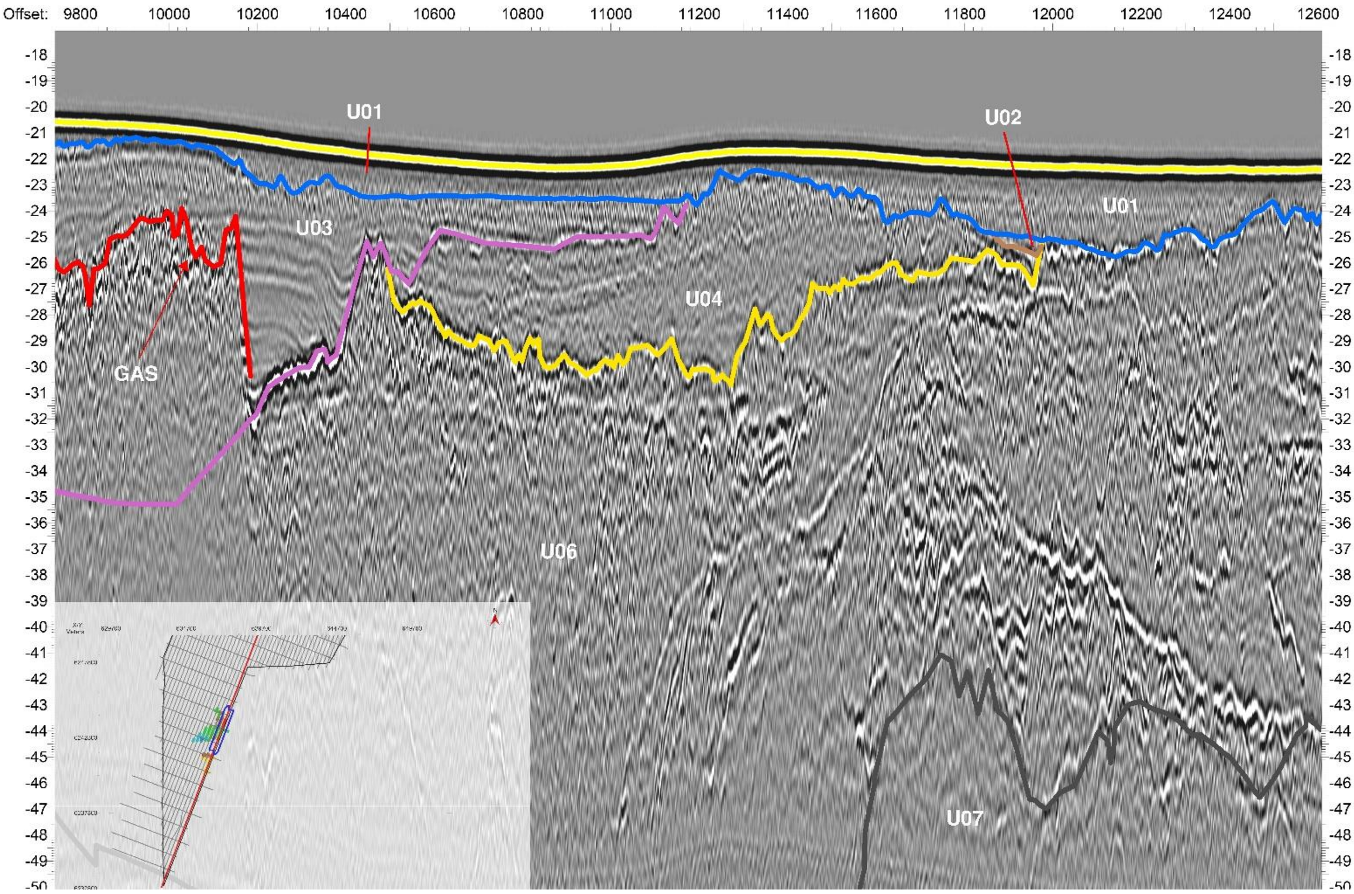


Figure 9-11 Seismic line A_KG_L022_UHR_T_MIG_STK. Example of U04, in this example bounded at the top by B01 (Blue) and B03 (Purple), and at the base by B04 (Yellow). The seismic facies is seen as mostly acoustically transparent with some subparallel reflectors at the left side of the figure. The overview map in the lower left corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U04 (see also enclosure 3.04).

U05

The unit is found across the site but disconnected and only locally in paleo channels where U02 and U03 are also deposited. U05 is clearly eroded to the top by U02 and U03, and in a few instances by U01. The unit is also seen as having an erosive base, where it is incising into the underlying U06. Enclosure 2.05 shows the depth below seabed of the top of U05, enclosure 3.05 shows the elevation, and enclosure 4.05 shows the thickness (isochore) of U05.

In Figure 9-12 an example of the seismic facies of U05 can be seen. It has a sub-parallel to chaotic nature with occasional transparent facies. There are often structures seen in the unit that show signs of a fluvial deposition in a high energy environment.

There are 2 CPT's penetrating thicker sections of U05, and the unit has been interpreted as being consisting of SAND (KG_05_CPT_B) and gravelly SAND (KG_13_DCPT_A). The unit is as mentioned discontinuous, and there are therefore many isolated areas that have not been penetrated by a geotechnical position. The unit is overall described as a competent sand unit, however, there is a risk that the unit has a more diverse lithology than what the CPT's are describing.

The correlation between the geophysical and the geotechnical data is often good. U05 stands out with its lithology of gravelly SAND compared to the CLAY units U01-U03. An easy noticeable change is also seen between U05 and the underlying TILL of U06.

The thickness of the unit is found to be up to 14 m at the deepest area, but the deepest parts are generally up to 10-11 m. Most of the unit is found to be less than 3 m thick.

The unit is interpreted as being a periglacial fluvial deposit closely connected to the initial incision of the channels that U01-U05 now inherits. The unit is interpretated to be related to rivers connecting the glacier front in south (see Figure 4-3) and later the early stages of the Baltic Ice Lake to marine environment in the northern Kattegat area.

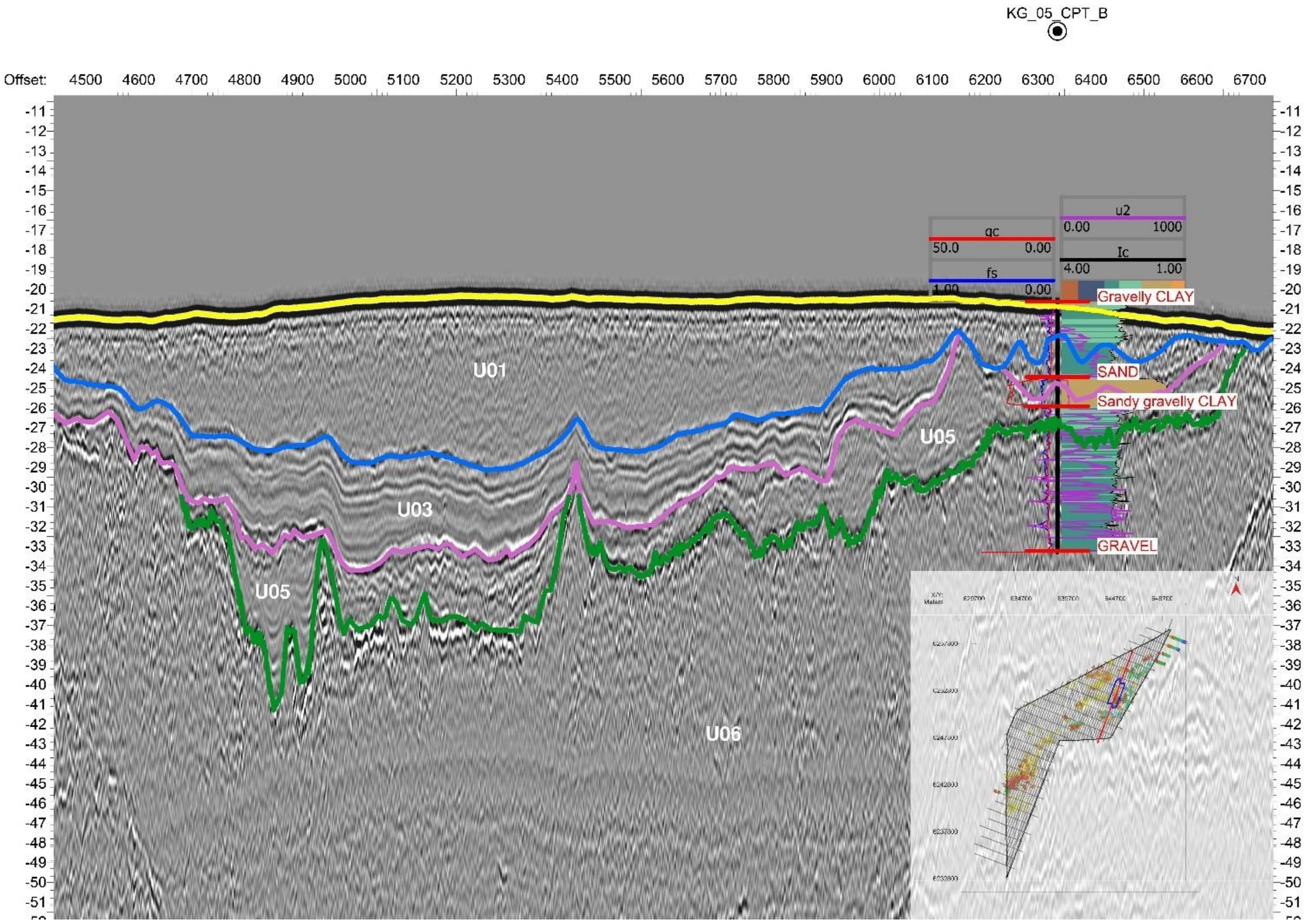


Figure 9-12 Seismic line A_KG_L038_UHR_T_MIG_STK. Example of U05, in this example bounded by B03 (purple) to the top and B05 (green) at the base. The seismic facies is seen as being somewhere semi-transparent and other places as having semi-chaotic to subparallel reflectors. Geotechnical position KG_05_CPT_B is penetrating the unit and shows a lithology of SAND. The overview map in the lower right corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U05 (see also enclosure 3.05).

9.9.3 Weichselian and Earlier Pleistocene

The Weichselian and early Pleistocene group includes the units deposited between the onset of the Pleistocene until the Late Weichselian. This group is expected to contain material deposited in the Elsterian, the Saalian, and the Weichselian ice advances, and could possibly contain deposits from interglacial periods as well. However, deposit from the Weichselian is expected to be dominating. The overriding of ice sheets in this area has mixed the sediments together, and it is therefore difficult to determine what deposits originate from which period. In the Kattegat OWF area, the deposits from the Early Pleistocene to late Weichselian are heavily deformed by glaciotectonic forces, and clear stratigraphic structures can generally not be found. Therefore, a single unit containing the deposits from this period has been interpreted, U06, which is a deformed mix of several types of lithologies.

U06

The unit is found across the entire site and is the deepest unit before moving into the Pre-Quaternary bedrock. The unit has an erosive base and is incising into the bedrock. Deeper valley structures are identified and the incisions go down to 137 m bsb. The deepest incision is in the middle of the northern half of the Kattegat OWF where it is oriented NE-SW, see enclosure 2.07 which shows the depth below seabed of the bottom of the unit (top of U07). Enclosure 2.06 shows the depth below seabed of the top of U06, enclosure 3.06 shows the elevation, and enclosure 4.06 shows the thickness (isochore) of U06.

The unit has been subject to extensive glacial deformation and the lithology is therefore highly variable. Attempts were made to further subdivide the unit, but the deformation has created internal surfaces that cannot be distinguished from bounding horizons. An example of this can be seen in Figure 9-13 where a test horizon in green is following a reflector connecting two CPT's. Within a short distance the lithology changes from being a gravelly SAND to a CLAY TILL, but with no clear indications in the seismic facies. The geotechnical interpretations showed primarily CLAY and SAND TILL, but also areas with silty and clean SAND as well as CLAY. A full description of all the lithologic groups that are found in this unit can be found in Table 9-4.

The correlation between the geotechnical and the geophysical data is generally good in U06, because it is easy to distinguish between the upper weak units of U01-U03 and the TILL of U06. It is also easily distinguishable when it is overlain by the SAND of U05. At the base the boundary between TILL and CHALK / LIMESTONE, there is a good correlation as well, but problems with correlation can occur if some of the CHALK has been eroded and mixed into the TILL.

U06 is described in the CPT's with a sandy top before reaching till below. As mentioned above it was not possible to follow any reflectors that could mark the sandy areas. Instead a rough estimation based only on the lithologies interpreted in the CPT's have been made, see Figure 9-14, where the boreholes with sand has been grouped together and marked by a beige colour and a black stippled outline. The sand was found with a thickness from a few meters up to approximately 20 m.

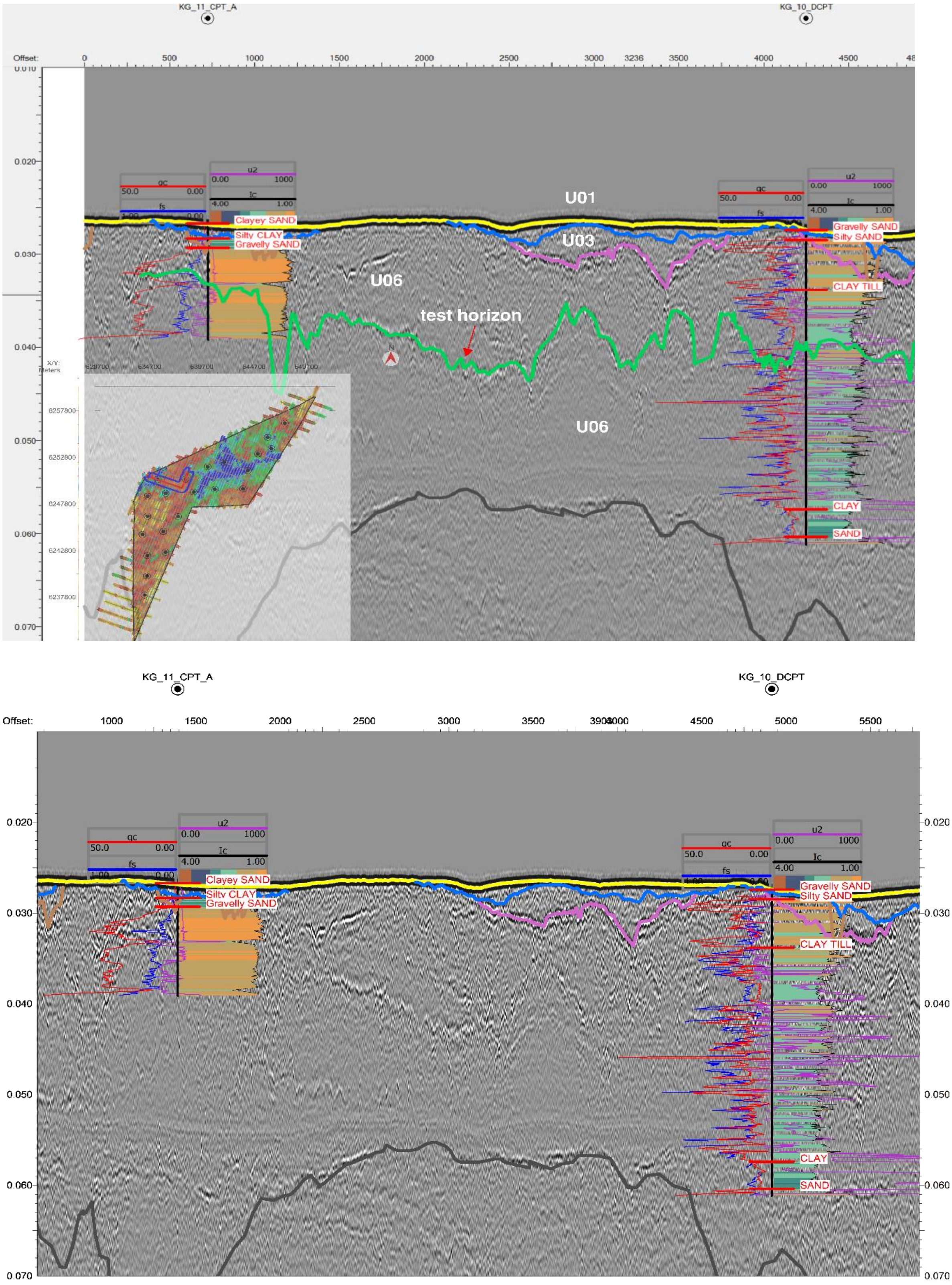


Figure 9-13 *Example of interpretation of U06 illustrating how attempts to correlate between lithologies in neighbouring boreholes were made during interpretation. Here a clean sand layer appears to transition into glacial till in a composite section between geotechnical positions KG_11_CPT_A and KG_10_DCPT along seismic lines A_KG_X015A_UHR_T_MIG_STK and A_KG_L006_UHR_T_MIG_STK. In the top a temporary test horizon (green) is shown and in the bottom the clean seismic facies can be seen for comparison. The overview map in the top lower left corner shows the position of the profile (red line) and elevation of top of U07 (see also enclosure 3.07).*

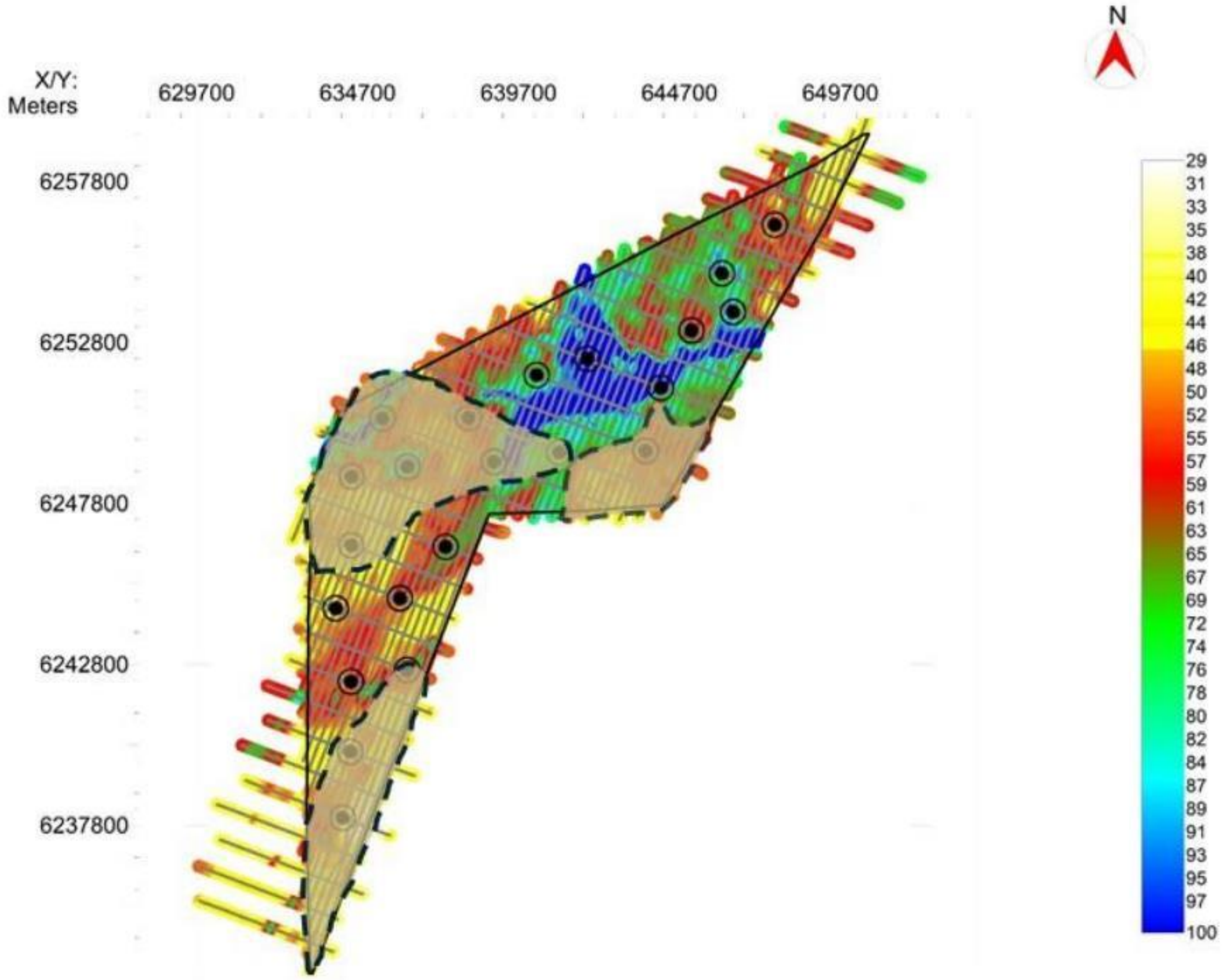


Figure 9-14 Map showing areas of U06 where a sandy top is found in the geotechnical data for the unit generally described as TILL. The beige areas marked by a stippled line are the areas where sand is found in the top of the unit. The thickness of the sand varies from a few meters up to approximately 20 m. The base of the unit is shown in elevation to MSL.

In Figure 9-15 an example of the seismic facies of U06 can be seen. The unit generally has a chaotic facies due to the glacial deformation, but undeformed areas with subparallel reflectors can also be found. Very strong internal reflections can be found at various places inside U06. These are proposed to be the base of a deformation event.

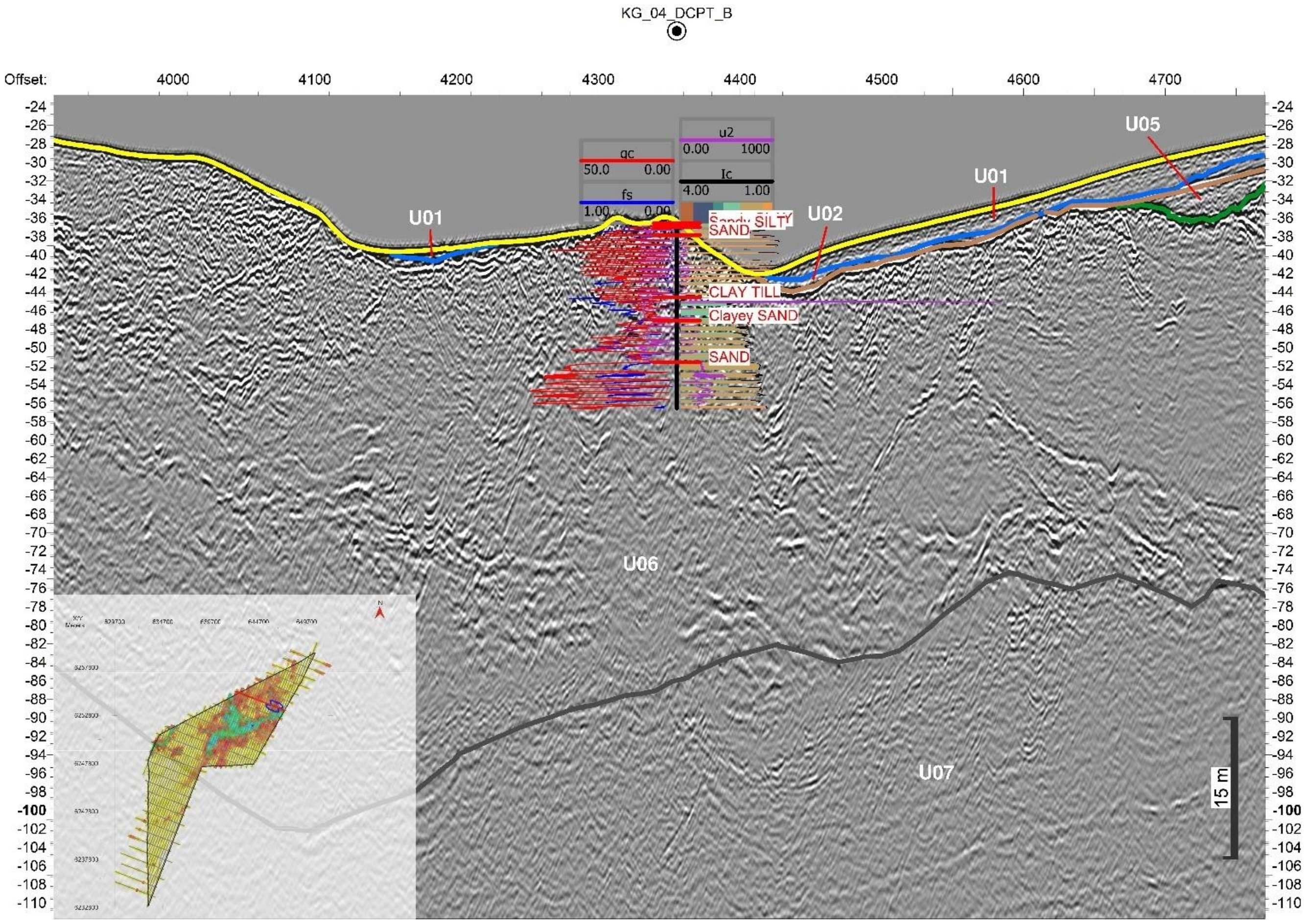


Figure 9-15 A_KG_X024_UHR_T_MIG_STK. Example of U06, which in this example is bounded by B05 (Green), B02 (Brown), and B01 (Blue) to the top and B06 (Black) at the base. The seismic facies is seen as being chaotic with some areas of an almost transparent facies. KG_04_DCPT_B is penetrating the unit and shows a lithology of SAND, CLAY TILL, Clayey SAND, and SAND. The overview map in the lower left corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U07 (see also enclosure 3.07).

There are several places were CPT's has met impassable obstructions in U06. Two times at KG_14_CPT(B), and at KG_22_CPT the CPT's were stopped at the very top of the unit when entering it. Also, at KG_22, KG_23 and KG_25 impassable obstructions were met, and these were internally in U06. These obstructions can be possible boulders which are expected to be encountered in till deposits. The obstructions were not observable in the seismic data, neither the SBP nor the 2D-UHRS.

The thickness of the unit varies between approximately 10 m and 132 m. The unit generally has a thickness between 10 and 50 m, with a general trend of thicker deposits of U06 in the northern part of the OWF area. The deepest areas are found in the incised channels into the bedrock, which are found in the northern part of Kattegat OWF area. The incisions are NE-SW trending.

The unit is interpreted as a highly variable unit with elements of subglacial, periglacial, proglacial and possibly interglacial marine depositions all mixed together by glacial deformation. Some areas are less deformed and has recognizable seismic facies, but no general trend regarding deformation zones were identified. As seen in Figure 9-14 there were sandy areas identified, but these were still heavily deformed, and no reflectors marked the lateral transition from SAND to TILL. In general, the unit is a high strength unit due to the over-consolidation created by the overriding ice sheet, and the SAND are found to be medium dense to very dense and the TILL of very high to extremely high strength.

9.9.4 Late Jurassic to Early Palaeocene

The bedrock in the Kattegat OWF area is described to consist of Danien (Early Palaeocene) limestone in the southern part of the area, Upper Cretaceous Chalk in the middle and Late Jurassic to Early Cretaceous mudstone in the northern part (Ref. /7/).

U07

The unit is the basal unit of the IGM and is found across the entire Kattegat OWF area. The unit has a base deeper than the maximum depth of investigation and is therefore interpreted by its top, which is B06. The top of the bedrock is shown on enclosure 2.07 in m bsb and as elevation on enclosure 3.07.

The unit is penetrated by boreholes across the site, and both CHALK (KG_25_BH_A, KG_21_BH, KG_07_BH) and LIMESTONE (KG_12_BH_A) was penetrated.

The correlation between the geophysical and geotechnical data was quite good for this unit, due to the clear changes from the TILL of U06 to the CHALK and LIMESTONE of U07 at the top of the unit.

In Figure 9-16 an example of the seismic facies of U07 can be seen, where parallel inclined internal reflections can be seen. The data quality is not good enough across the site to make these features visible except on few seismic lines. The bedrock showed is proposed to be lower Cretaceous to lower Jurassic MUDSTONE, though no geotechnical evidence for the Jurassic MUDSTONE is encountered. The seismic facies and the regional geological setting (Section 4) is pointing towards the unit being mudstone in the northern area as visualized in Figure 9-18.

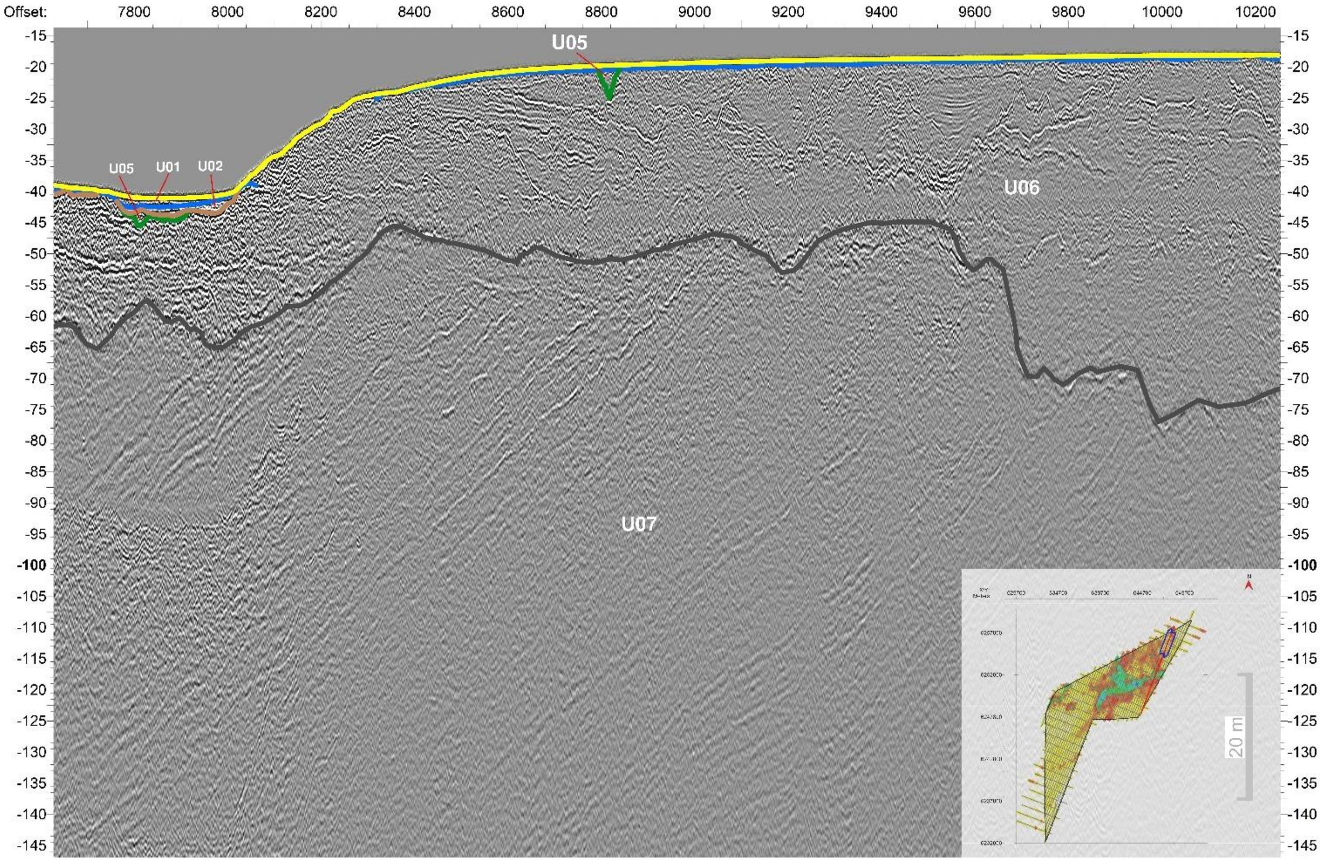


Figure 9-16 *Seismic line A_KG_L043_UHR_T_MIG_STK. Example of U07 seen bounded to the top by B06 (Black horizon). The unit has in this example parallel inclined reflectors but is also found with parallel horizontal reflectors and with a chaotic facies. The overview map in the lower right corner shows the position of the profile (red line), the displayed section (blue area), and elevation of top of U07 (see also enclosure 3.07).*

In Figure 4-1 it is indicated that the Pre-Quaternary deposits change from limestone/Chalk to mudstone in the east of the northern half of the Kattegat OWF area, coinciding with the Grenå-Helsingborg fault. Figure 9-17 illustrates an angular unconformity found in the northern part of the site indicating a possible boundary between Limestone, Chalk and Mudstone. There seem to be 2 distinct changes happening inside U07, marked with a stippled green and blue line in Figure 9-17. The borehole KG_12_BH only penetrates the first 10 cm of the limestone, and is therefore not conclusive, but it is proposed that the unconformity indicates changes from limestone to Chalk and from Chalk to mudstone. The Chalk seen in in the borehole description above the Limestone is interpreted as a flake included in the Till unit U06.

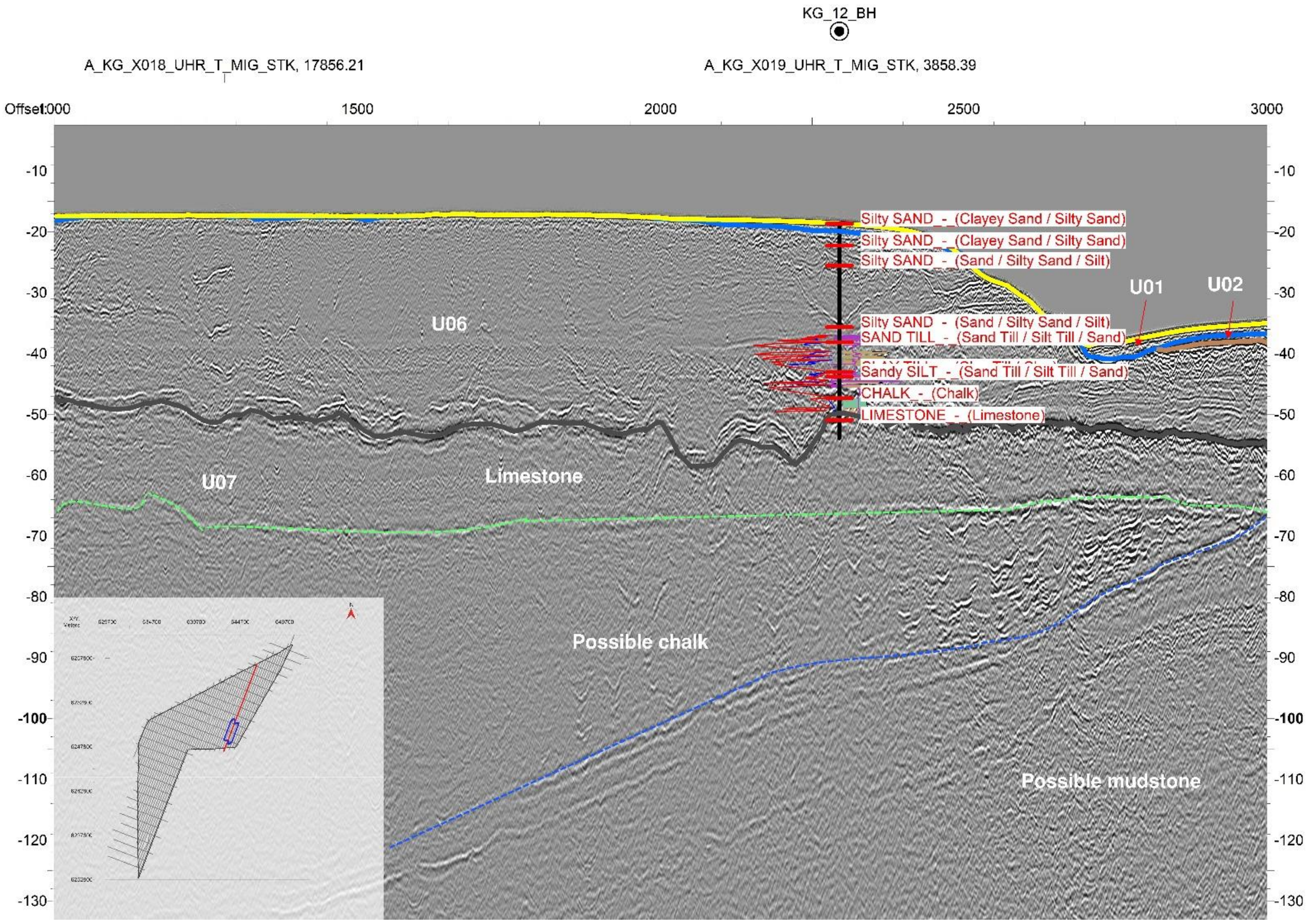


Figure 9-17 *Seismic line A_KG_L038_UHR_T_MIG_STK. Example of an angular unconformity seen in the bedrock due to tectonic uplift and erosion. Proposed boundaries between limestone, chalk and mudstone are drawn. These boundaries are not verified by geotechnical data (KG_12) and are not mapped in the Kattegat OWF IGM, but are all included in U07. The overview map in the lower left corner shows the position of the profile (red line) and the displayed section (blue area).*

In Figure 9-18 the boreholes in the Kattegat OWF area can be seen, and a proposition for the lithology of the topmost bedrock is given. This is only an estimate since borehole positions verifying this are sparse, and the change is only visible in few seismic lines (example given in Figure 9-17). The seismic quality is not very good where this change is expected, but where the seismic data is good, a difference in facies between the mudstone and the chalk can be seen. The boundaries in Figure 9-18 are based on the contents of the boreholes and the seismic profiles along with the Pre-Quaternary map composed by GEUS Ref. /7/. KG_02_BH does not confirm nor deny the thesis that mudstone can be found in the northern part of the survey area, since it ends in till material in U06 and does therefore not penetrate the change to Pre-Quaternary layers. As mentioned, KG_12_BH only penetrates 10 cm into the Proposed Danien Limestone, and it is therefore hard to say if it is just a flake of Limestone or if the Danien formation is in fact encountered with certainty.

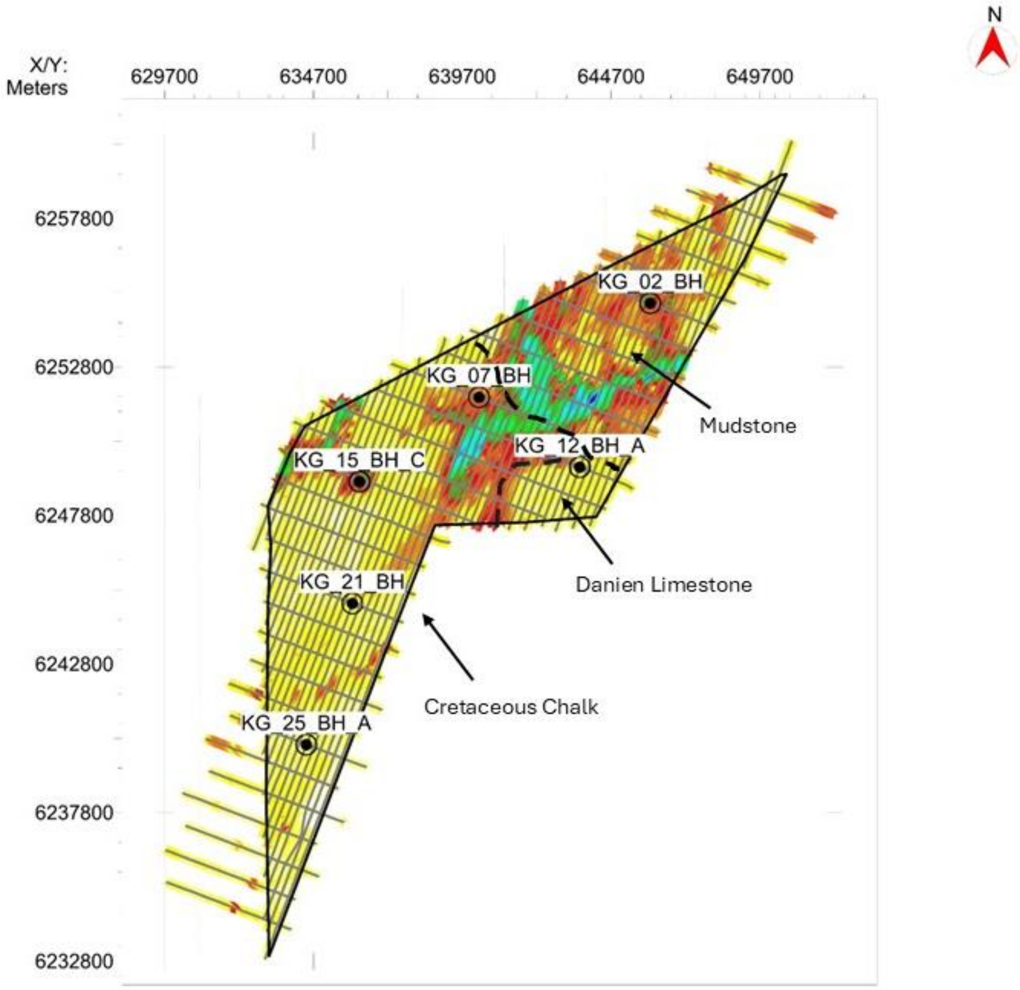


Figure 9-18 *Map of the top of the bedrock with the boreholes of Kattegat OWF marked. The black stippled lines mark the estimated boundaries between Danien Limestone, Chalk, and Mudstone. These lines are estimated based on the descriptions from the boreholes, seismic lines and GEUS Pre-Quaternary map.*

An example of a fault in U07 can be seen in Figure 9-5 and they can be assumed to be occurring in this unit throughout the site. The quality of the seismic data was not good enough for mapping out the faults.

As can be seen from enclosure 2.07 the top of the bedrock is found between 7 and 137 m bsb and can generally be said to be above 40 m bsb in the south and deeper located in the north, especially where the Pleistocene ice sheets has eroded the bedrock.

10 Geotechnical zonation and representative soil profiles

Based on the geotechnical and geophysical data, and the interpreted model, a soil zonation has been made. The soil zonation provides the basis for clustering the main geological deposits and structures relevant for the wind turbine foundations.

Overall good soil conditions feasible for OWF foundation design is found and the zonation focus on variation in soil distribution expected to affect design and installation. The soil zonation is simplified into one single map dividing the entire site into eight (8) different geotechnical zones. The simplification is made by selecting the most significant parameters in relation to foundation conditions.

The purpose of the geotechnical zonation map is to provide a geological overview of the Kattegat OWF project site with regards to foundation conditions. The map should ideally divide the Kattegat OWF project site into a limited number of provinces with similar foundation conditions.

The workflow of the process is presented in Figure 10-1.

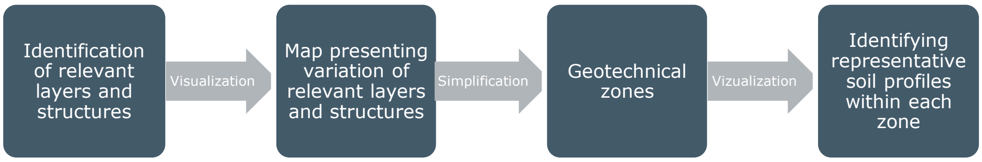


Figure 10-1 Workflow for dividing the area into geotechnical zones.

10.1.1 Identification of relevant layers and structures

For the geotechnical zonation of the Kattegat OWF project site, relevant layers and structures have been identified. For the identification of these relevant layers and structures, focus have been on the following:

- Soils at depths down to 50 m below seabed, as this depth range is considered important for wind turbine foundations.
- Mapping extent of weaker soil layers.
- Mapping thickness of competent glacial layer across the Kattegat OWF project site.
- Depth to Pre-Quaternary layers

Regarding weaker soil layers, it is noted that the OWF project site generally consists of good soil conditions in regard to foundation installation and design. Some weaker geotechnical units which are generally consolidated to slightly over-consolidated are present, namely unit U01, U02, U03 and U04. However, these geotechnical units have limited thickness with cumulative thickness generally below 10 m, and few exceptions with cumulative thickness up to 18 m. Hence, their presence does generally not challenge foundation design, but they have some effect on foundation dimensions.

The thickness of the underlying competent glacial layers is considered as one of the most important parameters for establishing a foundation design. The competent glacial layers comprise primarily dense to very dense sand and over-consolidated clay. Thicknesses of these layers range from 0 m to more than 100 m. U6 is identified as the competent glacial unit.

The depth to the Pre-Quaternary layers (U07) is considered as an important parameter for establishing a foundation design. The Pre-Quaternary layers consist of chalk, limestone or sandstone/mudstone differentiating across the site, and the depth to top of U07 ranges approximately from 8 m to more than 100 m. The Pre-Quaternary layers pose an increased risk and/or uncertainty for foundation design and installation compared to overlying glacial impacted material, hence the depth to Pre-Quaternary layers together with the thickness of glacial layers and thickness of weaker soil layers is of relevance to understand the risk related to foundation design and installation.

The three parameters mentioned above are all considered relevant when dividing the site into zones of comparable soil conditions.

Given the above considerations three maps have been prepared. These maps are considered to provide valuable input for the geotechnical zonation. The presented maps are as follows:

- Figure 10-2 presents a map showing the combined thickness of ground model units interpreted as soft sediments, namely unit U01, U02, U03 and U04. The map hence shows the thickness of layers considered as poor material for foundation design and when present for large thickness can result in heavy WTG foundations.

- Figure 10-3 presents a map showing the thickness of competent glacial layer namely unit U06. The map hence shows the thickness of layers considered as good material for foundation design and when present for large thickness can result in light WTG foundations.

- Figure 10-4 presents a map showing the depth below seabed to top of pre-quaternary material, namely unit U07. The map hence shows the depth to the layers which can result in special consideration of foundation design and installation is required.

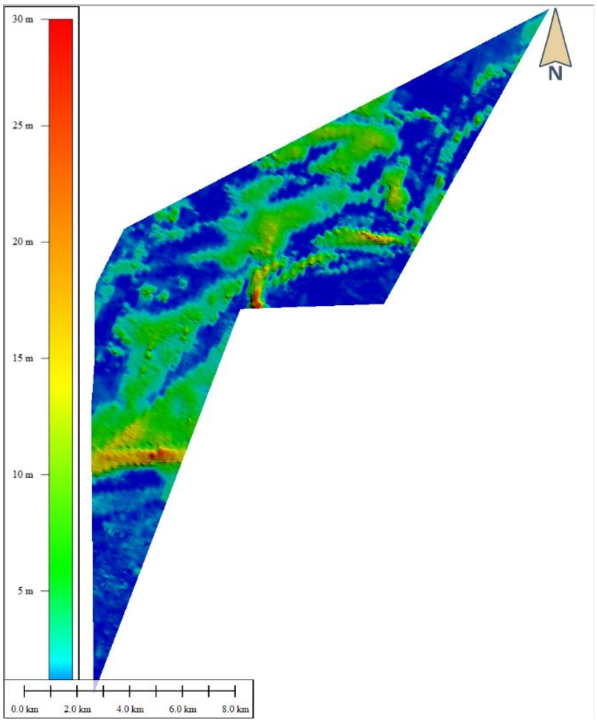


Figure 10-2 Combined thickness of soft sediments derived from units U01, U02, U03 and U04.

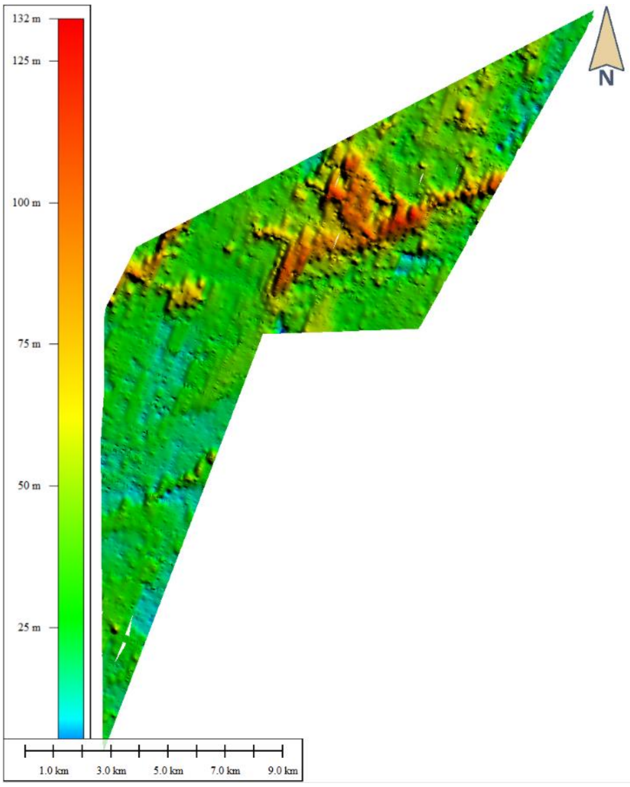


Figure 10-3 Combined thickness of competent glacial material, defined by unit U06.

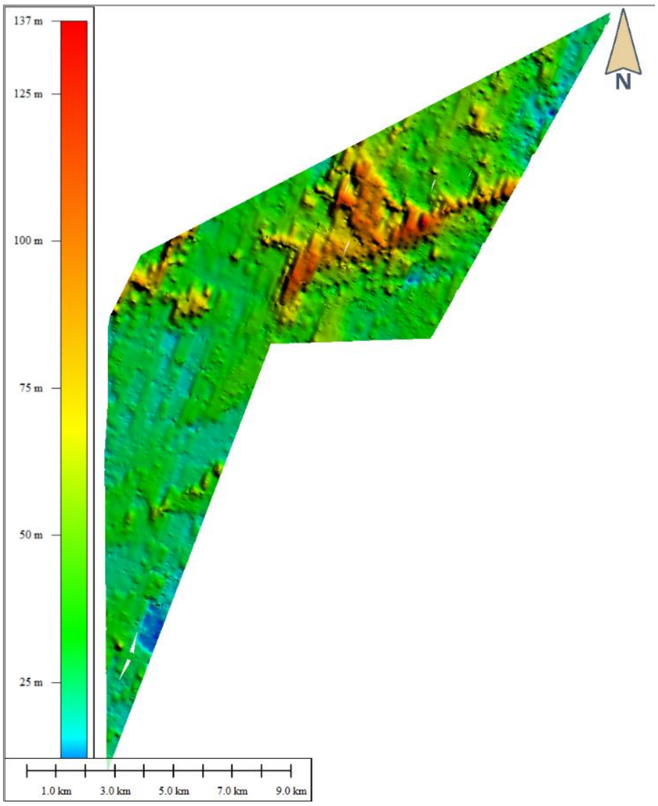


Figure 10-4 *Depth below seabed to top of pre-quaternary layers and deeper units defined as top of unit U07.*

It should be noted that bathymetry is not included as a parameter, as it is not represented directly by a soil unit. The channel areas and relative steep slopes (Enclosure 1.01) should be considered when considering the foundation design and installation methods. However, as illustrated clearly in the Conceptual Geological Model (see section 5) the Holocene and Late Weichselian soil unit distributions are related to the bathymetric features.

10.2 Variation of relevant layers and structures

Based on Figure 10-2 to Figure 10-4, the following criteria relevant for foundation design have been defined for the combined thickness of soft sediments defined from unit U01, U02, U03 and U04, and for the depth to top of pre-quaternary and deeper units. For simplification of the zonation, only criteria for accumulated thickness of soft sediments and depth to pre-quaternary material is considered, due to grouping of glacial thickness can be directly derived from the two other criteria (by not considering unit U05 which is assumed valid due to the low thickness of this unit across the site). The defined criteria are as follows:

- Combined thickness of soft sediments defined from unit U01, U02, U03 and U04 between 2 m and 8 m.
- Combined thickness of soft sediments defined from unit U01, U02, U03 and U04 greater than 8 m.

- Depth below seabed to top of pre-quaternary units between 25 m and 35 m.
- Depth below seabed to top of pre-quaternary units less than 25 m.

The above-mentioned criteria are in Figure 10-5 plotted on a map of the Kattegat OWF project site. This map is also provided as Enclosure 7.02.

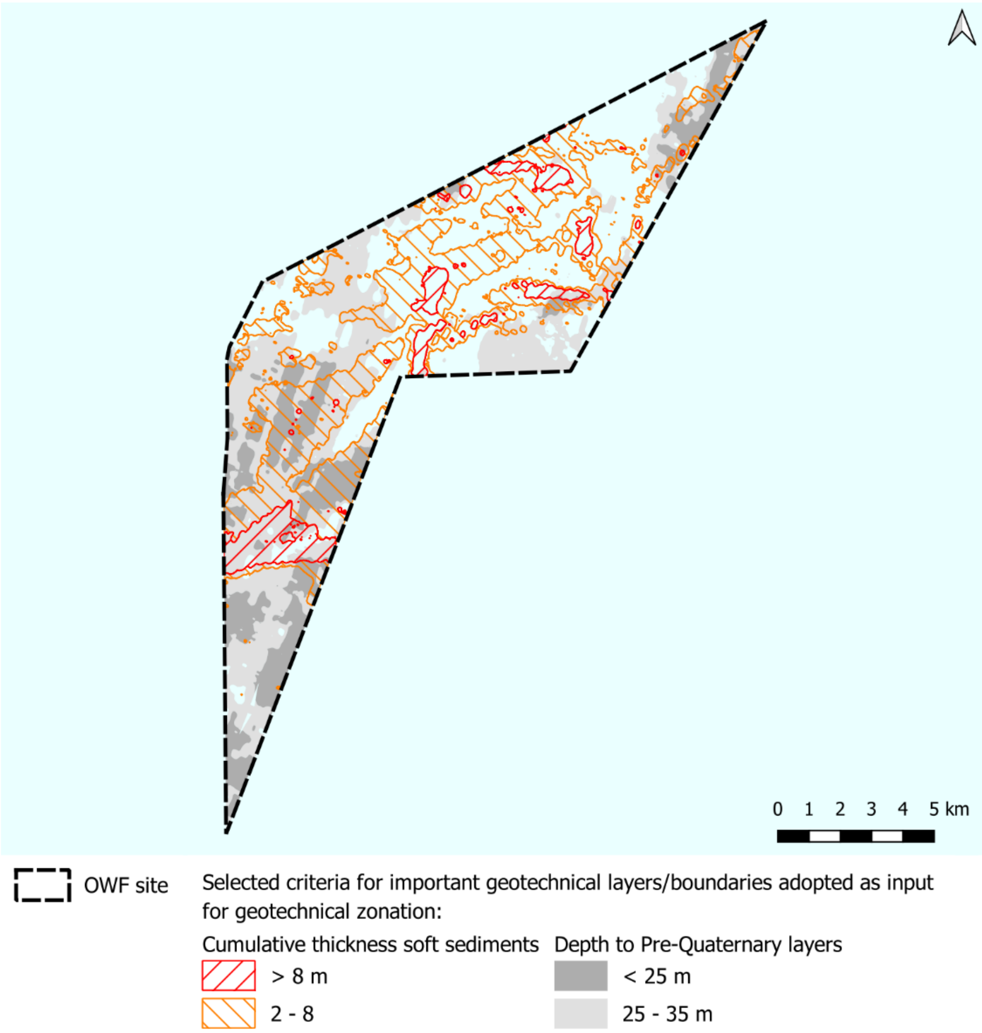


Figure 10-5 Map showing extent/variation across site of relevant layers and structures.

10.3 Geotechnical zones

Geotechnical zones have been established based on the content of Figure 10-5. The geotechnical zones represent a simplification of Figure 10-5 aiming to have a limited number of geotechnical zones. For the simplification the following has been considered:

- Due to the low combined thickness of soft sediments (U01, U02, U03 and U04) at large parts of the site, the lowest criterion considered have been selected as 2 m as values smaller than this is expected to be insignificant for design. The upper criterion of 8 m thickness is selected based on the variation across the site, and the clay is expected to have significant impact on design from larger values with expected high-level foundation geometries.

- Depth to top of pre-quaternary material is split from criteria of 25 m and 35 m due to installation risks associated with expected high-level foundation geometries.

Based on the above considerations eight (8) geotechnical zones have been defined, see Figure 10-6. Due to uncertainties in the seismic interpretation and the gridding, minor areas have been filtered out. In practice this means that all mapped elements smaller than 50.000 m² have been filtered out. This also results in a more comprehensible map. The geotechnical zonation map can also be seen on Enclosure 7.01.

Geotechnical zones I, II and III generally show good ground conditions for WTG foundation design and installation due to large thickness of competent glacial material, with the conditions being most competent for Geotechnical zone I. Geotechnical zones IV and V are categorised by medium ground conditions for WTG foundation design, which combined with depth to top of pre-quaternary material potentially can result in additional consideration for foundation installation and increased foundation cost. For Geotechnical zones VI, VII and VIII the thickest deposits of soft clay at the site are combined with low depths to pre-quaternary material resulting in a low thickness of glacial material. Thus, in these zones more expensive WTG foundations are expected to be required compared to other geotechnical zones.

The eight geotechnical zones can broadly be divided into two groups, where zone I to zone III is one group for which the distance to pre-quaternary layers is large, and zone IV to VIII is another group for which the distance to pre-Quaternary layers is less. For both groups it can generally be concluded that the zones with lower number are more favourable than the zones with higher number. It is however based on current available information not possible to conclude whether zones I to III are more or less favourable than zones IV to VIII. Zones IV to VIII all contain a potential installation risk as pile driving into pre-quaternary layers may be difficult or not possible. This installation risk is dependent on the foundation type adopted and on the properties of the pre-quaternary layers.

The characteristics of the geotechnical zones are described in detail in section 10.4 and a summary table is given in Table 10-8.

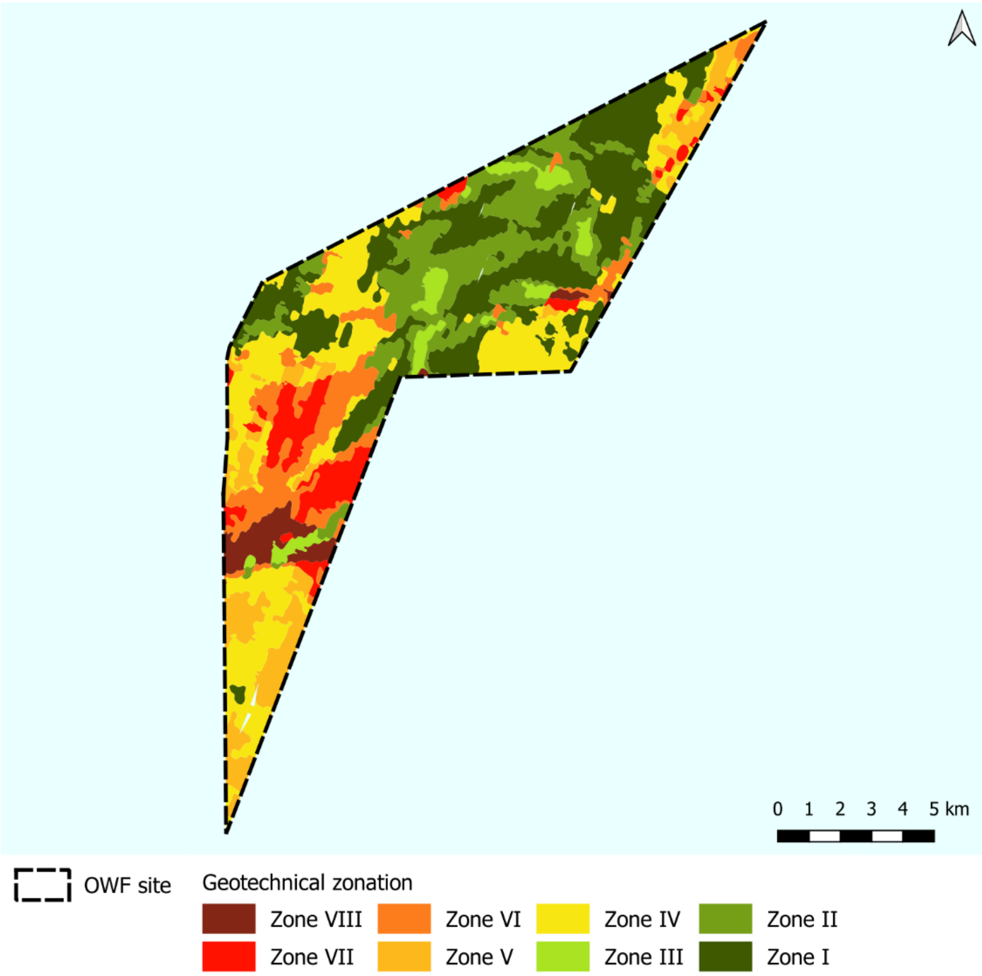


Figure 10-6 Geotechnical zonation. Overall good soil conditions feasible for OWF foundation design is found and the zonation illustrates variation in soil distribution expected to affect design and installation. Geotechnical zones I, II and III generally show good ground conditions due to large thickness of competent glacial material. Geotechnical zones IV and V are categorised by medium ground conditions for WTG foundation design. Geotechnical zones VI, VII and VIII are categorised with thickest deposits of soft clay at the site combined with low depths to pre-quaternary material.

10.4 Representative soil profile for each geotechnical zone

The eight (8) geotechnical zones are described in the following subsections, and further, representative soil profiles are presented. The representative profiles are selected based on geotechnical location tests present within each zone. It should be noted not all CPT tests are performed down to sufficient depth for presenting the trend which the geotechnical zone is categorising. Table 10-1 presents an overview of geotechnical locations within each of the defined geotechnical zones together with the percentage distribution between the established zones at the site. A summary of the following sections is found in section 10.4.9.

Table 10-1 Overview of geotechnical test locations within each geotechnical zone.

Geotechnical zone	Geotechnical locations within zone	Coverage [%]
I	KG_04, KG_06, KG_07, KG_09, KG_10, KG_14, KG_15, KG_20	26.6
II	KG_02, KG_05, KG_11, KG_13, KG_23	17.8
III	-	4.1
IV	KG_01, KG_12, KG_17	21.7
V	KG_21, KG_22, KG_25, KG_26	9.5
VI	-	10.4
VII	KG_19	6.5
VIII	KG_24	3.4

10.4.1 Geotechnical zone I

This zone is characterised by having less than 2 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located deeper than 35 m below seabed.

The representative profile for this zone is selected as KG_04 where the CPT profile is presented in Figure 10-7 and the stratigraphy in table format is presented in Table 10-2.

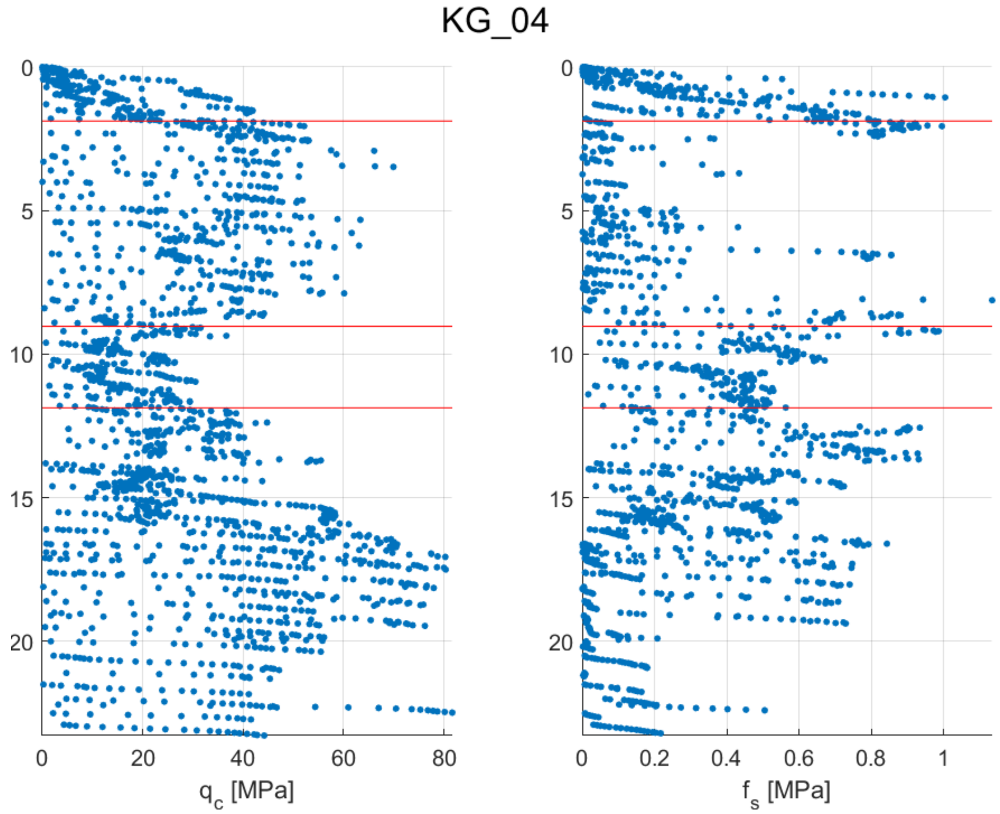


Figure 10-7 *q_c and f_s from CPT measurements for KG_04 found as representative for zone I. More information about the location can be found in Appendix A.*

Table 10-2 *Soil stratigraphy for KG_04 found as representative for zone I.*

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	1.9	UC06	Clay
2	1.9	9.0	US06	Sand
3	9.0	11.9	UC06	Clay
4	11.9	23.3	US06	Sand

10.4.2 Geotechnical zone II

This zone is characterised by having between 2 m and 8 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary layers being located deeper than 35 m below seabed.

The representative profile for this zone is selected as KG_13 where the CPT profile is presented in Figure 10-8 and the stratigraphy in table format is presented in Table 10-3.

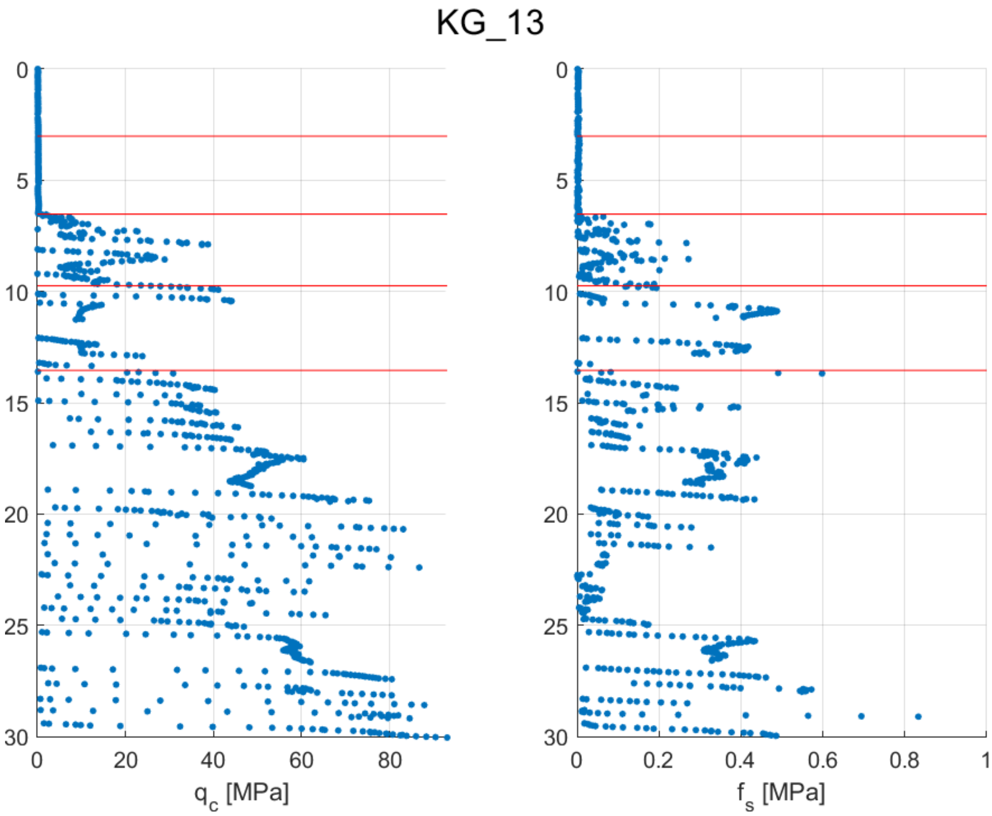


Figure 10-8 q_c *and* f_s *from CPT measurements for KG_13 found as representative for zone II. More information about the location can be found in Appendix A.*

Table 10-3 *Soil stratigraphy for KG_13 found as representative for zone II.*

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	3.0	UC01	Clay
2	3.0	6.5	UC02	Clay
3	6.5	9.7	US05	Sand
4	9.7	13.5	UC06	Clay
5	13.5	30.0	US06	Sand

10.4.3 Geotechnical zone III

This zone is characterised by having more than 8 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located deeper than 35 m below seabed.

None of the geotechnical test locations performed within the site is located within this zone, hence no representative CPT is selected for the geotechnical zone.

10.4.4 Geotechnical zone IV

This zone is characterised by having less than 2 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located between 25 m and 35 m below seabed.

The representative profile for this zone is selected as KG_12 where the CPT profile is presented in Figure 10-9 and the stratigraphy in table format is presented in Table 10-4.

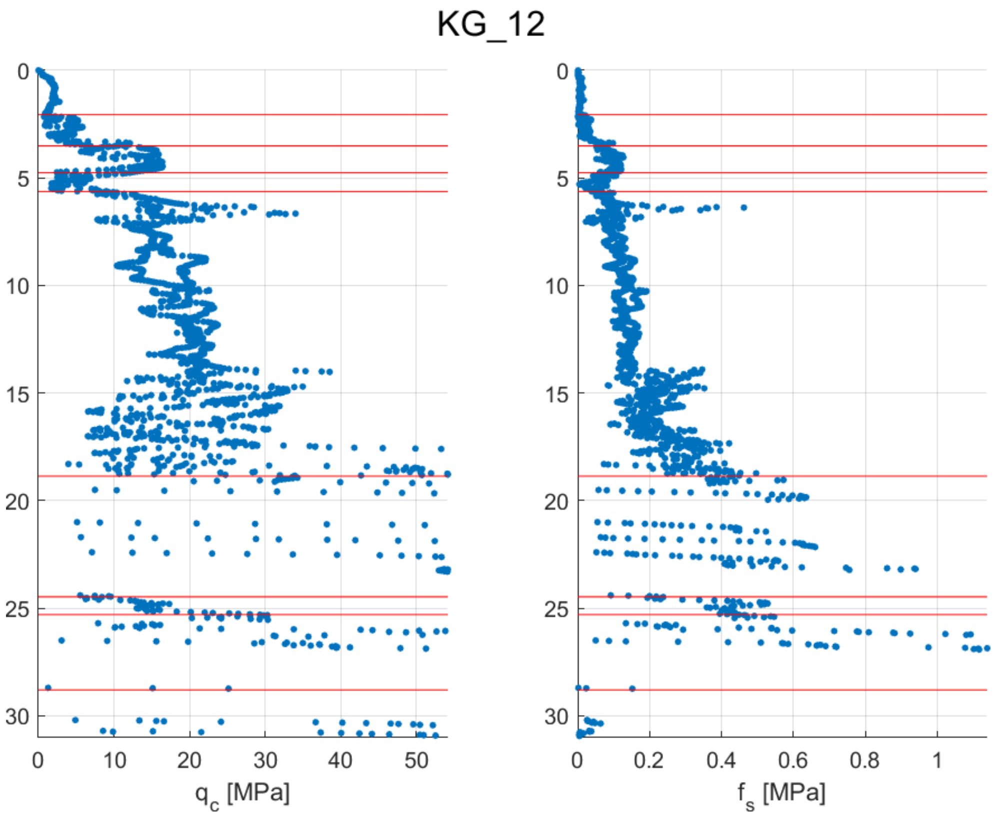


Figure 10-9 q_c and f_s from CPT measurements for KG_12 found as representative for zone IV. More information about the location can be found in Appendix A.

Table 10-4 Soil stratigraphy for KG_12 found as representative for zone IV.

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	2.1	UC01	Clay
2	2.1	3.5	US06	Sand
3	3.5	4.8	US06	Sand
4	4.8	5.6	US06	Sand
5	5.6	18.9	US06	Sand
6	18.9	24.5	US06	Sand
7	24.5	25.3	UC06	Clay
8	25.3	28.8	US06	Sand
9	28.8	31.0	UC07	Chalk

10.4.5 Geotechnical zone V

This zone is characterised by having less than 2 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located less than 25 m below seabed. The lowest depth of the pre-quaternary layer within the geotechnical zone is found to be 9 m below seabed.

The representative profile for this zone is selected as KG_21 where the CPT profile is presented in Figure 10-10 and the stratigraphy in table format is presented in Table 10-5.

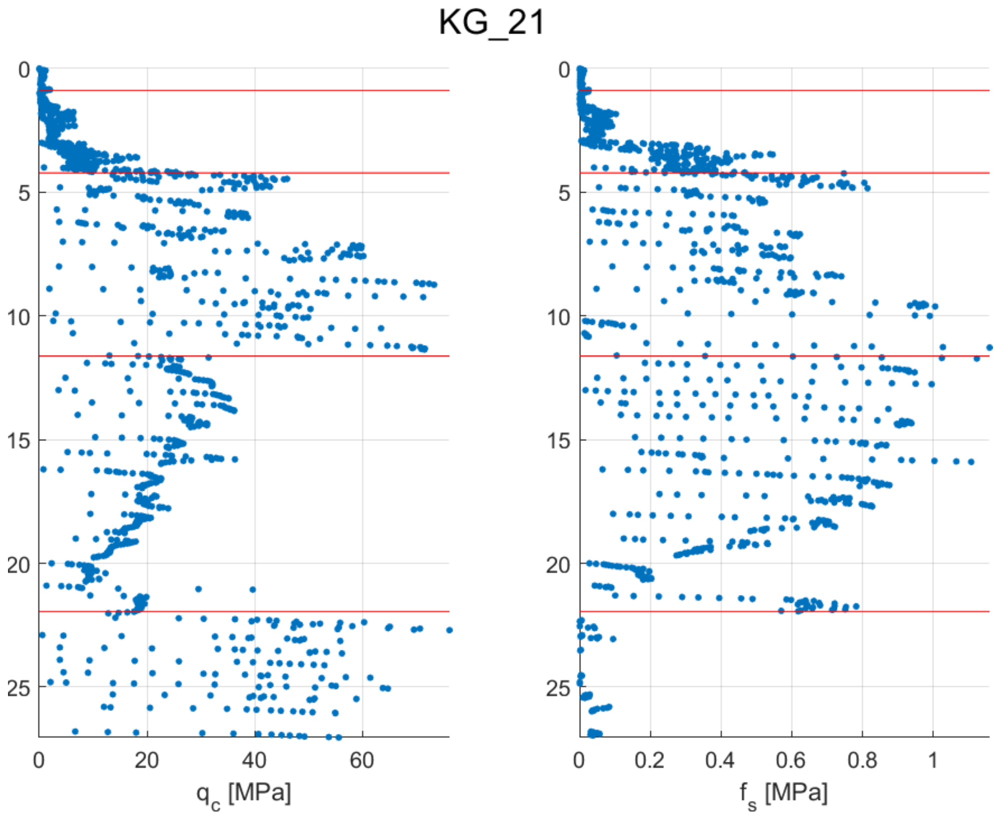


Figure 10-10 *q_c and f_s from CPT measurements for KG_21 found as representative for zone V. More information about the location can be found in Appendix A.*

Table 10-5 *Soil stratigraphy for KG_21 found as representative for zone V.*

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	0.9	US01	Sand
2	0.9	4.2	UC06	Clay
3	4.2	11.6	US06	Sand
4	11.6	22.0	UC06	Clay
5	22.0	27.0	UC07	Chalk

10.4.6 Geotechnical zone VI

This zone is characterised by having between 2 m and 8 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located between 25 m and 35 m below seabed.

None of the geotechnical test locations performed within the site is located within this zone, hence no representative CPT is selected for the geotechnical zone.

10.4.7 Geotechnical zone VII

This zone is characterised by having between 2 m and 8 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located less than 25 m below seabed. The lowest depth of the pre-quaternary layer within the geotechnical zone is found to be 15 m below seabed.

The representative profile for this zone is selected as KG_19 where the CPT profile is presented in Figure 10-11 and the stratigraphy in table format is presented in Table 10-6.

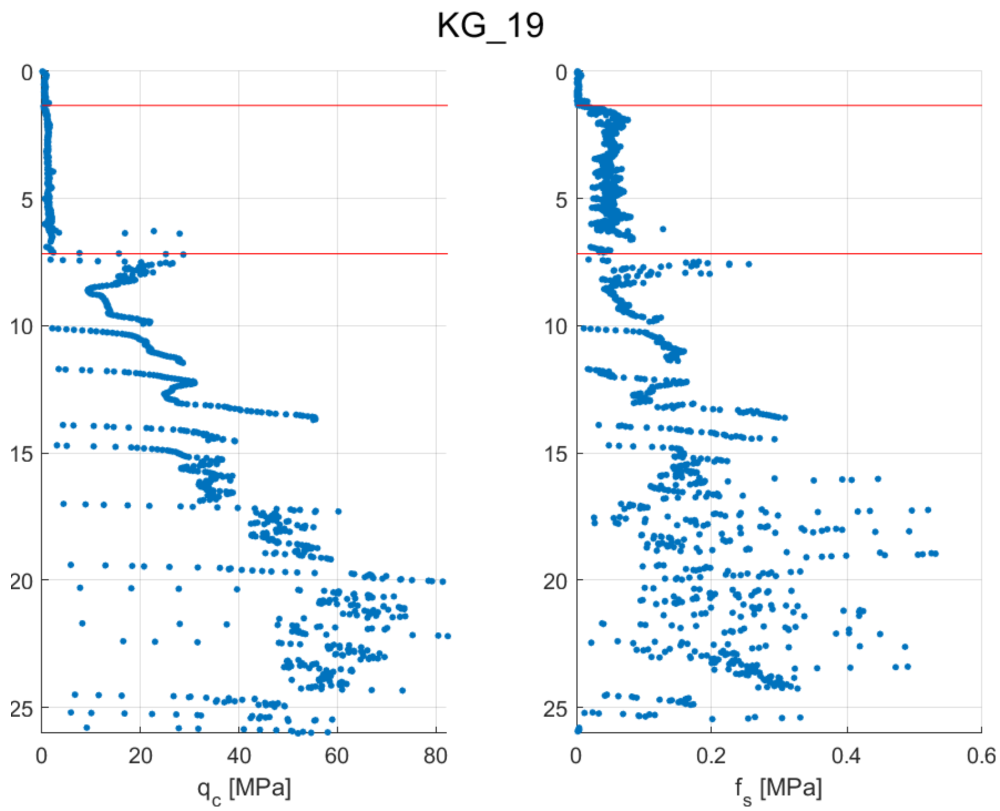


Figure 10-11 *q_c and f_s from CPT measurements for KG_19 found as representative for zone VII. More information about the location can be found in Appendix A.*

Table 10-6 *Soil stratigraphy for KG_19 found as representative for zone VII.*

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	1.3	UC01	Clay
2	1.3	7.2	UC03	Clay
3	7.2	26.0	US06	Sand

10.4.8 Geotechnical zone VIII

This zone is characterised by having more than 8 m of cumulative thickness of soft sediments (unit U01, U02, U03 and U04) and the top of pre-quaternary material being located less than 35 m below seabed. The lowest depth of the pre-quaternary layer within the geotechnical zone is found to be 20 m below seabed.

The representative profile for this zone is selected as KG_24 where the CPT profile is presented in Figure 10-12 and the stratigraphy in table format is presented in Table 10-7.

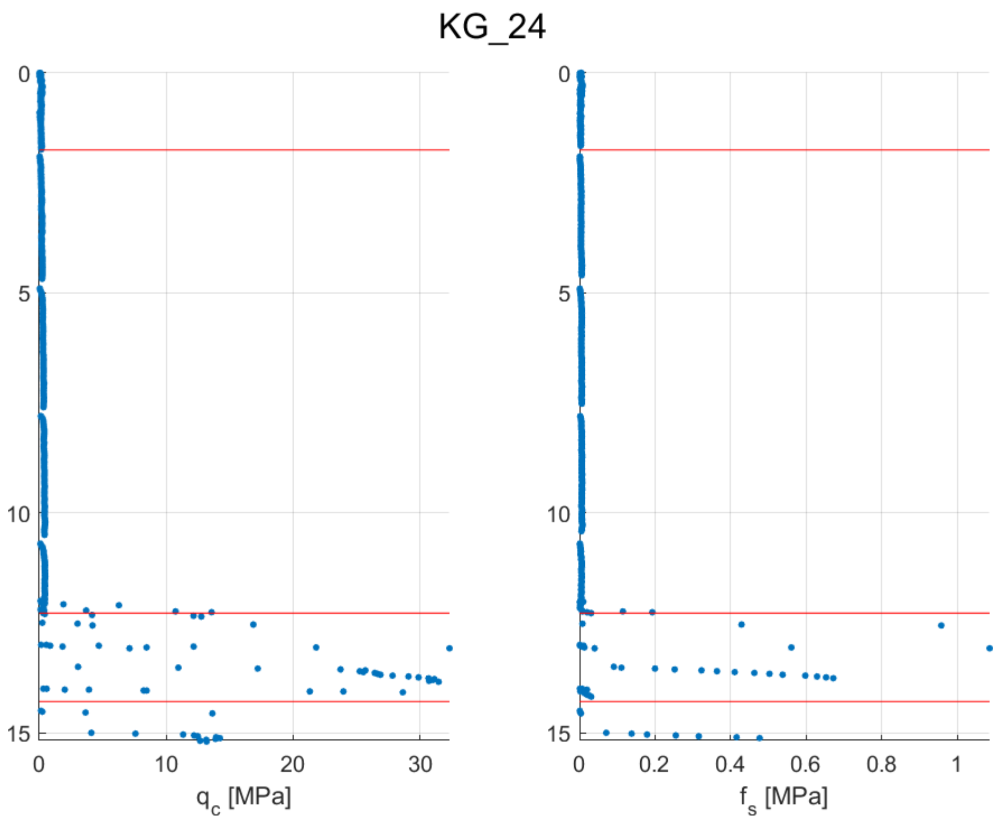


Figure 10-12 q_c *and* f_s *from CPT measurements for KG_24 found as representative for zone VIII. More information about the location can be found in Appendix A.*

Table 10-7 *Soil stratigraphy for KG_24 found as representative for zone VIII.*

Layer	Top [m]	Bottom [m]	Unit	Geotechnical material
1	0.0	1.8	UC01	Clay
2	1.8	12.3	UC02	Clay
3	12.3	14.3	US06	Sand
4	14.3	15.2	UC06	Clay

10.4.9 Summary

Based on the previous sections per geotechnical zone, a summary of the geotechnical zonation can be found in Table 10-8.

Table 10-8 Summary of geotechnical zonation.

Geotechnical zone	Representative location	Description
I	KG_04	Cumulative thickness soft sediments < 2 m Depth to Pre-Quaternary layers > 35 m
II	KG_13	Cumulative thickness soft sediments 2 m – 8 m Depth to Pre-Quaternary layers > 35 m
III	-	Cumulative thickness soft sediments > 8 m Depth to Pre-Quaternary layers > 35 m
IV	KG_12	Cumulative thickness soft sediments < 2 m Depth to Pre-Quaternary layers 25 m – 35 m
V	KG_21	Cumulative thickness soft sediments < 2 m Depth to Pre-Quaternary layers < 25 m
VI	-	Cumulative thickness soft sediments 2 m – 8 m Depth to Pre-Quaternary layers 25 m – 35 m
VII	KG_19	Cumulative thickness soft sediments 2 m – 8 m Depth to Pre-Quaternary layers < 25 m
VIII	KG_24	Cumulative thickness soft sediments > 8 m Depth to Pre-Quaternary layers < 35 m

11 Leg penetration analysis

This section describes a high-level leg penetration risk assessment. The assessment is performed to provide an indication of potential geotechnical risks associated with jack-up operations at the Kattegat OWF project site.

The assessment is intended to provide an overview of the potential behaviour of two selected generic vessel configurations, which can inform on potential jack-up risks during the next project phases and provide a basic understanding of how the risks vary from different vessel configurations across the site.

In general, a leg penetration analysis performed at an offshore wind farm site, can help in:

- determining whether a jack-up is suitable for operating at a site or not,
- knowing what leg penetration behaviour and risks to anticipate,
- identifying and being able to mitigate possible geotechnical hazards.

Furthermore, leg penetration analysis is part of site-specific assessment that needs to be performed for all offshore wind farm sites once the project has matured further.

11.1 Selection of vessels

To provide a range of possibilities in terms of leg penetration behaviour and a good basic understanding of jack-up operations at the Kattegat OWF project site, two different vessel configurations have been selected for the current study.

To select the appropriate vessel configurations, experience from previous leg penetration analyses (performed by COWI) has been used as database. The specifications of the vessels considered are confidential, however the vessels are selected to provide insight into the possible range of penetration behaviours, where the limits of the range roughly correspond to a generic installation vessel and a generic operation and maintenance (O&M) vessel. The range of penetration behaviour was deduced from several leg penetration analyses for representative soil conditions at the Kattegat OWF project site.

The first vessel (further denoted Generic Installation Vessel) is a four-legged vessel, equipped with a large spudcan and a maximum preload of 105 MN, whereas the second vessel (further denoted Generic O&M Vessel) is a four-legged vessel, equipped with a smaller spudcan and a maximum preload of 7 MN.

The foundation pressure applied to the seabed is dependent on the spudcan area and geometry, which is confidential. The ratio of foundation pressure between the Generic Installation Vessel and the Generic O&M Vessel is around a factor 2.

The final decision on the type of vessel to be adopted for the Kattegat OWF project site is expected to consider a multitude of factors, including:

- vessel suppliers tendering for the installation/maintenance work,
- type of foundation solution,
- crane capacity, incl. lifting height and (horizontal) reach,
- deck size and capacity regarding planned operations, e.g., how many installation units can be stored at once,
- amount and complexity of structural adjustments to be made to adopt vessel to planned operations,
- available leg length for soil penetration depth based on expected water depth and required air gap at site,
- speed, capacity, and size of the vessel,
- distance to the port,
- installation method, etc.

These are only a few of the factors that should be considered when selecting a certain jack-up vessel for installation works. All of them contribute to the final cost (and required duration) of the installation and should therefore be given special attention.

11.2 Geotechnical risks during jack-up

The main geotechnical risks that can be encountered during jack-up operations at an offshore wind site will be elaborated in the following subsections, cf. Ref. /11/. These are intended to give a high-level understanding of the spudcan behaviour and potential effects on the operations and how these effects may generally be handled or mitigated. During operations it is the responsibility of the owners, operators, and crew on jack-ups to exercise sound judgement based on their education, training and experience, while taking into account the leg penetration assessments provided, including related recommendations.

The term "preloading" should be well understood before discussing the risks. Preloading is defined by the installation of the spudcans by vertical loading of the soil beneath a jack-up leg spudcan with the objective of ensuring sufficient foundation capacity under assessment situations through to the time when the maximum load is applied and held. In general preloading shall be carried out corresponding to at least 1.5 times the actual maximum load during operations.

It is to be noted that the terms that describe the risk types used in this report might differ from the terms presented in various literature, therefore the description of the risks, failure mechanisms and particularities are more important than the actual terms. To highlight the most important characteristics of each of the risks, these have been gathered in Table 11-1.

Table 11-1 Overview of main characteristics of the geotechnical risks during jack-up.

Risk	Description	Circumstance	Effect	Observation	Consequence
Leg scour	Formation of local scour hole around spudcan	Cohesionless soil at seabed	Loss/reduction of soil bearing capacity	To be monitored continuously	Small [1)]
Squeezing	Thin and soft soil layer is squeezed horizontally	Thin, soft layer in between strong/stiff layers	Controllable leg settlements during initial preloading operations	Controllable penetration rate	Small
Fast leg penetration	Leg footing penetrates rapidly through strong layer and down to a soft layer	Thicker, soft layer below a strong/stiff layer	Structural damage, stability issues, personnel safety	Occurs during preloading before reaching maximum preload	Medium
Punch through	Leg footing penetrates rapidly through strong layer and down to a soft layer	Thicker, soft layer below a strong/stiff layer	Structural damage, significant stability issues, personnel safety	Occurs during operations after reaching maximum preload	High
Deep penetration	Leg has insufficient length to reach a stable penetration level	Penetration depth larger than available leg length	Non-operational, Lack of stability, risk for adjacent structures	To be mitigated before operations start	High
Difficulties during leg extraction	High resistance when attempting to extract legs after operations	Large suction below spudcan and large weight of soil above spudcan (can be caused by deep penetration in soft soils)	Operational downtime, structural damage, soil alteration at the location due to mitigation measures	To be mitigated before operations start	High

1) *Consequence is generally small when (initial phase of) operations consider scour adequately but can be large when scour occurs (very) fast or when their circumstance exists in combination with a soil stratigraphy where scour can result in a later risk of punch through, and insufficient attention should have been paid to the (possible) existence of these circumstances. Scour is dependent on the current velocity (at seabed), and this could consequently be larger at a later moment in time than during the preloading phase.*

Further to Table 11-1, other risks for jack-up assessment can be mentioned from seabed conditions as an effect from large seabed slopes, previous jack-up footprints and boulders, or deterioration of soil stiffness and strength from previous jack-up at the location. However, these are not considered for the categorisation of jack-up risks in the performed analyses, hence no further considerations of these have been performed.

11.2.1 Leg scour

Under certain flow and seabed conditions, seabed erosion may occur when temporarily introducing spudcans and/or jack-up legs. The presence of a spudcan/leg will cause the water flow in its vicinity to change. This local change in the flow will cause an increase in the sediment transport capacity on the seabed close to the structure, which can lead to the formation of a local scour hole.

When scour occurs the maximum bearing capacity of the soil beneath the spudcan will decrease due to loss of supporting soil. If the bearing capacity drops to a level below the footing load, additional penetration will occur.

Furthermore, scour may cause the spudcan to be loaded eccentrically and exert a corresponding load and bending moment on the spudcan and leg.

Relevant scour typically occurs when one or more of the situations below are encountered:

- shallow water depths at jack-up locations,
- (very) shallow spudcan penetrations into seabed,
- cohesionless soil at seabed level.

Some of the most common mitigation measures are:

- if possible, planning of operations for periods when current velocities are lowest and during benign weather,
- monitor scour during operations and take actions in accordance with observations,
- for operations with long durations, scour protection such as gravel beds, prefabricated mattresses and front mats can be used,
- excavation to obtain larger initial penetration.

11.2.2 Squeezing

The potential for squeezing is present when a relative thin and soft layer is sandwiched between the leg footing and a harder layer or when the thin, soft layer is present between two stronger layers. The thin soil layer can in such cases squeeze laterally between the hard layers, when the vertical stress on this layer is large enough and occurs over sufficiently large finite area.

Ref. /12/ presents two criteria to be used to make an initial check for a possible risk of squeezing, see equations and figure below. If both geometrical criteria are satisfied, there is a potential risk of squeezing.

$$B > 3.45\,T$$

$$\frac{D}{B} \leq 2.5$$

B is the width of the spudcan,

T is the thickness of the soft layer,

D is the thickness of the soil above the soft layer.

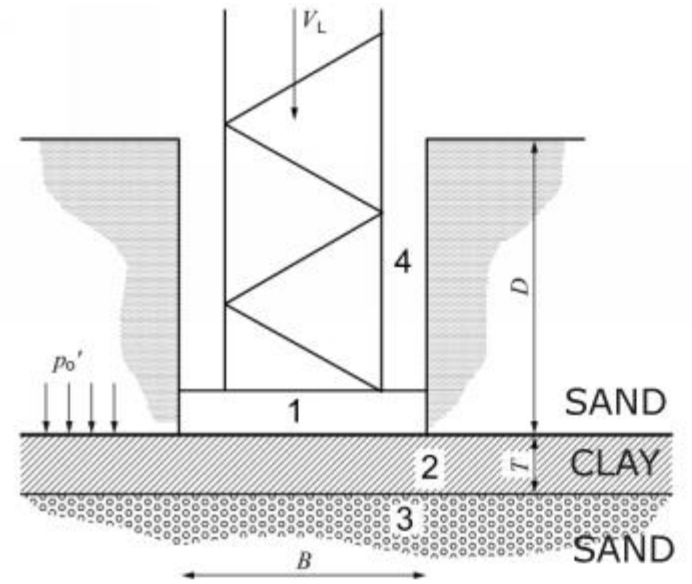


Figure 11-1 Sketch illustrating relevant parameters regarding squeezing, Ref. /12/.

It is important to note, however, that an actual risk of squeezing will only be present if the strength of the soft layer is insufficient relative to the vertical stress to be imposed on it. The difference in strength of the two materials (strong vs soft) should therefore be considered on top of the criteria shown above, which only relate to the geometry of the spudcan and soil situation.

The risk of squeezing generally leads to controllable leg settlements occurring during initial preloading operations. Therefore, most of the times no measures are taken to mitigate it.

11.2.3 Fast leg penetration

Fast leg penetration occurs in circumstances where a leg footing is temporarily supported by a stronger layer of soil that overlies a weaker layer and where the vertical footing load, as it is increased up to the preload, subsequently exceeds the bearing capacity of the soil, allowing the leg to penetrate rapidly through the stronger upper layer into the layer below.

In principle this is a punch through, see section 11.2.4, but as it occurs at a load level below the preload, the situation can be managed and is thus generally only referred to as fast (or rapid) leg penetration.

In such circumstances the upper soil layer may for instance be sand or stiff clay overlying soft clay. This type of failure is different to a squeezing failure described in section 11.2.2, as in this case the soil mass fails through large continuous soil failure surfaces rather than by many small internal soil shear failures within the weaker layer, which (only) cause the soil of the weaker layer to displace laterally. The penetration rates for squeezing are usually more controllable than penetration rates for fast leg penetration.

As the risk of fast leg penetration is defined to occur during preloading, it is important to make sure close and continuous monitoring is performed according to standards and the preloading is performed without jacking up completely out of the water (with zero air gap), such that in case a leg experiences fast/larger penetration than the others, the situation can be handled and the vessel will not tilt more than the allowable limit.

11.2.4 Punch through

The failure mechanism of punch through is the same as described above for fast leg penetration and occurs in circumstances where a leg footing has become temporarily supported by a stronger layer of soil that overlies a weaker layer, and where the vertical footing load, as it is increased, subsequently exceeds the foundation bearing capacity allowing the footing to penetrate rapidly through the upper layer into the layer below.

The main difference between fast leg penetration and punch through is that the former is defined as occurring before reaching the maximum preload, therefore occurring during close and continuous monitoring and with zero air gap, whereas the latter describes the potential occurrence of the same phenomenon, but after preloading (when the jack-up has an air gap), this making it (more/very) dangerous for the operations, possibly resulting in significant tilting of the jack-up with all related consequences. Because they are described by the same failure mechanism, sometimes both types of risk are referred to as "rapid penetration".

Depending on the local soil conditions in terms of stratigraphy and strength of materials, it is sometimes difficult to predict which of the two types of risks (fast leg penetration and punch through) is expected at a certain location. Conducting a leg penetration analysis using a range of parameters usually helps in identifying the expected risk, provided that the soil data is reliable.

The quality of soil data is therefore one of the most important factors in estimating the penetration behaviour that will occur during jack-up operations.

When the soil conditions show a significant reduction in soil strength with penetration depth, then there is a potential for punch through to occur. However, Ref. /13/ suggests several procedures to mitigate punch through:

- carry out a detailed soil survey at the Kattegat OWF project site,

- if spudcan data from previous penetrations at the location is available, use this to back analyse and confirm the prediction methods for bearing capacity,

- ensure procedures for reducing the spudcan loads during the potential punch through phases, including the use of buoyancy (preload in water) and zero air gap (prevent vertical displacement using buoyancy of the hull) and preloading of one leg at a time,

- consider the use of jetting system (if available) to penetrate the harder soils.

To conclude, an important observation provided in Ref. /13/ states that "*Whereas mitigation techniques exist to allow for the possibility of punch-through during the installation phase, there is none for the in-service condition. It is vital, therefore, that soil data is assessed carefully, and that actual penetration behaviour is used to verify predicted behaviour.*"

Therefore, reliable soil data is the most important factor in estimation and mitigation of potential risk of punch through.

11.2.5 Deep penetration

The risk of deep penetration exists when the leg penetration is larger than the available leg length of the jack up vessel.

Deep penetration occurs when the soil conditions are so soft, that they do not provide sufficient bearing capacity to reach the maximum preloading. This means that there is no available leg length left, but the leg has not reached a stable penetration level.

It is important to highlight situations in which the leg length of the vessel to be used may not be sufficient, as there will then generally be the need to employ a different vessel at the specific location/site. However, in some cases the selection of another vessel can be avoided. This is the case when there is the possibility to operate at a given location with smaller operational loads than considered for the initial assessment and these loads, and the related preloads, lead to less and feasible leg penetrations.

Deep penetration may also pose a potential risk for adjacent structures.

11.2.6 Difficulties during leg extraction

The process of extracting the legs after operations at a certain location might sometime prove to be difficult and it is important to include this in the risk overview, such that the right measures are taken beforehand.

When extracting a leg and spudcan from a deep penetration in clay, the weight of the leg and the soil above the spudcan is to be overcome, together with the mobilised friction in the soil above the spudcan, and the suction below the spudcan. When the spudcan is in low permeable clay, the water cannot run freely to the bottom of the spudcan during extraction.

This implies that no equalising water pressure can develop below the spudcan during spudcan extraction. Thus, a resulting suction is developed below the spudcan, acting downwards, counteracting the retraction process.

According to Ref. /12/, leg extraction difficulties can be caused by conditions including the following:

- deeply penetrated spudcan in soft clay or loose silt,

- skirted or caisson-type spudcan where uplift resistance can be greater than the installation reaction,

- sites where the soil exhibits increased strength with time (this of course depends on the duration of the operations).

Ref. /12/ suggests jetting and/or excavation of the surface soils as mitigation measures against difficulties during leg extraction. A remark is added regarding soil alteration at the location due to these mitigation measures, which can affect future emplacement of jack-ups at the specific site. Another mitigation measure to prevent difficulties during leg extraction can be performance of stomping movement to reduce the suction underneath the spudcan.

It should be noted difficulties during leg extraction can occur only by the suction created from the bottom of the spudcan getting in contact with clay, if the generated suction is strong enough. The performed analyses do not consider the suction from bottom of spudcan in clay causing retraction difficulties alone. Hence, high penetration depth in clay is required for the risk of difficulties during leg extraction being considered.

11.3 Risk categories across the Kattegat OWF project site

At the Kattegat OWF project site, 22 unique soil investigation locations have been grouped into four different categories. For each of the categories, the primary geotechnical risks are defined and a graphical representation of all the locations and their corresponding category is presented in Enclosure 7.03 and 7.04 considering the Generic Installation Vessel and the Generic O&M Vessel, respectively. In addition to the individual location specific assessments, a risk categorisation of the site based on the integrated ground model and same criteria as for the location specific assessment is performed to split the site into zones representing the jack-up assessment risks, which is also presented in Enclosure 7.03 and 7.04.

It is important to acknowledge that the assessment presented here, and the associated evaluation of the geotechnical risk(s) is based on local soil data for the location specific categorisation, and cautious assumptions for the zonation of the site. Hence, the outcome from the location specific assessments should be seen as the most representative as these applies to specific conditions at the location, while the zonation across the site is based on global trends for the units present at the site which potentially can be found different in case a geotechnical test is performed and different design soil profiles is found representative.

When estimating the risk(s) at each location during this categorisation process, the CPT results and borehole logs have been considered, together with the soil strength of the layers which is derived based on CPT results as outlined in chapter 7 and 8. The strength of sand layers is characterized by friction angle and the strength of clay layers by the undrained shear strength.

To categorize the geotechnical locations, the following factors have been considered:

- Stratigraphy at each location, based on CPT results and borehole data. For categorization purposes, only the first 30 meters starting from the seabed have been considered, as the influence on the penetration behaviour for larger depths is considered negligible in relation to the currently assumed vessel configurations and spudcan geometries.

- The strength properties used for the assessment requires a constant value per layer. For estimating this, the required strength parameters for sand and clay are determined from the average of the value when disregarding the lowest and highest 10% of the data within the considered layer for removing small outliers. The derived strength profiles considered for the assessment are presented in Appendix H.

- Penetration risk analysis was performed following ISO guidelines, as per Ref. /14/.

In Table 11-2 below, a summary of the four categories across the Kattegat OWF project site when considering operations with both vessels, including their description and corresponding risks, is presented. It must be noted the outcome from a leg penetration analysis is dependent on the combination of stratigraphy, layer thicknesses, strength properties, vessel configurations etc. Hence, generic values for presented criteria in Table 11-2 are based on sensitivity analyses, COWI experience and assumptions with slightly conservatism included.

For dividing the Kattegat OWF project site into different zones representing the different risk categories for jack-up assessment, the same criteria from Table

11-2 is considered to define a risk associated to each of the ground model units. Thicknesses and depths of layers presenting a risk across the site is evaluated from the integrated ground model, while the geotechnical clay layers presenting a risk based on the strength is evaluated from derived undrained shear strength values in section 8.3.2 and presented in Appendix D.4. A list of the ground model units and description of their consideration in the leg penetration zonation is listed in Table 11-3. It should be noted the layers marked with risks in Table 11-3 need to fulfil the criteria in Table 11-2 for being categorised with a risk in the leg penetration zonation.

Table 11-2 Summary table presenting categories and corresponding potential risks.

Category	Description	Potential risk(s)
1	Category 1 comprises locations where in the first 30 meters below the seabed, where mainly sand and/or very competent silt/clay layers are encountered. For locations where soft clay layers are present, the criteria presented for category 2 to 4 are not fulfilled. › If sand is encountered at seabed level, there might be a risk of scour.	› Leg scour
2	Category 2 comprises locations where in the first 30 meters below the seabed only sand is encountered, except for an interbedded thin clay layer, which presents the potential for squeezing. › If sand is encountered at seabed level, there might be a risk of scour. According to Ref. /12/ and considering the spudcan geometry of both vessels, the following criteria has been applied in order to select locations within Category 2: › Thickness of clay layer to be: › < 3.2 m (Generic Installation Vessel), › < 1.0 m (Generic O&M Vessel). › Top of clay layer to be: › ≤ 27.6 m depth (Generic Installation Vessel), › ≤ 8.7 m depth (Generic O&M Vessel). The formula given in Ref. /12/ is not dependent on the strength of clay layer. In the current assessment it was however considered relevant to consider that only a clay layer with a corresponding conservative c_u as per below has the potential of squeezing (1): › < 350 kPa (Generic Installation Vessel) › < 200 kPa (Generic O&M Vessel)	› Leg scour › Squeezing
3	Category 3 comprises location where in the first 30 meters below the seabed thick clay layer is present but no sand layer with sufficient thickness overlies. › If sand is encountered at seabed level, there might be a risk of scour. To select locations within Category 3, the following criteria has been applied: › Depth of soft clay layer base to be (2): › > 20.0 m (Generic Installation Vessel),	› Leg scour › Deep penetration › Difficulties during leg extraction

Category	Description	Potential risk(s)
	› > 10.0 m (Generic O&M Vessel). › Strength of clay layer c_u (1): › < 175 kPa (Generic Installation Vessel), › < 100 kPa (Generic O&M Vessel). › Thickness of potential interbedded sand layer(s) (for the sand layer not being able to create punch through or fast leg penetration) (1): › < 1.0 m (Generic Installation Vessel), › < 0.5 m (Generic O&M Vessel). In the event of deep penetration occurring, the spudcan can penetrate deep into clay layer, thus leading to potential retraction difficulties, due to suction below spudcan and weight of soil above spudcan.	
4	Category 4 comprises locations where in the first 30 meters below the seabed, sand is encountered and overlies a thick clay layer, which presents potential for rapid penetration, i.e., the risk of fast leg penetration (if rapid penetration occurs during preloading) or punch through (if rapid penetration occurs during operations). › If sand is encountered at seabed level, there might be a risk of scour. To select locations within Category 4, the following criteria has been applied: › Thickness of clay layer to be (in order not to consider squeezing): › > 3.2 m (Generic Installation Vessel), › > 1.0 m (Generic O&M Vessel). › Strength of clay layer c_u (1): › < 175 kPa (Generic Installation Vessel), › < 100 kPa (Generic O&M Vessel). › Thickness of overlying sand layer (for the sand layer being able to affect the spudcan behaviour) (1): › > 1.0 m (Generic Installation Vessel), › > 0.5 m (Generic O&M Vessel). In the event of fast leg penetration or punch through occurring, the spudcan can penetrate deep into clay layer, thus leading to potential retraction difficulties, due to suction below spudcan and weight of soil above spudcan.	› Leg scour › Fast leg penetration › Punch through › Deep penetration › Difficulties during leg extraction

(1) Value derived from sensitivity analysis of parameter.

(2) Deep penetration depends on the combined thickness of water depth, soil penetration and required air gap for vessel during jack-up operation compared to the available leg length from vessel. Due to the available leg length for soil penetration is site dependent and vessel dependent, a generic value is estimated for the performed assessment.

Table 11-3 Overview of integrated ground model unit risk consideration for jack-up assessments.

Ground model unit	Unit description	Generic Installation Vessel	Generic O&M Vessel
U01	Very low strength clay with parts being sand.	No sand overlying layer, hence only risk from category 3 is possible.	No sand overlying layer, hence only risk from category 3 is possible.
U02	Very low strength clay.	No sand overlying layer, hence only risk from category 3 is possible.	No sand overlying layer, hence only risk from category 3 is possible.
U03	Very low strength clay with parts being sand.	No sand overlying layer, hence only risk from category 3 is possible.	No sand overlying layer, hence only risk from category 3 is possible.
U04	Clay layer with expected low strength.	No sand overlying layer, hence only risk from category 3 is possible.	No sand overlying layer, hence only risk from category 3 is possible.
U05	Categorised as sand layer, not considered posing a risk.	-	-
U06	Categorised as mainly sand layer with parts interpreted as high-strength clay layer, not considered posing a risk.	-	-
U07	Pre-quaternary material interpreted as high strength, not considered posing a risk.	-	-

Considering that operations at the offshore wind site are performed with either one of the vessels selected in the study, the outcome of the analyses and the final categorisation per geotechnical location and risk zonation are shown in Figure 11-2 and Figure 11-3. These figures are presented in larger format in Enclosure 7.03 and 7.04, respectively. It is observed that the categorisation based on the integrated ground model does not match well with the categorisation based on local geotechnical investigation data. The explanation for the poor match between geotechnical location analyses and the ground model analyses for both generic vessels is the leg penetration risk assessment is sensitive to the local stratigraphy and the presence and thickness of sand layers above soft clay layers. This is partly seen from the ground model not being capable of capturing the interbedded sand layers in the top clay units but mainly due to the ground model can’t capture the differentiation of soil material within the glacial U06 unit, hence all of unit U06 is considered as a sand in the ground model analyses, as defined in Table 11-3.

Comparison of the location specific results of the leg penetration analysis shown on Enclosures 7.03 and 7.04 with the zonation presented in Figure 10-6 (and Enclosure 7.01) shows that the higher leg penetration risk mainly occurs in the geotechnical zones with the presence of normally consolidated soft clays, which is also expected based on the considered criteria for the leg penetration analyses and the descriptions for the geotechnical zones defined from the zonation.

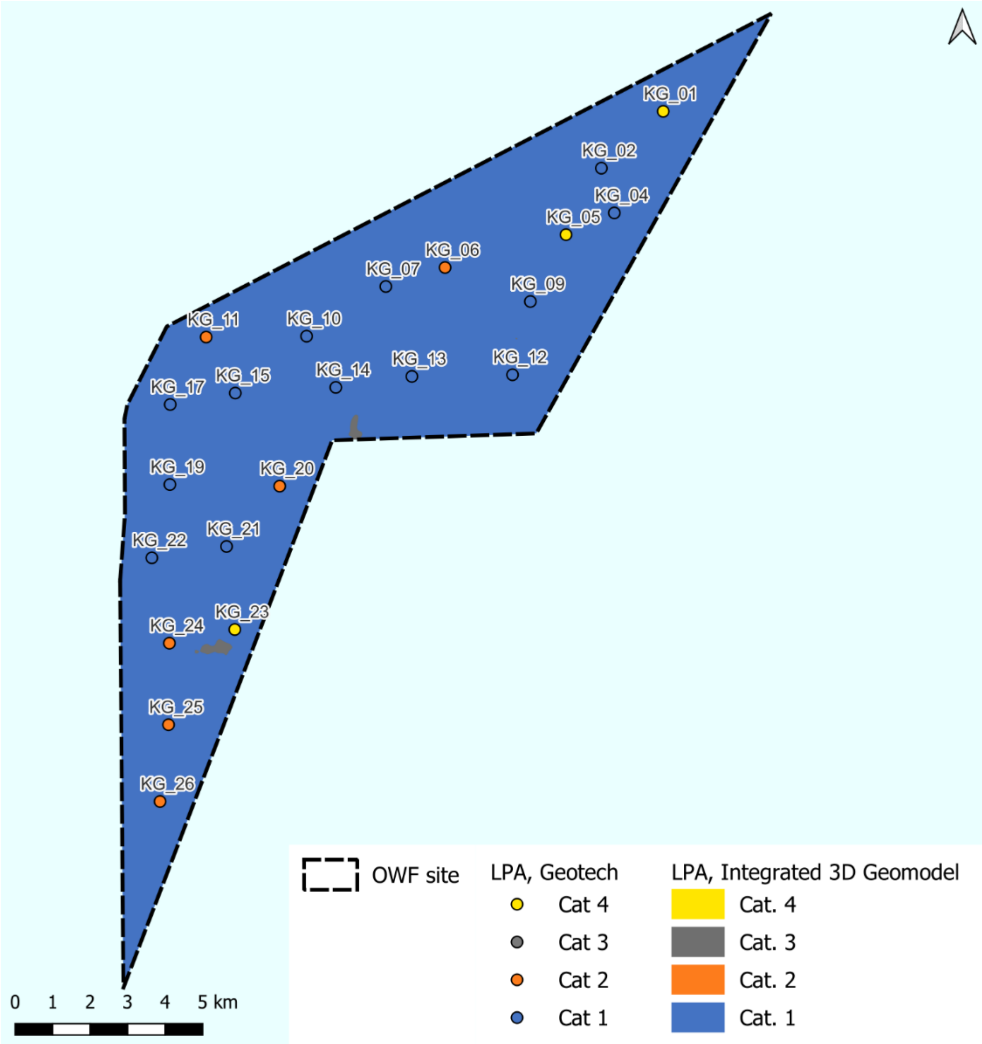


Figure 11-2 Results from leg penetration analysis for Generic Installation Vessel.

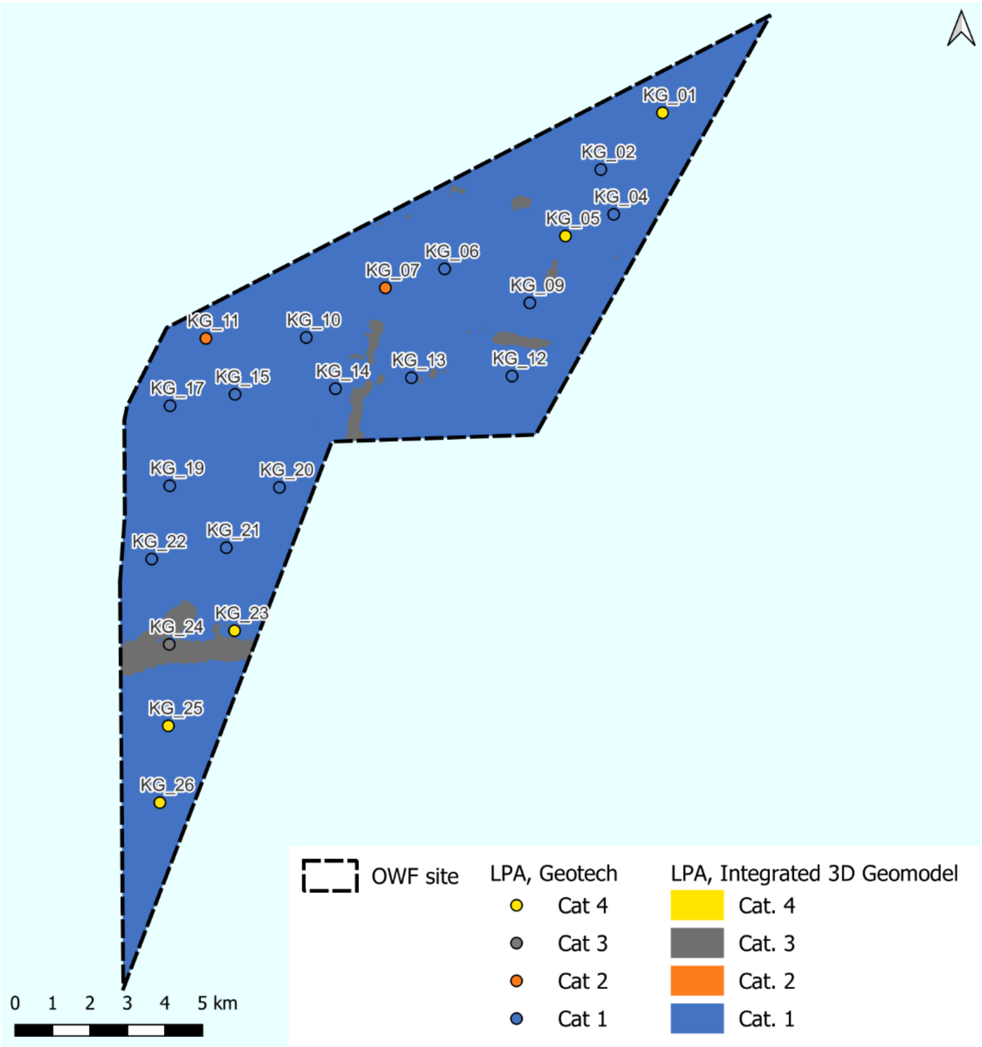


Figure 11-3 Results from leg penetration analysis for Generic O&M Vessel.

12 List of deliverables

Lists of appendixes, enclosures, and digital data delivered with this report.

Appendixes	
Number	Title
Appendix A	Interpreted stratigraphy at CPT locations
Appendix B	CPT for geotechnical units
Appendix C	Calculated soil properties per CPT location
Appendix D	CPT plots per geotechnical unit including properties from laboratory testing
Appendix E	Cone factor assessment
Appendix F	Range of soil properties per geotechnical unit
Appendix G	Conceptual geological model
Appendix H	Soil profiles for LPA assessment

Enclosures	
Number	Title
1.01	Overview map Bathymetry
1.02	Overview map Cross sections, 2D UHRS Survey lines and GT locations
2.01	Depth to top of soil unit U01 [mbsb]
2.02	Depth to top of soil unit U02 [mbsb]
2.03	Depth to top of soil unit U03 [mbsb]
2.04	Depth to top of soil unit U04 [mbsb]
2.05	Depth to top of soil unit U05 [mbsb]
2.06	Depth to top of soil unit U06 [mbsb]
2.07	Depth to top of soil unit U07 [mbsb]
3.01	Elevation of top of soil unit soil unit U01 [DTU21 MSL]
3.03	Elevation of top of soil unit soil unit U03 [DTU21 MSL]
3.03	Elevation of top of soil unit soil unit U03 [DTU21 MSL]
3.04	Elevation of top of soil unit soil unit U04 [DTU21 MSL]
3.05	Elevation of top of soil unit soil unit U05 [DTU21 MSL]
3.06	Elevation of top of soil unit soil unit U06 [DTU21 MSL]
3.07	Elevation of top of soil unit soil unit U07 [DTU21 MSL]
4.01	Isochore of soil unit U01 [m]
4.02	Isochore of soil unit U02 [m]
4.03	Isochore of soil unit U03 [m]
4.04	Isochore of soil unit U04 [m]
4.05	Isochore of soil unit U05 [m]
4.06	Isochore of soil unit U06 [m]
5.01	Geohazards - shallow gas
6.01	Cross section A_KG_X007_UHR
6.02	Cross section A_KG_X011_UHR
6.03	Cross section A_KG_X014_UHR
6.04	Cross section A_KG_X017A_UHR
6.05	Cross section A_KG_X018_UHR
6.06	Cross section A_KG_X021_UHR
6.07	Cross section A_KG_X025_UHR
6.08	Cross section A_KG_L005_UHR
6.09	Cross section A_KG_L011_UHR
6.10	Cross section A_KG_L016A_UHR
6.11	Cross section A_KG_L022_UHR
6.12	Cross section A_KG_L038_UHR
7.01	Geotechnical zonation
7.02	Variation of relevant geotechnical layers/boundaries
7.03	Jack-up Risk Assessment. Generic Installation Vessel
7.04	Jack-up Risk Assessment. O&M Vessel

Digital deliverables	
Item	Format
Kingdom Suite Project (version 2023) including spatial geological model *)	Kingdom project
Depth grids to top of all soil unit interfaces [mbsb]	GeoTIFF and AXCII.xyz
Elevation grids of top of all soil unit interfaces [DTU21 MSL]	GeoTIFF and AXCII.xyz
Isochore grids of all soil units [vertical layer thickness, m]	GeoTIFF and AXCII.xyz
Shallow gas interfaces as elevation grid	GeoTIFF and AXCII.xyz
Geotechnical zones	ESRI Shapefile
Jackup risk assessment categories - Polygons	ESRI Shapefile
Jackup risk assessment categories - Points	ESRI Shapefile
Calculated soil properties from Appendix C	Excel file

**) The launch file for the Kingdom Suite Project is named Kattegat II. This has historical reasons as this was the original name of the site. The name was later and during the project changed from "Kattegat II" to "Kattegat".*

13 Conclusions

A 3D Integrated Geological Model (IGM) has been established for the entire Kattegat OWF project site. The model comprises an integrated interpretation of the newly (2023) gathered geotechnical and seismic data. The report provides detailed geotechnical and geological information on the geological layers in the model including stratigraphical descriptions, lithological descriptions, and geotechnical characteristics.

The result is an IGM which contains detailed information on the spatial distribution of the layers as well as the characteristic geotechnical parameters. It contains seven (7) integrated soil units consisting of Holocene, Pleistocene, or Late Jurassic to Early Palaeocene deposits.

A Conceptual Geological Model is also provided which visualizes the geological layers and their variation for the entire site in two conceptual profiles for the northern and southern part respectively.

The sediments generally comprise 0-8 m relative soft Holocene and Late Weichselian soils overlaying competent Pleistocene soils of a general thickness of more than 25 m. Bedrock is found deeper than 30 m over most of the site. Potential geohazards include a prominent seabed channel feature, evidence of limited areas with shallow gas, peat and boulders. Further, glacial deformation can create a lager variability in geotechnical properties of the Pleistocene soils whereas faulting is found to be confined to bedrock layers.

The digital IGM is delivered as a 3D layered model in a Kingdom suite project and GIS-ready files. Enclosures provided with the report present the soil units with respect to depth below seabed, thickness, elevation for top of unit, and lateral extent. Appendices present the geotechnical interpretations.

Twelve (12) cross sections distributed over the entire Kattegat OWF project site show the layering in the model. The cross sections follow the seismic survey lines and display CPT logs (qc, fs, u2, and Ic) and geological descriptions at top of layers from boreholes located on the seismic survey lines.

A geotechnical zonation is provided presenting thickness and depth of grouped units of importance into eight (8) geotechnical zones. In establishing the geotechnical zones focus has been on the low and high strength deposits and geological structures assessed to be important for the WTG foundation design and installation works. The soil zonation maps have been simplified into a single map showing the eight selected geotechnical zones which provide a geological/geotechnical overview of the entire site relevant for foundation conditions.

Geotechnical zones I, II and III generally show good ground conditions for WTG foundation design and installation due to large thickness of competent glacial material, with the conditions being most competent for Geotechnical zone I.

Geotechnical zones IV and V are categorised by medium to good ground conditions for WTG foundation design, which combined with depth to top of pre-quaternary material potentially can result in additional consideration for foundation installation is required.

For Geotechnical zones VI, VII and VIII the thickest deposits of soft clay at the site are combined with low depths to pre-quaternary material resulting in a low thickness of glacial material. Thus, in these zones more expensive WTG foundations are expected to be required compared to other geotechnical zones.

The eight geotechnical zones provide a detailed overview of the geotechnical soil conditions in relation to WTG foundation design. It can be concluded that the soil conditions of the site are overall good and feasible for OWF foundation design.

The leg penetration risk has been assessed for each of the geotechnical survey locations for two generic vessels – an installation vessel and an O&M vessel – and a risk category has been assigned for each survey location. The results from the performed assessment show large variance of jack-up behaviour across the Kattegat OWF project site, which is also in accordance with expectations based on the results from the geotechnical zonation. The highest leg penetration risks are seen in the geotechnical zones with thickest layers of normally consolidated soft clays.

Additionally, the established criteria for risk categorisation have been applied to the integrated ground model to cover the Kattegat OWF project site with zones representing the assessed jack-up risks. By comparing the results from the ground model analyses and the geotechnical location specific analyses it is evident that small-scale, local differences within the units between sandy and clayish material are not captured in the ground model. The purpose of the ground model is however to capture only main features impacting the foundation design, and not small-scale variations within the units. The resolution and the spatial distribution of the geophysical data available for the ground model do not allow for capturing small-scale variations between deposits of sand and clay. The small-scale variations can however still be important in relation to jack-up assessments and thus, local assessment and mitigation will remain relevant.

With respect to the purpose of the pre-investigations initiated by Energinet Eltransmission A/S it can be concluded that the new IGM provides a strong basis for developers to evaluate the ground conditions spatially and the IGM can be applied for planning of the positioning of WTG's as well as the foundation design.

14 References

Ref. /1/ Danish Offshore Wind 2030 - Lot 1 – Kattegat, Volume II Measured and Derived Final Results, Revision 2, Gardline, May 2024.

Ref. /2/ Robertson and Cabal, 2015: Guide to Cone Penetration Testing, 6th Edition.

Ref. /3/ DNV-RP-C207, Statistical representation of soil data, September 2021.

Ref. /4/ Lunne, T., Robertson, P. K., and Powell, J. J. M., 1997: Cone Penetration Testing in Geotechnical Practice, 1st edition.

Ref. /5/ Mayne, P. W & Sharp, J. 2019 - CPT Approach to Evaluating Flow Liquefaction Using Yield Stress Ratio.

Ref. /6/ Jamiolkowski, M., Lo Presti, D. C. F. & Manassero, M. 2003 - Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT.

Ref. /7/ GEUS 2023: Screening of seabed geological conditions for the offshore wind farm area Kattegat and the adjacent cable corridor area, Desk study for Energinet. Report for Energinet Eltransmission A/S. GEUS

Ref. /8/ Huuse, M. L. A., 2000: Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quaternary Science Reviews, 19, 1233-1253

Ref. /9/ Erlström, M., Kornfält, K.-A. & Sivhed, U., 2001: Berggrundskartan 2D Tomelilla NO/2E Simrishamn NV. Sveriges geologiska undersökning Af 213.

Ref. /10/ GEOxyz. Geophysical and Geological Survey Report For Kattegat II, Rev 2.0, BE5376H-711-02-RR, 24/11/2023

Ref. /11/ LOC, January 2013, Geotechnical engineering for jack-ups, Ref no. LOC/CM/MANUAL/2013/R0.1-4.

Ref. /12/ European Standard EN ISO 19905-1, Petroleum and natural gas industries – Site-specific assessment of mobile offshore units – Part 1: Jack-ups, February 2016.

Ref. /13/ MSL Engineering Ltd., 2004, Guidelines for jack-up rigs with particular reference to foundation integrity (HSE Research Report 289).

Ref. /14/ ISO 19905-1:2016: Petroleum and natural gas industries, Site-specific assessment of mobile offshore units, Part 1: Jack-ups.

Appendix A Interpreted stratigraphy at CPT locations

The CPT measurements and general CPT correlations (from left: soil behaviour type, soil behaviour type index, measured cone tip resistance, measured cone skin resistance, friction ratio and measured pore water pressure) together with stratigraphy per geotechnical test location is presented in this Appendix as shown in the example in Figure A-1. The soil behaviour type have three different methodologies, where the blue dots represent the soil behaviour type based on Ic, the red dots represent the normalised cone resistance and friction ratio chart, and the yellow dots represent the normalised cone resistance and pore pressure chart, cf. the presented methodologies in section 7.2.1, 7.2.2 and 7.2.3, respectively.

The figures show the interpreted soil stratigraphy, where each considered layer boundary is marked with a red line. Additionally, interpreted horizons from the Kingdom model and the borehole logs received within the AGS-file is presented in as purple horizontal dashed lines and green dashed lines, respectively. Identifications of units, horizons and borehole log numbers are presented in the right side of the figures. The numbering from the borehole logs is presented in Table A-1 corresponding to the received values in the AGS-file together with the acquired description from the AGS-file.

On a few locations it is interpreted that two consecutive layers with same units are present. This is due to an observation, that the soil behaviour/properties change. However, in interaction with the geophysical interpreted horizons, it is not assessed, that these layers should be divided any further or processed differently.

All figures per geotechnical test location are presented in the following pages.

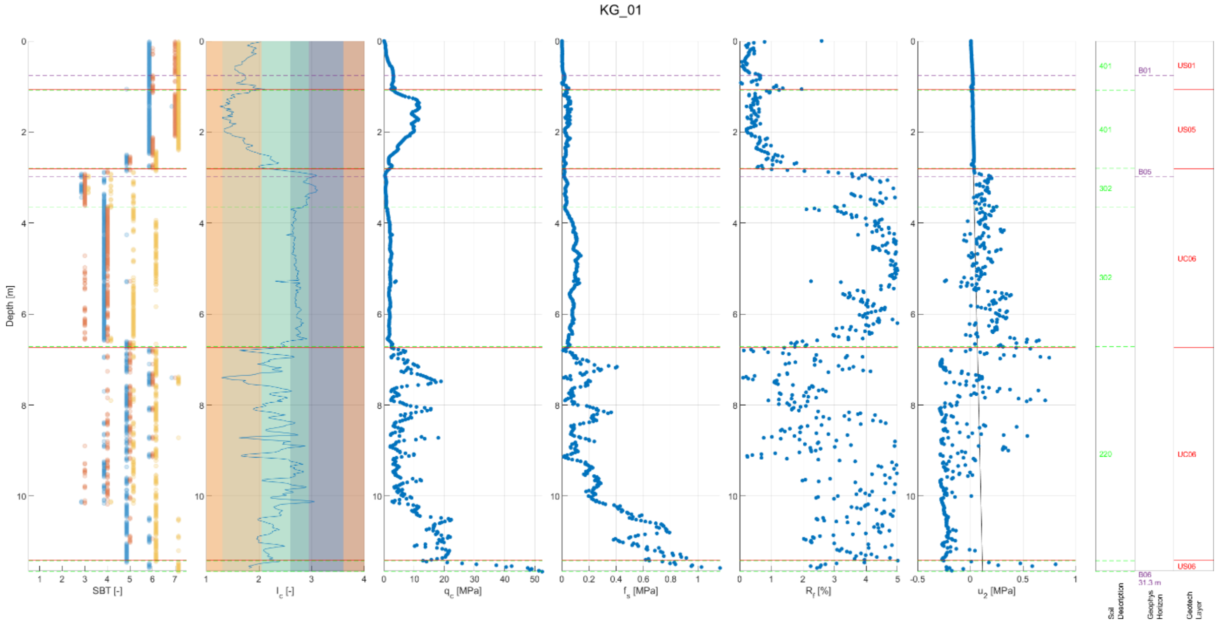
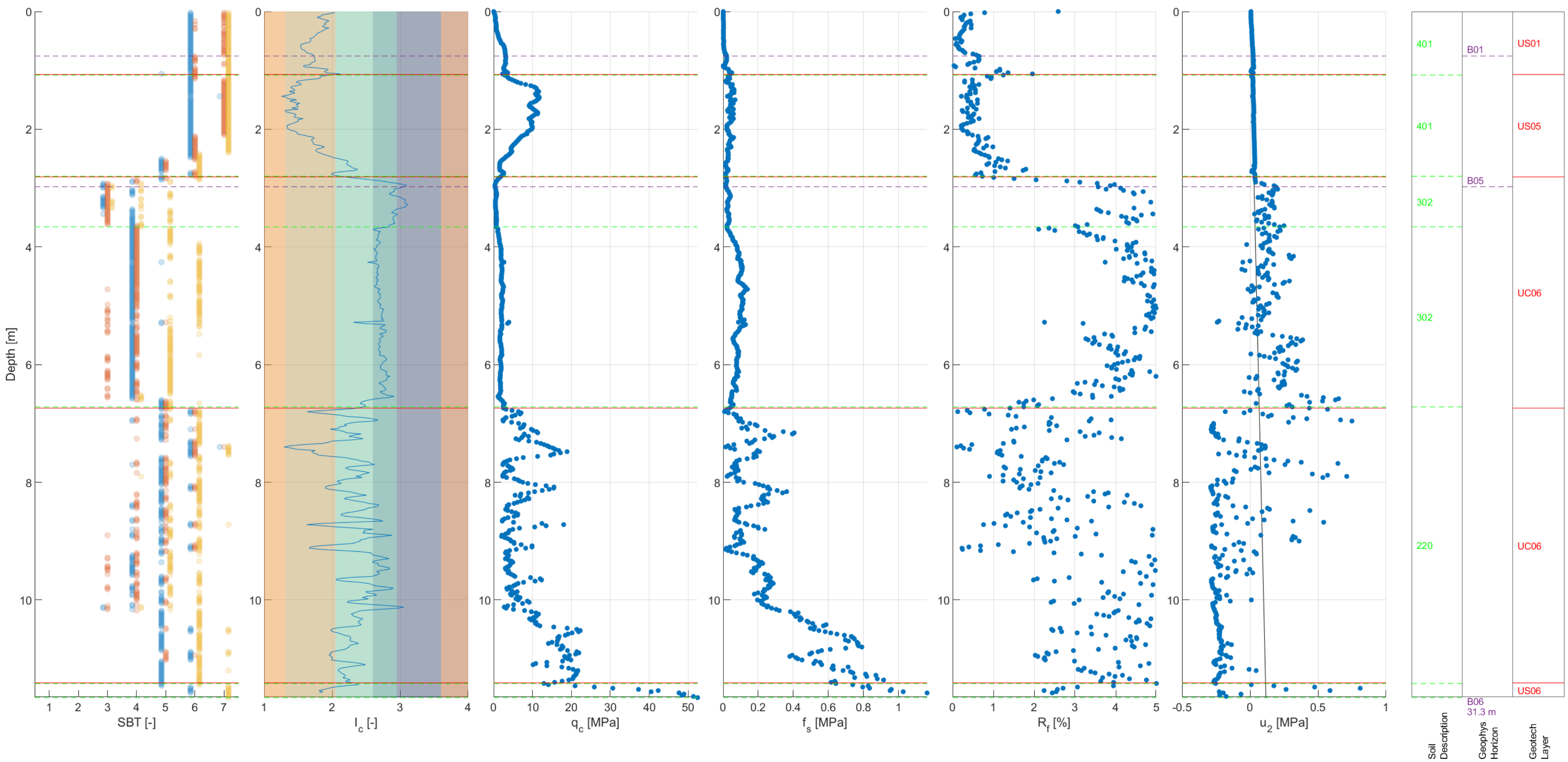


Figure A-1 Example of interpreted stratigraphy for KG_01.

Table A-1 Borehole legends and descriptions from received AGS-file.

Legend	Description	Legend	Description
201	CLAY	402	Clayey SAND
202	Silty CLAY	403	Silty SAND
203	Sandy CLAY	404	Gravelly SAND
204	Gravelly CLAY	407	clayey silty SAND
207	Silty sandy CLAY	408	clayey silty gravelly SAND
208	Silty gravelly CLAY	409	clayey silty gravelly cobbly SAND
211	Silty sandy gravelly CLAY	410	Clayey gravelly SAND
214	Silty sandy gravelly cobbly CLAY	412	Silty gravelly SAND
220	Sandy gravelly CLAY	501	GRAVEL
302	Clay/Silt	504	Sandy GRAVEL
303	Sandy SILT	804	LIMESTONE
306	Clayey sandy SILT	805	CHALK
401	SAND		

KG_01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R_f [%]
u_2 [MPa]
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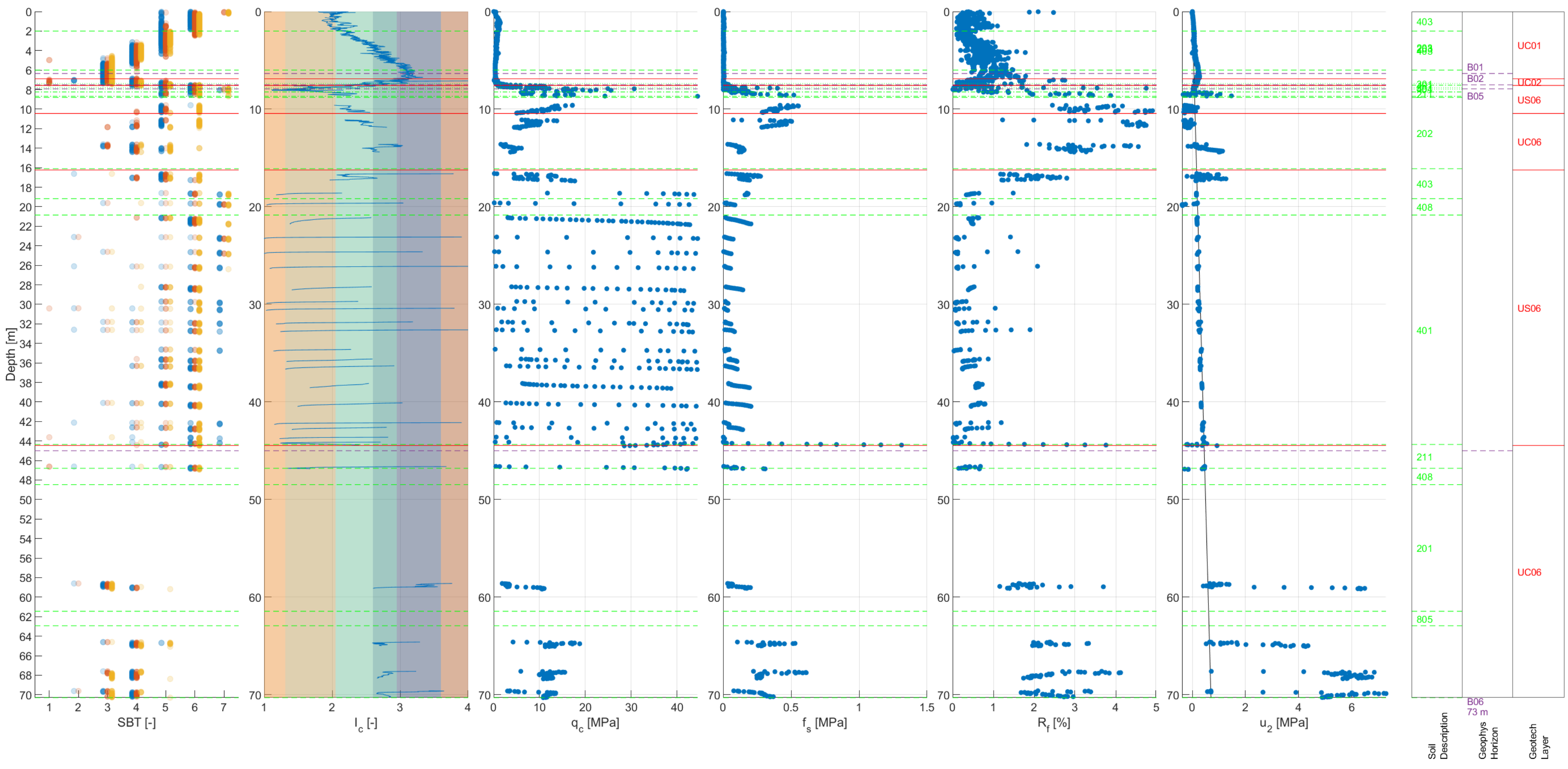
401
302
302
220
B01
B05
B06
31.3 m
US01
US05
UC06
UC06
US06
Soil Description
Geophys Horizon
Geotech Layer

KG_02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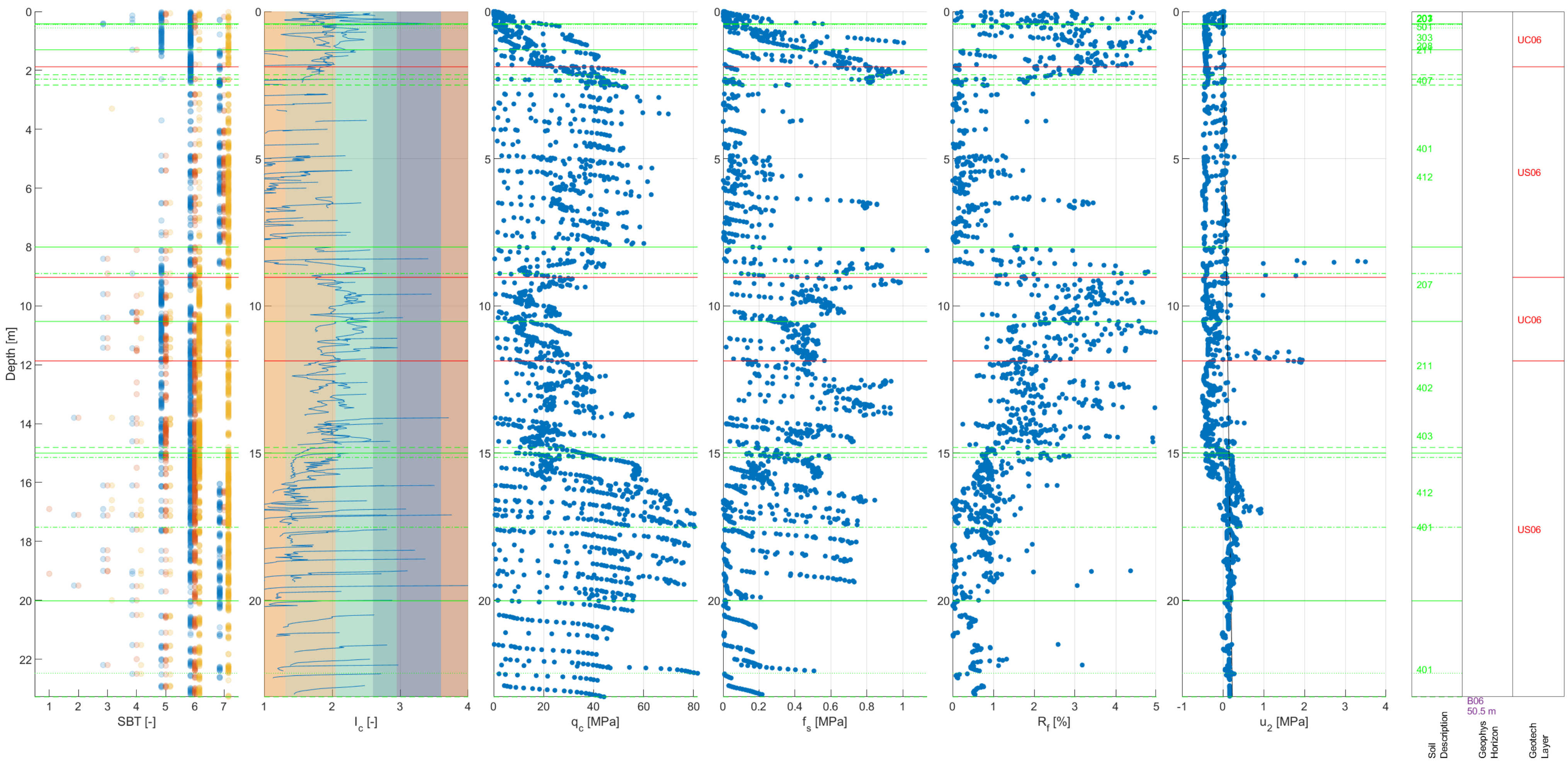
Soil Description
Geophys Horizon
Geotech Layer
403
202
201
202
403
408
401
211
408
201
805
B01
B02
B05
B06
73 m
UC01
UC02
US06
UC06
US06
UC06

KG_04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Soil Description
Geophys Horizon
Geotech Layer
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US06
UC06
US06
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303
407
401
412
207
211
402
403
412
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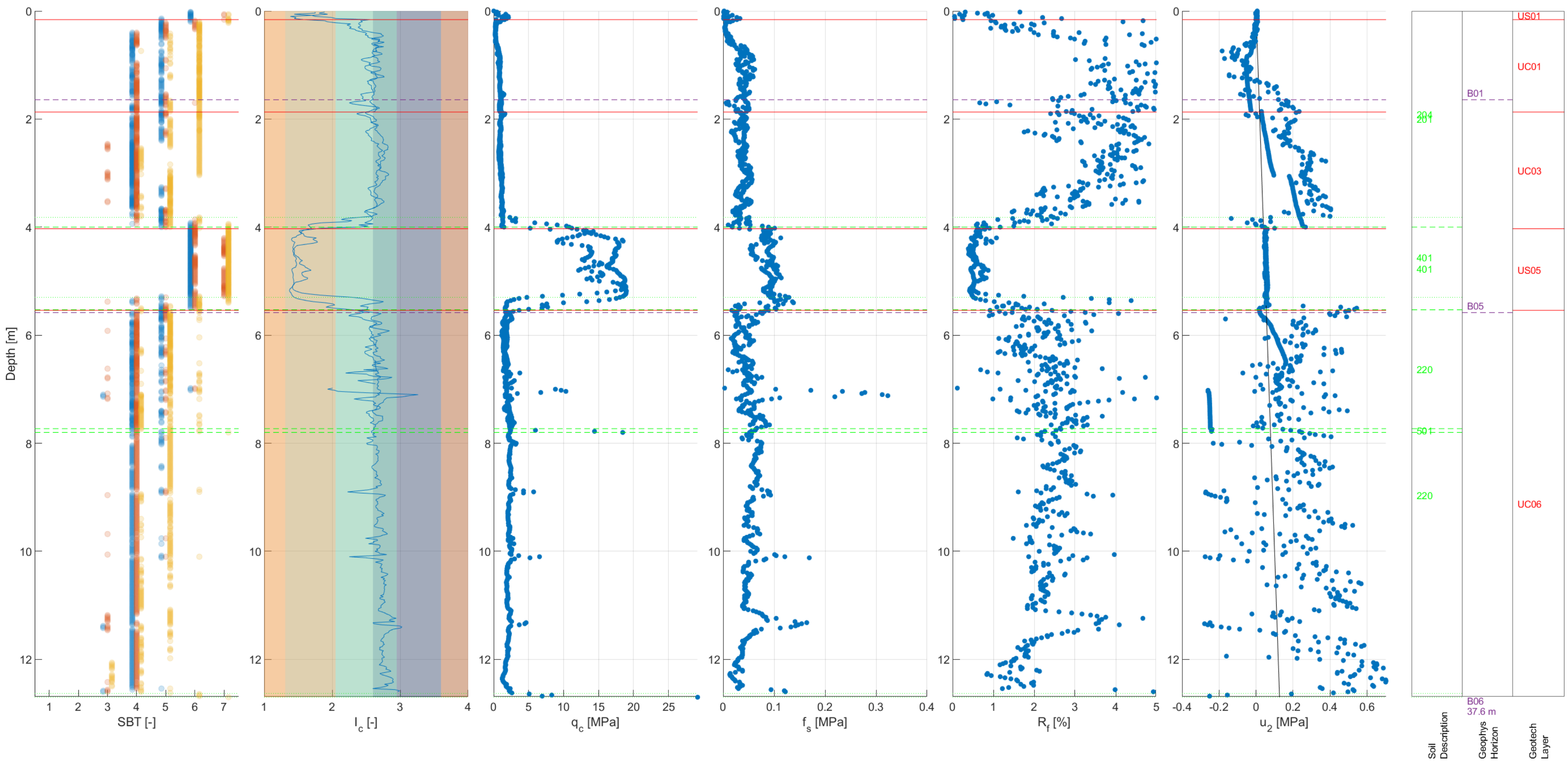
KG_05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UC01
B01
204
201
UC03
401
401
US05
B05
220
S01
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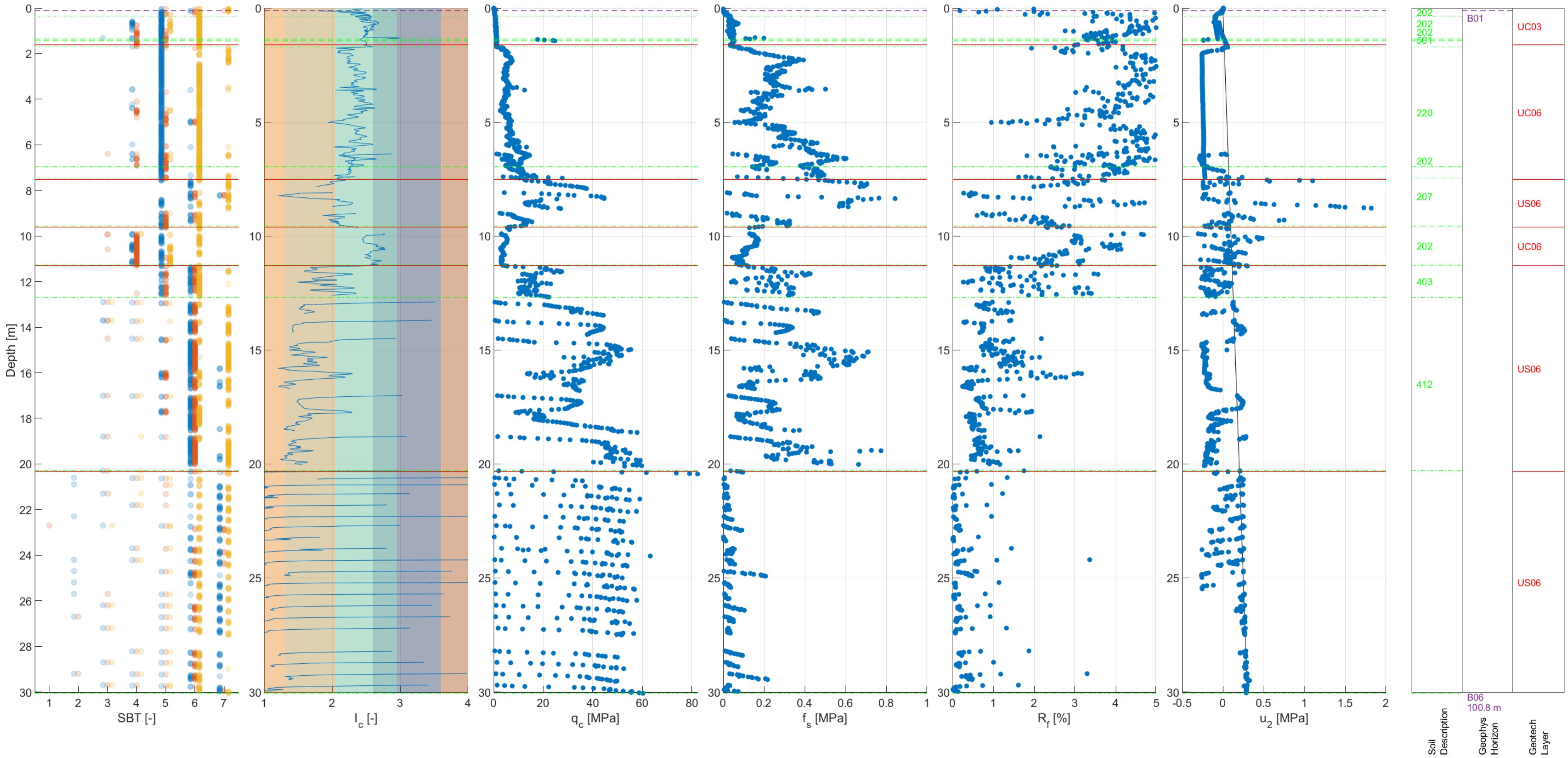
UC06
B06
37.6 m
Soil Description
Geophys Horizon
Geotech Layer

KG_06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501
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B06
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UC06
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UC06
US06
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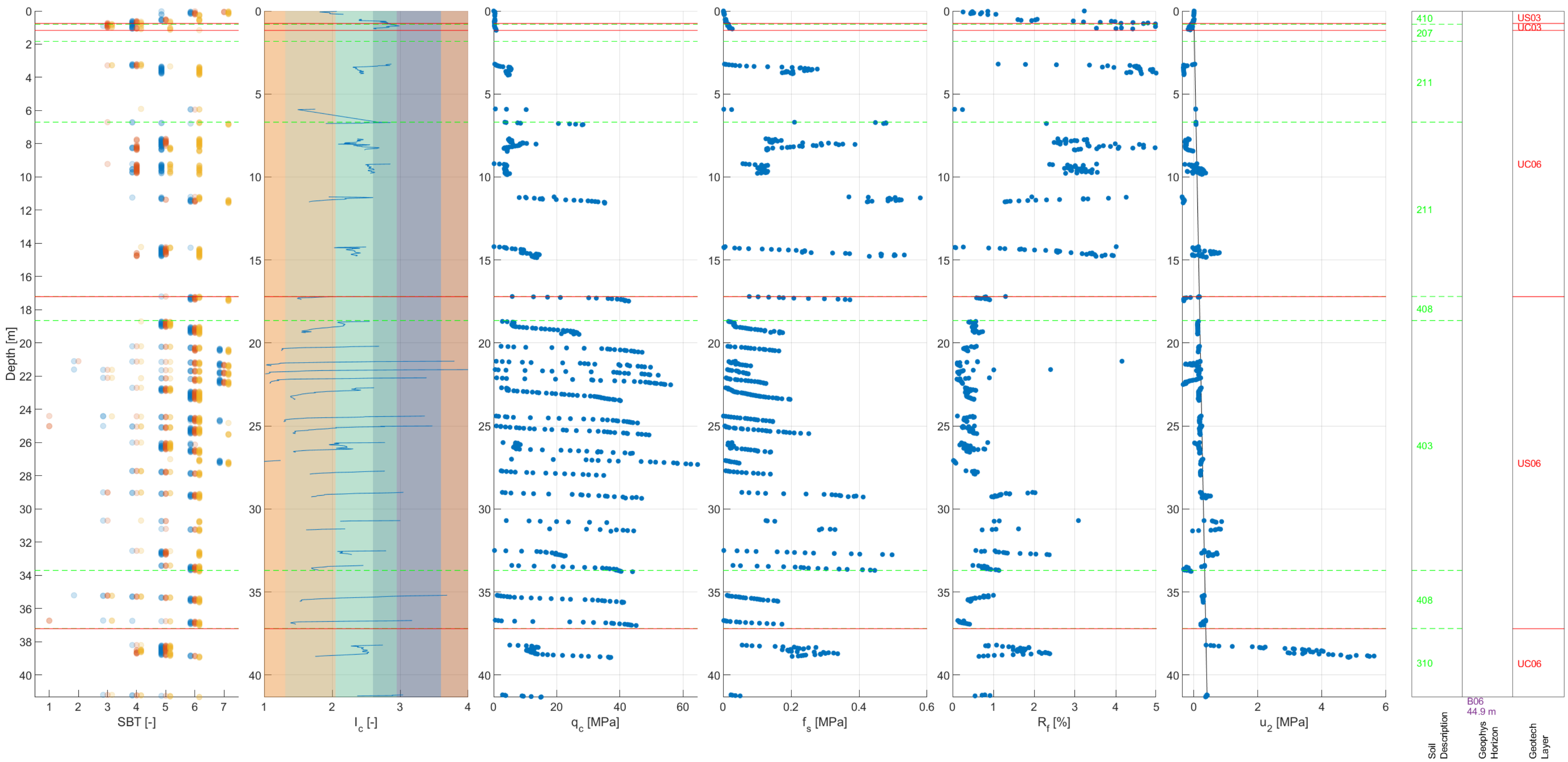
KG_07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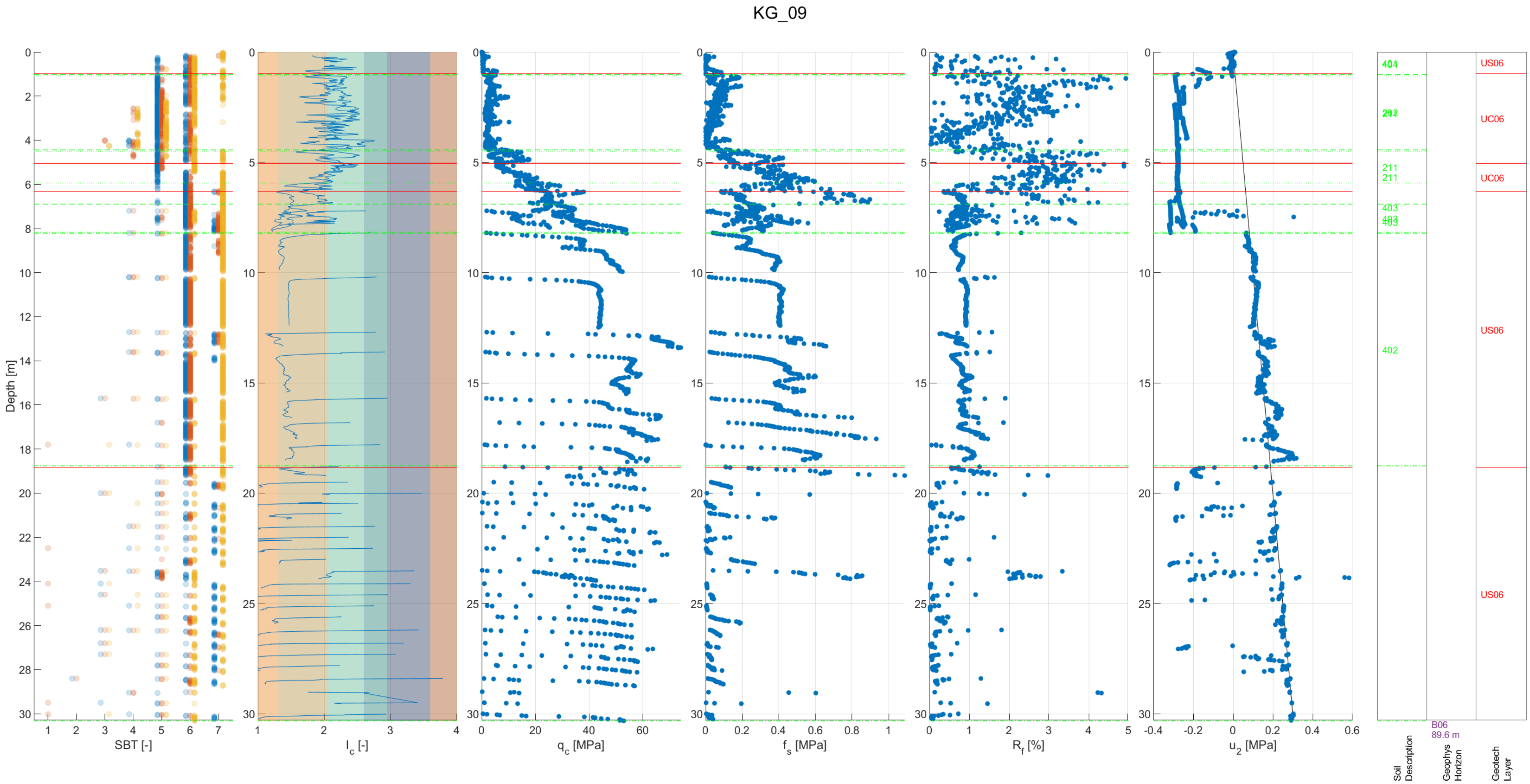
Soil Description
Geophys Horizon
Geotech Layer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UC06
US06
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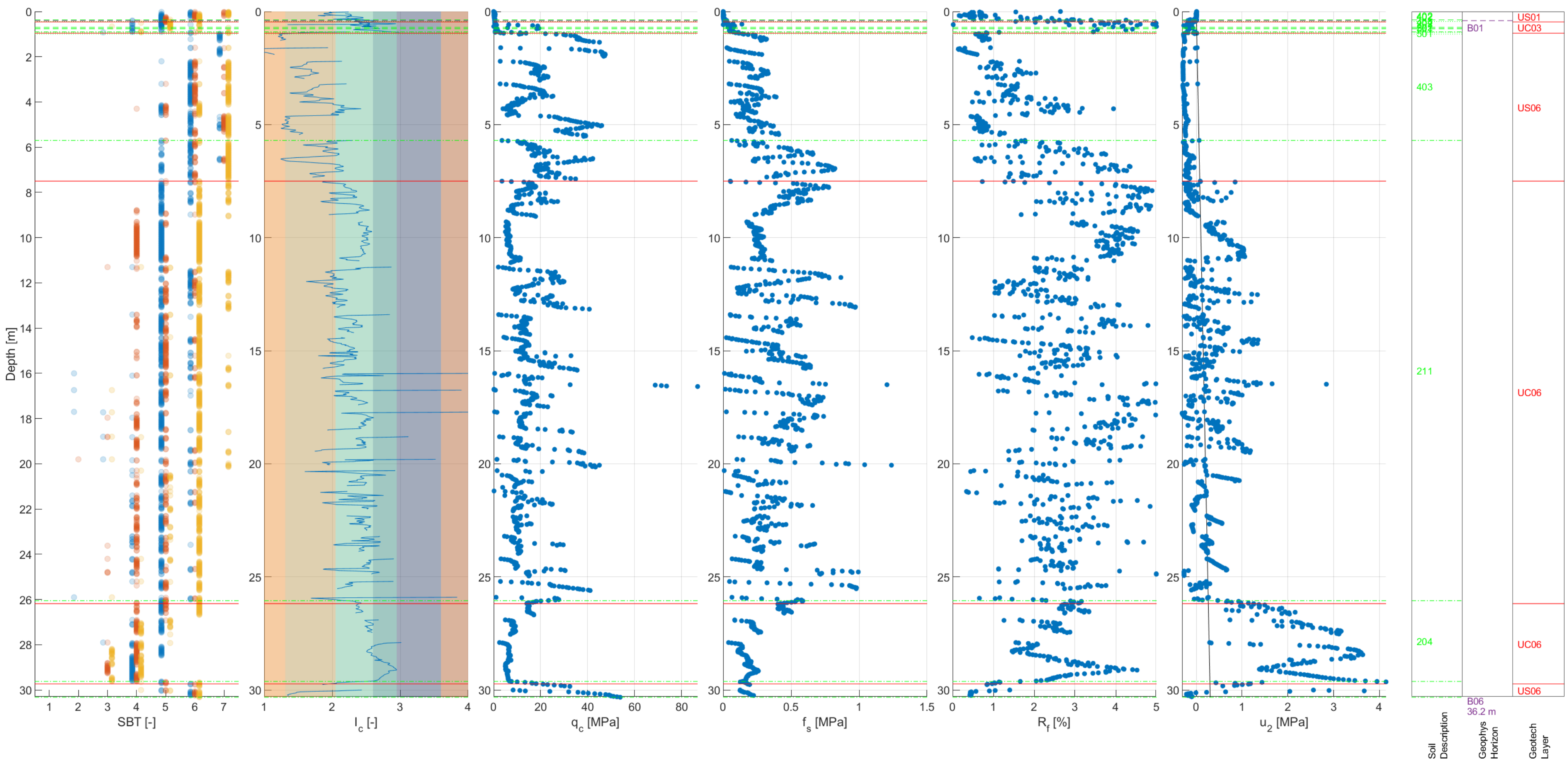
KG_10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B06
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UC03
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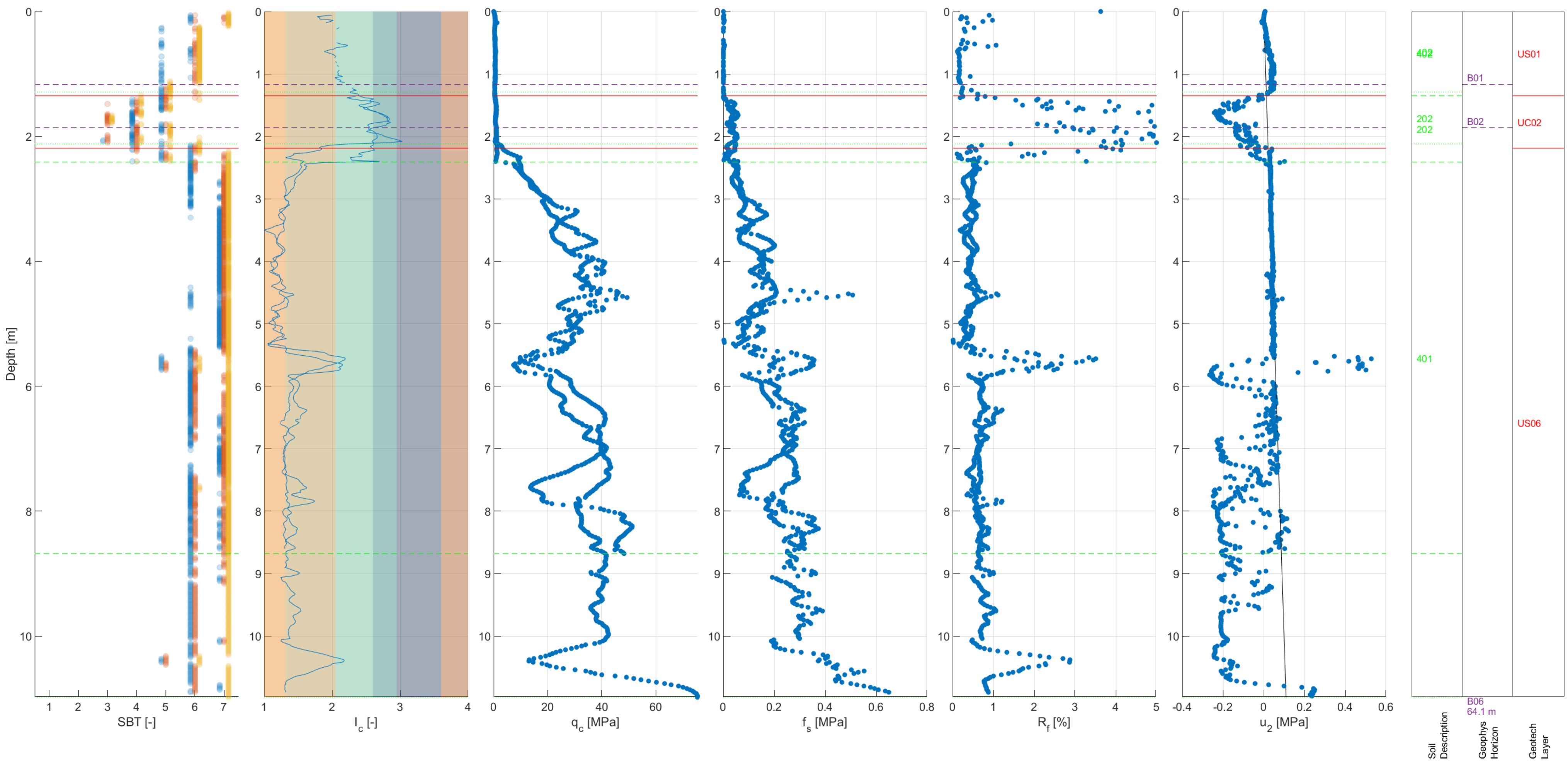
KG_11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Soil Description
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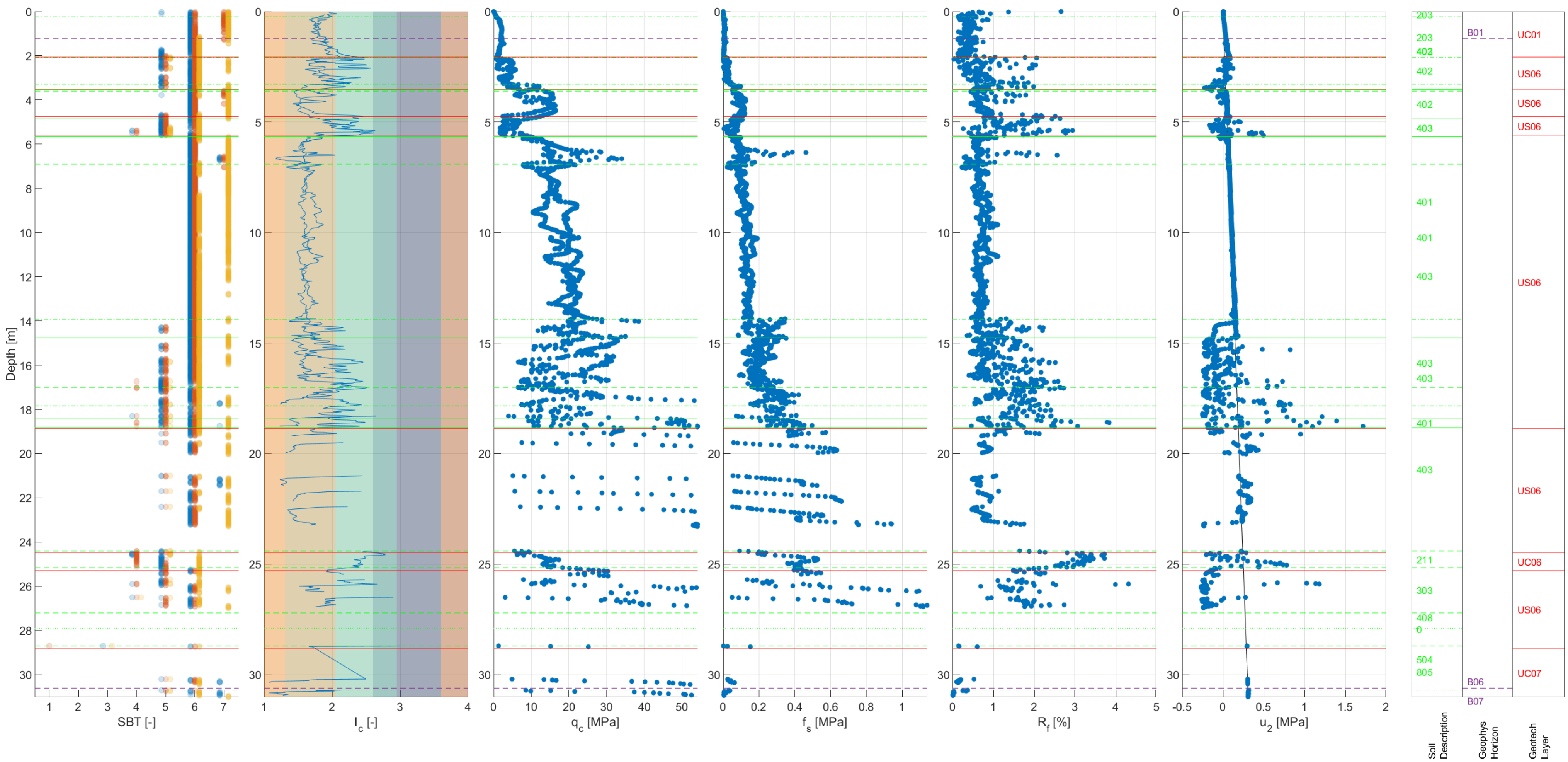
202
202
B02
UC02
401
US06
B06
64.1 m

KG_12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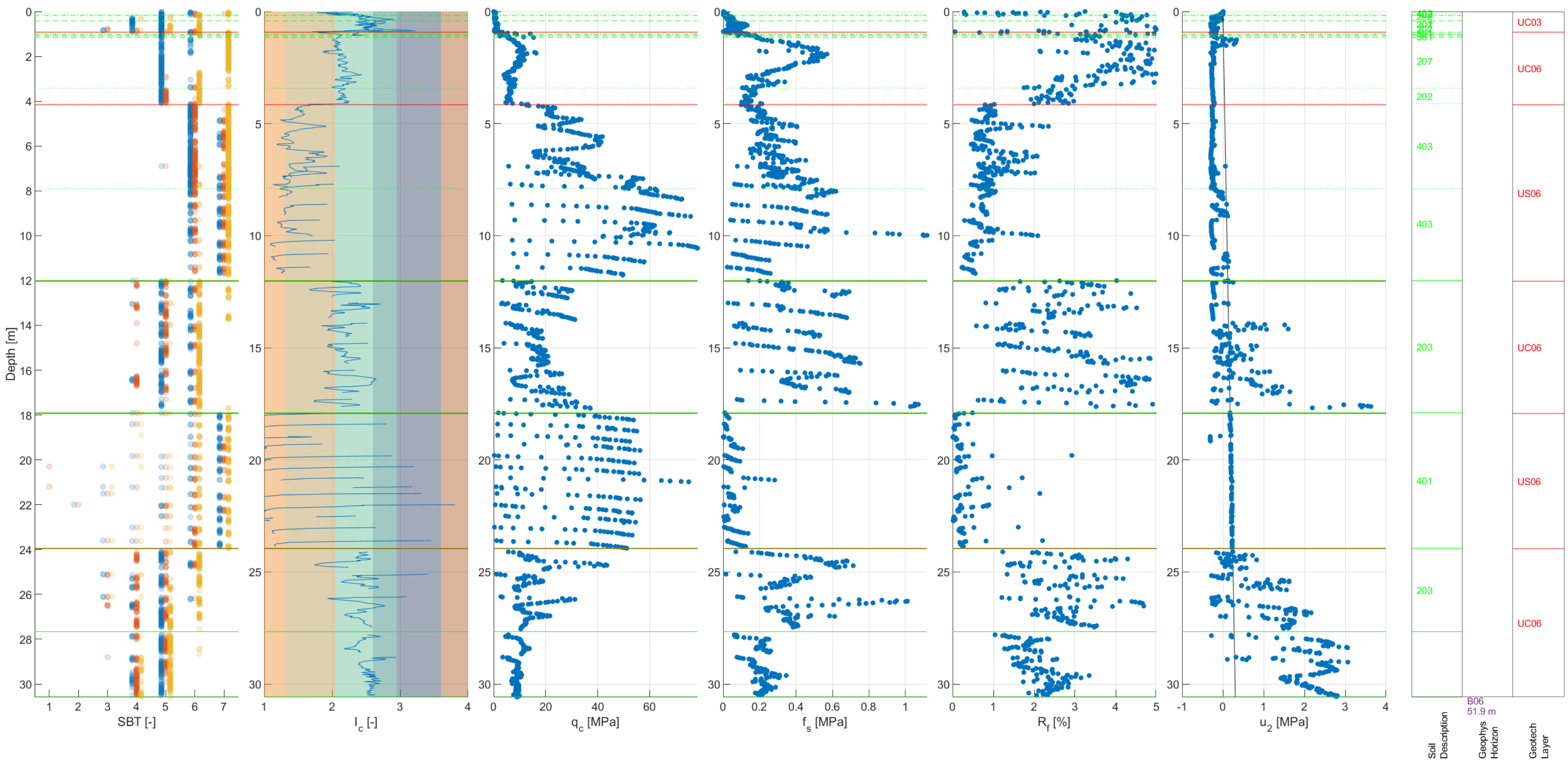
805
B01
B06
B07
UC01
US06
US06
US06
US06
US06
UC06
US06
UC07

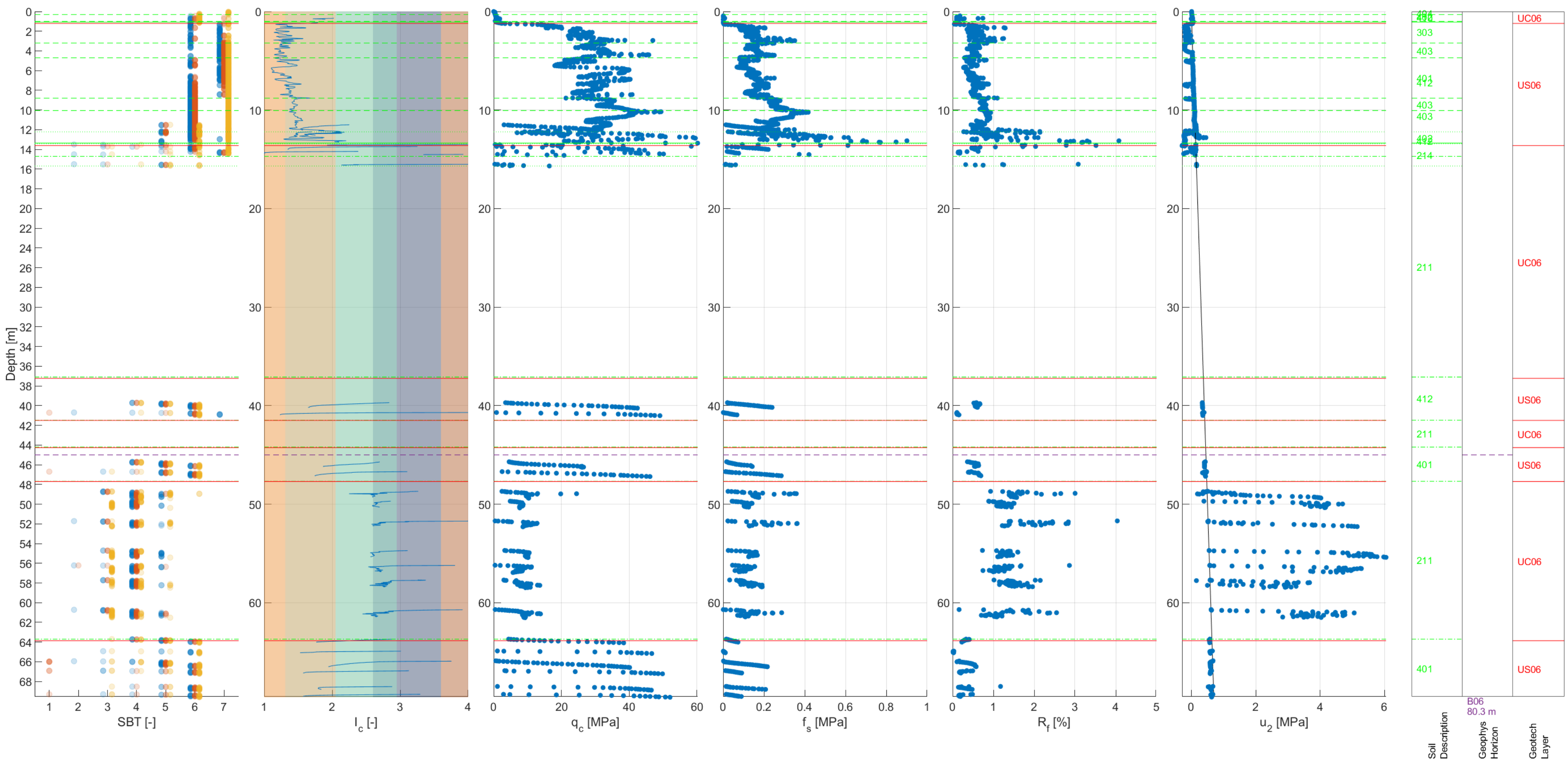
KG_13


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
UC01
UC02
US05
UC06
US06
B01
B02
B05
B06
36 m
202
404
401

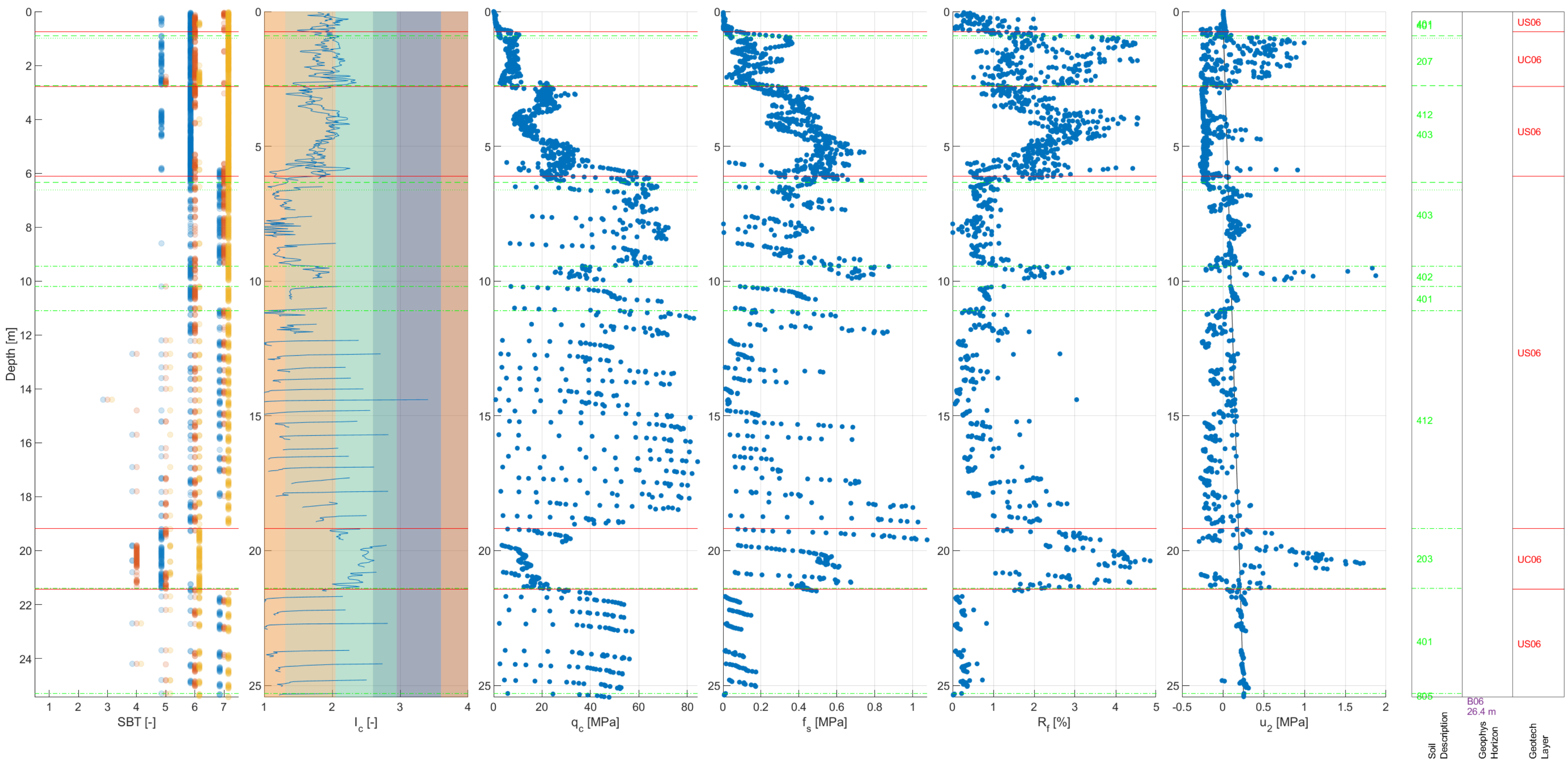
KG_14


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
207
202
403
403
203
401
203
UC03
UC06
US06
UC06
US06
UC06
B06
51.9 m
Soil Description
Geophys Horizon
Geotech Layer

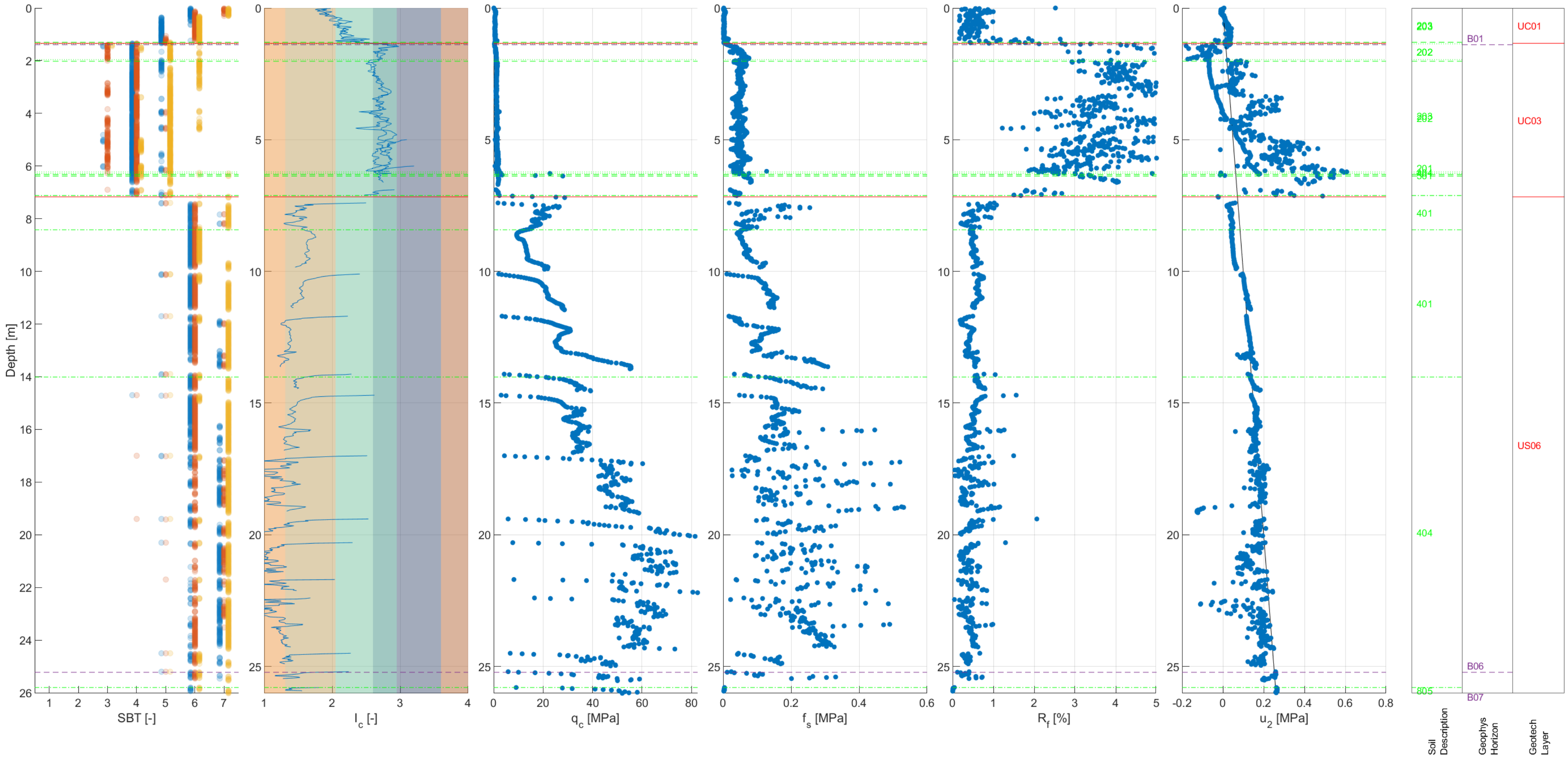
KG_15


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
UC06
US06
UC06
US06
UC06
US06
UC06
US06
B06
80.3 m
303
403
403
403
211
412
211
401
211
401

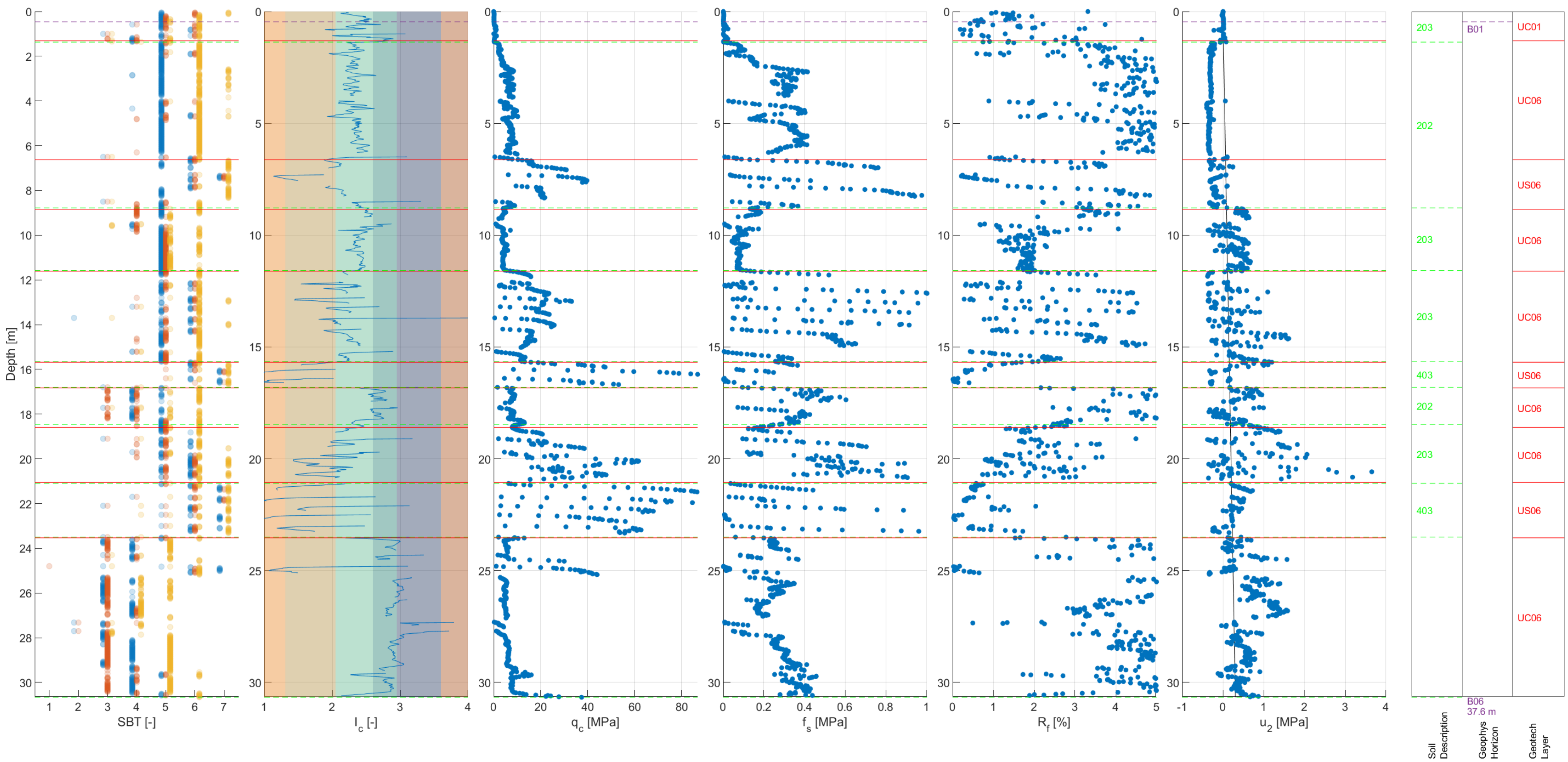
KG_17


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
401
207
412
403
403
402
401
412
203
401
805
US06
UC06
US06
US06
UC06
US06
B06
26.4 m

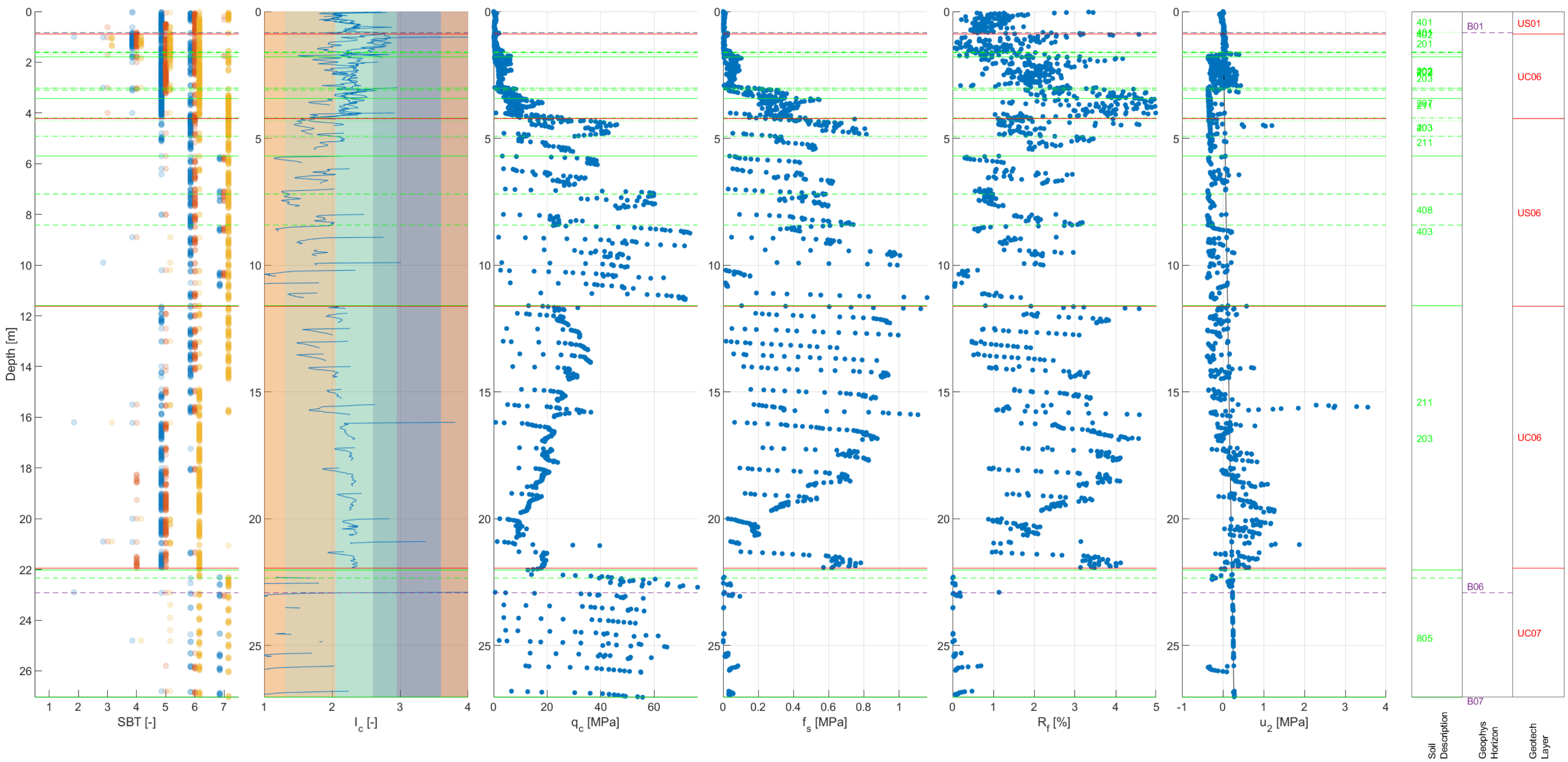
KG_19


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
UC01
UC03
US06
B01
B06
B07
203
202
401
404
805

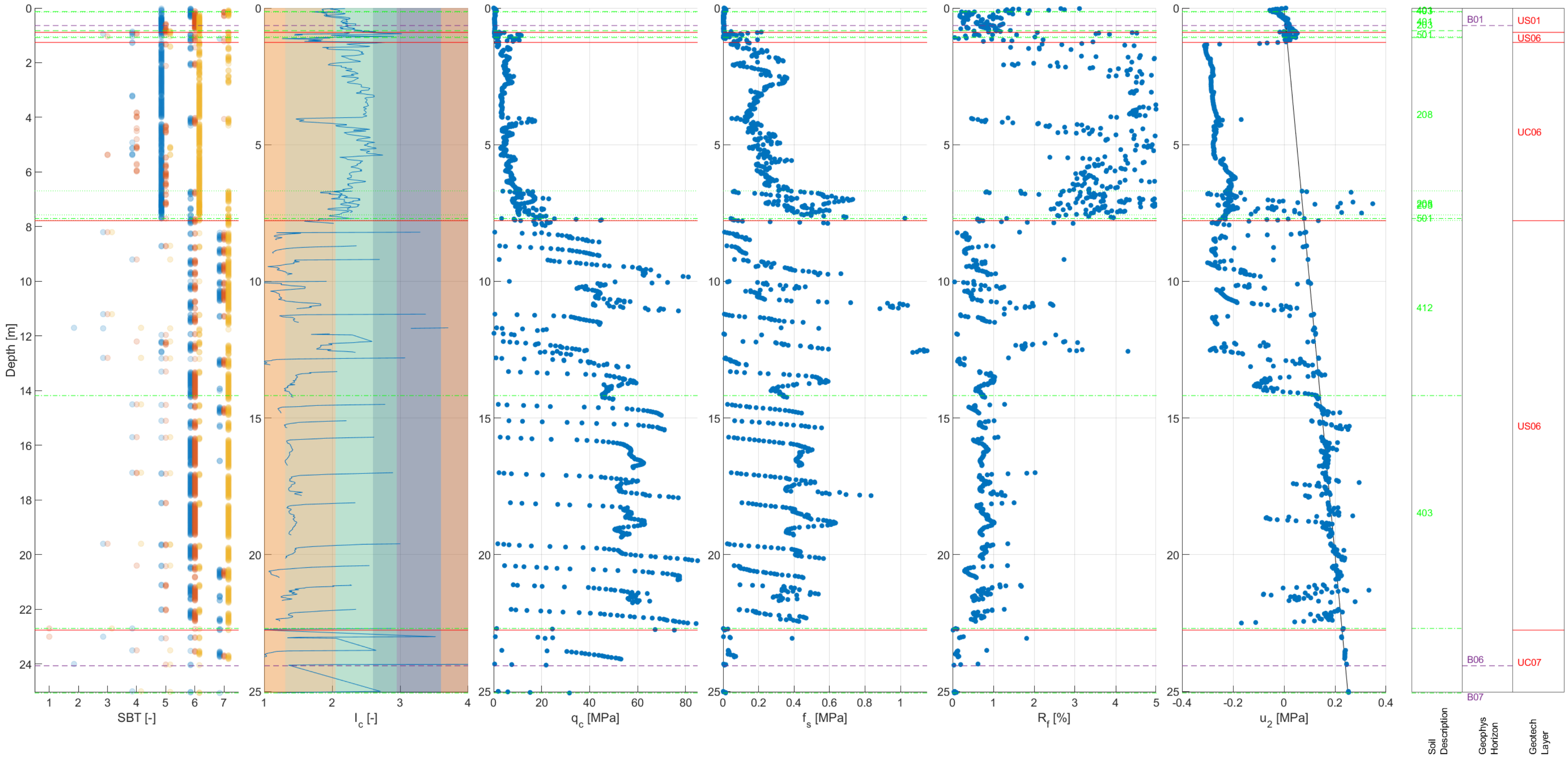
KG_20


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
203
202
203
203
403
202
203
403
B01
B06
37.6 m
UC01
UC06
US06
UC06
UC06
US06
UC06
UC06
US06
UC06
Soil Description
Geophys Horizon
Geotech Layer

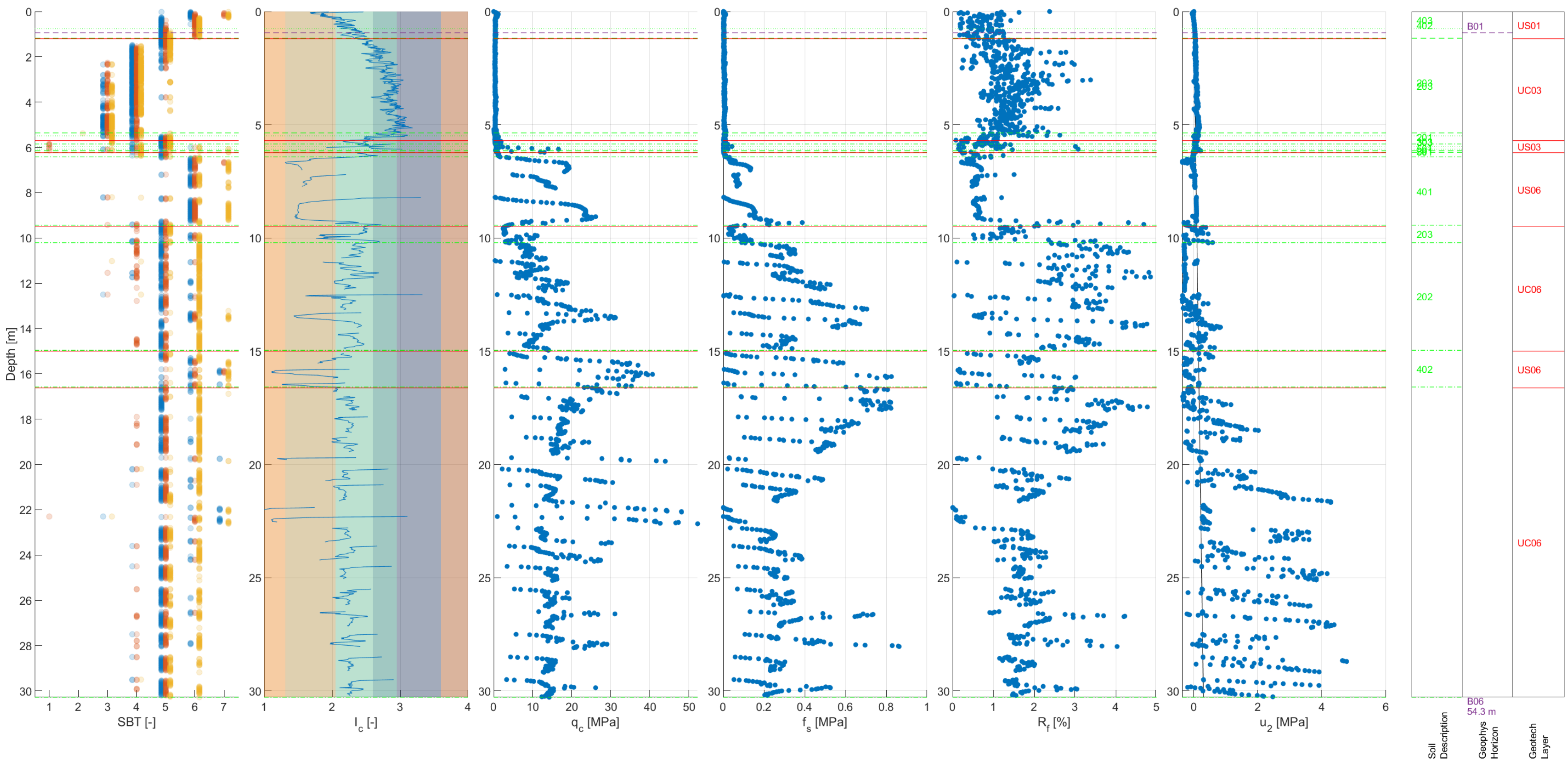
KG_21


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
401
201
203
211
408
403
211
203
805
B01
B06
B07
US01
UC06
US06
UC06
UC07

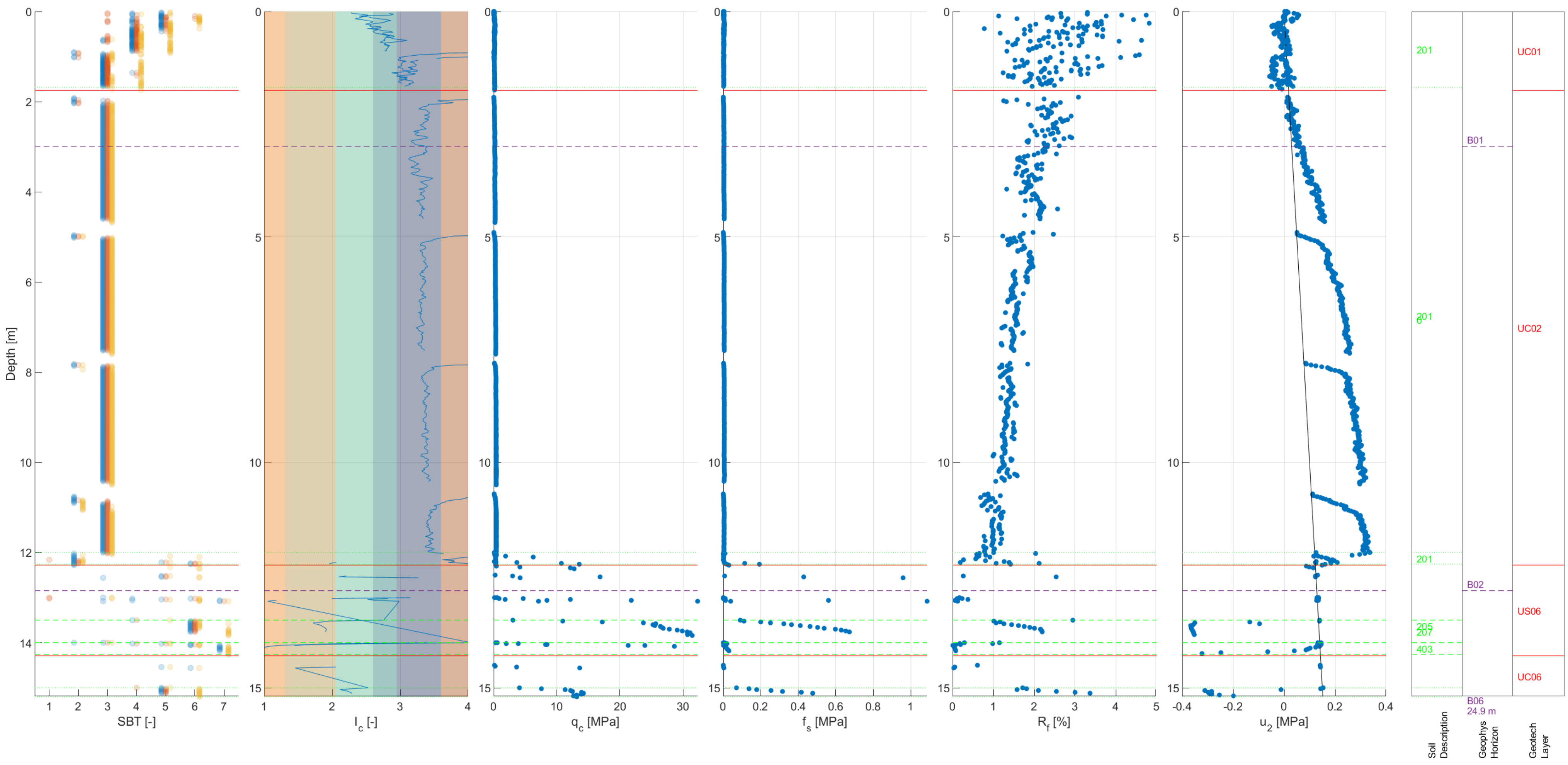
KG_22

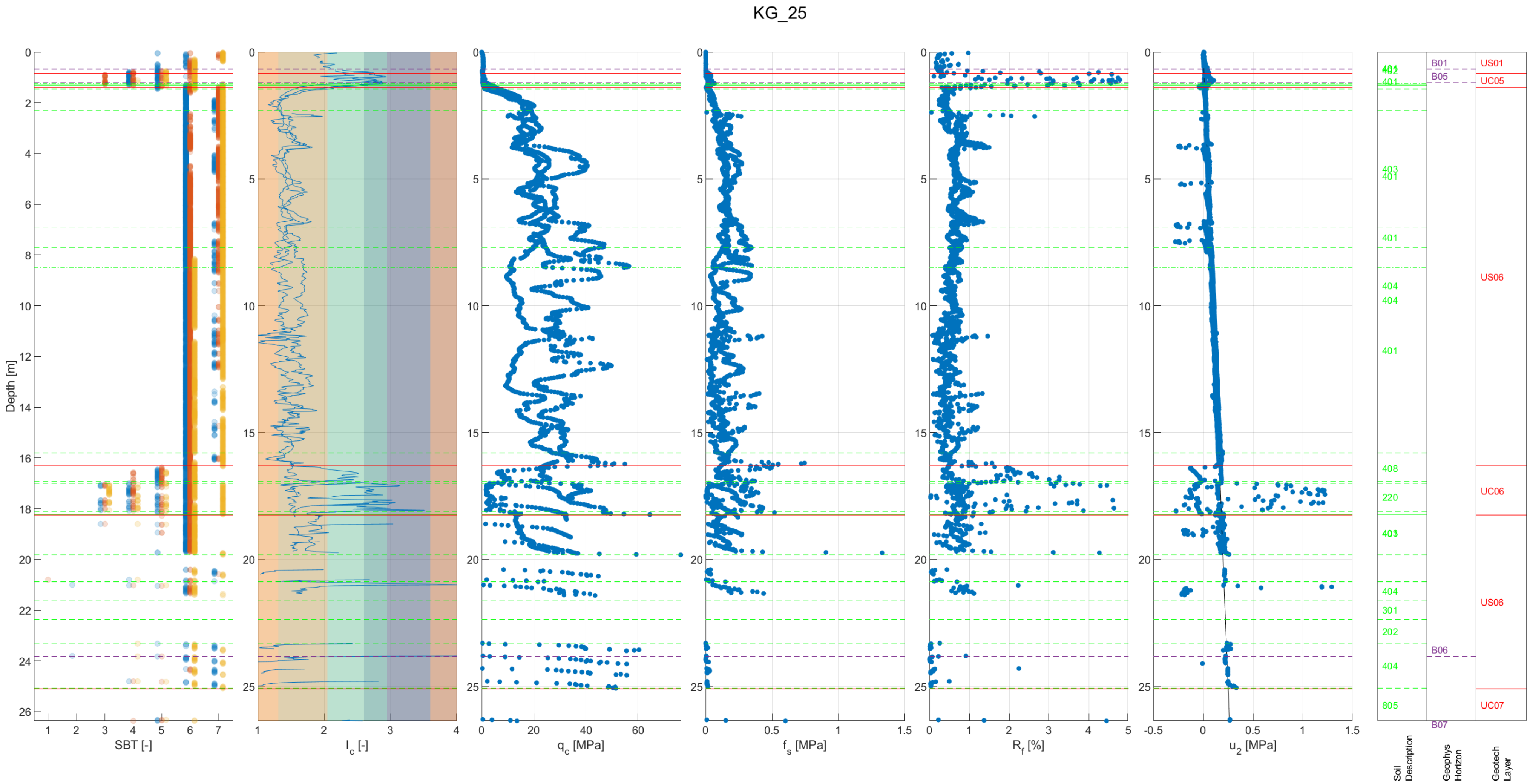

Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
208
412
403
B01
B06
B07
US01
US06
UC06
US06
UC07

KG_23

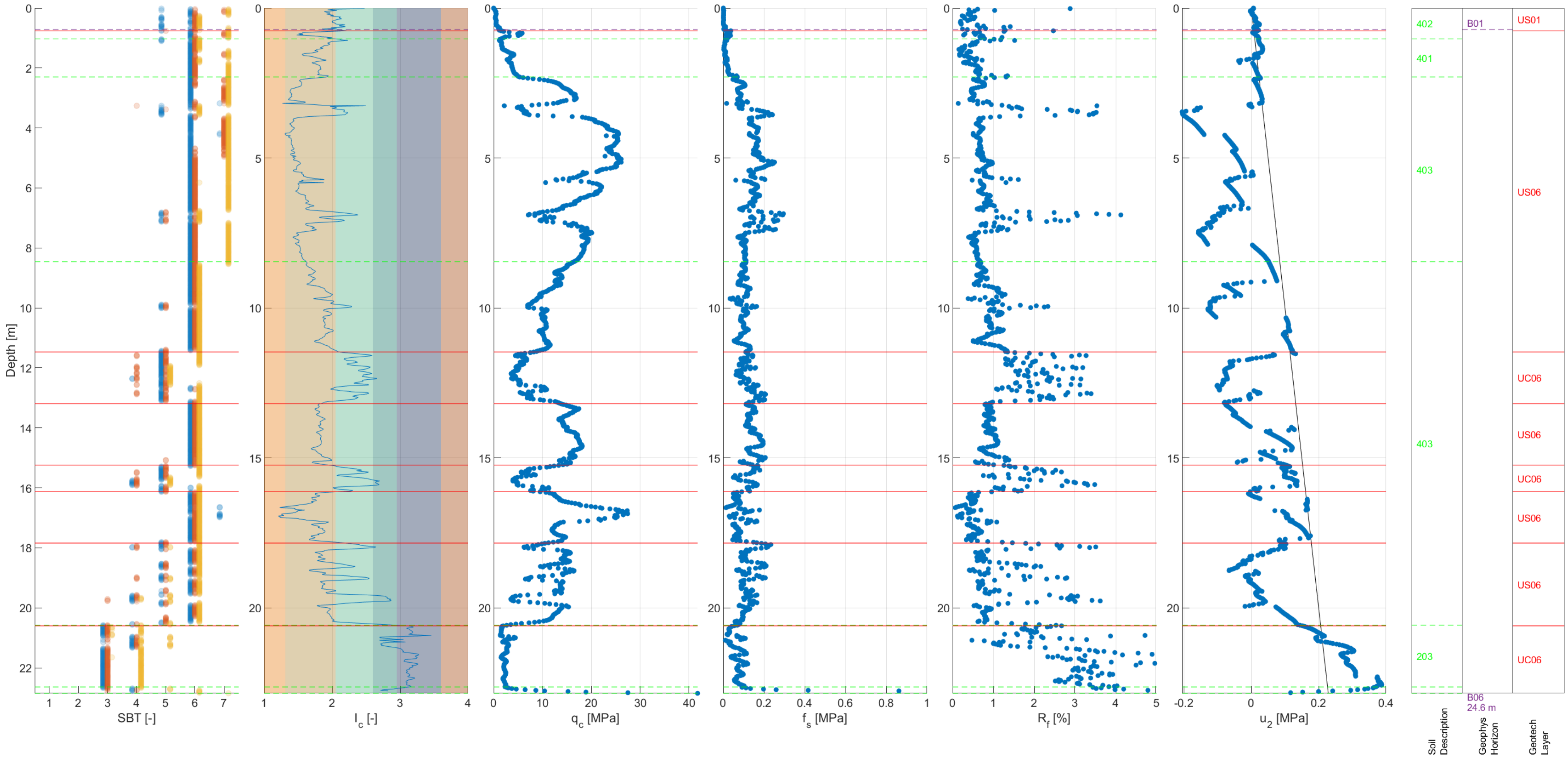

Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
B01
B06
54.3 m
US01
UC03
US03
US06
UC06
US06
UC06
401
203
202
402

KG_24


Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
201
UC01
B01
UC02
201
B02
US06
205
207
403
UC06
B06
24.9 m
Soil Description
Geophys Horizon
Geotech Layer


KG_25
Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
B01
B05
B06
B07
US01
UC05
US06
UC06
US06
UC07
401
403
404
408
220
301
202
805

KG_26

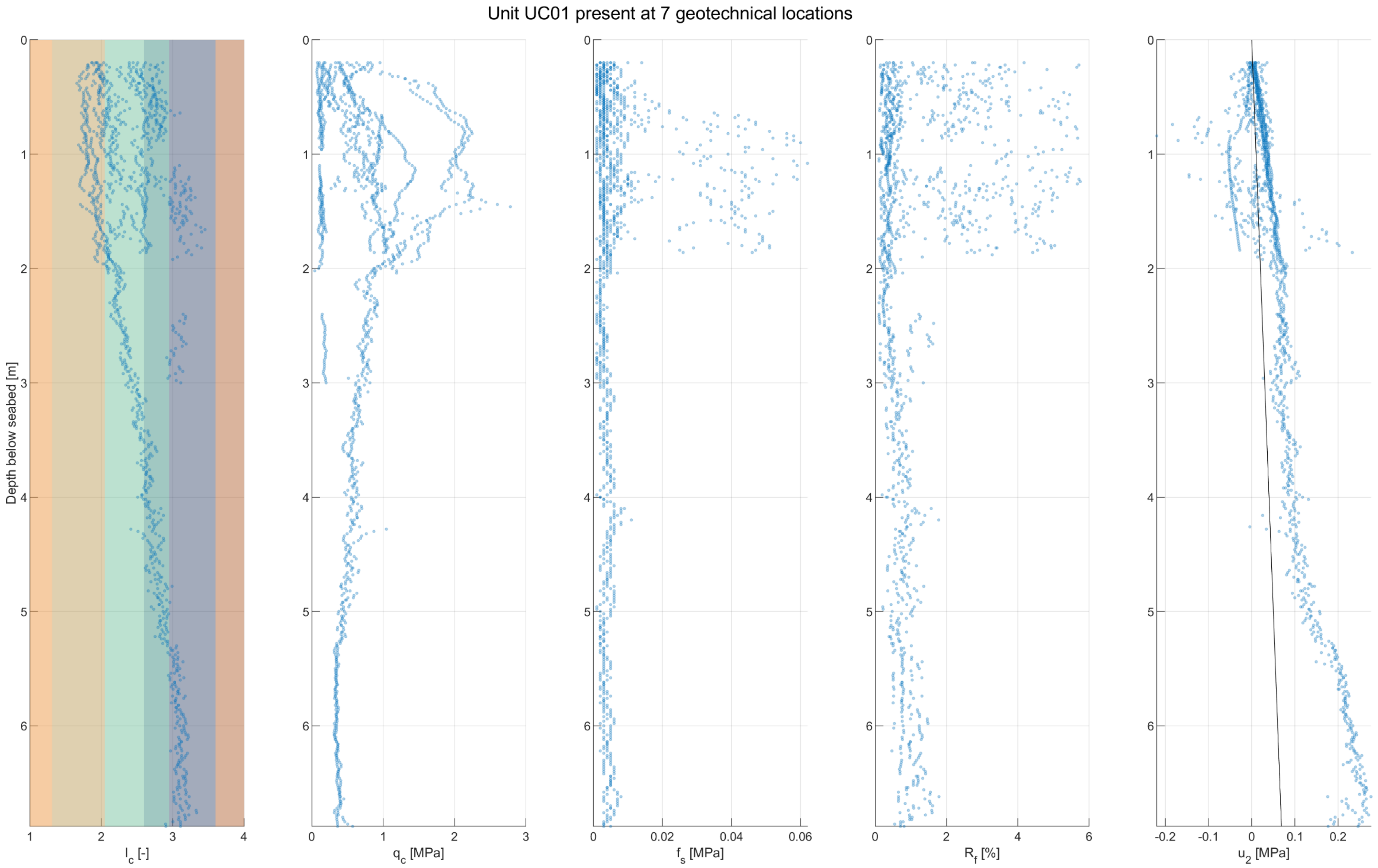

Depth [m]
SBT [-]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]
Soil Description
Geophys Horizon
Geotech Layer
402
401
403
403
203
B01
B06
24.6 m
US01
US06
UC06
US06
UC06
US06
US06
UC06

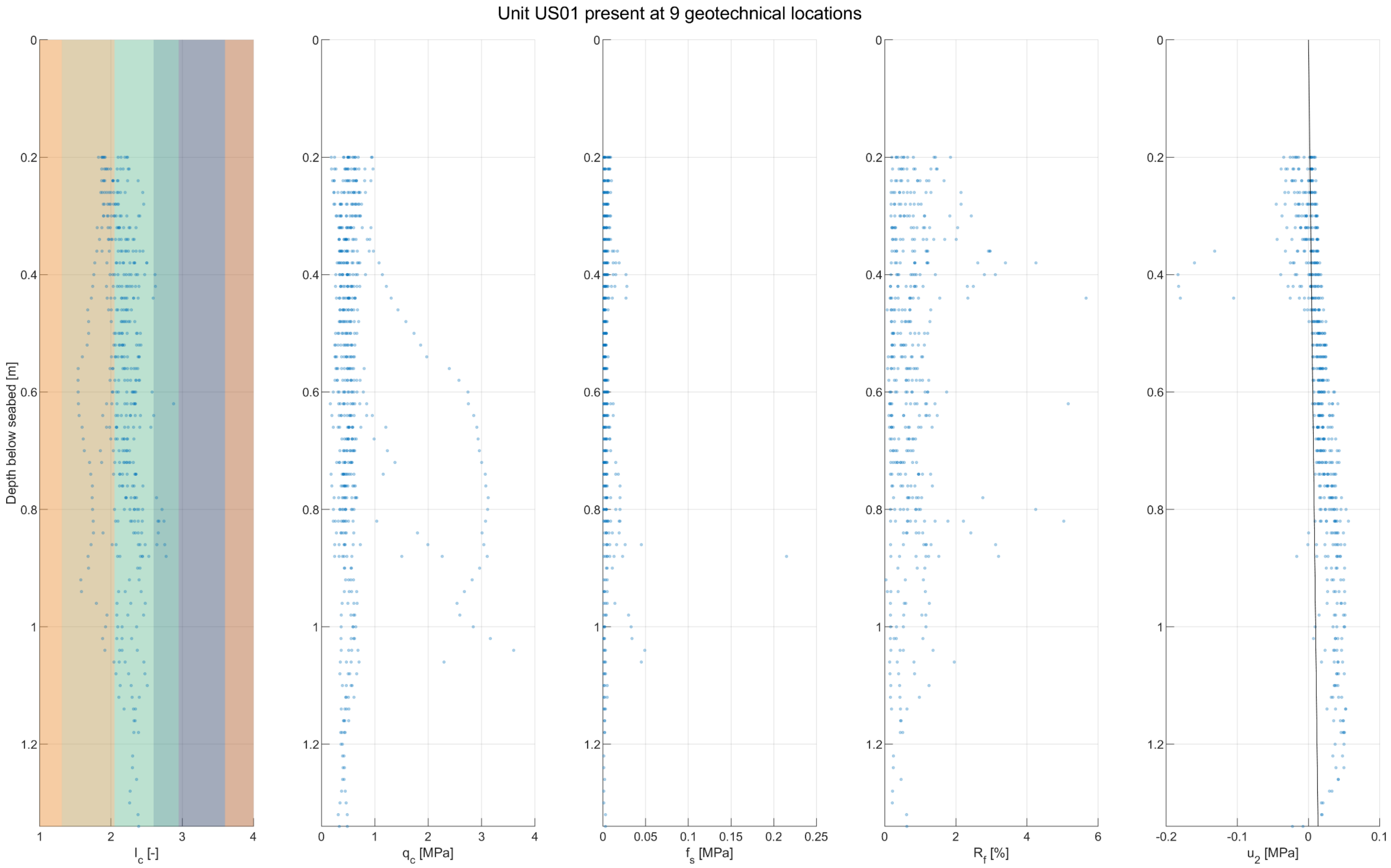
Appendix B CPT for geotechnical units

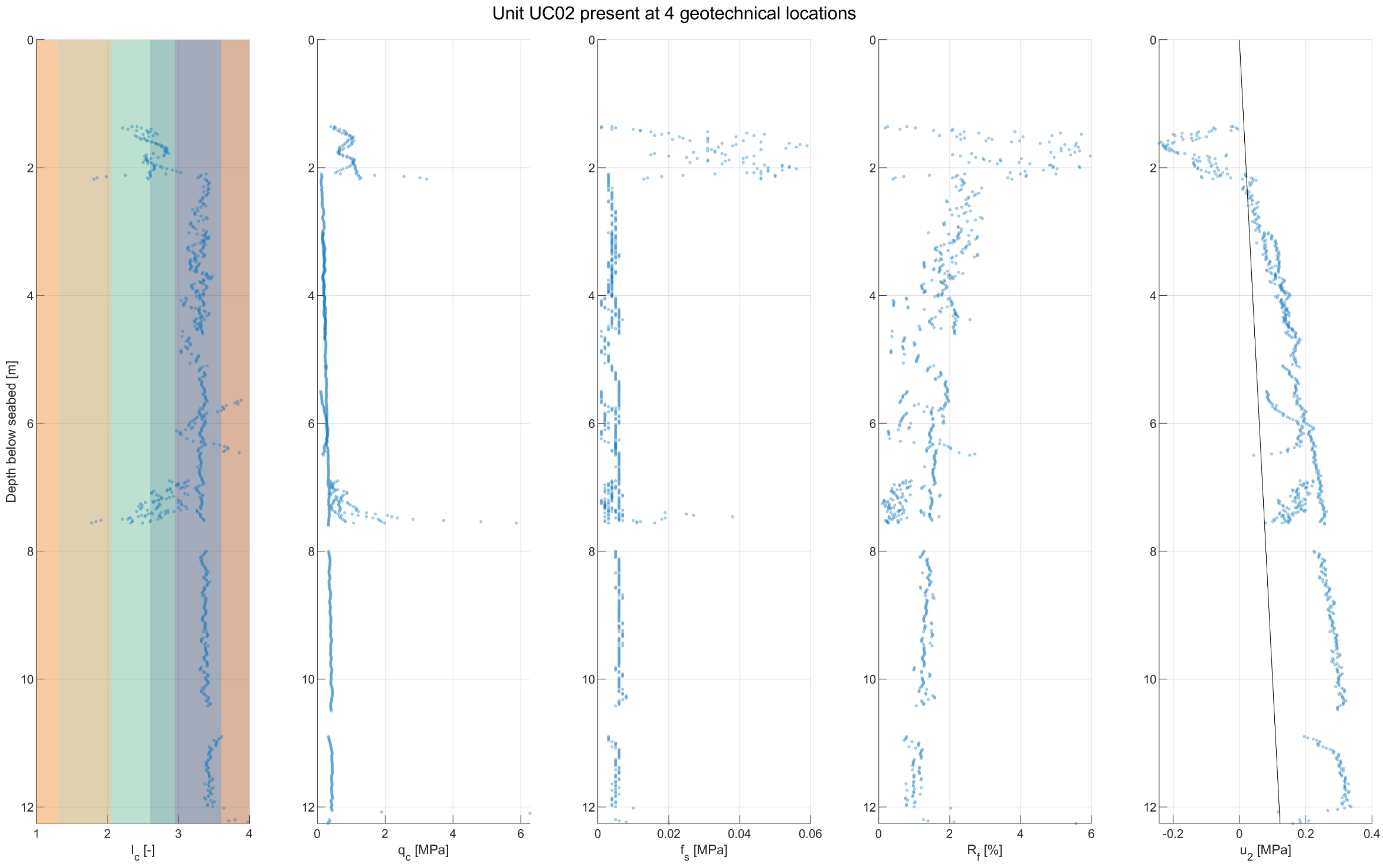
This appendix presents the CPT data available from each of the geotechnical units and present the data in Robertson soil classification charts. The scatter data in the Robertson SBT charts are considering a colour for indicating the density of data in different areas. For presenting the data per unit, the first 20 cm of each CPT push has been removed from the data sample as these are not found representative for the actual unit properties.

B.1 CPT data presented by geotechnical units

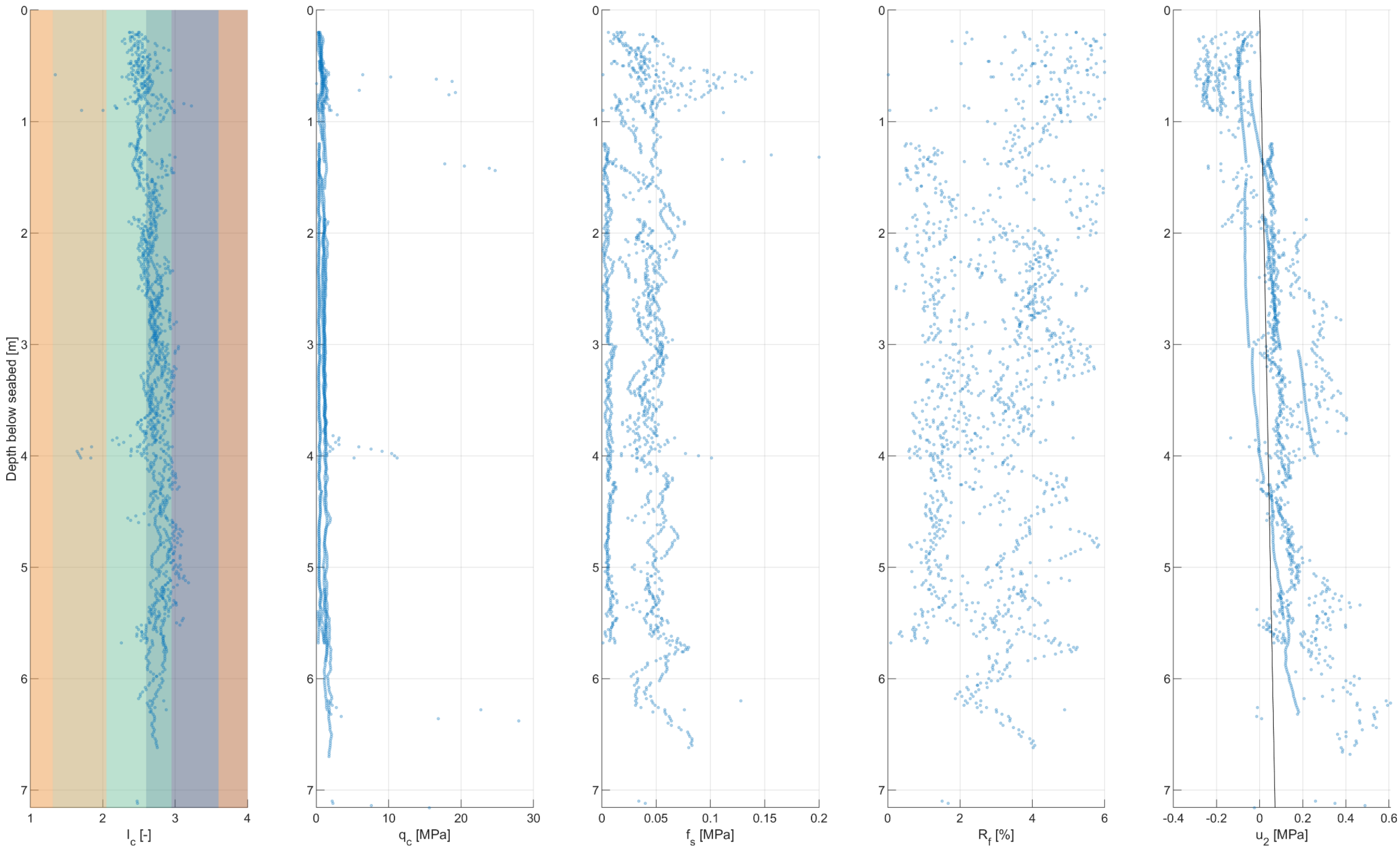
CPT data is presented in graphs on the following pages.

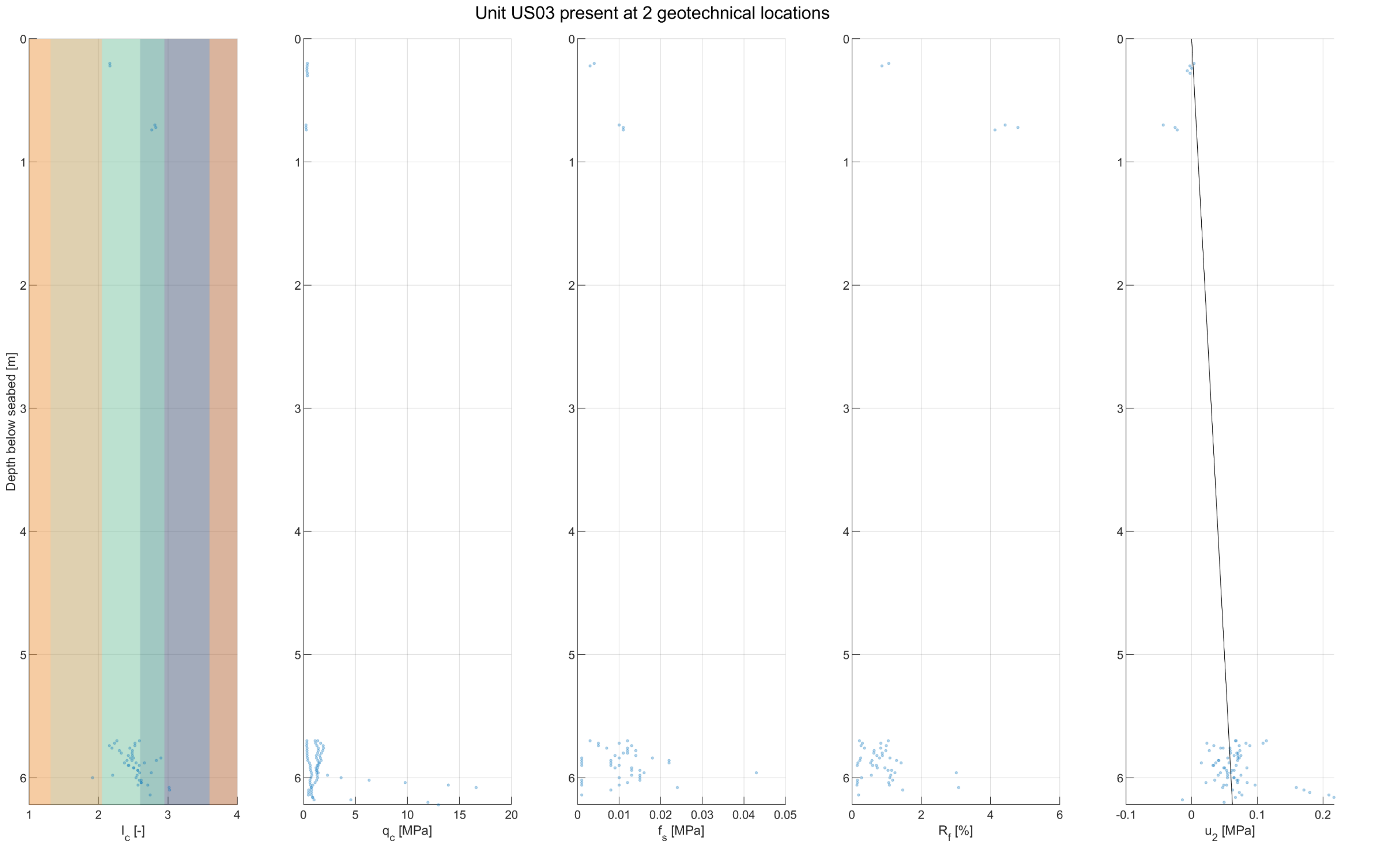

Unit UC01 present at 7 geotechnical locations
Depth below seabed [m]
0
1
2
3
4
5
6
1
2
3
4
Ic [-]
0
1
2
3
qc [MPa]
0
0.02
0.04
0.06
fs [MPa]
0
2
4
6
Rf [%]
-0.2
-0.1
0
0.1
0.2
u2 [MPa]


Unit US01 present at 9 geotechnical locations
Depth below seabed [m]
0
0.2
0.4
0.6
0.8
1
1.2
1
2
3
4
Ic [-]
0
1
2
3
4
qc [MPa]
0
0.05
0.1
0.15
0.2
0.25
fs [MPa]
0
2
4
6
Rf [%]
-0.2
-0.1
0
0.1
u2 [MPa]

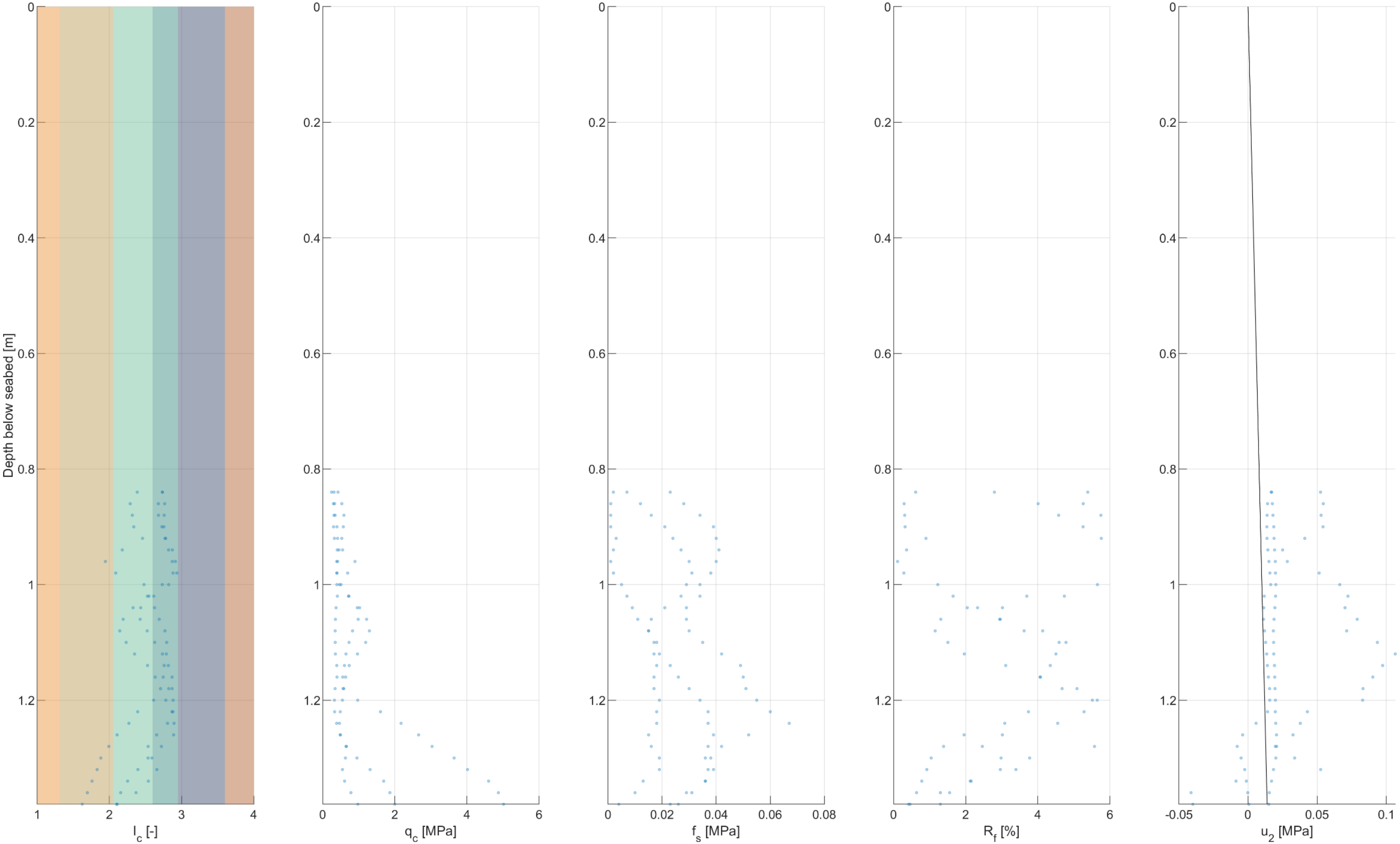

Unit UC02 present at 4 geotechnical locations
Depth below seabed [m]
0
2
4
6
8
10
12
1
2
3
4
Ic [-]
0
2
4
6
qc [MPa]
0
0.02
0.04
0.06
fs [MPa]
0
2
4
6
Rf [%]
-0.2
0
0.2
0.4
u2 [MPa]

Unit UC03 present at 7 geotechnical locations

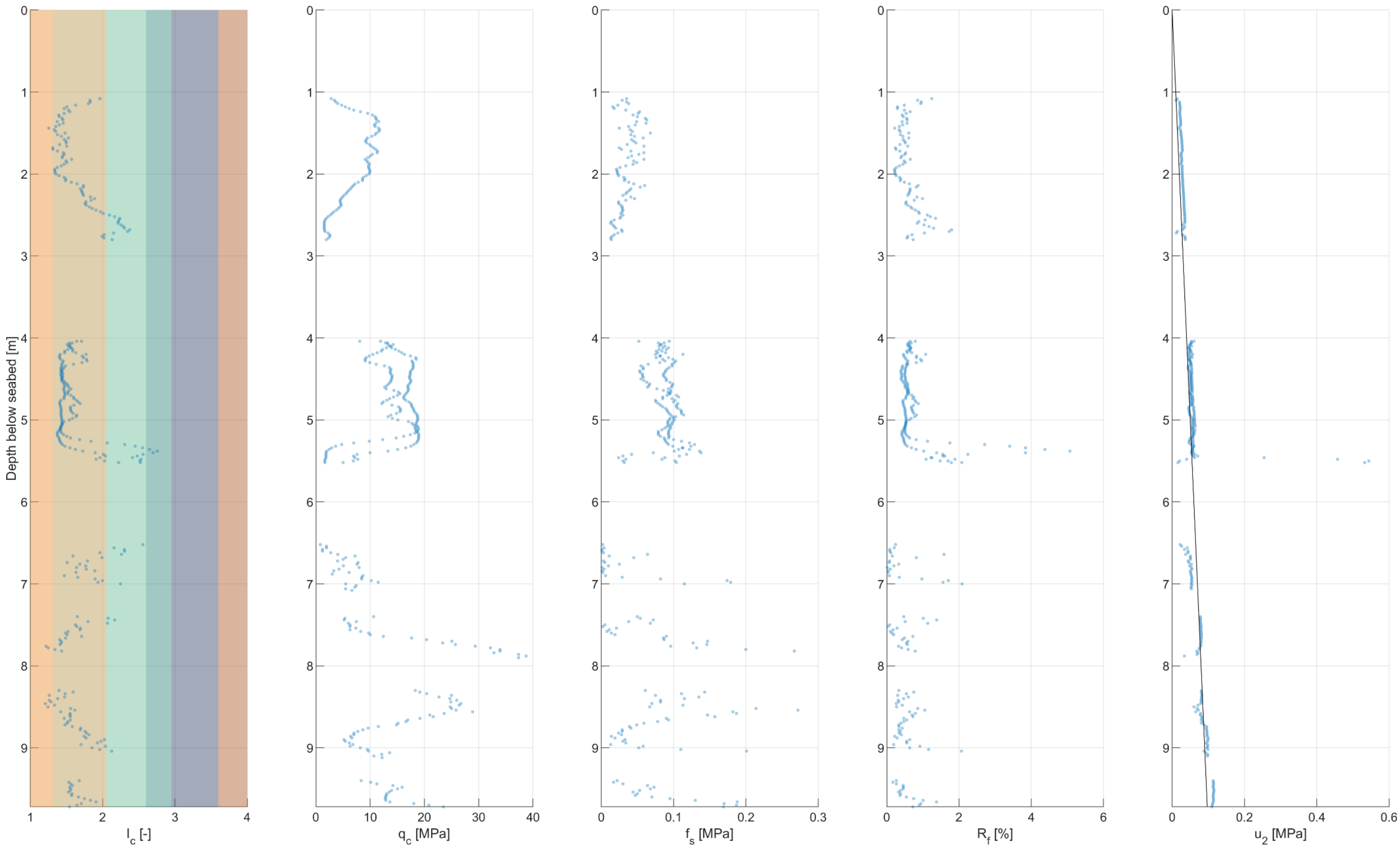



Unit US03 present at 2 geotechnical locations
Depth below seabed [m]
0
1
2
3
4
5
6
1
2
3
4
Ic [-]
0
5
10
15
20
qc [MPa]
0
0.01
0.02
0.03
0.04
0.05
fs [MPa]
0
2
4
6
Rf [%]
-0.1
0
0.1
0.2
u2 [MPa]

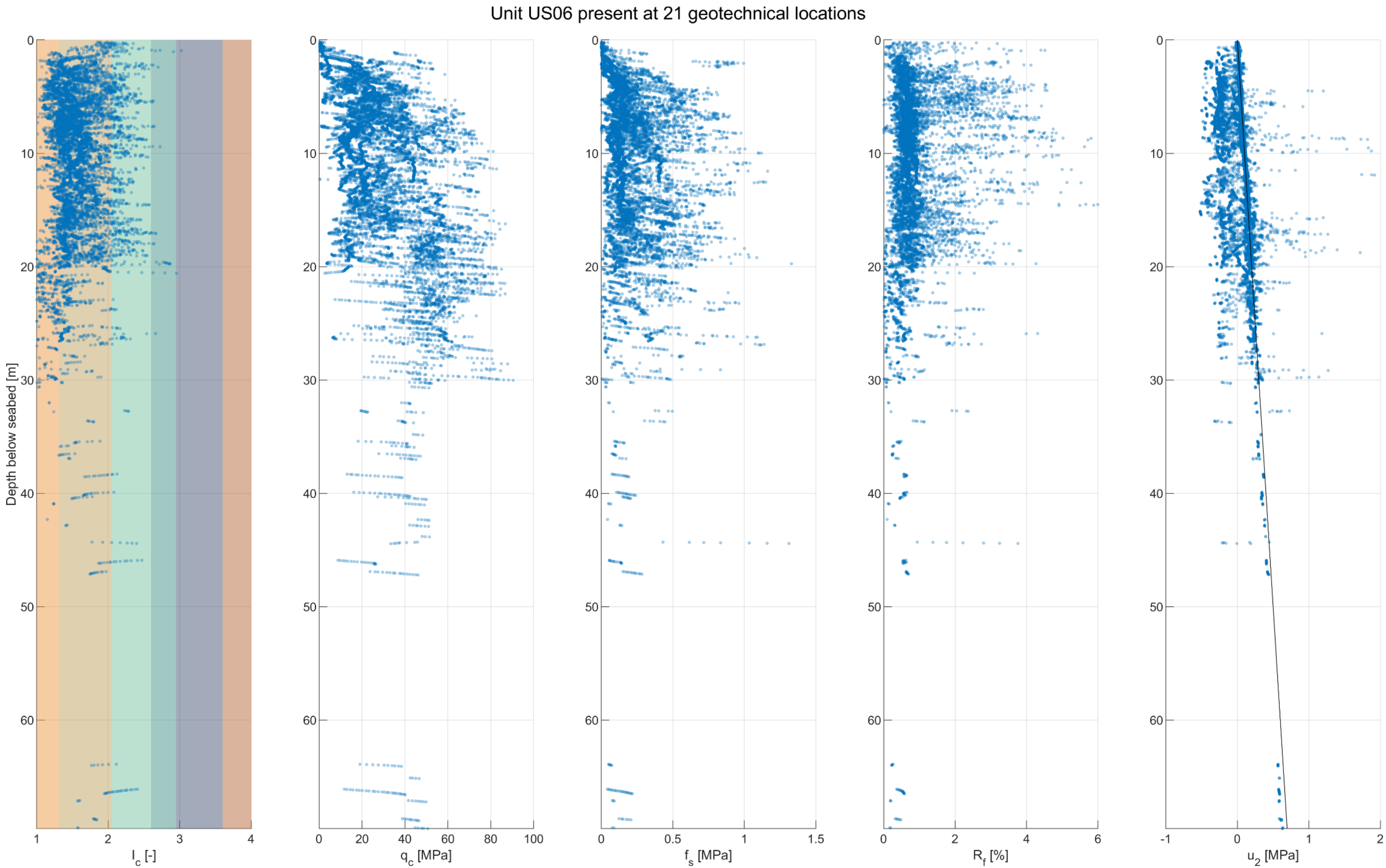
Unit UC05 present at 1 geotechnical locations



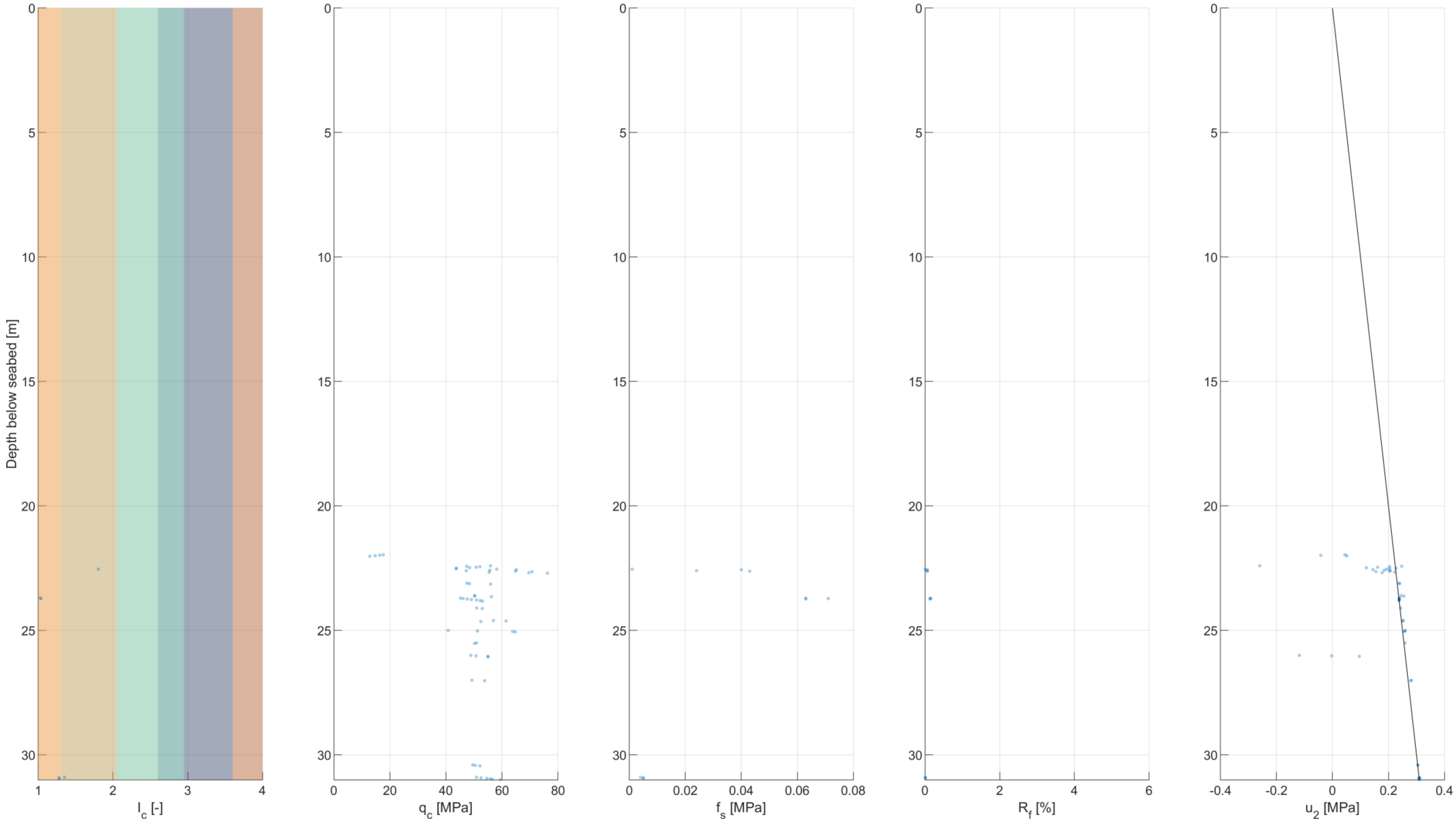
Unit US05 present at 3 geotechnical locations




Unit UC06 present at 20 geotechnical locations
Depth below seabed [m]
I_c [-]
q_c [MPa]
f_s [MPa]
R_f [%]
u_2 [MPa]


Unit US06 present at 21 geotechnical locations
Depth below seabed [m]
0
10
20
30
40
50
60
1
2
3
4
I_c [-]
0
20
40
60
80
100
q_c [MPa]
0
0.5
1
1.5
f_s [MPa]
0
2
4
6
R_f [%]
-1
0
1
2
u_2 [MPa]

Unit UC07 present at 4 geotechnical locations



B.2 Presentation of geotechnical unit groupings by Robertson charts

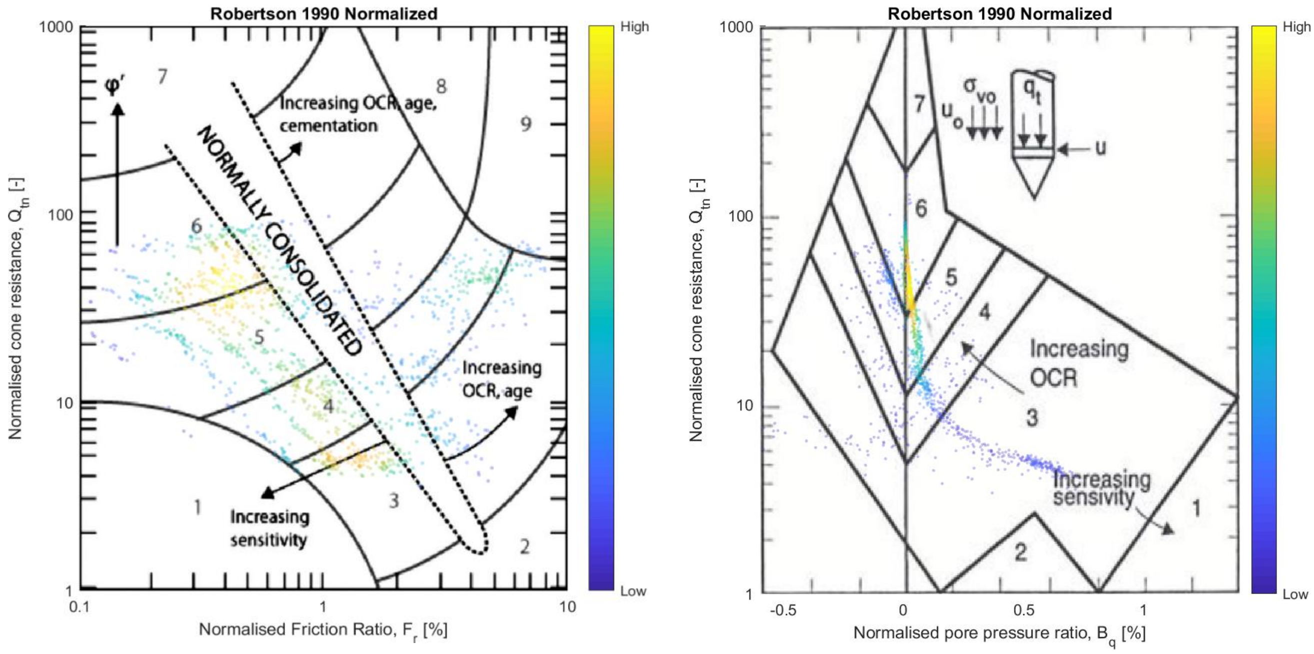


Figure B-1 CPT data plotted in Robertson SBT chart for UC01.

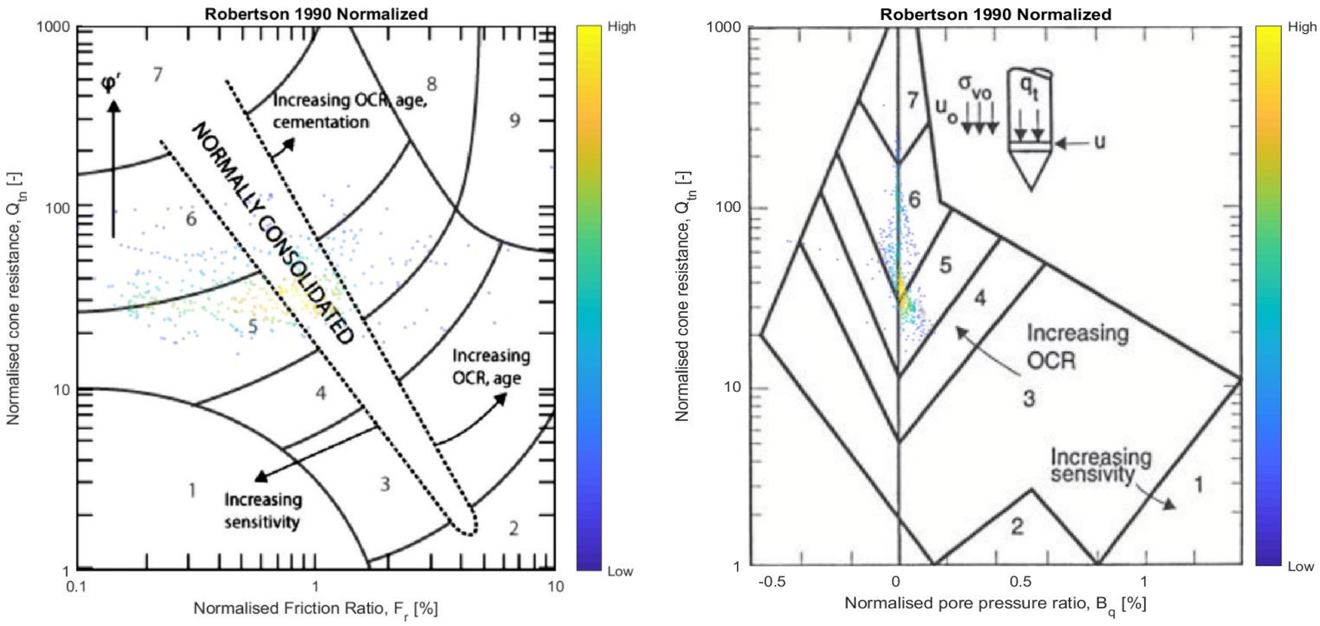


Figure B-2 CPT data plotted in Robertson SBT chart for US01.

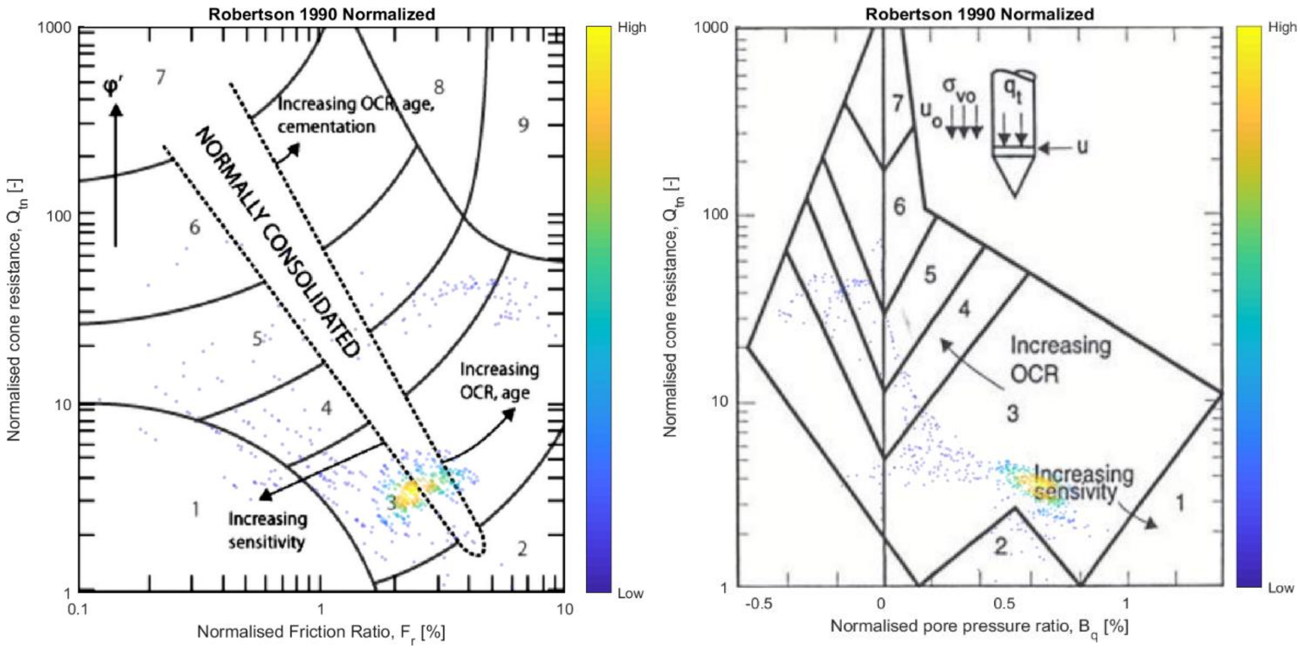


Figure B-3 CPT data plotted in Robertson SBT chart for UC02.

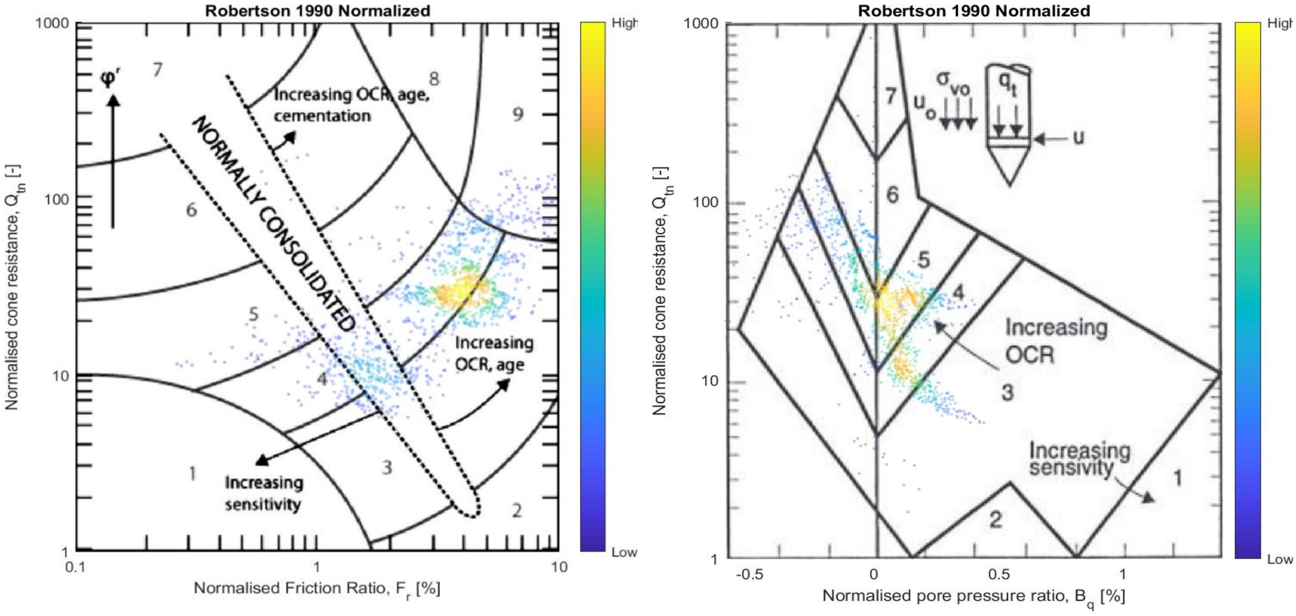


Figure B-4 CPT data plotted in Robertson SBT chart for UC03.

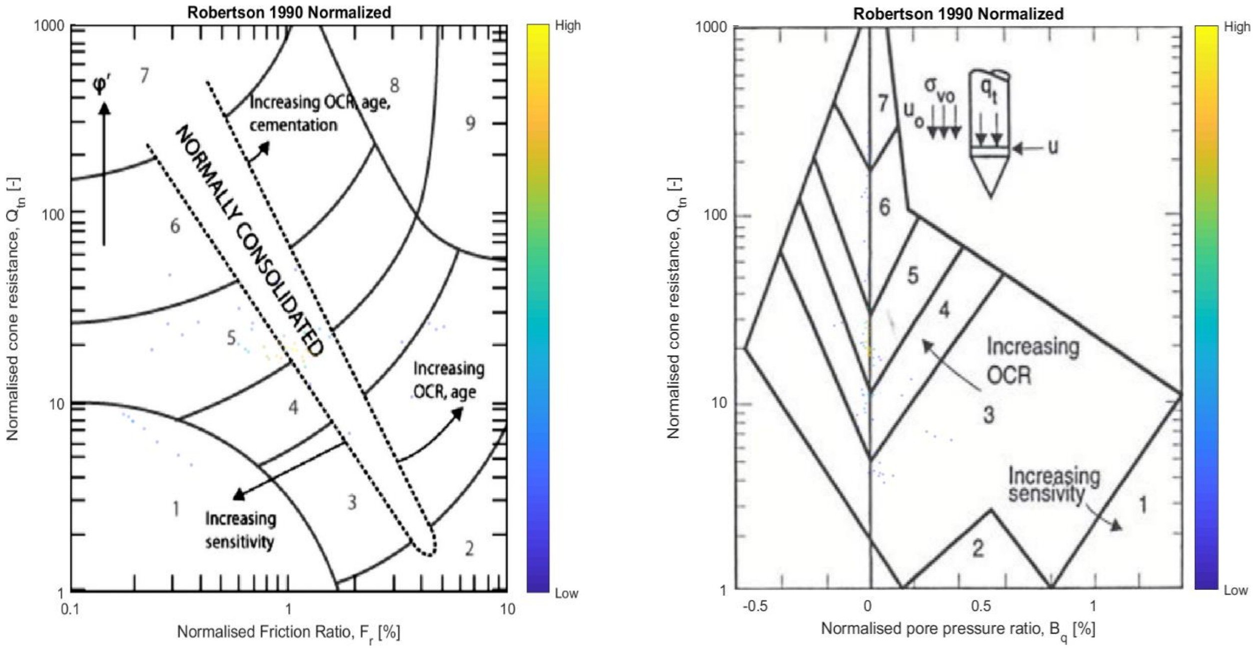


Figure B-5 CPT data plotted in Robertson SBT chart for US03.

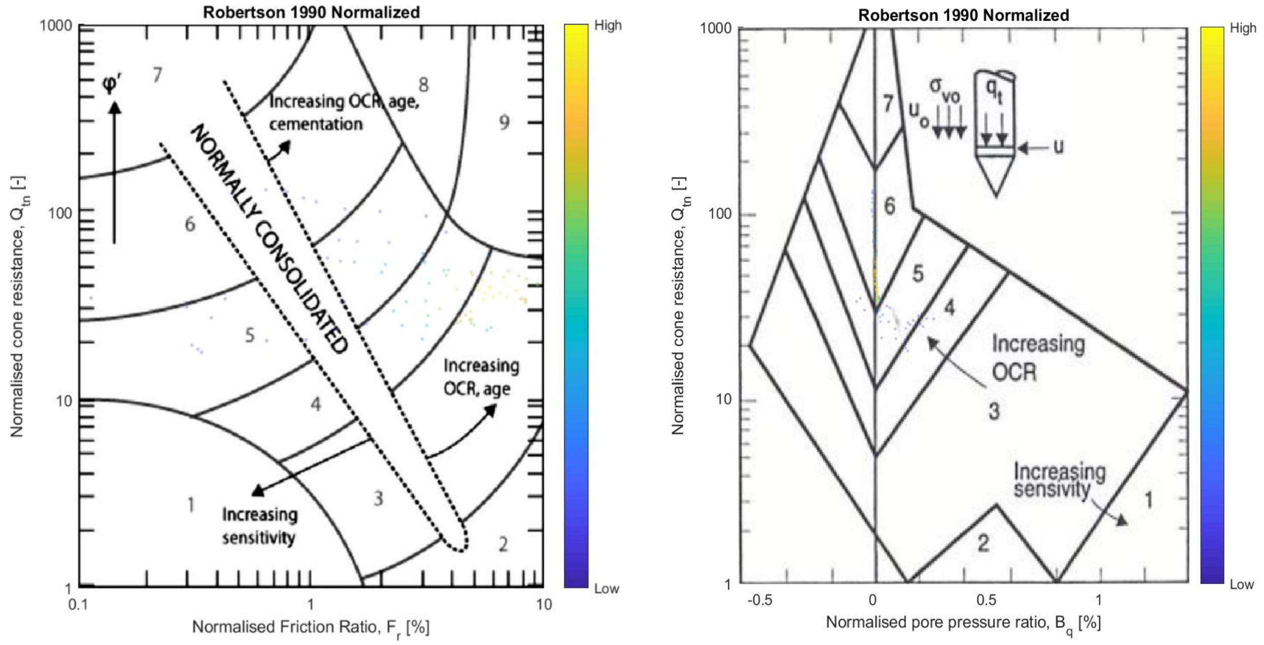


Figure B-6 CPT data plotted in Robertson SBT chart for UC05.

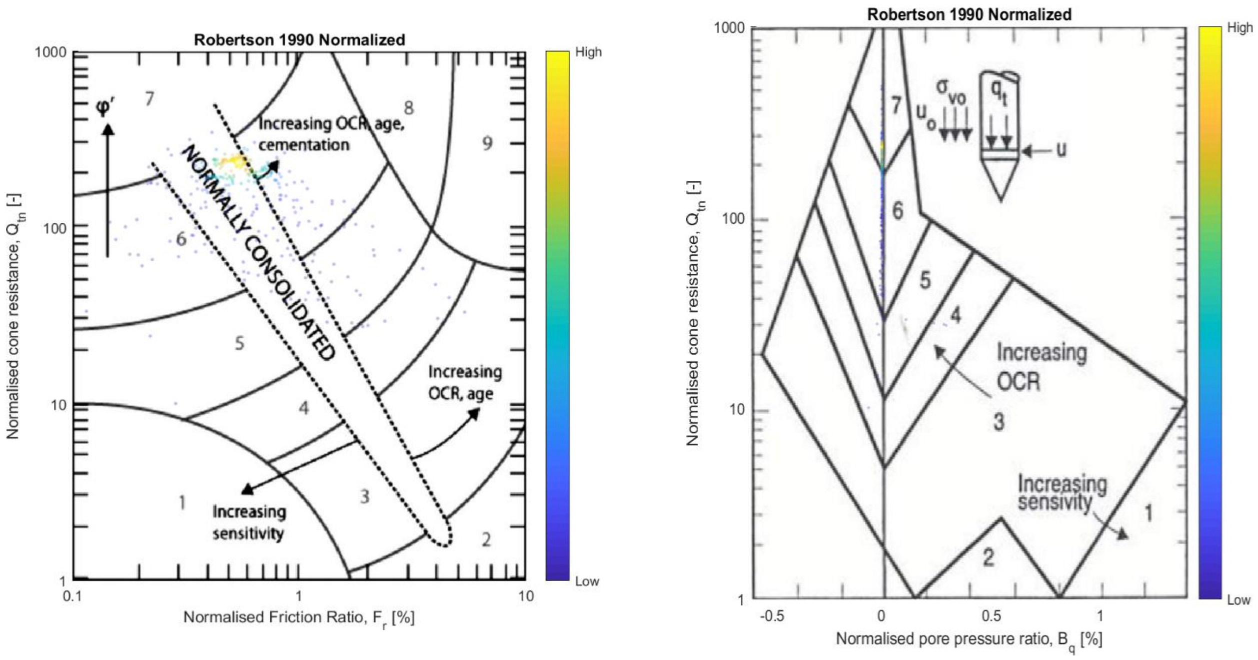


Figure B-7 CPT data plotted in Robertson SBT chart for US05.

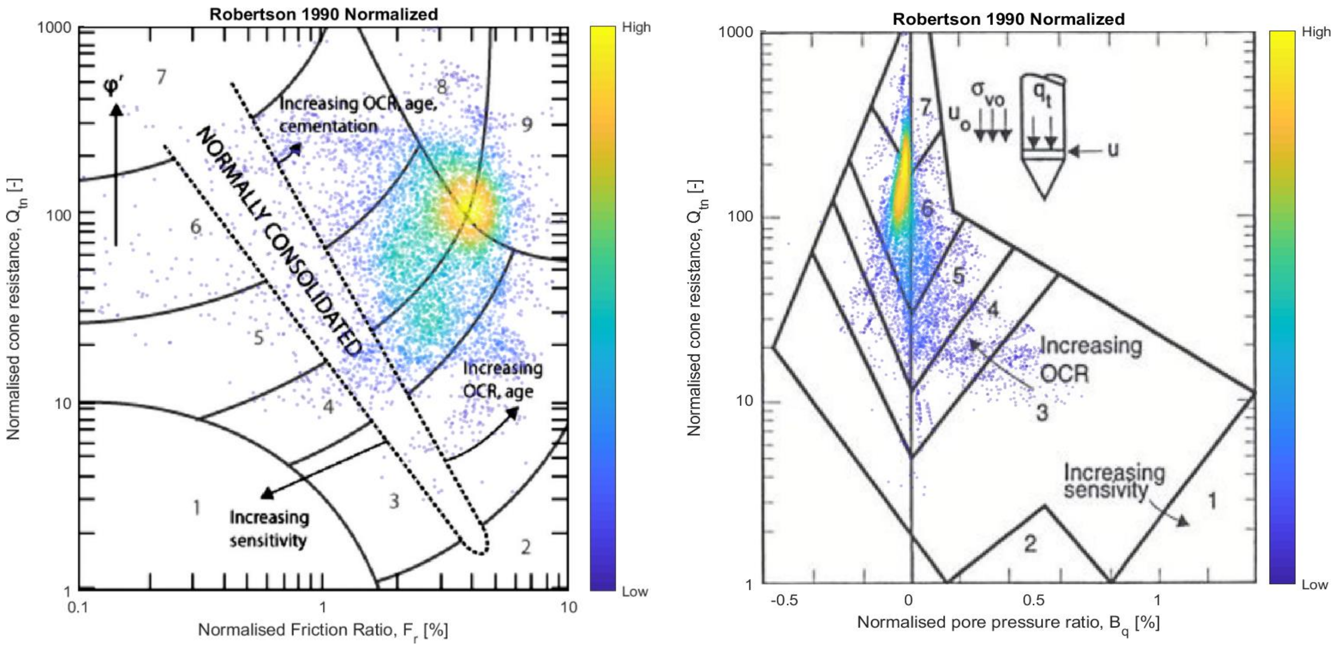


Figure B-8 CPT data plotted in Robertson SBT chart for UC06.

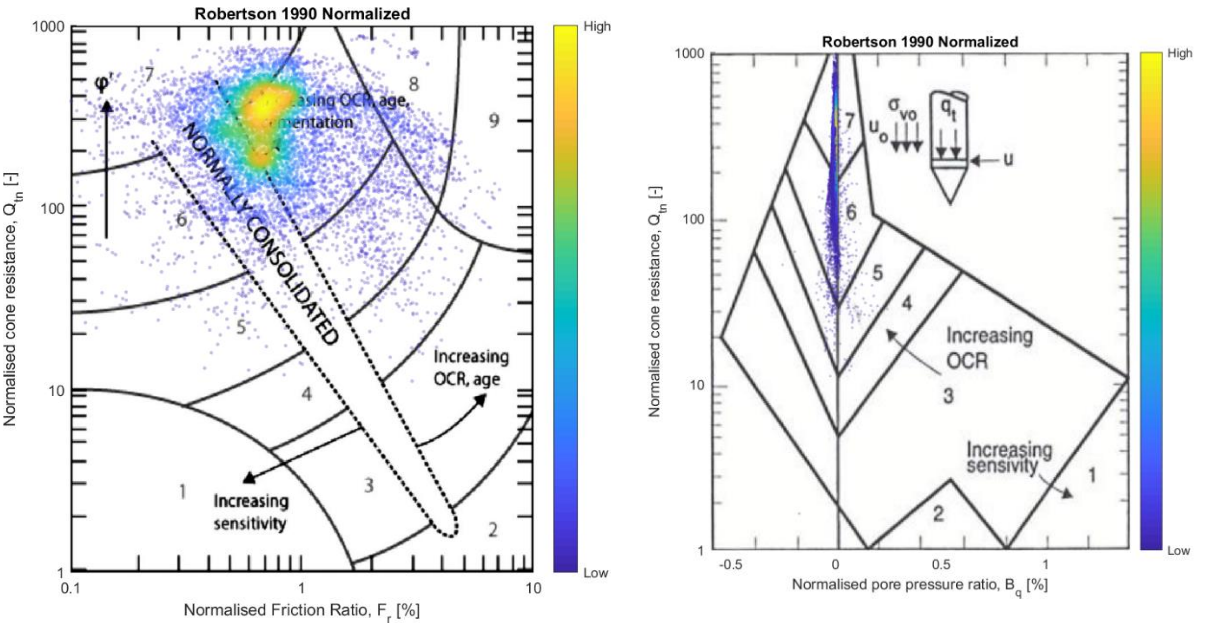


Figure B-9 CPT data plotted in Robertson SBT chart for US06.

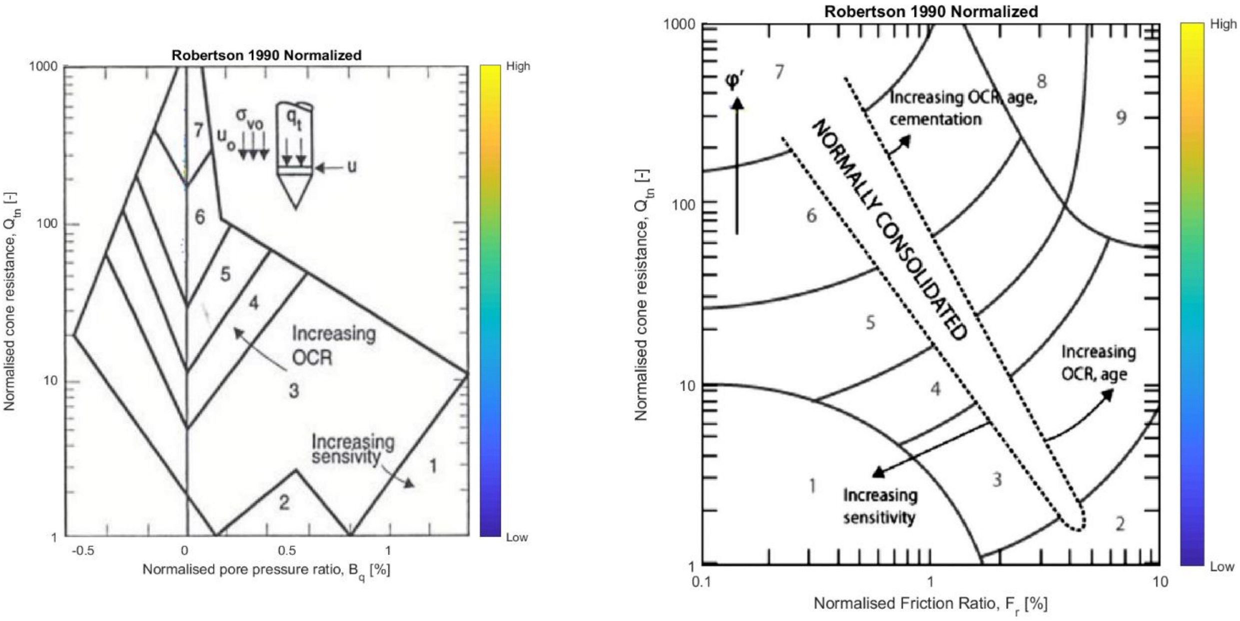


Figure B-10 CPT data plotted in Robertson SBT chart for UC07.

Appendix C Calculated soil properties per CPT location

This appendix presents the state-, stiffness- and strength properties with depth per geotechnical test location. An example for one location can be seen in Figure C-1. The parameters presented in the figures are derived from the methodology presented in section 8. The red horizontal lines represent the interpreted stratigraphy at the location. It is noticeable that the undrained shear strength, c_u, is only interpreted for clay units, whereas the friction angle, φ', is interpreted for sand units.

The friction angle subplots show a vertical line "I_D limit". This line indicates a maximum value of φ' provided that the relative density used to interpret the friction angle has been limited to I_D = 100%. Nevertheless, CPT-interpretation of the relative density may estimate values above 100%, hence in this case, φ' exceeds the limit line. This description also applies for the figures presented in D.3.

All figures per geotechnical test location are presented in the following pages. The data are also delivered as part of the digital delivery.

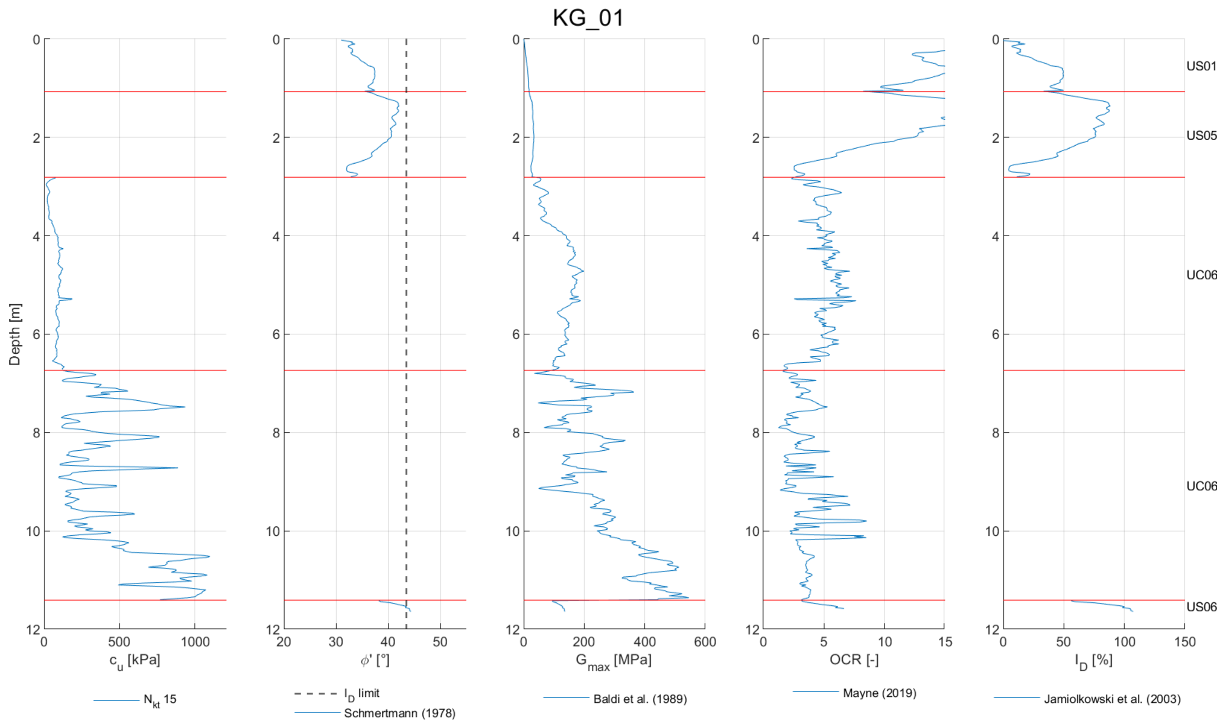
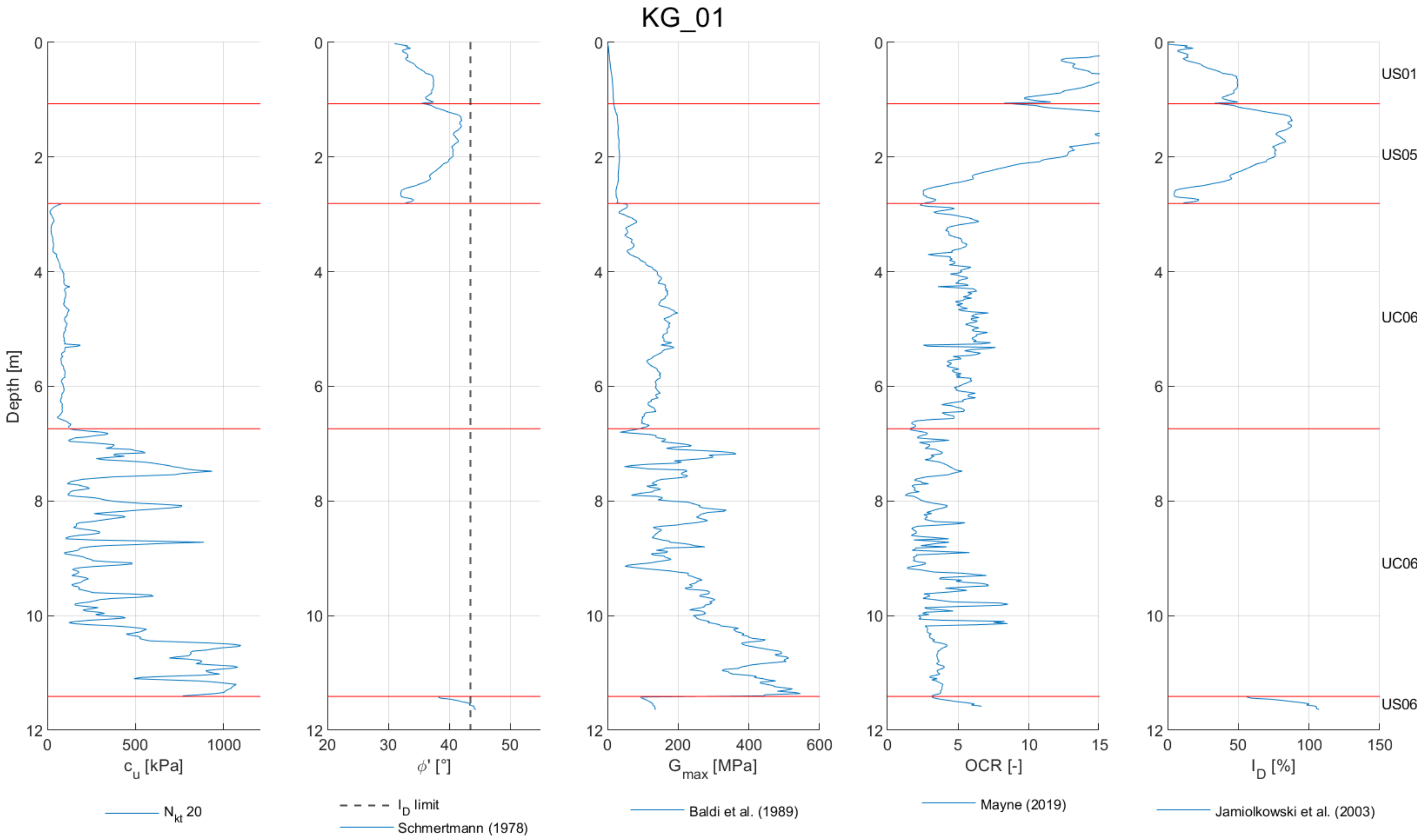
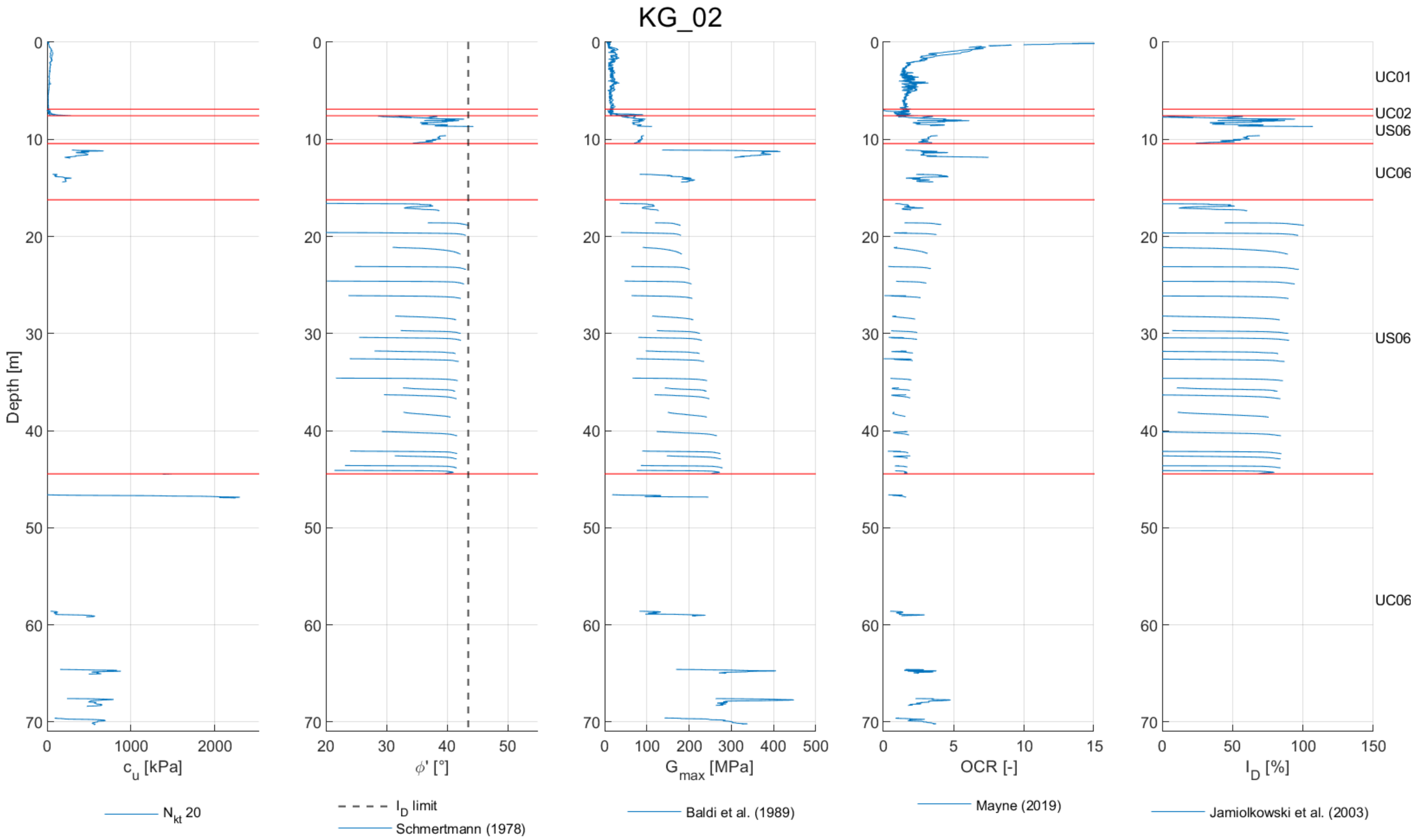
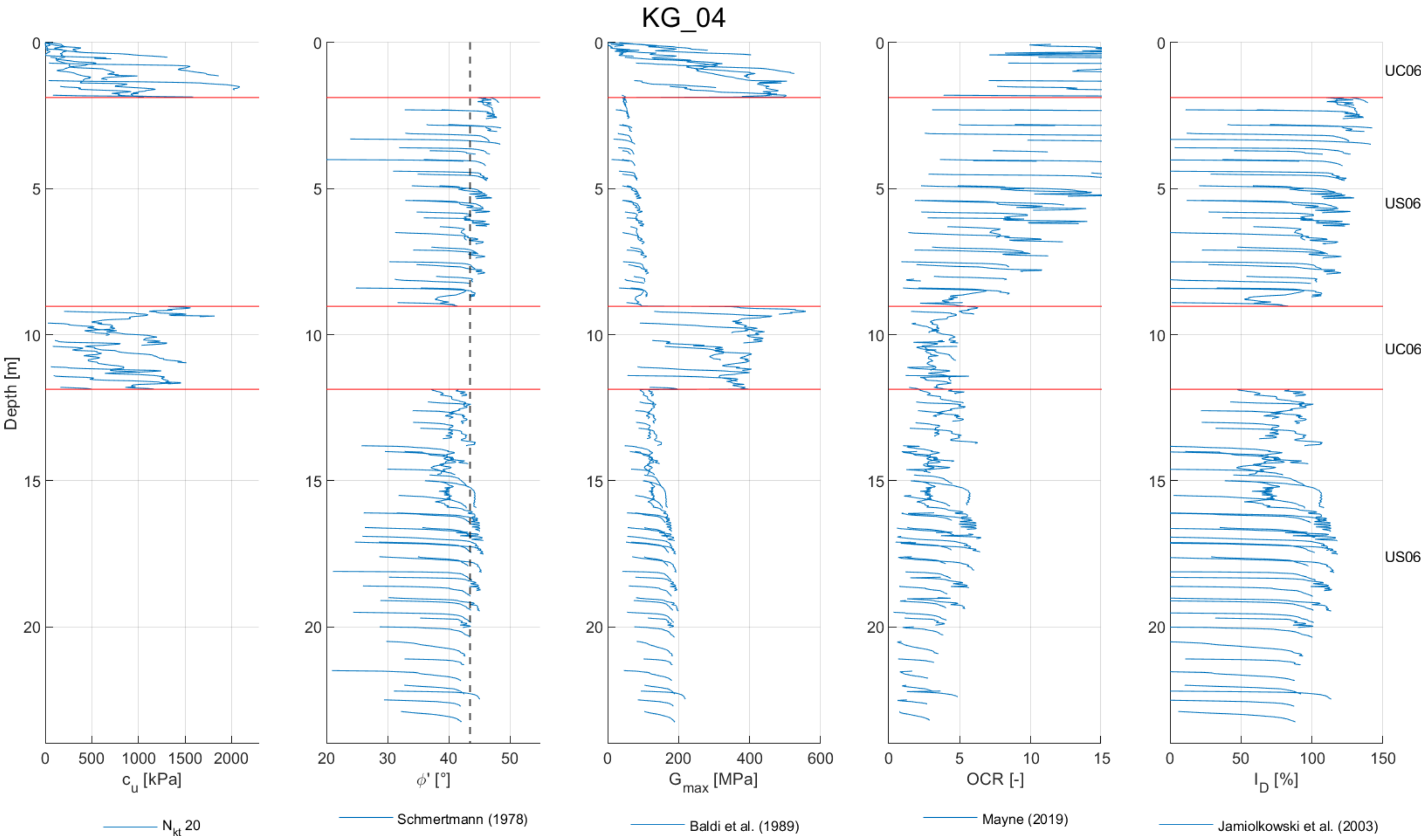
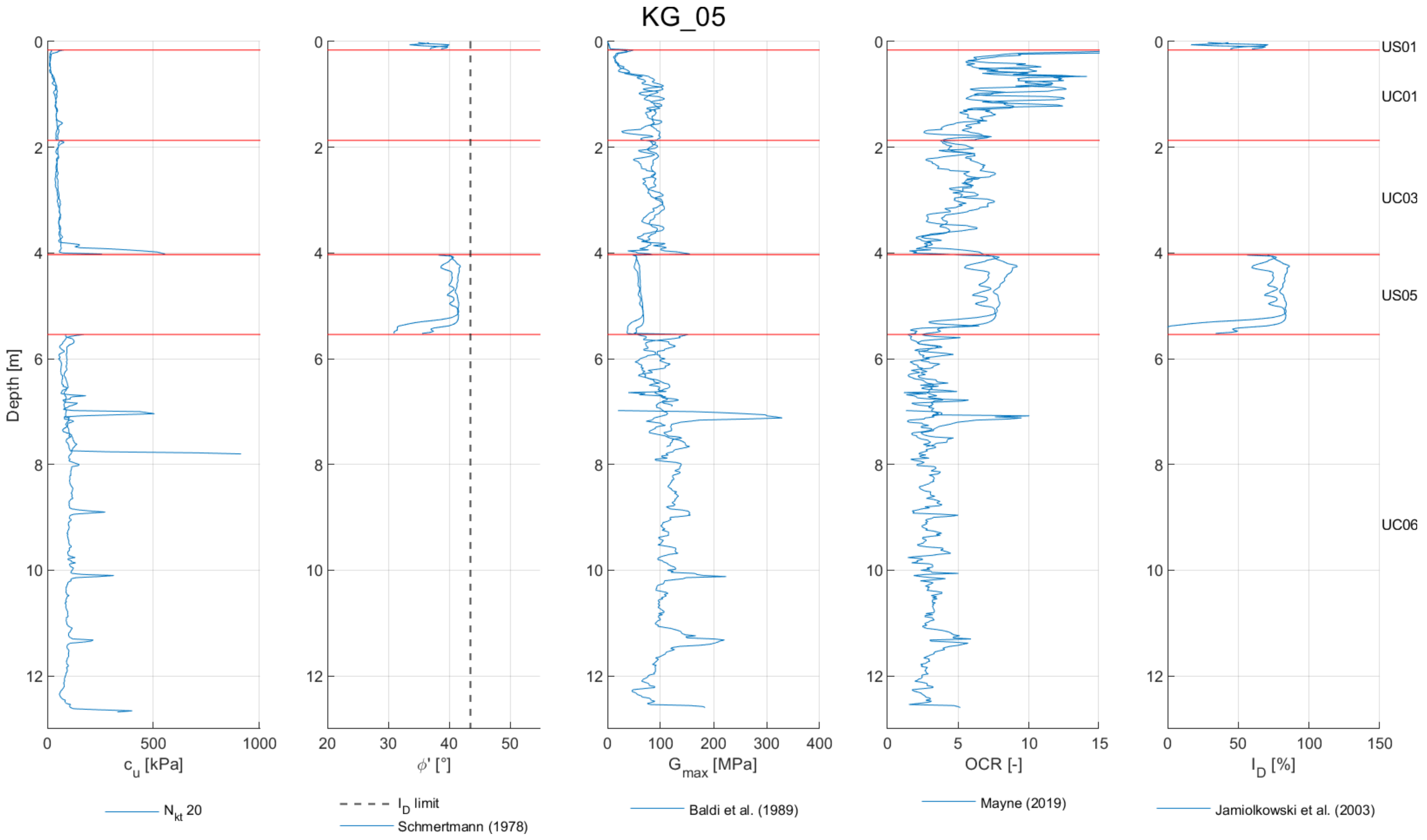


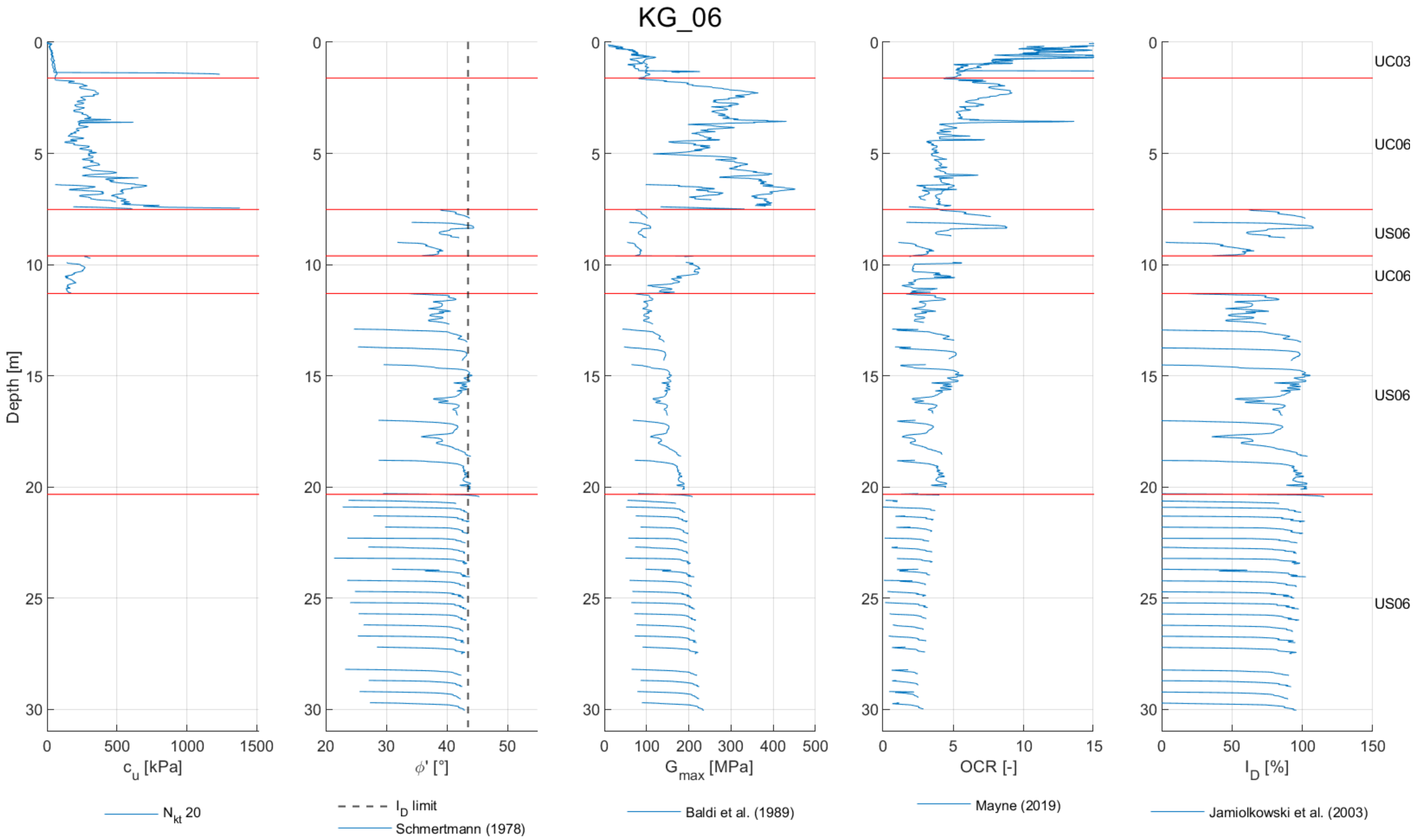
Figure C-1 Example of interpreted properties for KG_01.

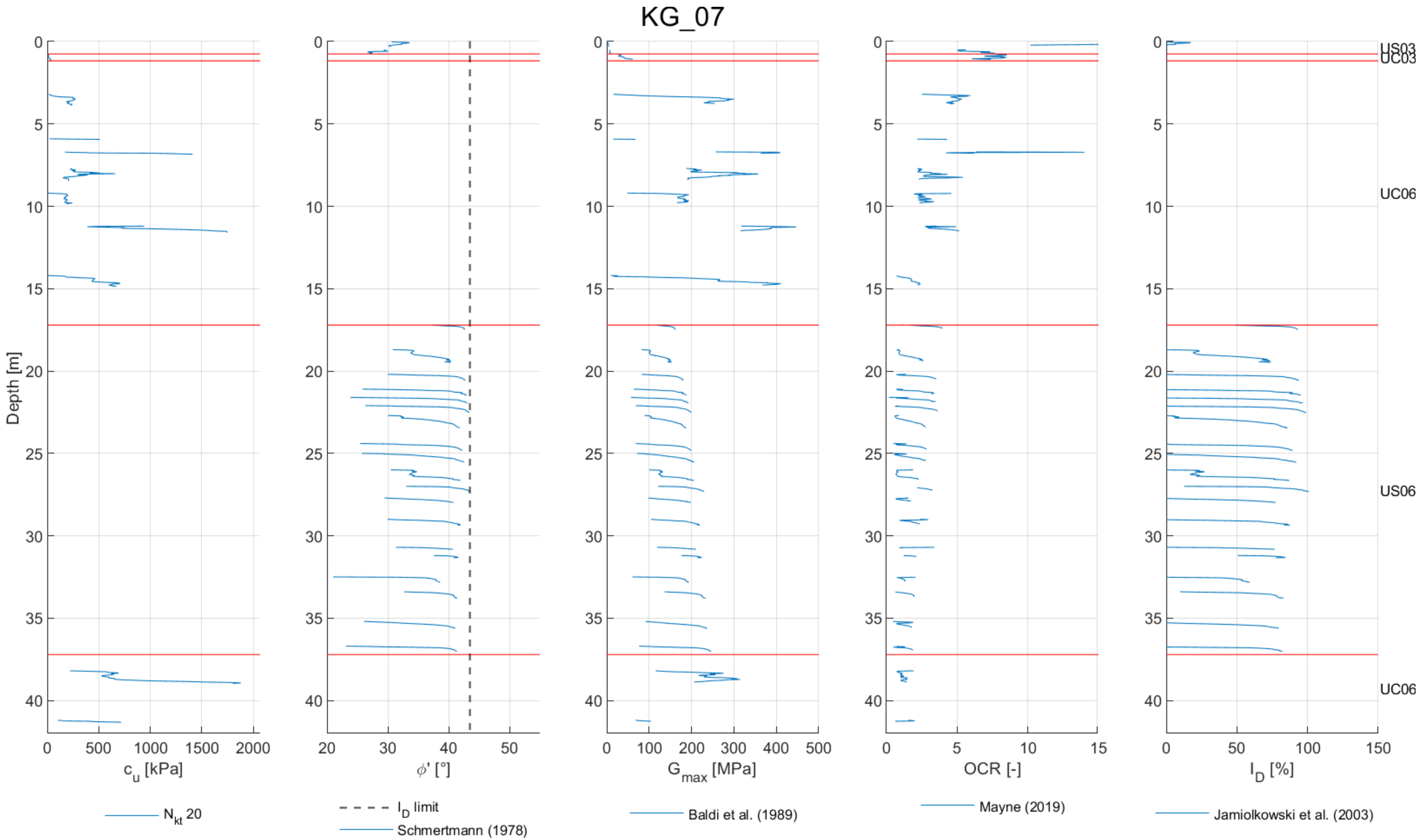

KG_01
Depth [m]
c_u [kPa]
N_kt 20
φ' [°]
I_D limit
Schmertmann (1978)
G_max [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US01
US05
UC06
UC06
US06

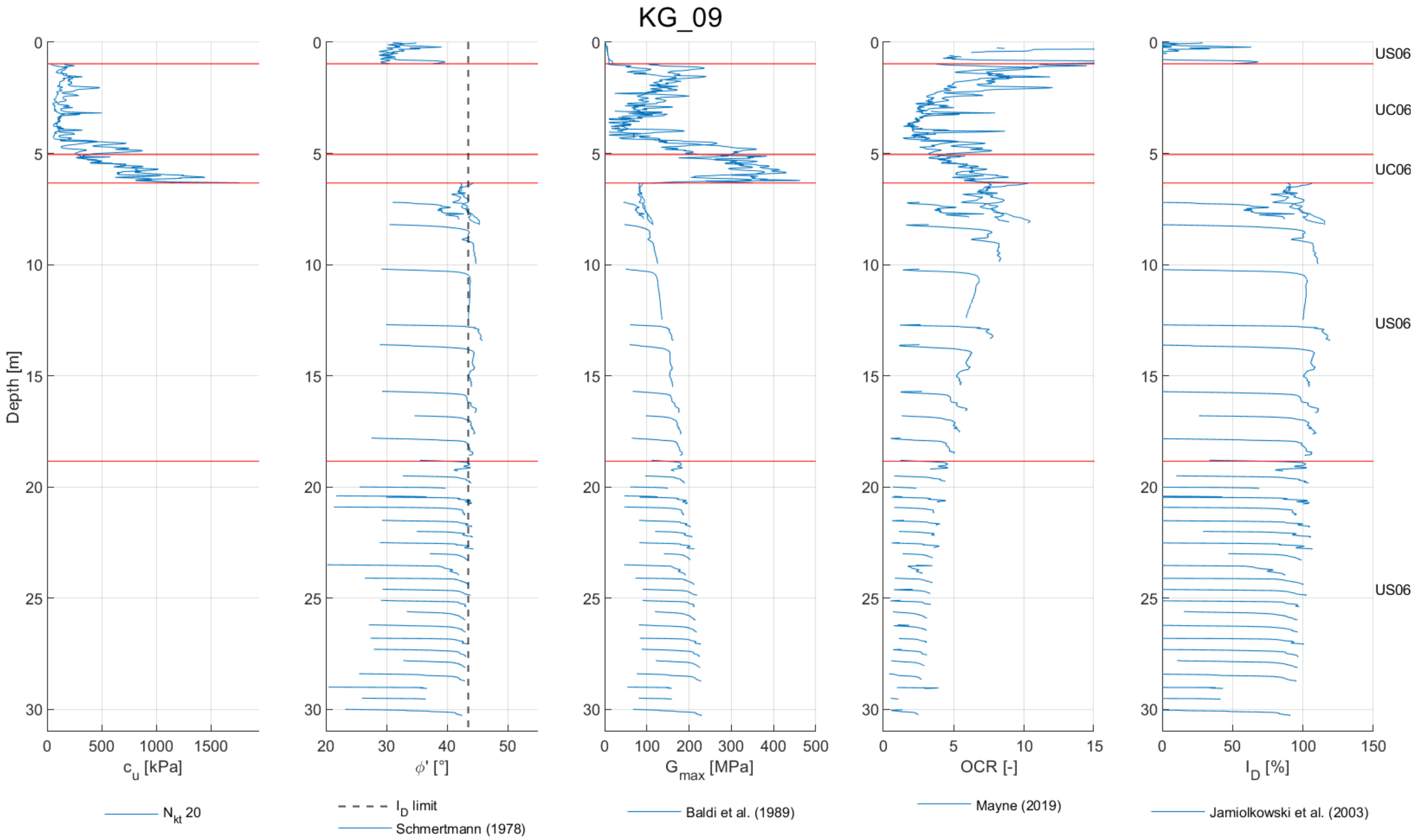

KG_02
Depth [m]
c_u [kPa]
ϕ' [°]
G_{max} [MPa]
OCR [-]
I_D [%]
UC01
UC02
US06
UC06
US06
UC06
N_{kt} 20
I_D limit
Schmertmann (1978)
Baldi et al. (1989)
Mayne (2019)
Jamiolkowski et al. (2003)

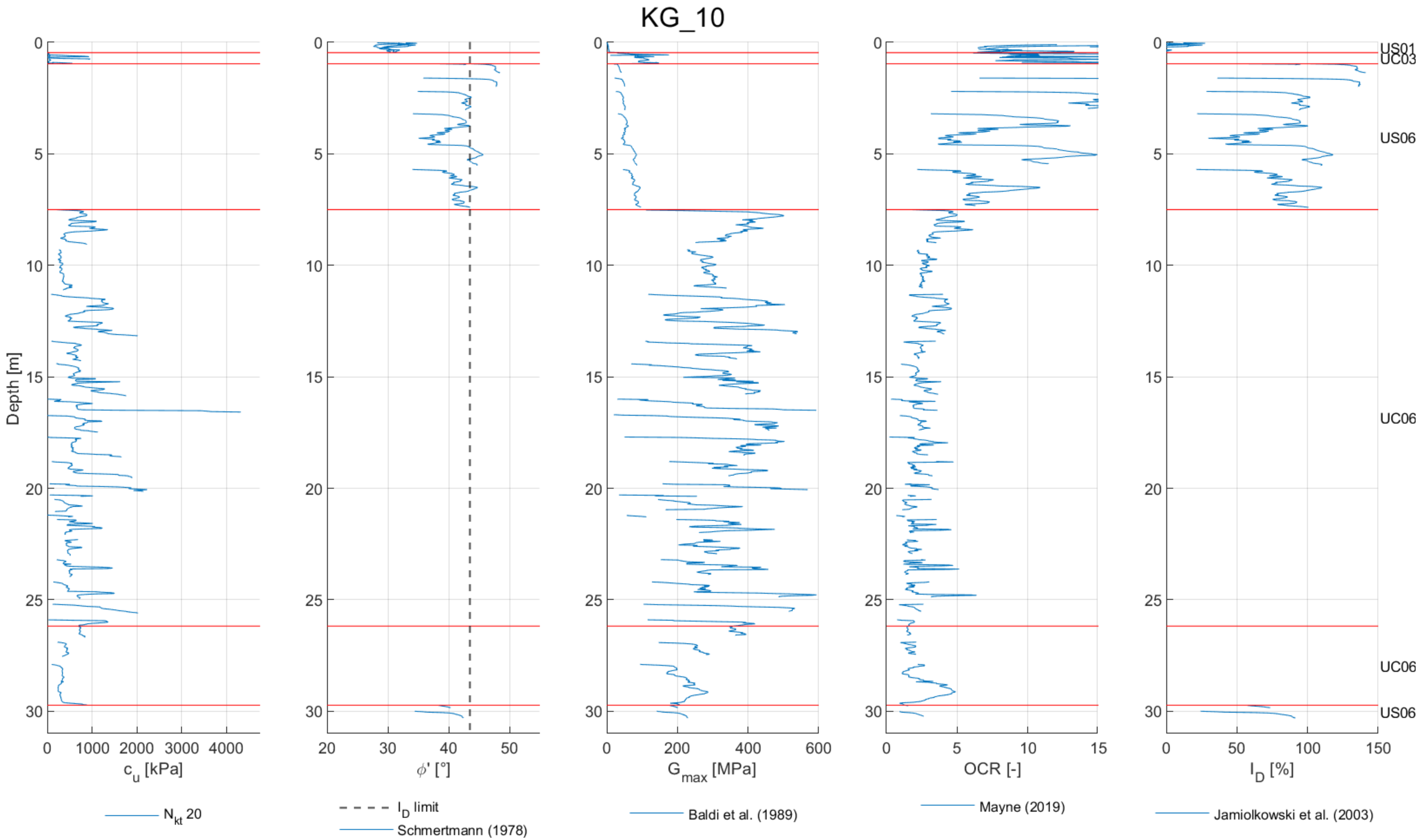

KG_04
Depth [m]
c_u [kPa]
ϕ' [°]
G_{max} [MPa]
OCR [-]
I_D [%]
UC06
US06
UC06
US06
N_{kt} 20
Schmertmann (1978)
Baldi et al. (1989)
Mayne (2019)
Jamiolkowski et al. (2003)

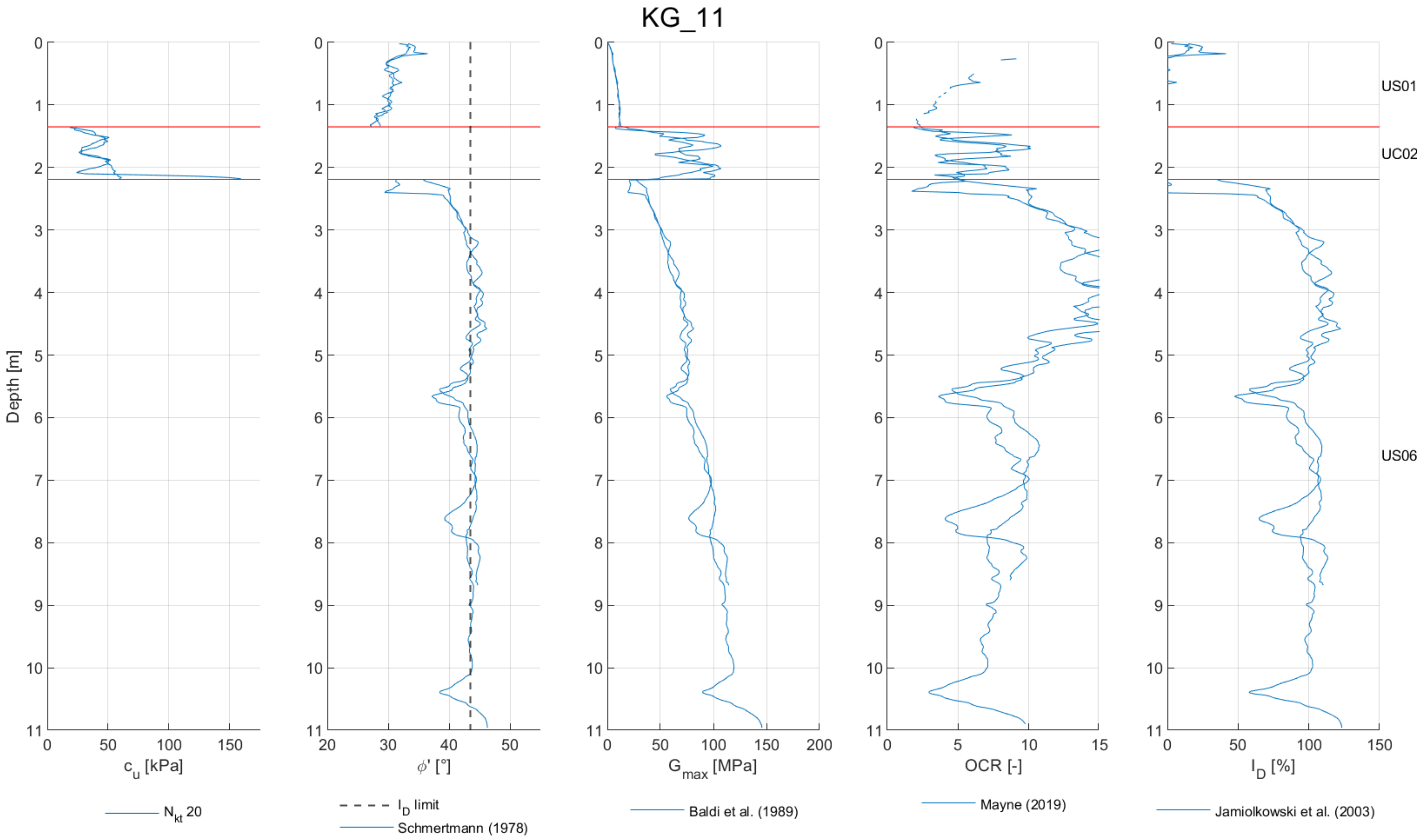

KG_05
Depth [m]
0
2
4
6
8
10
12
0
500
1000
c_u [kPa]
N_{kt} 20
20
30
40
50
ϕ' [°]
I_D limit
Schmertmann (1978)
0
100
200
300
400
G_{max} [MPa]
Baldi et al. (1989)
0
5
10
15
OCR [-]
Mayne (2019)
0
50
100
150
I_D [%]
Jamiolkowski et al. (2003)
US01
UC01
UC03
US05
UC06

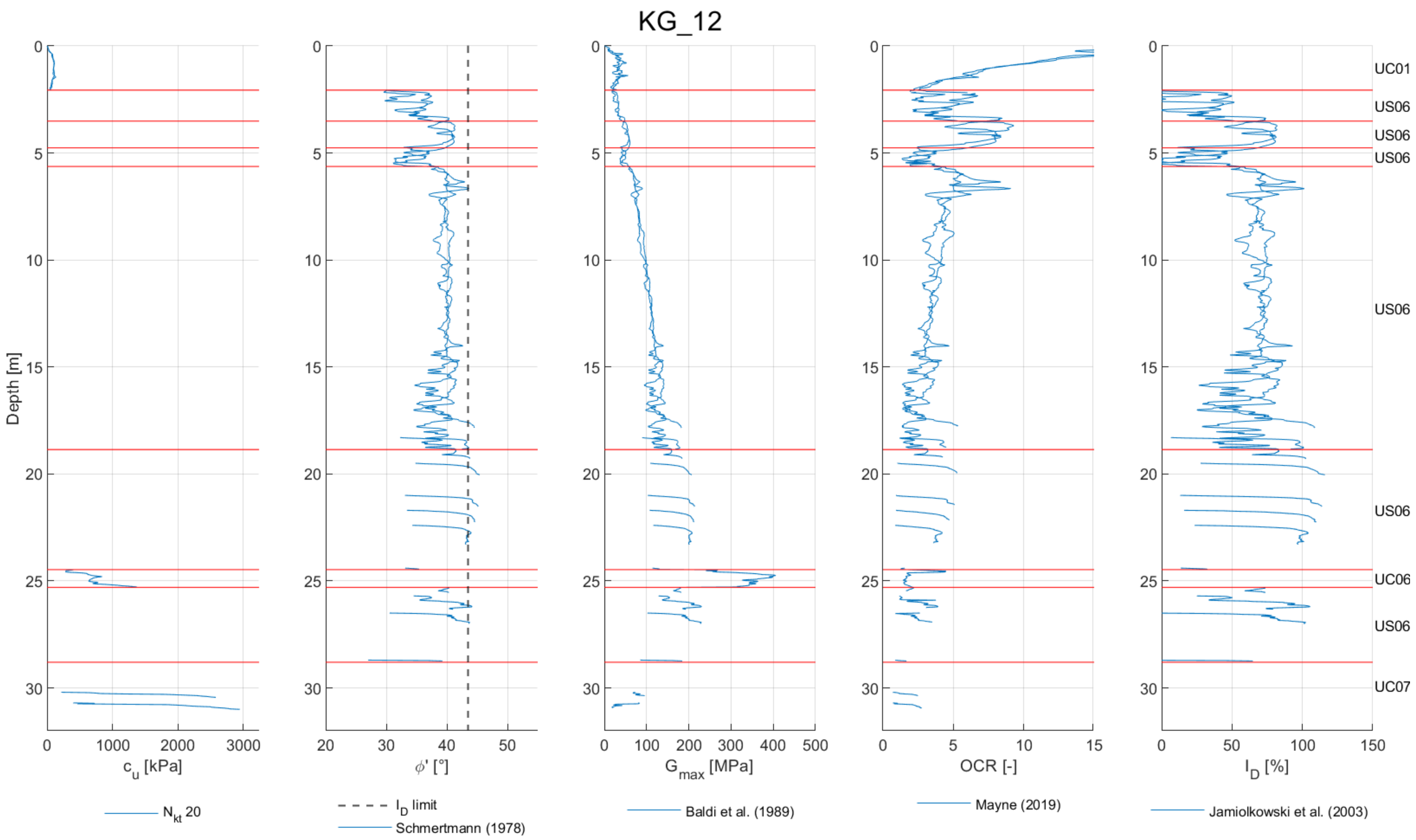

KG_06
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC03
UC06
US06
UC06
US06
US06

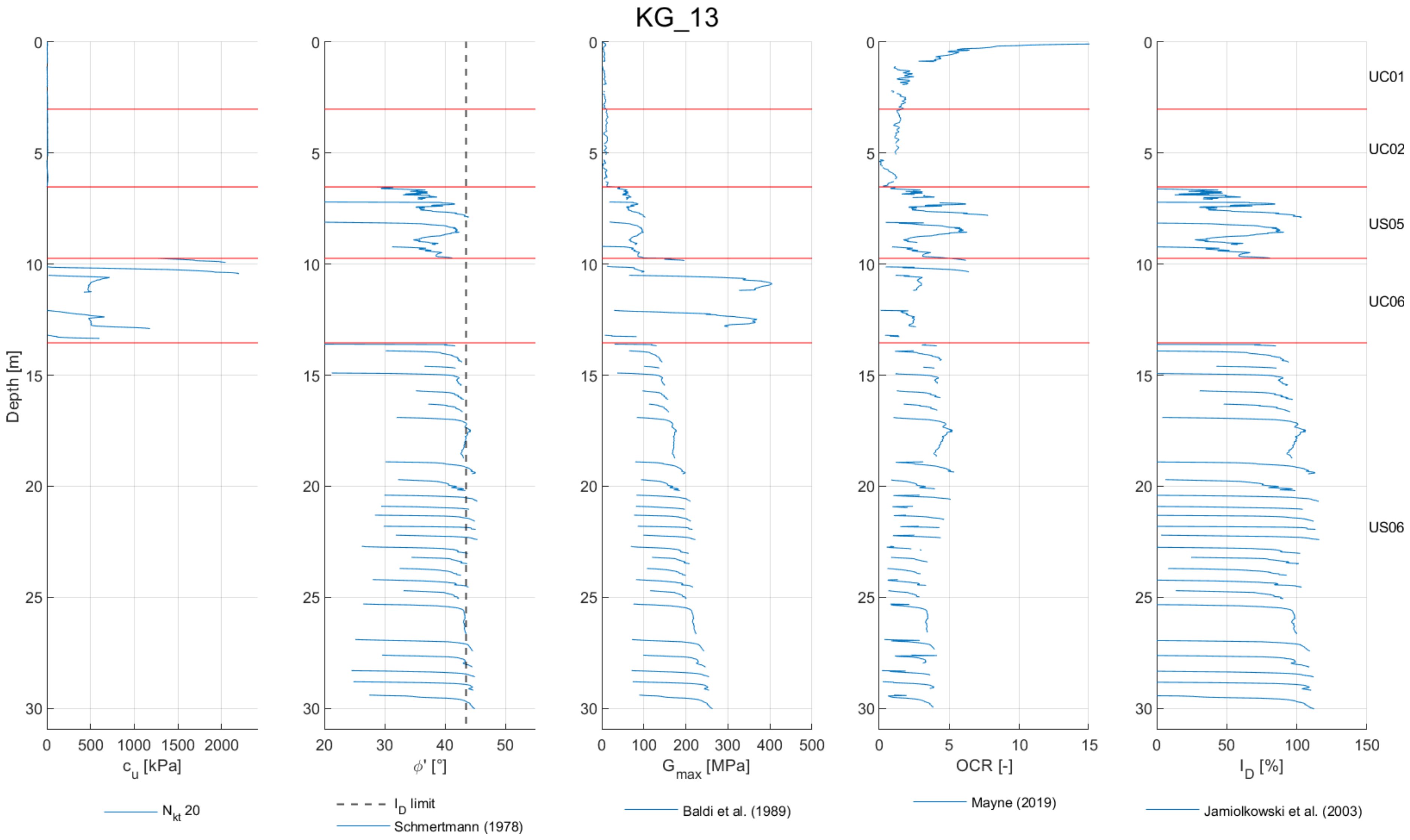

KG_07
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US03
UC03
UC06
US06
UC06

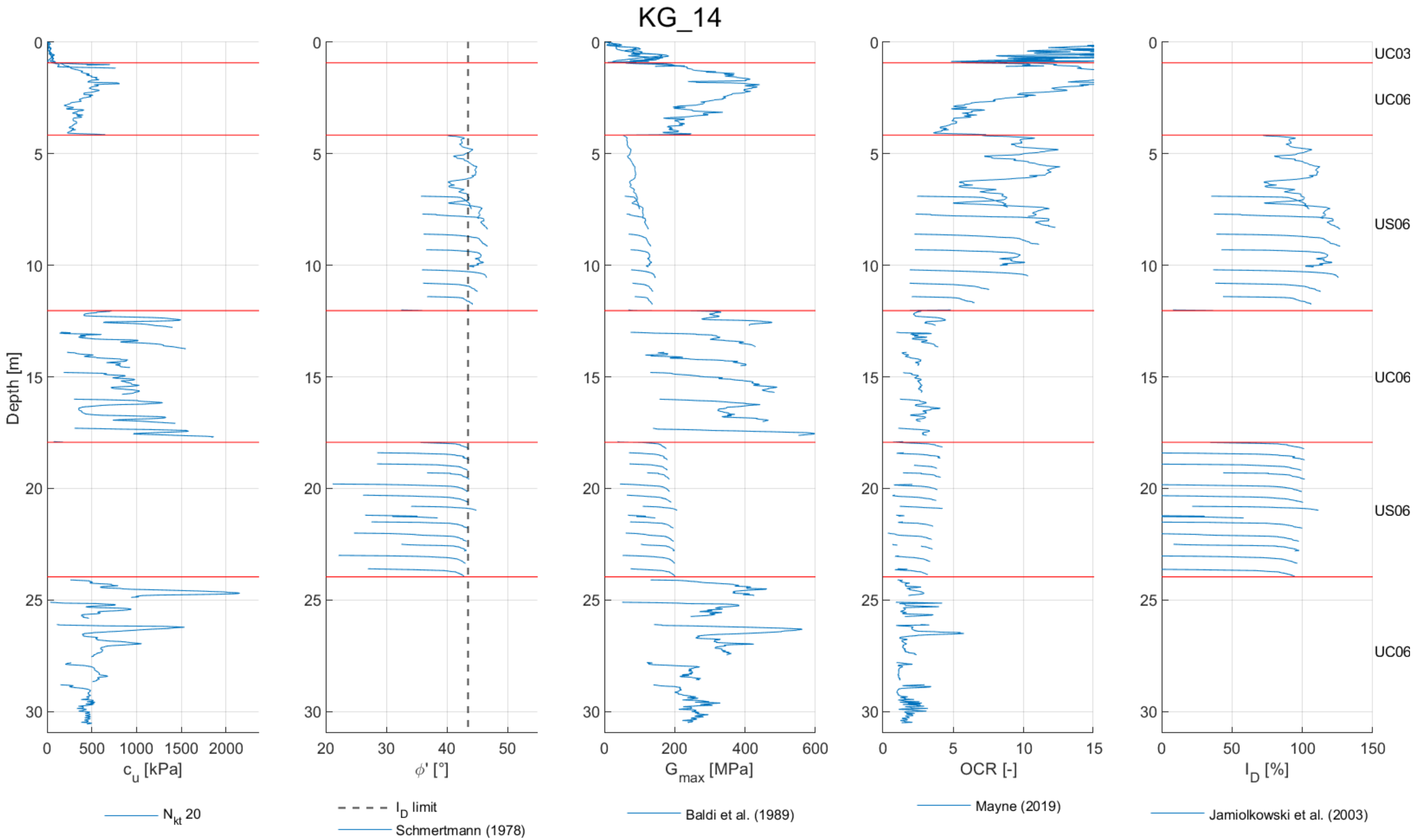

KG_09
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US06
UC06
UC06
US06
US06

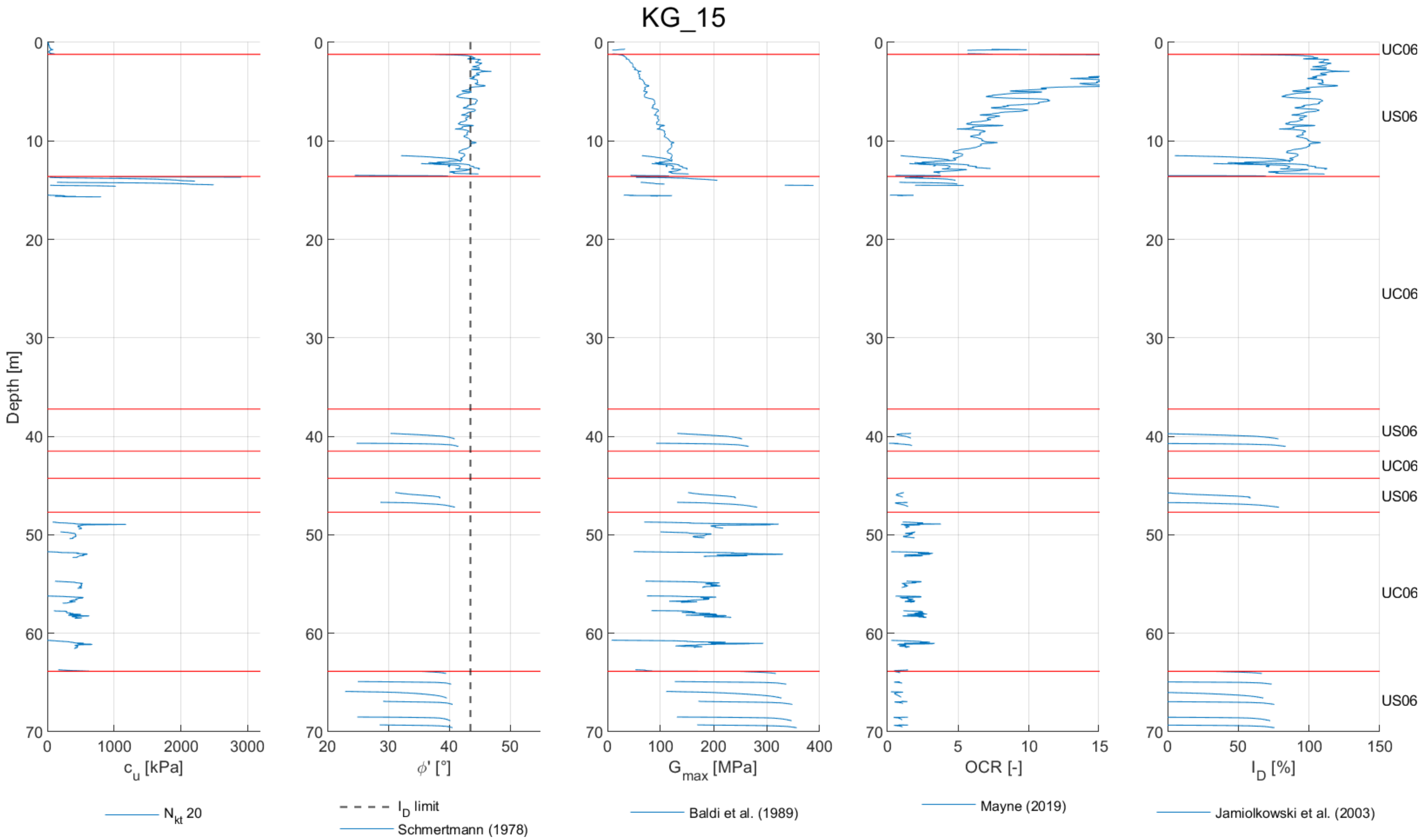

KG_10
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US01
UC03
US06
UC06
UC06
US06

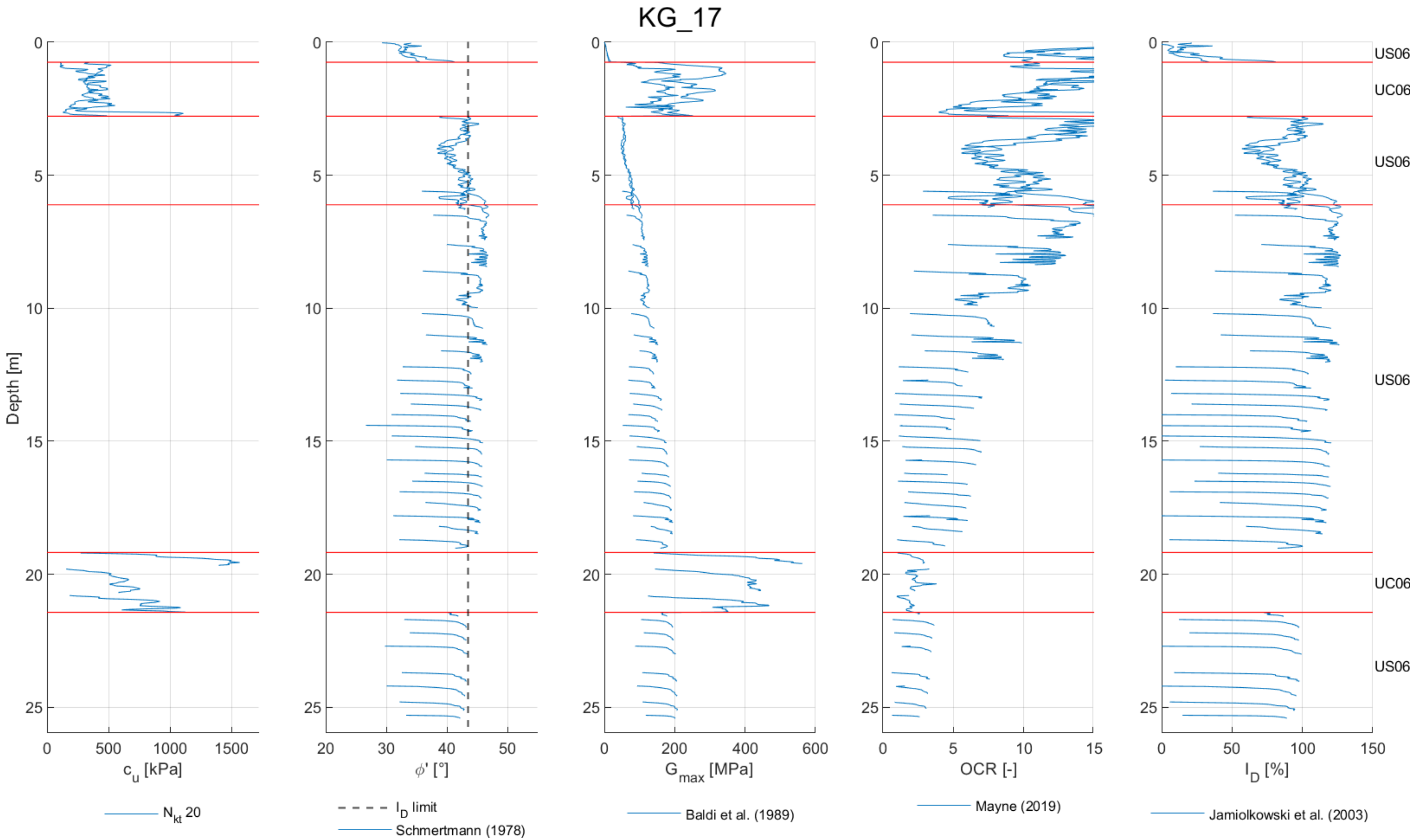

KG_11
Depth [m]
c_u [kPa]
ϕ' [°]
G_{max} [MPa]
OCR [-]
I_D [%]
US01
UC02
US06
N_{kt} 20
I_D limit
Schmertmann (1978)
Baldi et al. (1989)
Mayne (2019)
Jamiolkowski et al. (2003)

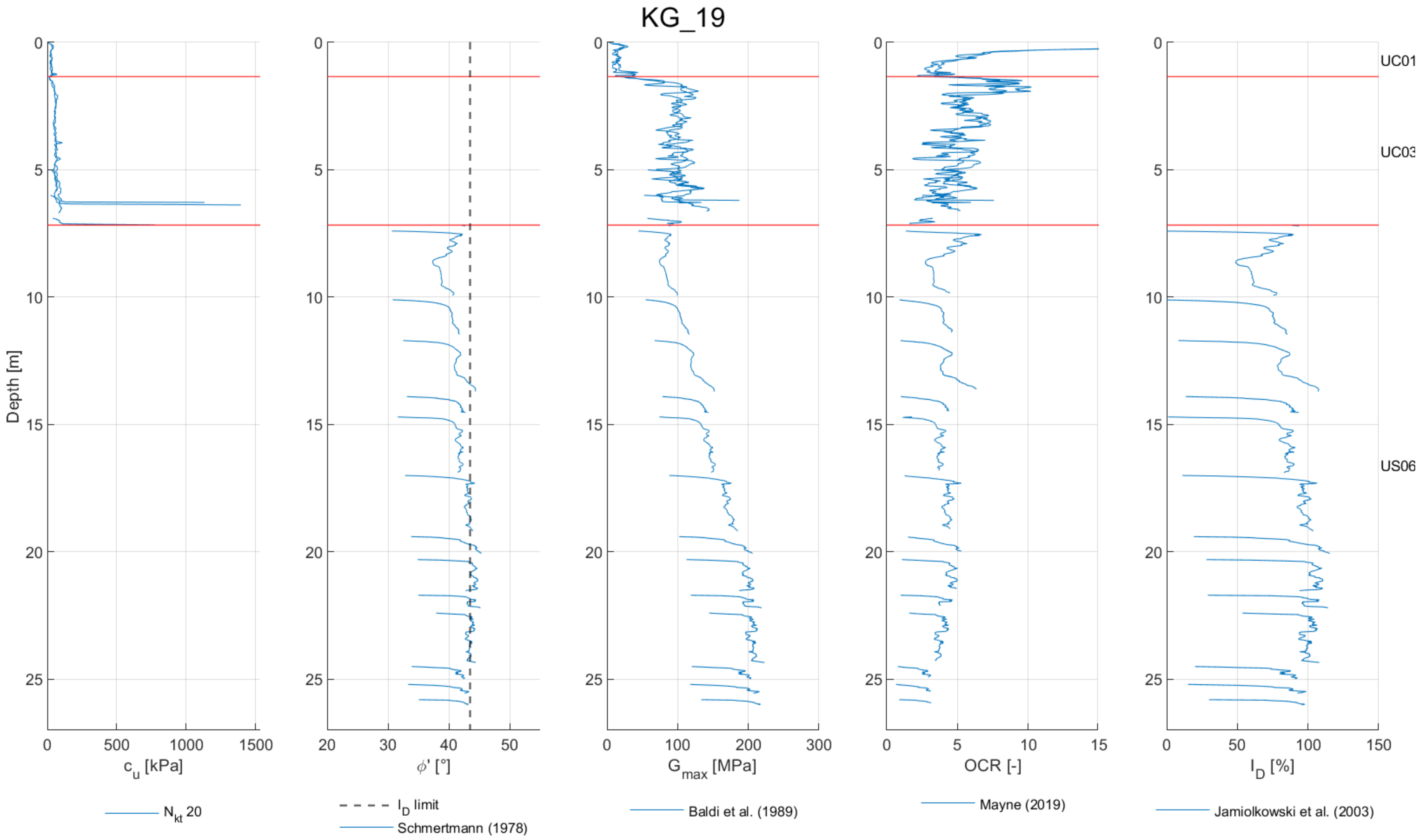

KG_12
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC01
US06
US06
US06
US06
US06
UC06
US06
UC07

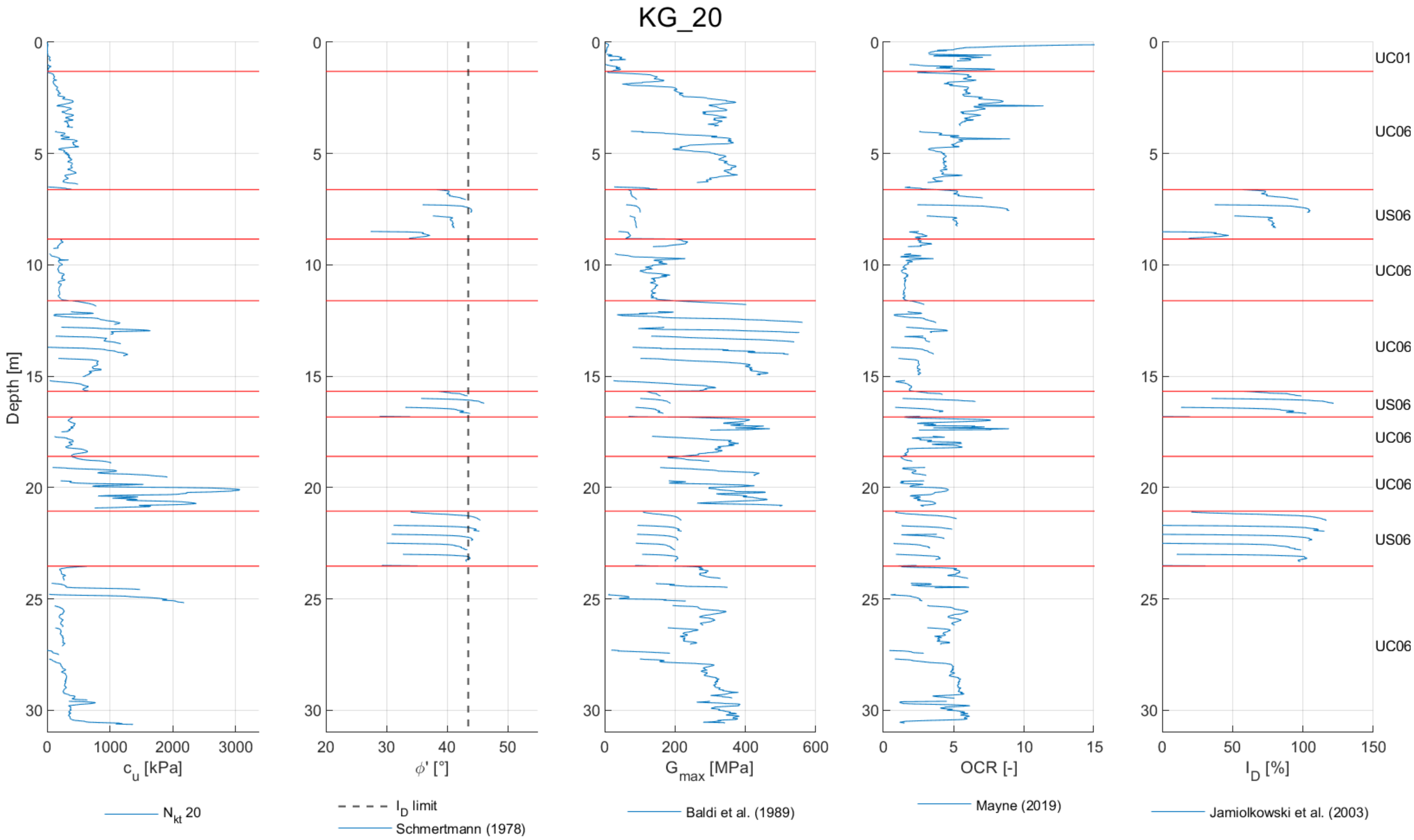

KG_13
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC01
UC02
US05
UC06
US06

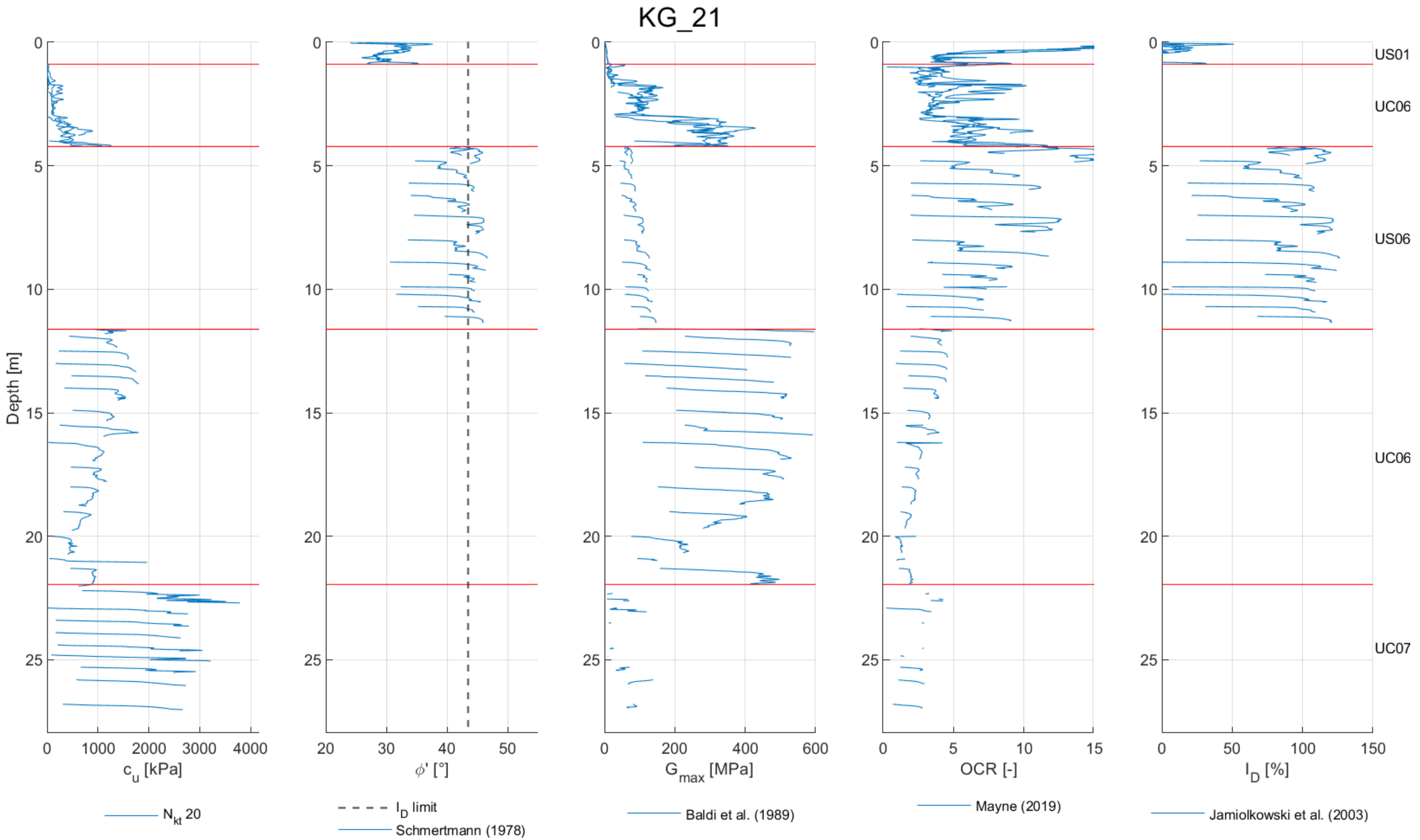

KG_14
Depth [m]
0
5
10
15
20
25
30
0 500 1000 1500 2000
c_u [kPa]
N_kt 20
20 30 40 50
ϕ' [°]
I_D limit
Schmertmann (1978)
0 200 400 600
G_max [MPa]
Baldi et al. (1989)
0 5 10 15
OCR [-]
Mayne (2019)
0 50 100 150
I_D [%]
Jamiolkowski et al. (2003)
UC03
UC06
US06
UC06
US06
UC06

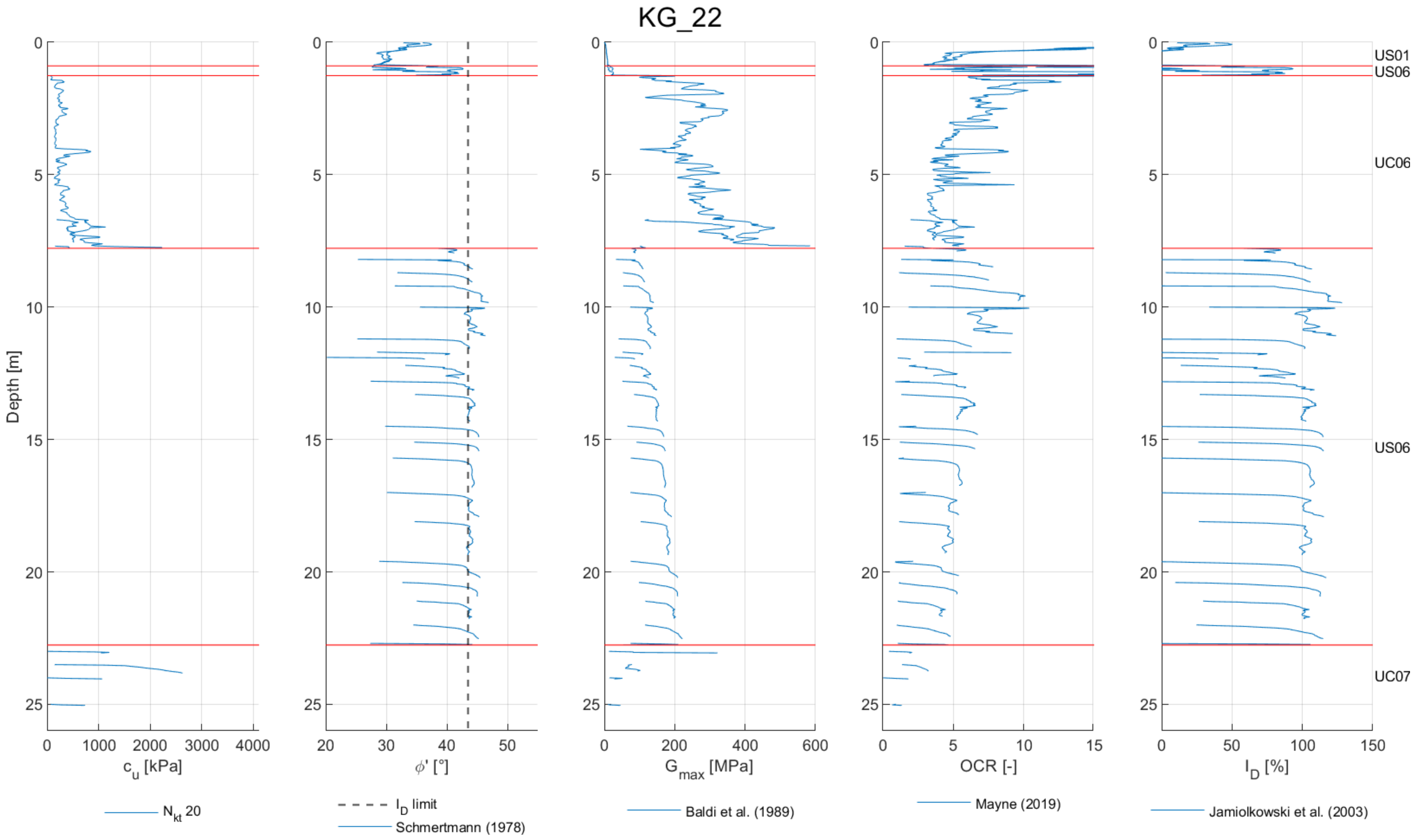

KG_15
Depth [m]
c_u [kPa]
N_kt 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_max [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC06
US06
UC06
US06
UC06
US06
UC06
US06

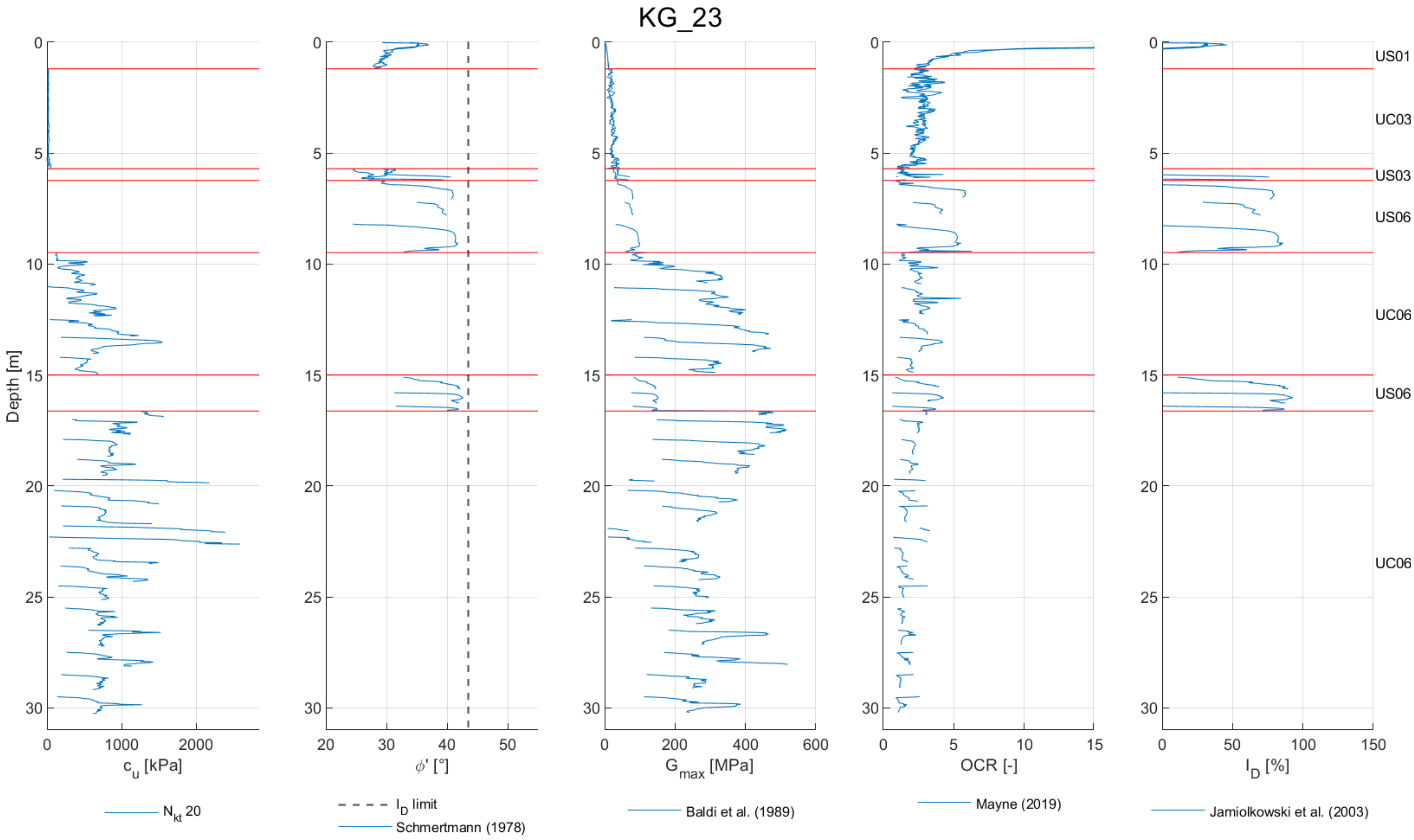

KG_17
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US06
UC06
US06
US06
UC06
US06

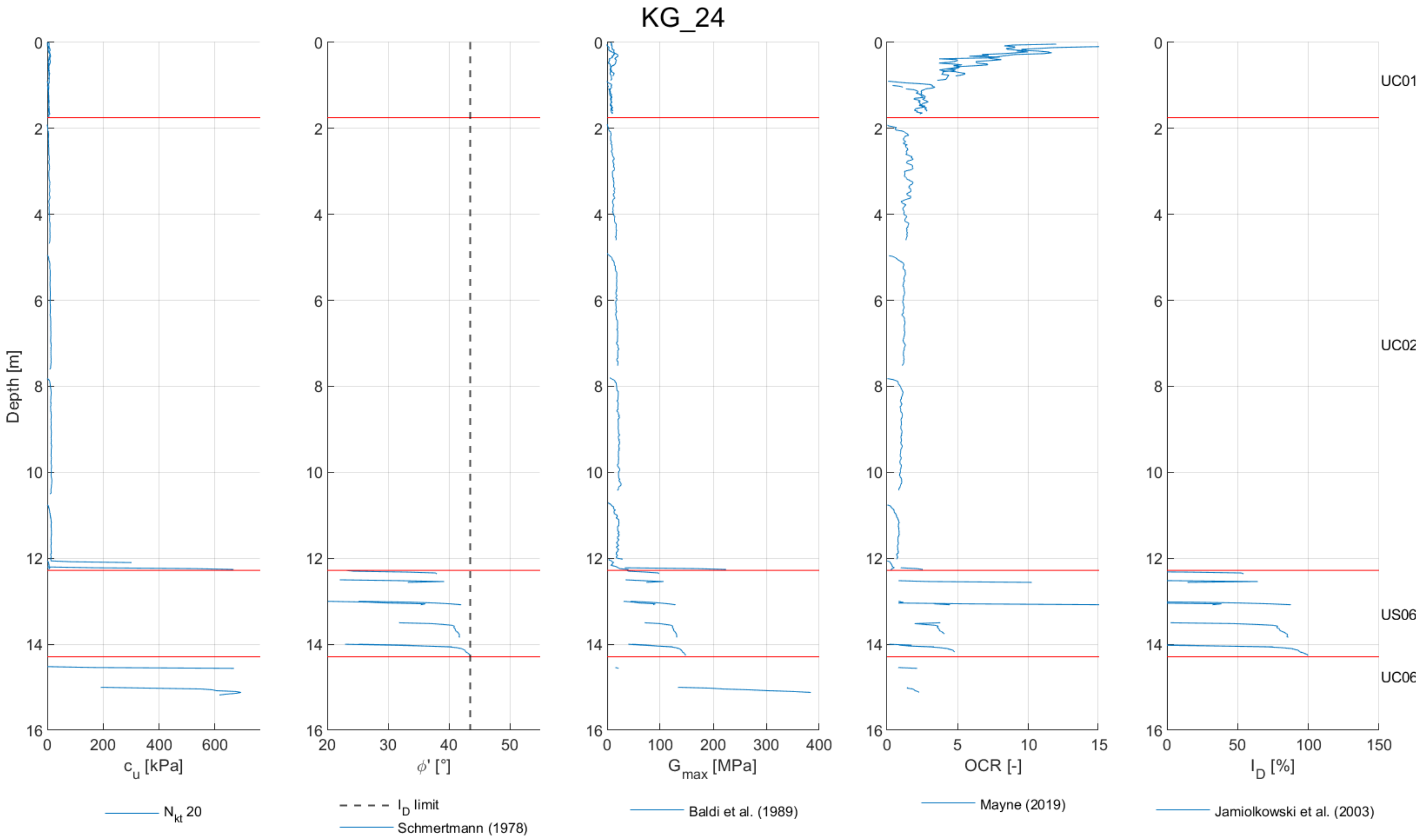

KG_19
Depth [m]
c_u [kPa]
N_{kt} 20
φ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC01
UC03
US06

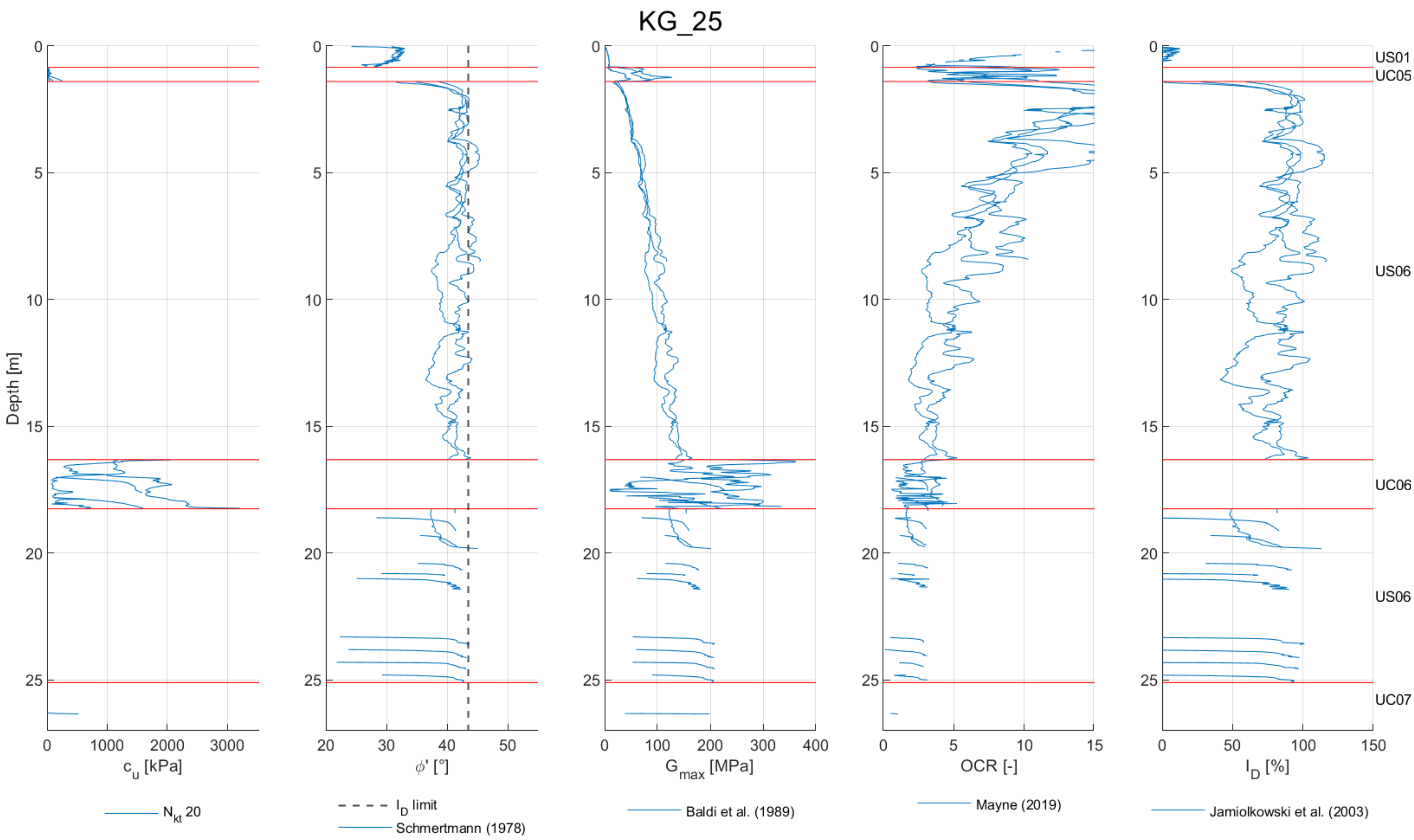

KG_20
Depth [m]
c_u [kPa]
N_kt 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_max [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
UC01
UC06
US06
UC06
UC06
US06
UC06
UC06
US06
UC06

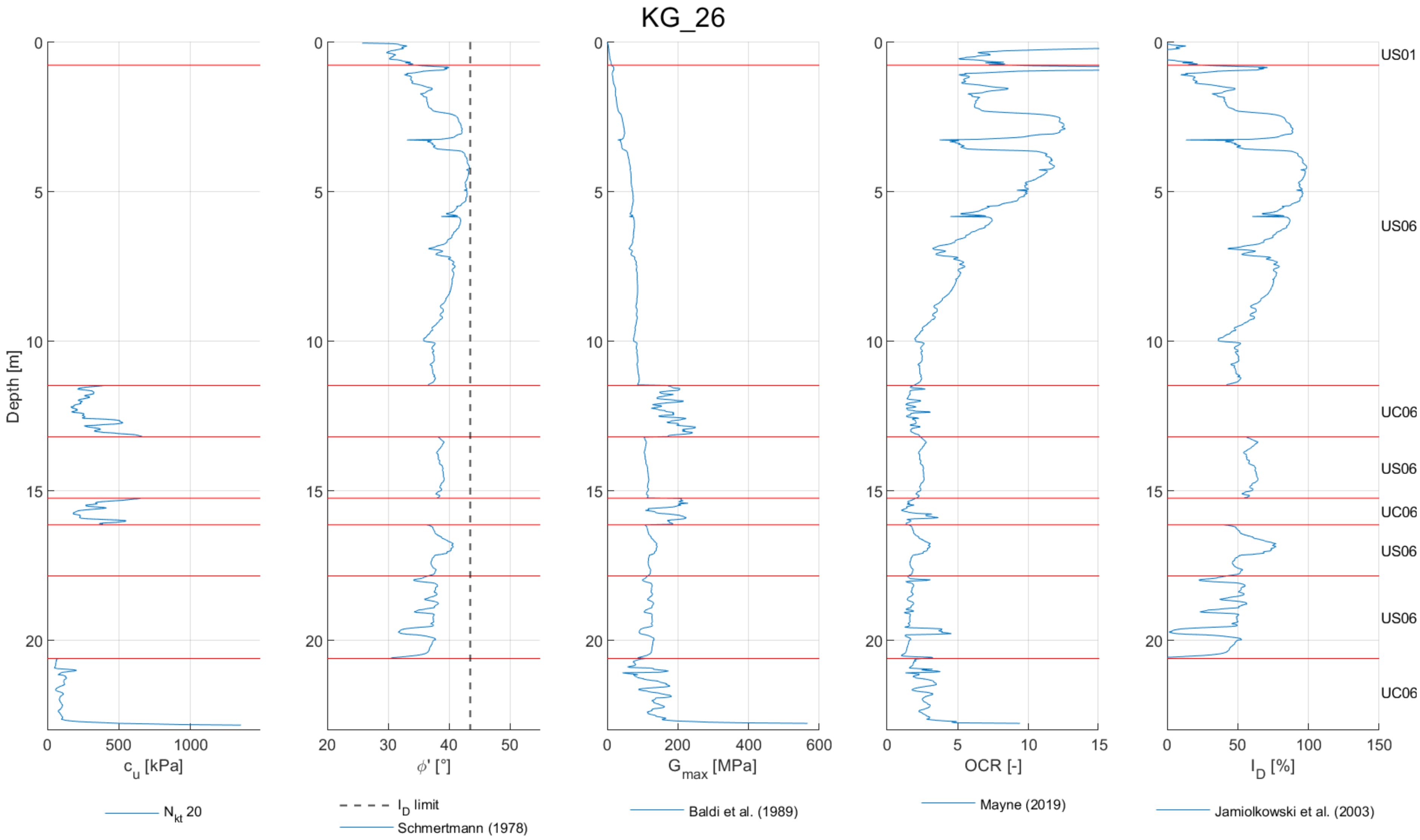

KG_21
Depth [m]
0
5
10
15
20
25
0 1000 2000 3000 4000
c_u [kPa]
N_{kt} 20
20 30 40 50
ϕ' [°]
I_D limit
Schmertmann (1978)
0 200 400 600
G_{max} [MPa]
Baldi et al. (1989)
0 5 10 15
OCR [-]
Mayne (2019)
0 50 100 150
I_D [%]
Jamiolkowski et al. (2003)
US01
UC06
US06
UC06
UC07


KG_22
Depth [m]
c_u [kPa]
ϕ' [°]
G_{max} [MPa]
OCR [-]
I_D [%]
US01
US06
UC06
US06
UC07
N_{kt} 20
I_D limit
Schmertmann (1978)
Baldi et al. (1989)
Mayne (2019)
Jamiolkowski et al. (2003)


KG_23
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US01
UC03
US03
US06
UC06
US06
UC06


KG_24
Depth [m]
0
2
4
6
8
10
12
14
16
0 200 400 600
c_u [kPa]
N_{kt} 20
20 30 40 50
ϕ' [°]
I_D limit
Schmertmann (1978)
0 100 200 300 400
G_{max} [MPa]
Baldi et al. (1989)
0 5 10 15
OCR [-]
Mayne (2019)
0 50 100 150
I_D [%]
Jamiolkowski et al. (2003)
UC01
UC02
US06
UC06

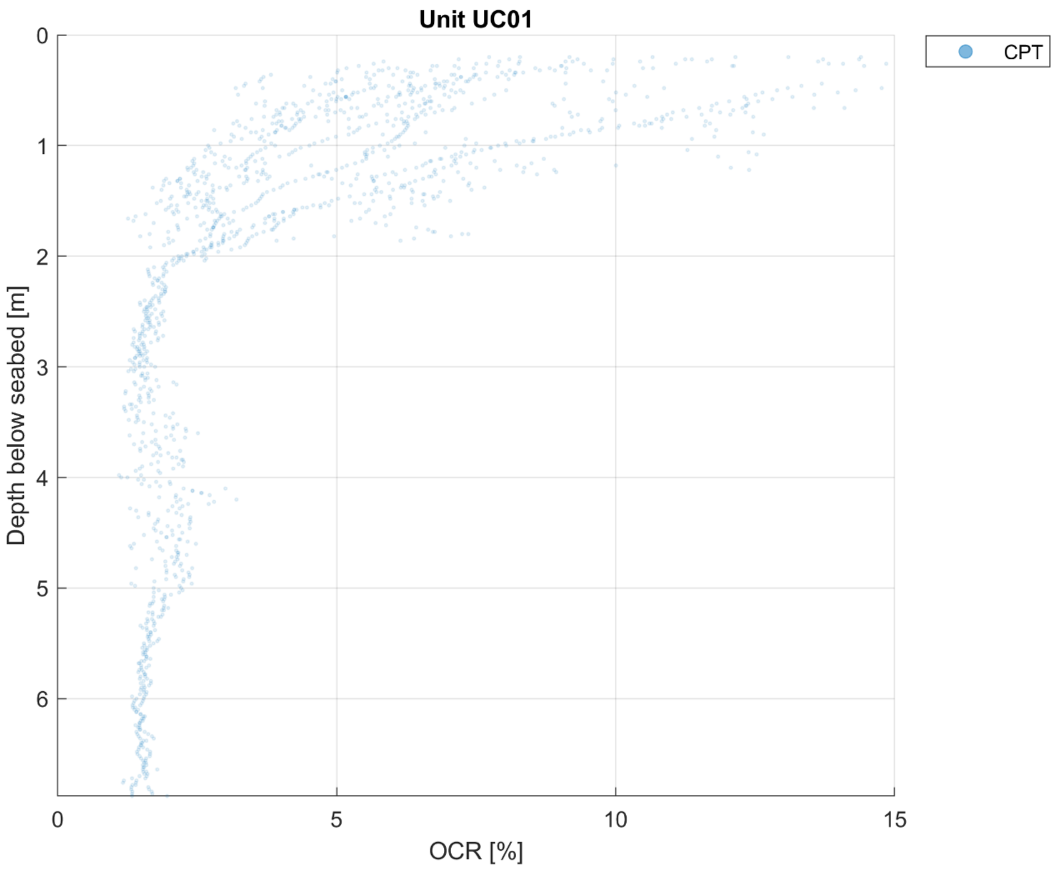

KG_25
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US01
UC05
US06
UC06
US06
UC07

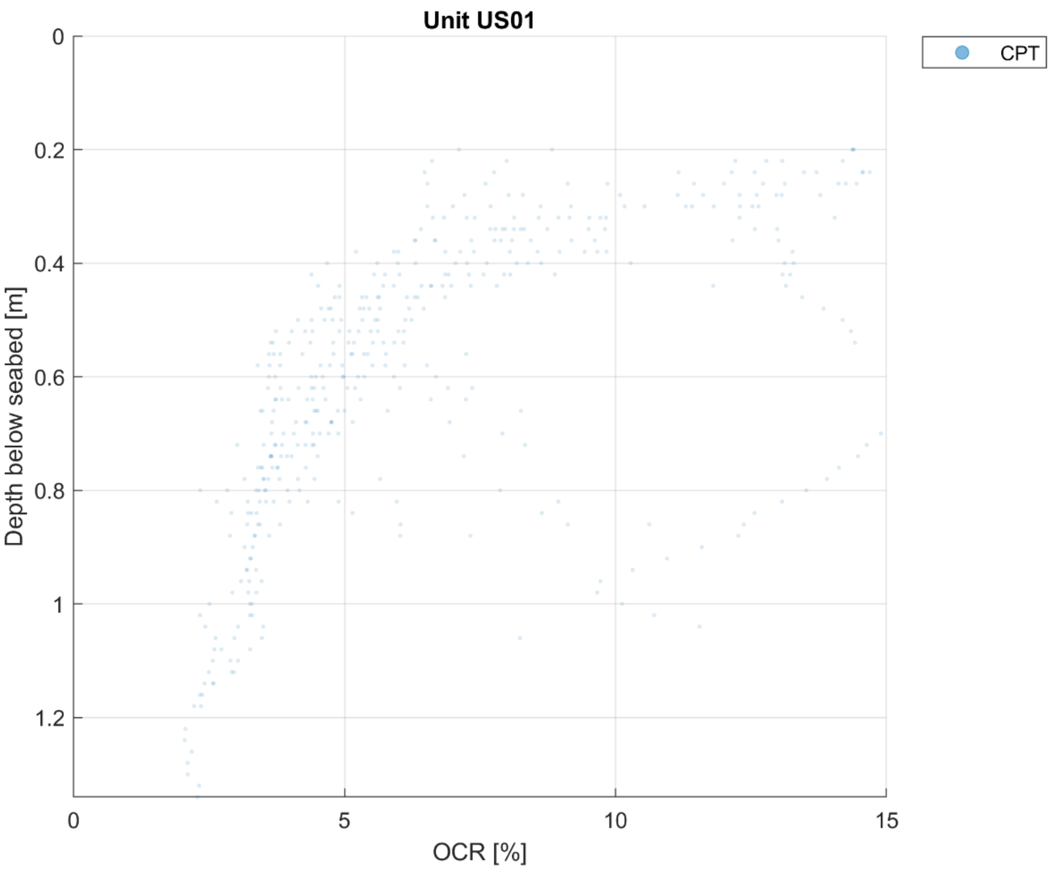

KG_26
Depth [m]
c_u [kPa]
N_{kt} 20
ϕ' [°]
I_D limit
Schmertmann (1978)
G_{max} [MPa]
Baldi et al. (1989)
OCR [-]
Mayne (2019)
I_D [%]
Jamiolkowski et al. (2003)
US01
US06
UC06
US06
UC06
US06
US06
UC06

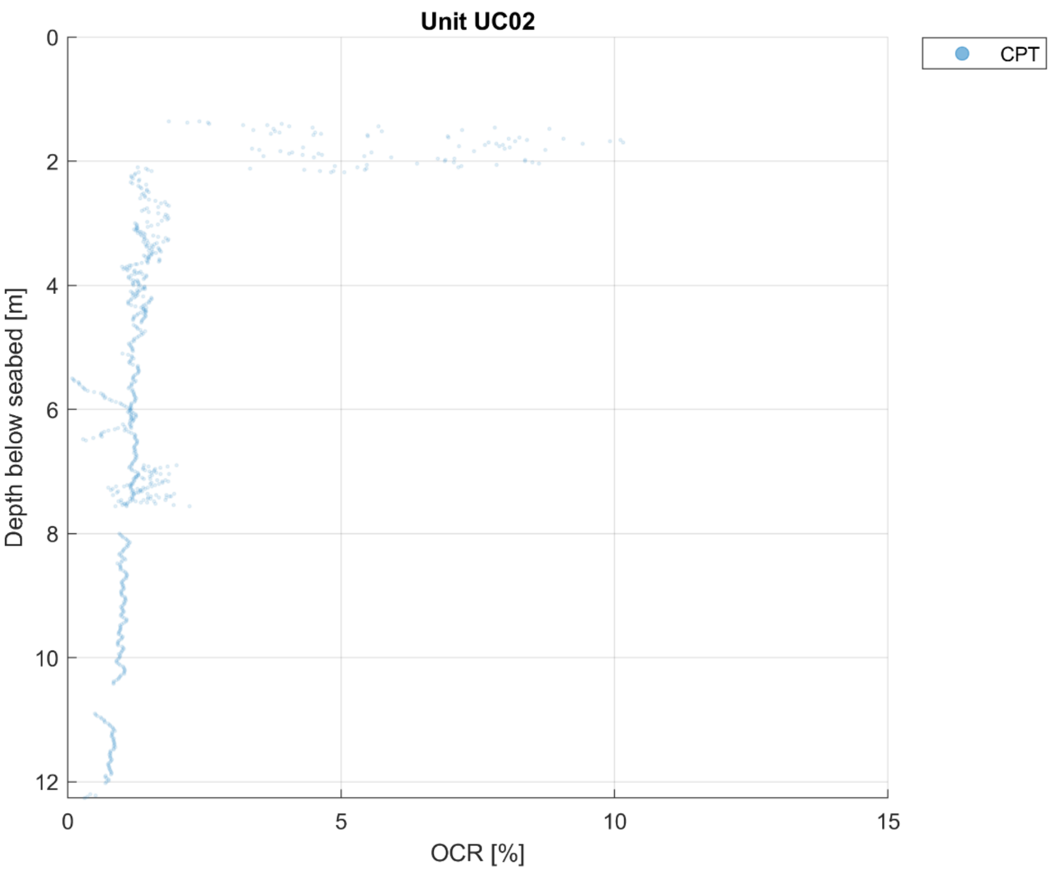
Appendix D CPT plots per geotechnical unit including properties from laboratory testing

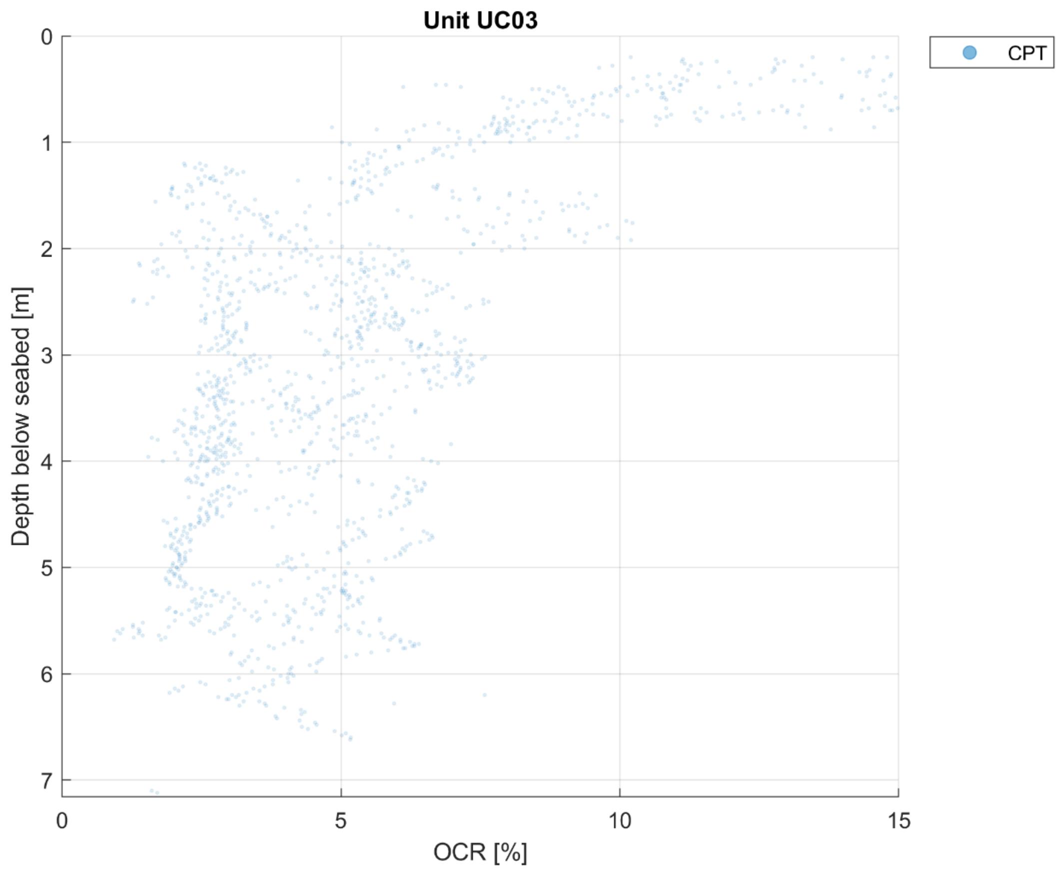
This appendix presents the derived soil properties per unit. For presenting the data per unit, the first 20 cm of each CPT push has been removed from the data sample as these are not found representative for the actual unit properties.

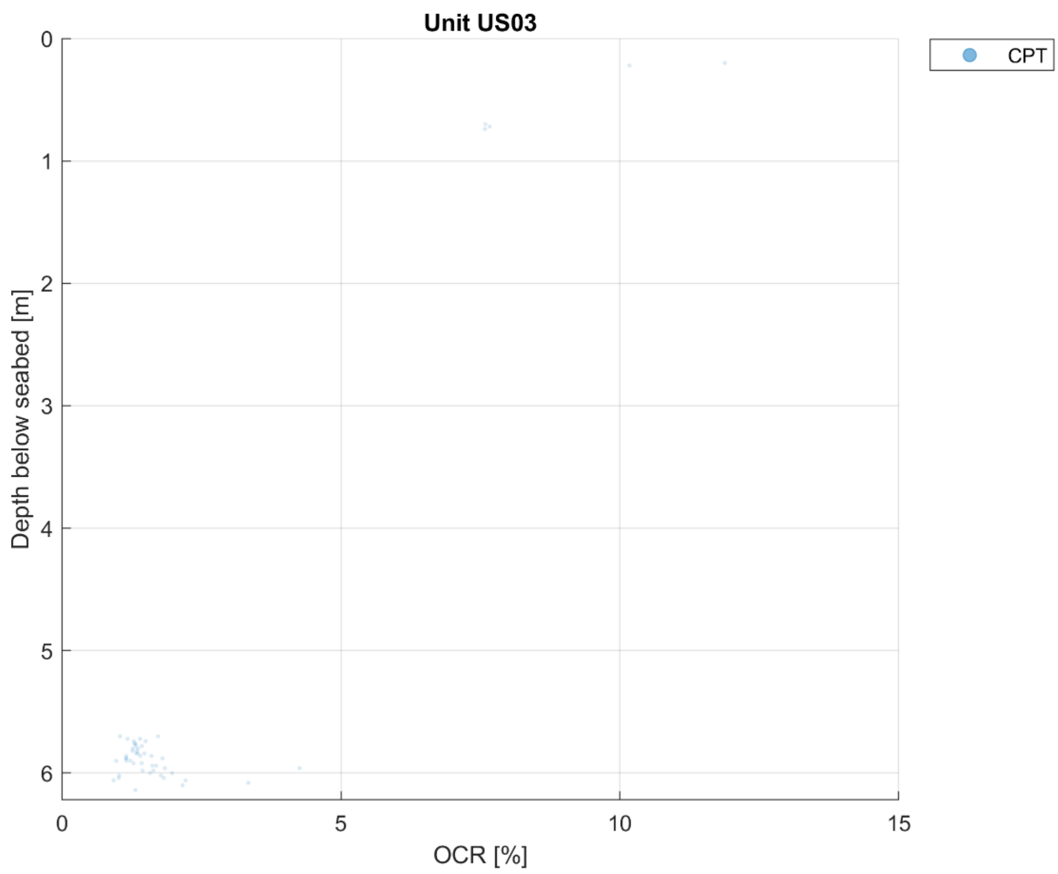
D.1 Over-consolidation ratio

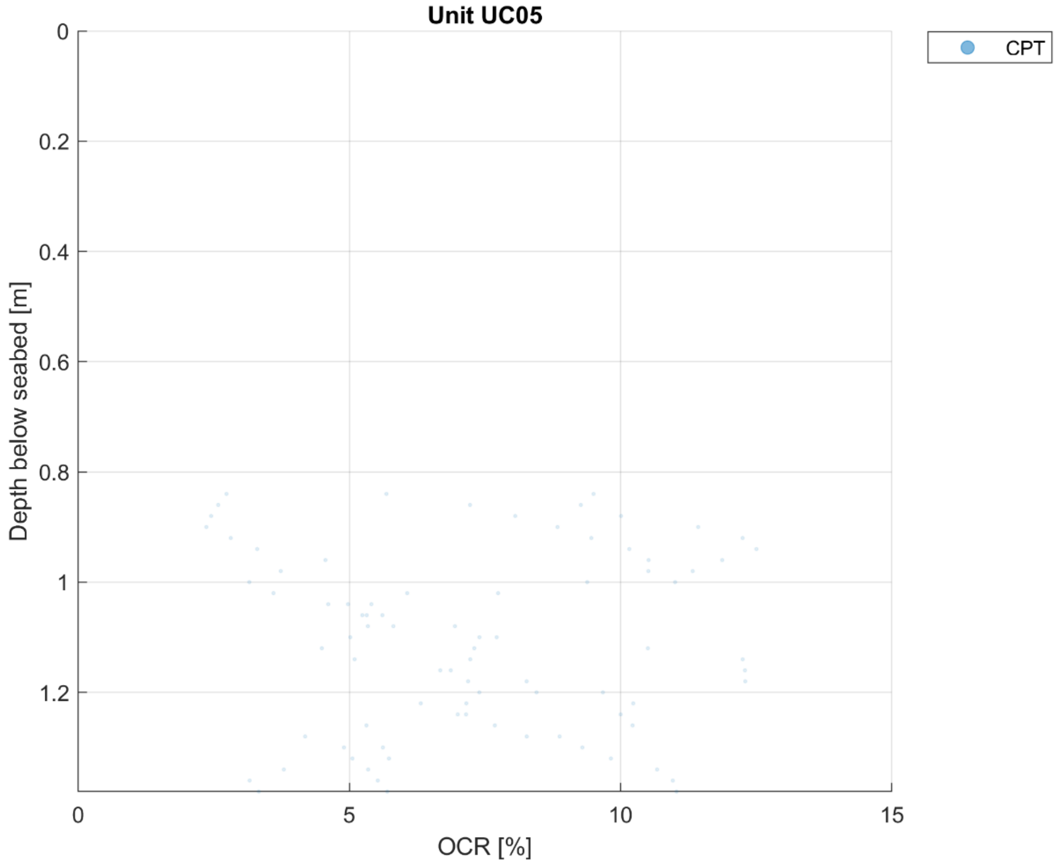


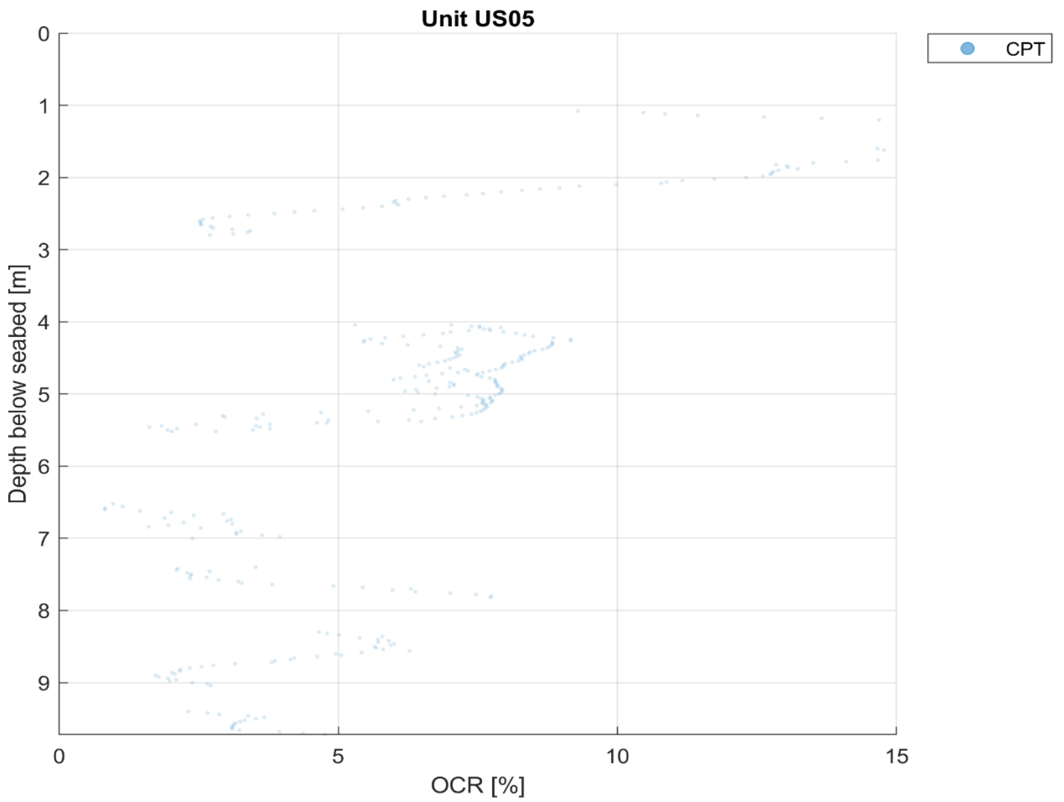

Unit US01
CPT
Depth below seabed [m]
OCR [%]
0
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15

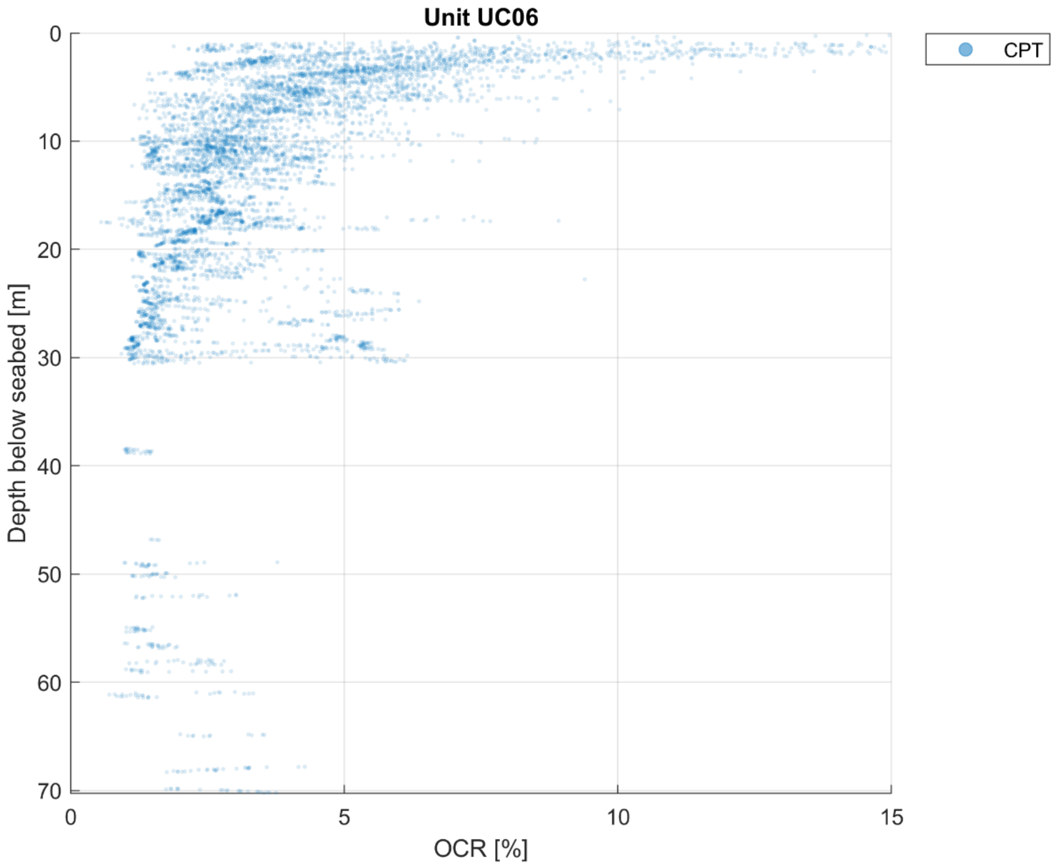

Unit UC02
CPT
Depth below seabed [m]
OCR [%]
0
2
4
6
8
10
12
0
5
10
15

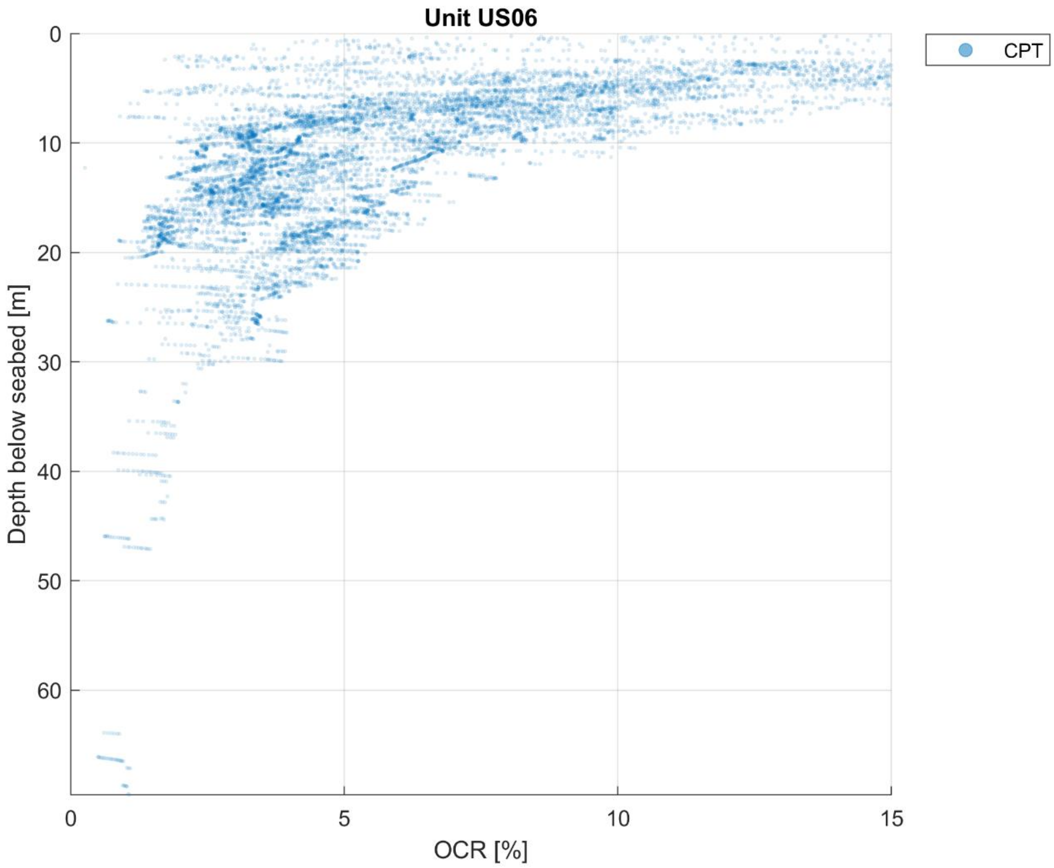

Unit UC03
CPT
Depth below seabed [m]
OCR [%]
0
1
2
3
4
5
6
7
0
5
10
15

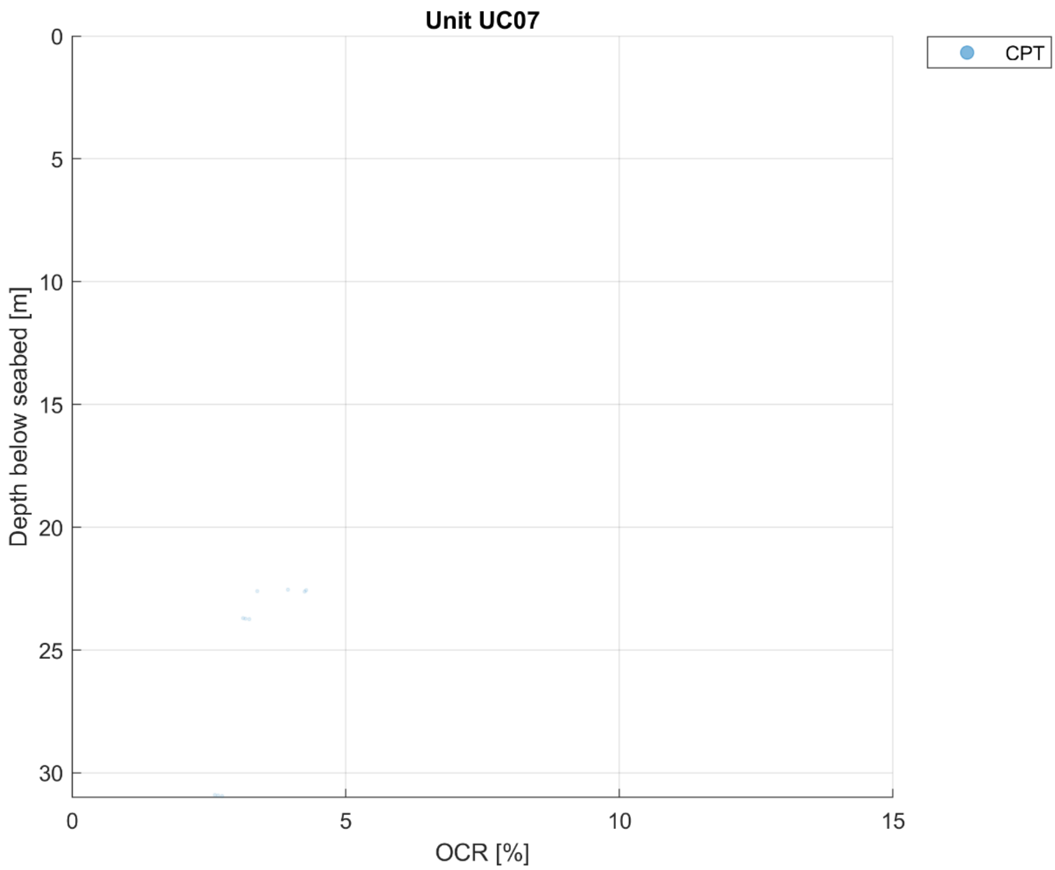

Unit US03
CPT
Depth below seabed [m]
OCR [%]
0
1
2
3
4
5
6
0
5
10
15


Unit UC05
CPT
Depth below seabed [m]
0
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15
OCR [%]

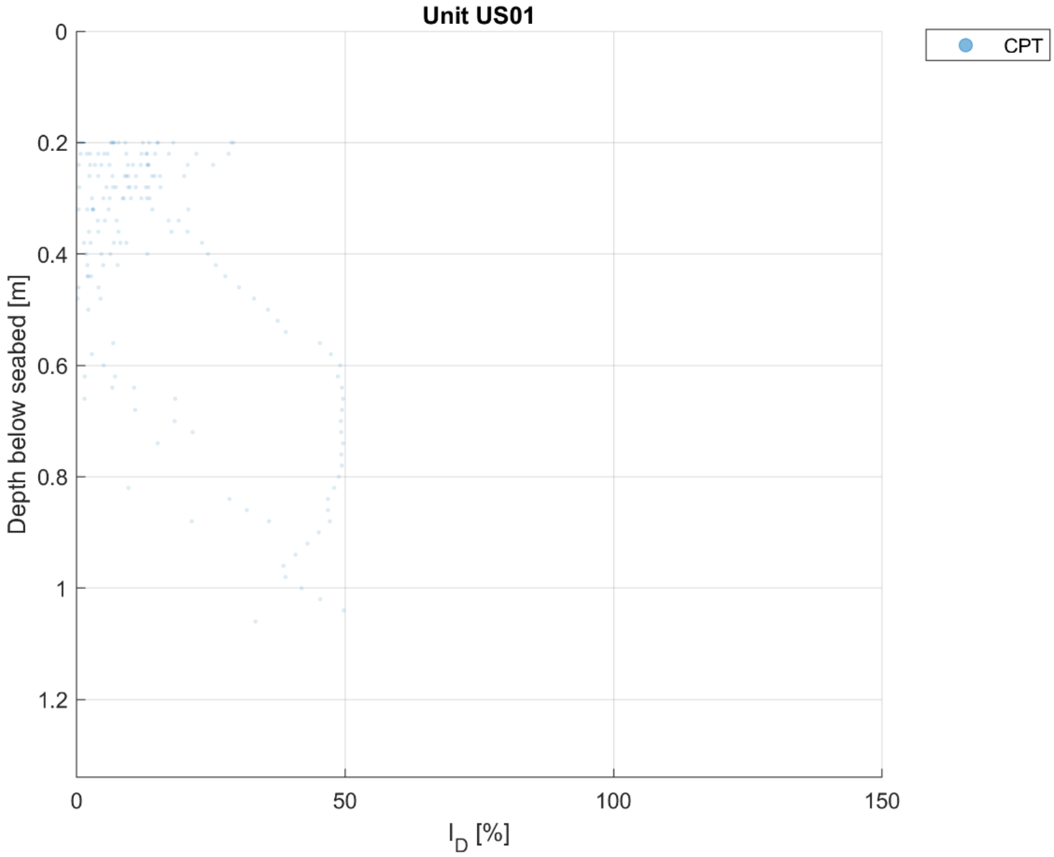

Unit US05
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
7
8
9
0
5
10
15
OCR [%]

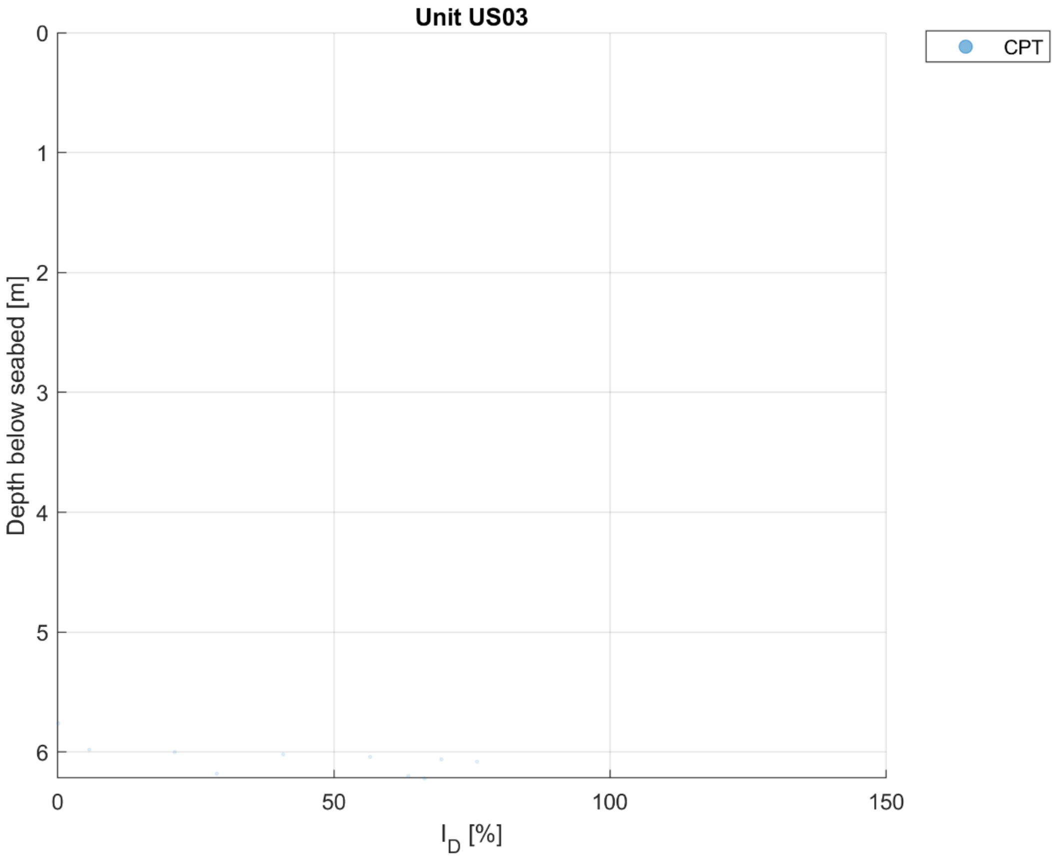

Unit UC06
CPT
Depth below seabed [m]
OCR [%]
0
10
20
30
40
50
60
70
0
5
10
15

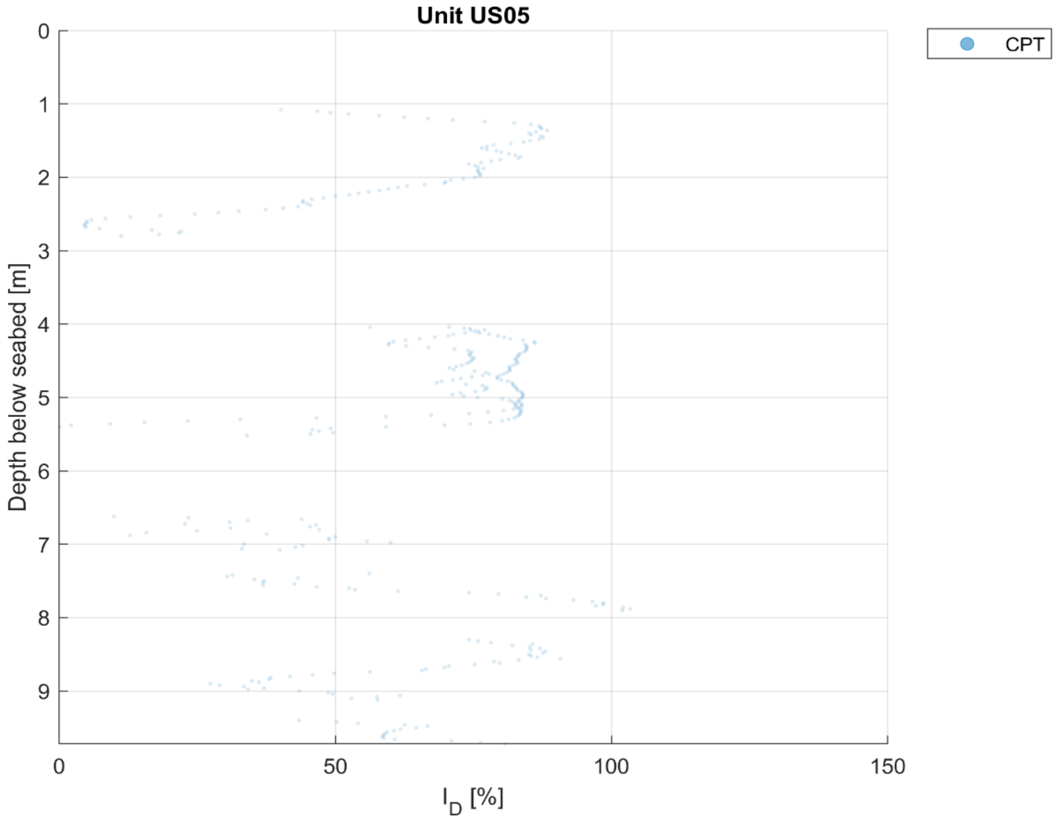

Unit US06
CPT
Depth below seabed [m]
OCR [%]
0
10
20
30
40
50
60
0
5
10
15

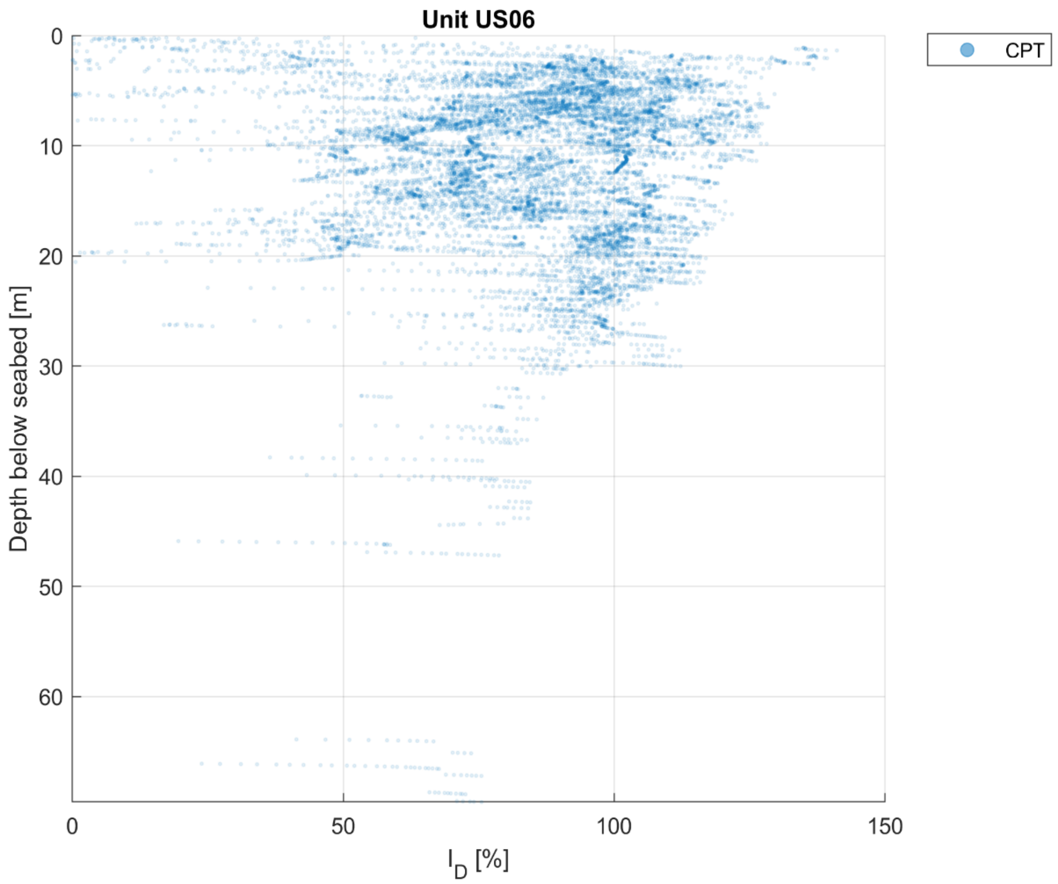

Unit UC07
CPT
Depth below seabed [m]
0
5
10
15
20
25
30
OCR [%]
0
5
10
15

D.2 Relative density

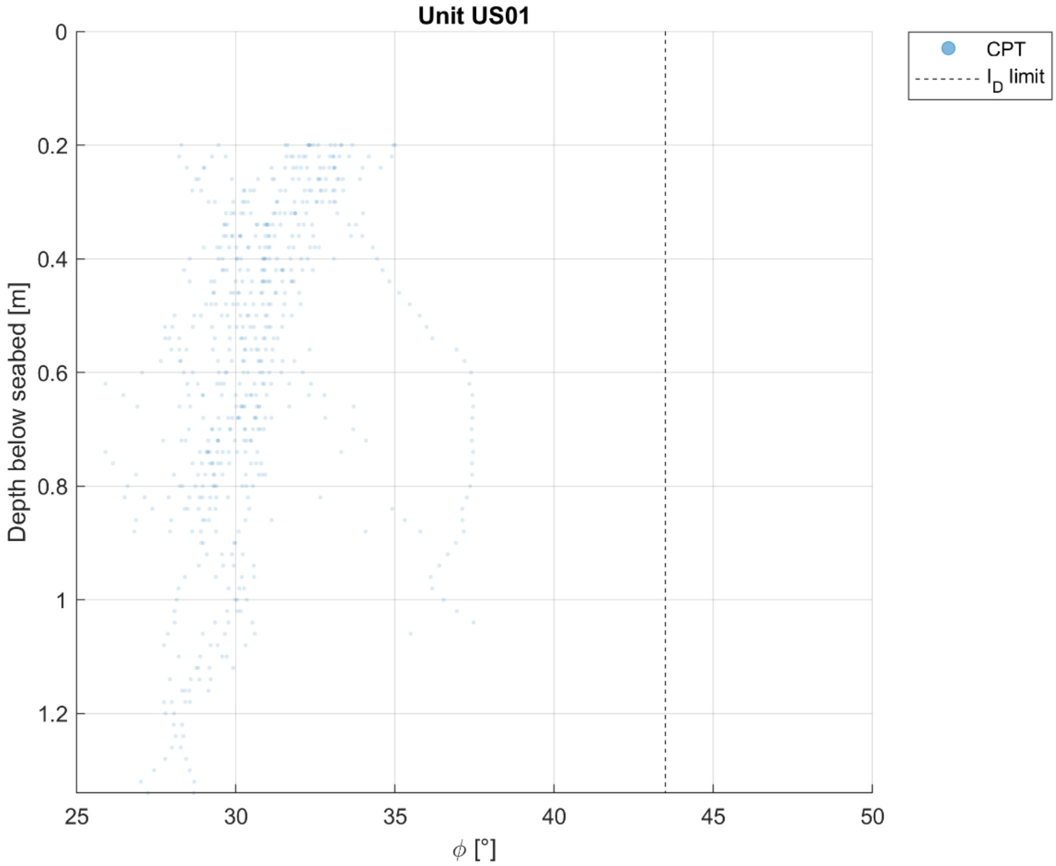


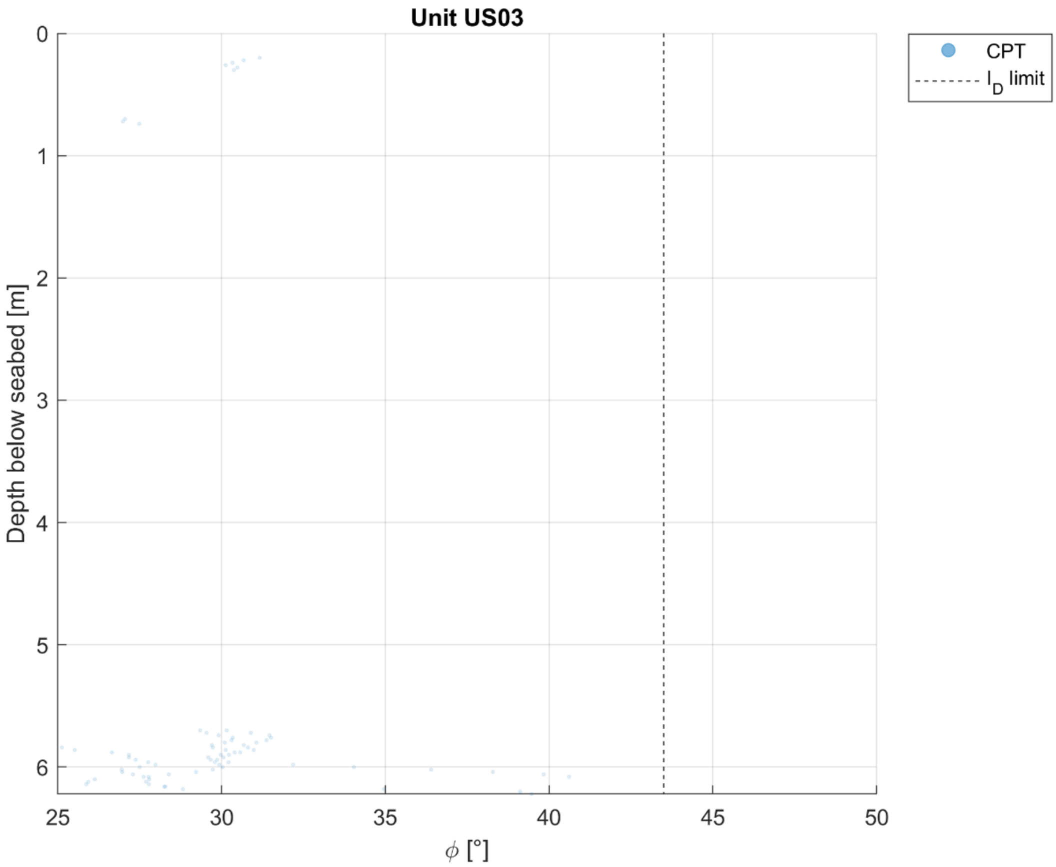


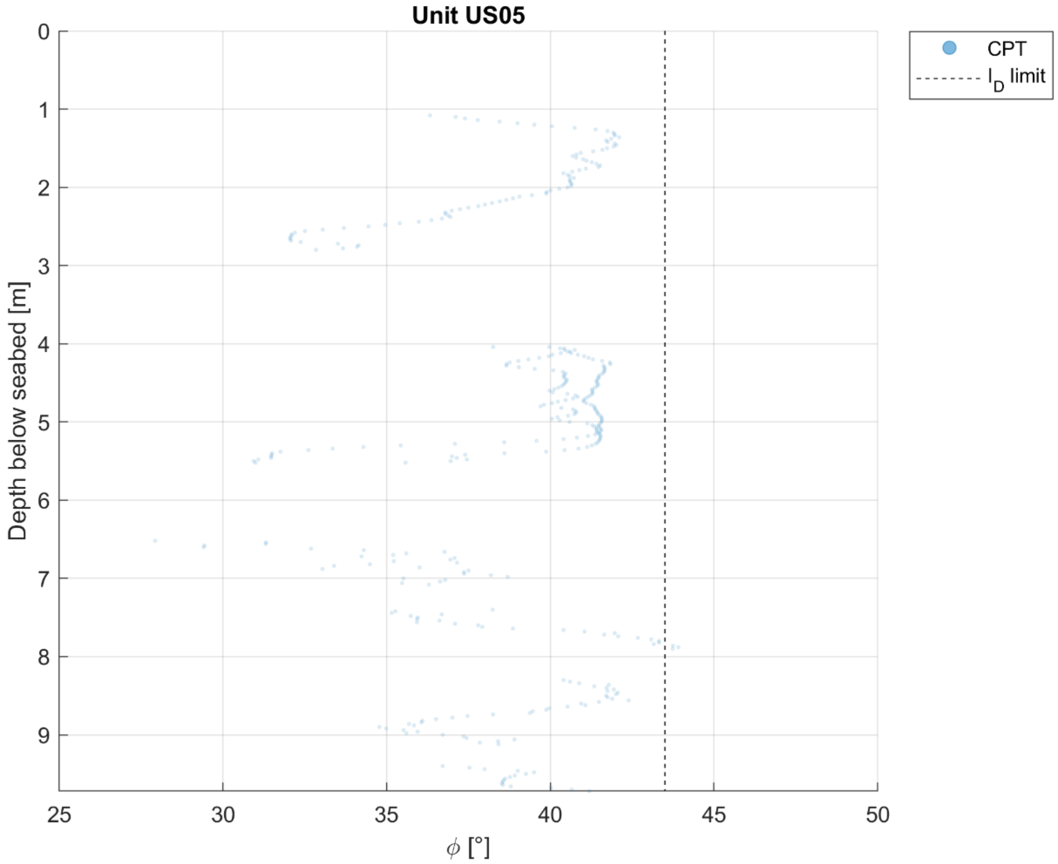

Unit US05
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
7
8
9
0
50
100
150
I_D [%]

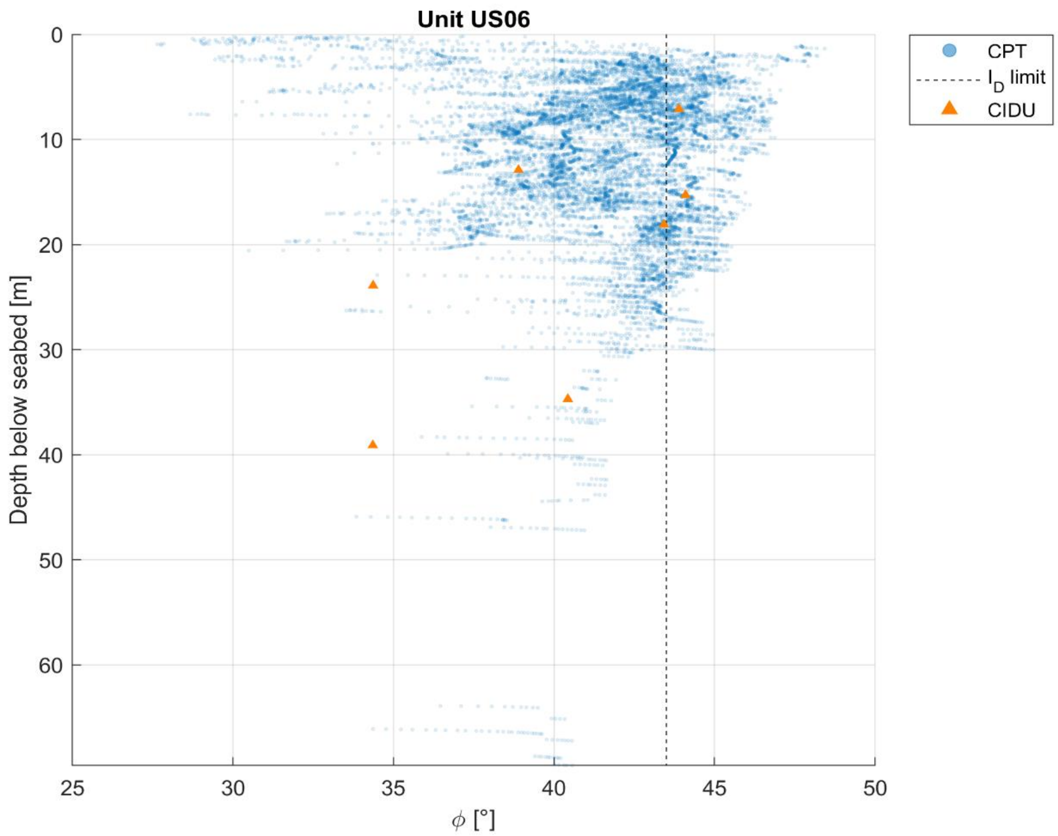

Unit US06
CPT
Depth below seabed [m]
0
10
20
30
40
50
60
0
50
100
150
I_D [%]

D.3 Friction angle

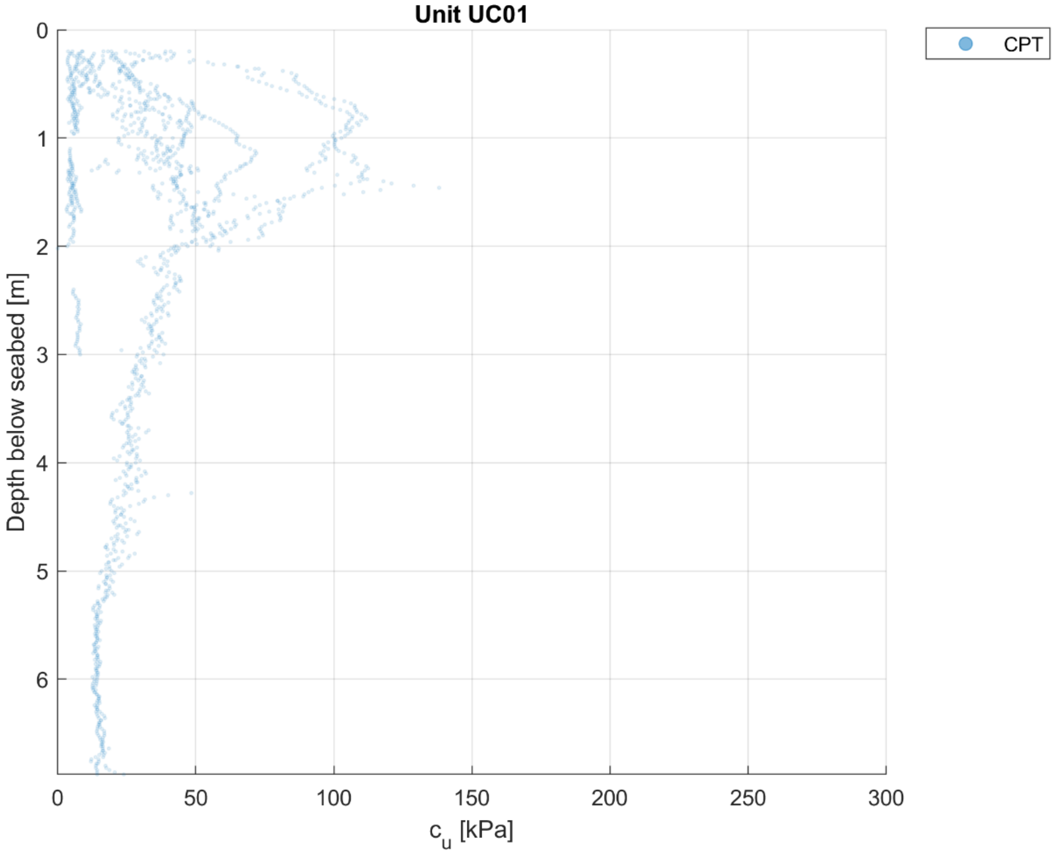


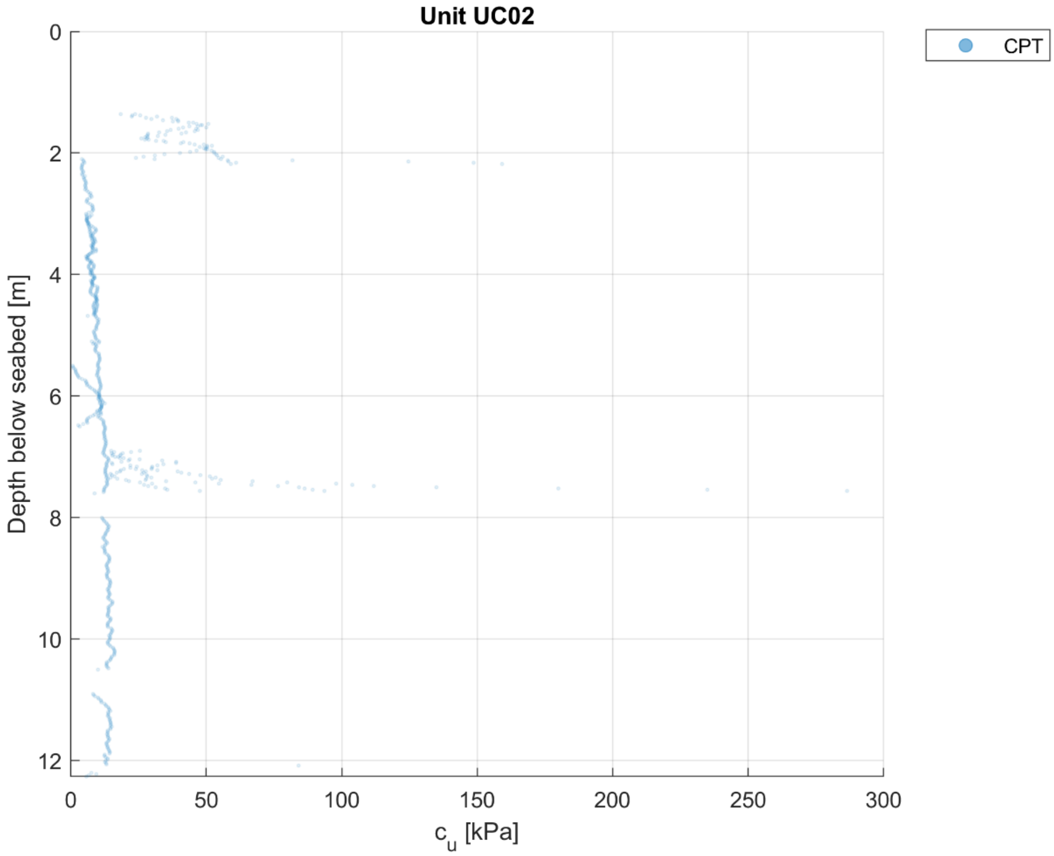


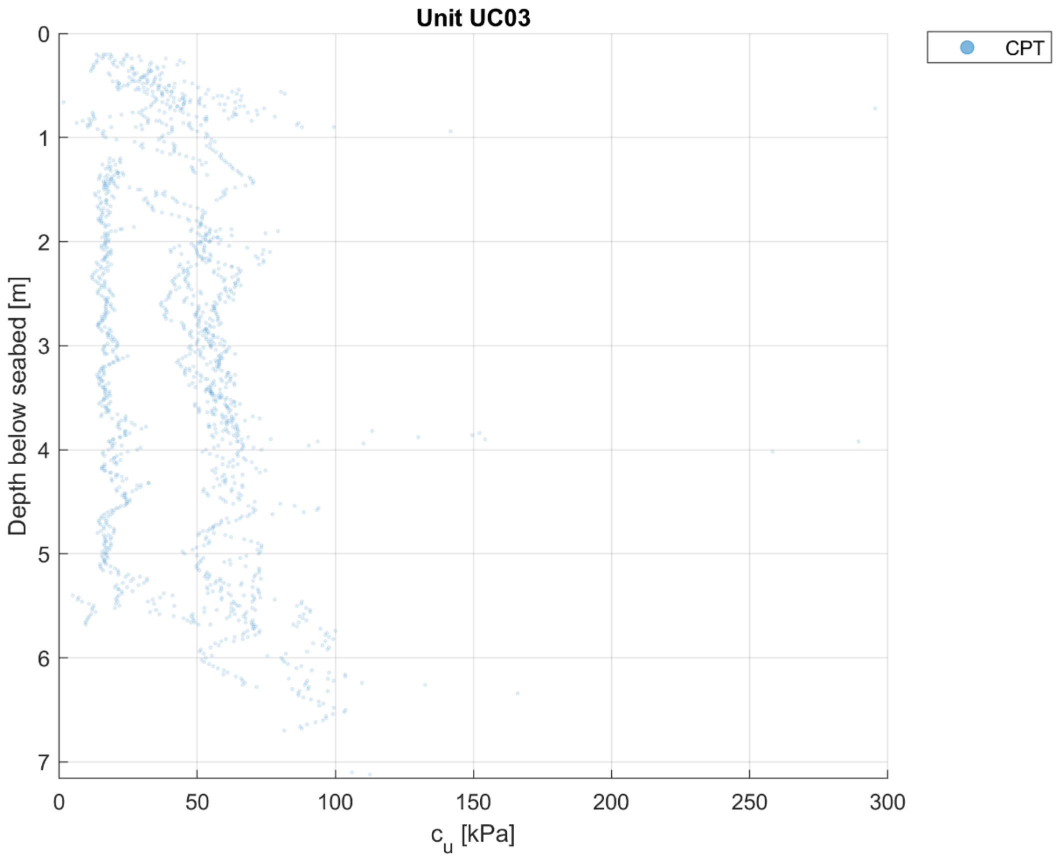

Unit US05
CPT
I_D limit
Depth below seabed [m]
ϕ [°]
0
1
2
3
4
5
6
7
8
9
25
30
35
40
45
50

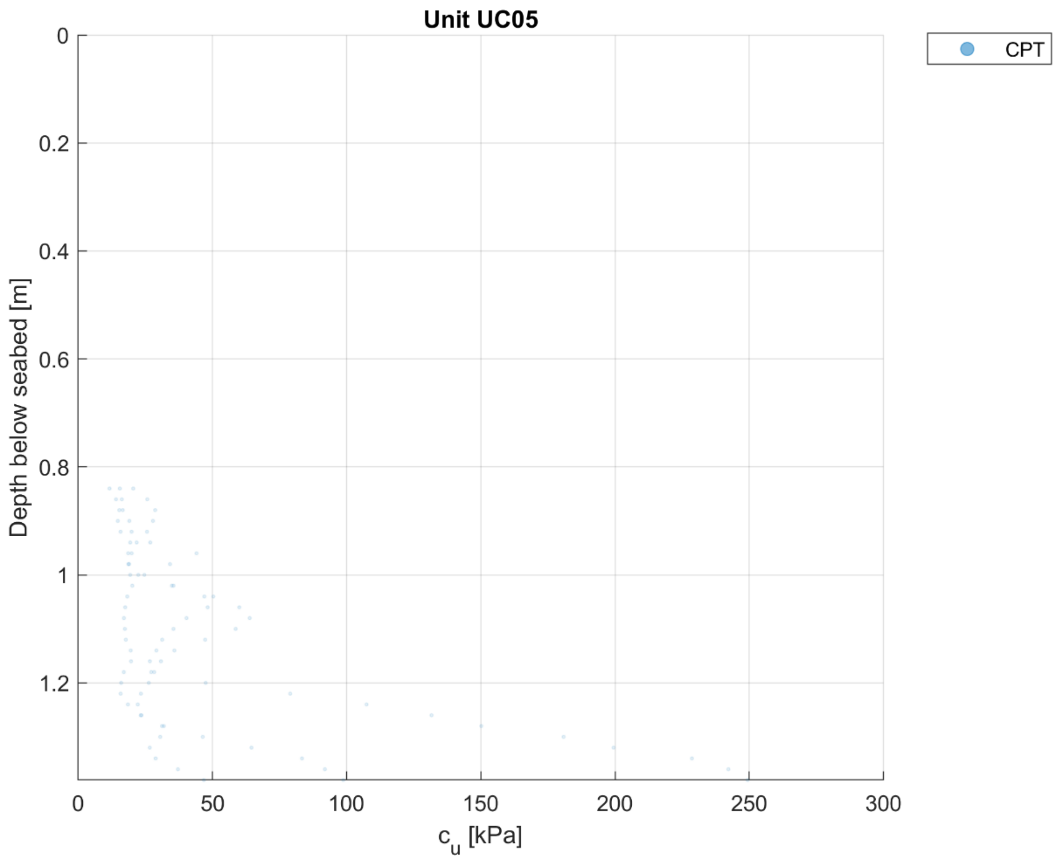

Unit US06
CPT
I_D limit
CIDU
Depth below seabed [m]
ϕ [°]
0
10
20
30
40
50
60
25
30
35
40
45
50

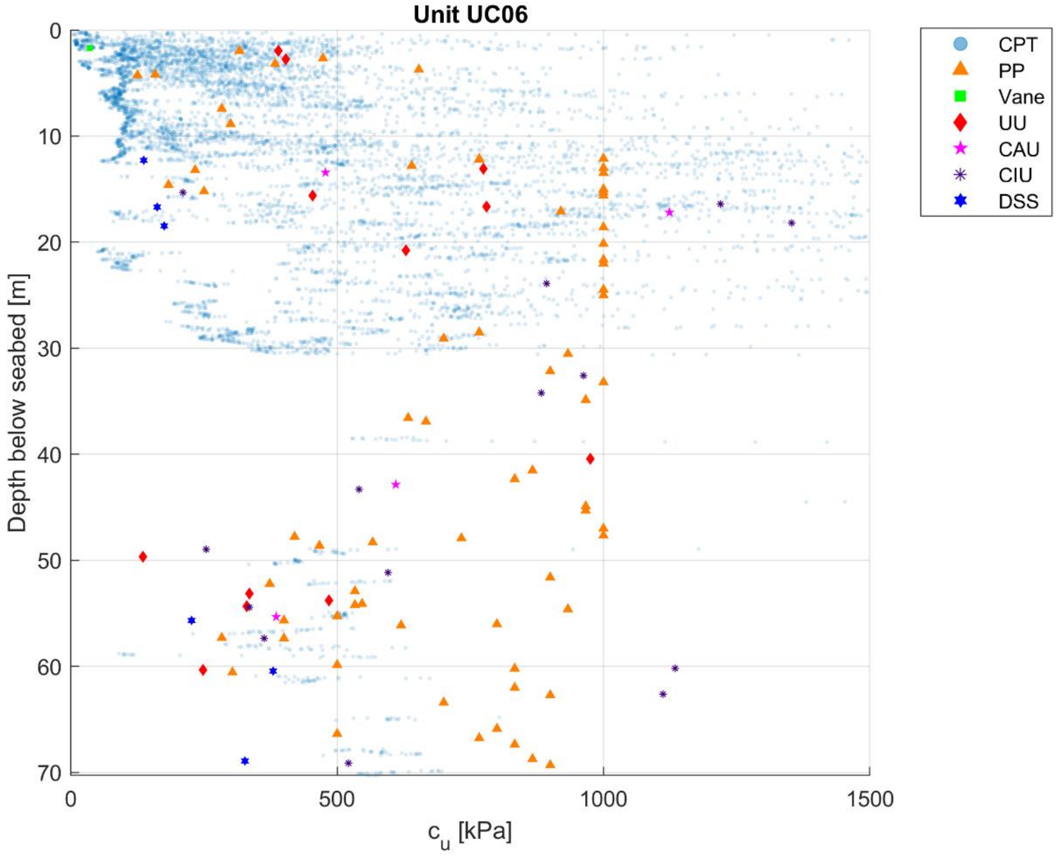
D.4 Undrained shear strength

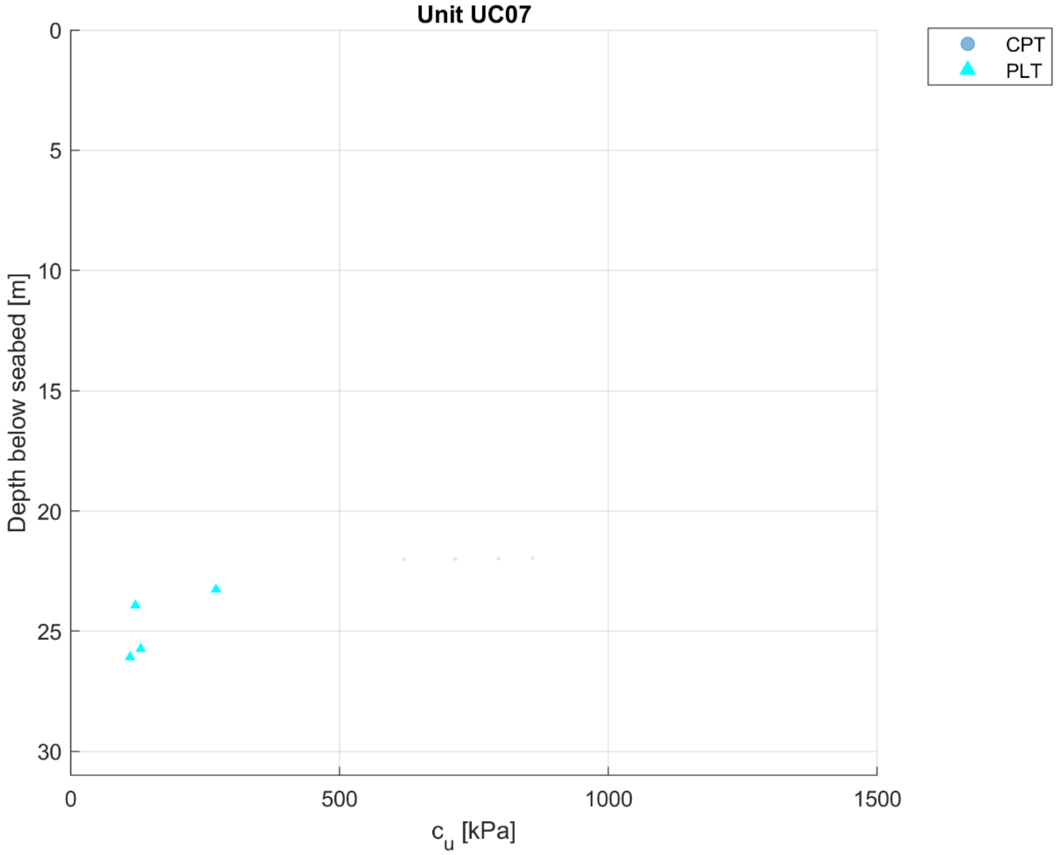




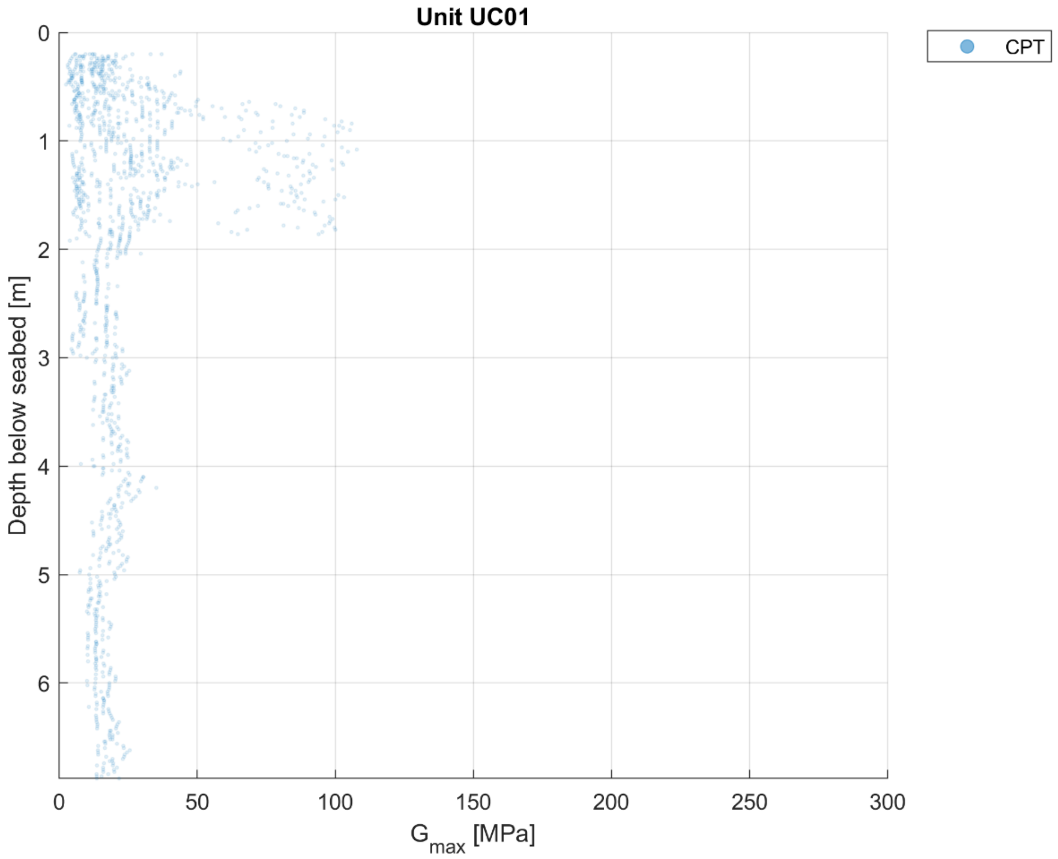

Unit UC03
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
c u [kPa]

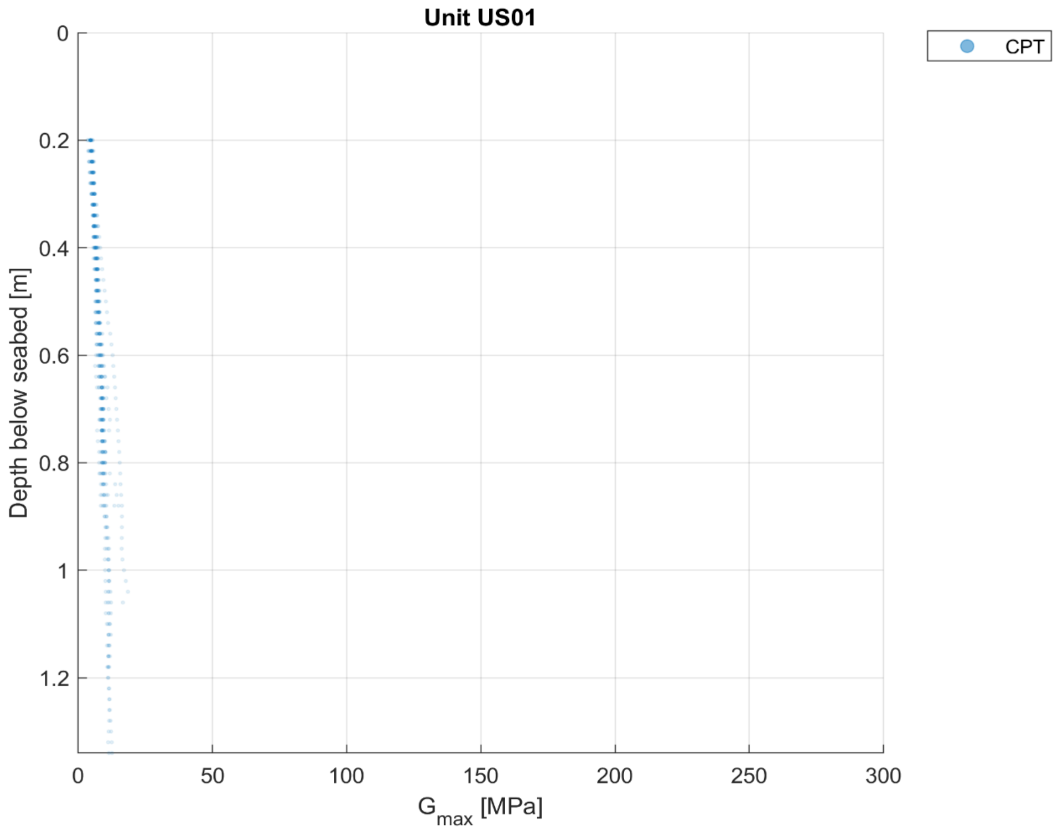

Unit UC05
CPT
Depth below seabed [m]
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
c u [kPa]

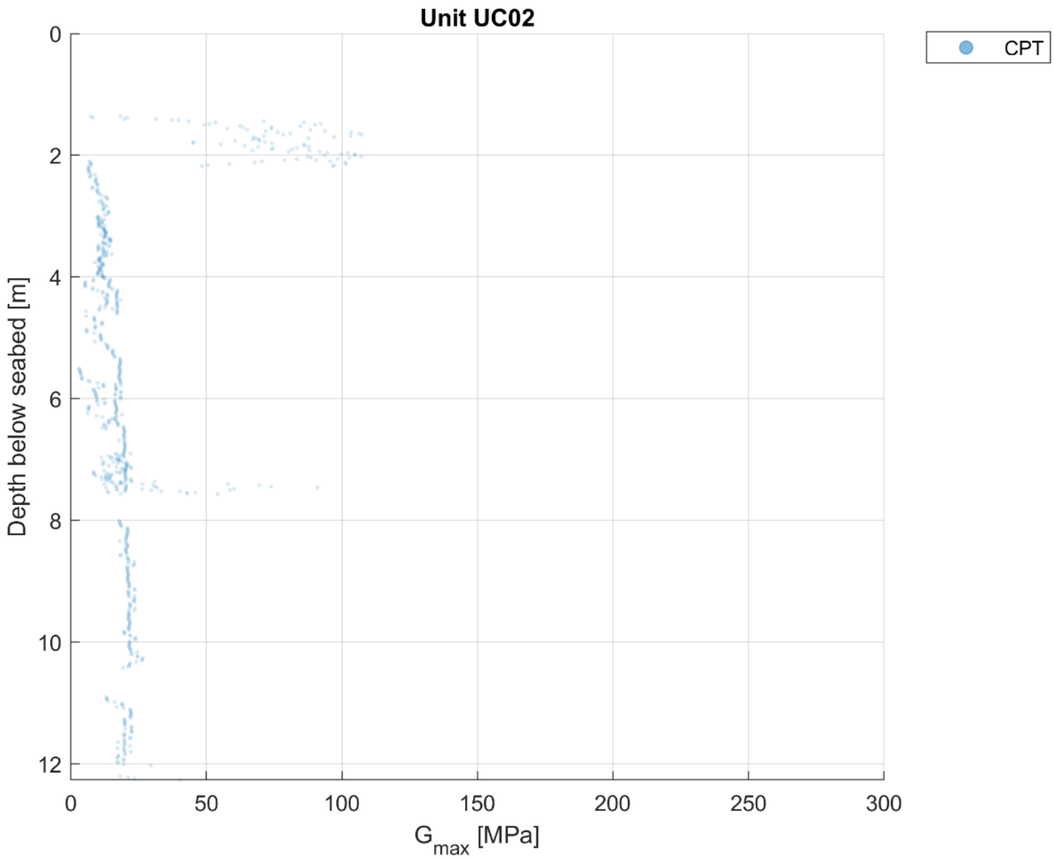

Unit UC06
Depth below seabed [m]
c_u [kPa]
CPT
PP
Vane
UU
CAU
CIU
DSS

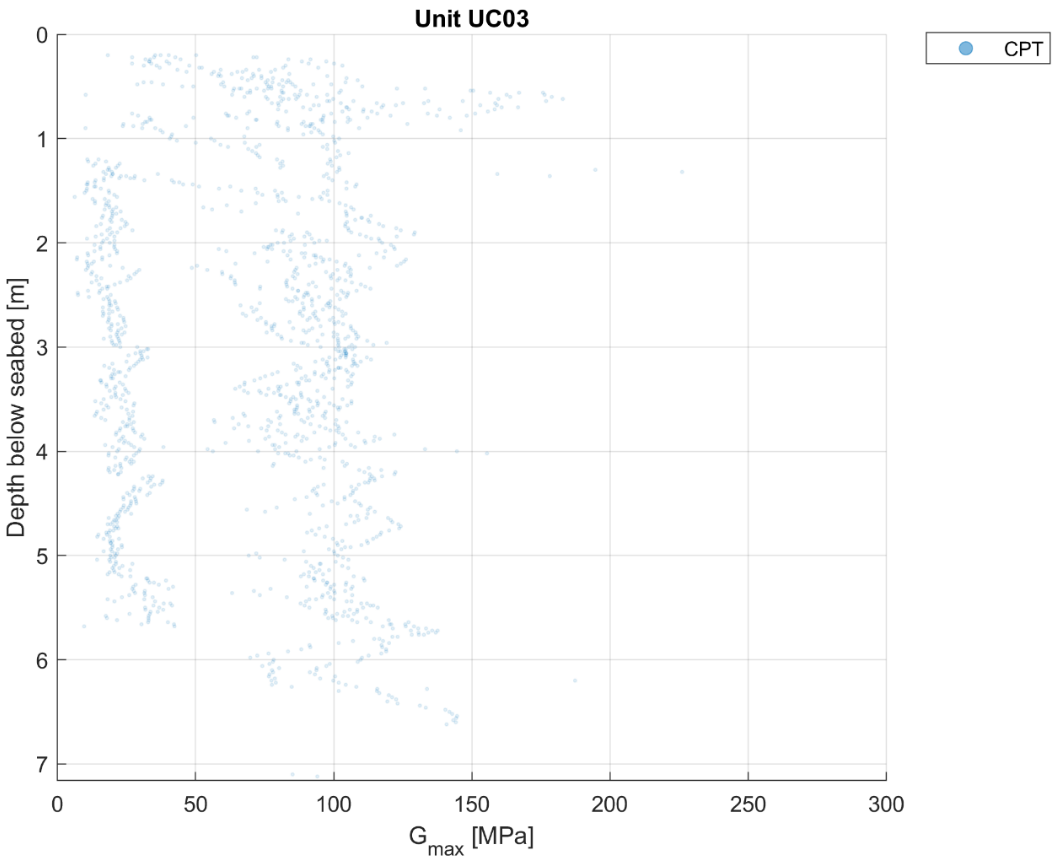

Unit UC07
Depth below seabed [m]
c_u [kPa]
CPT
PLT

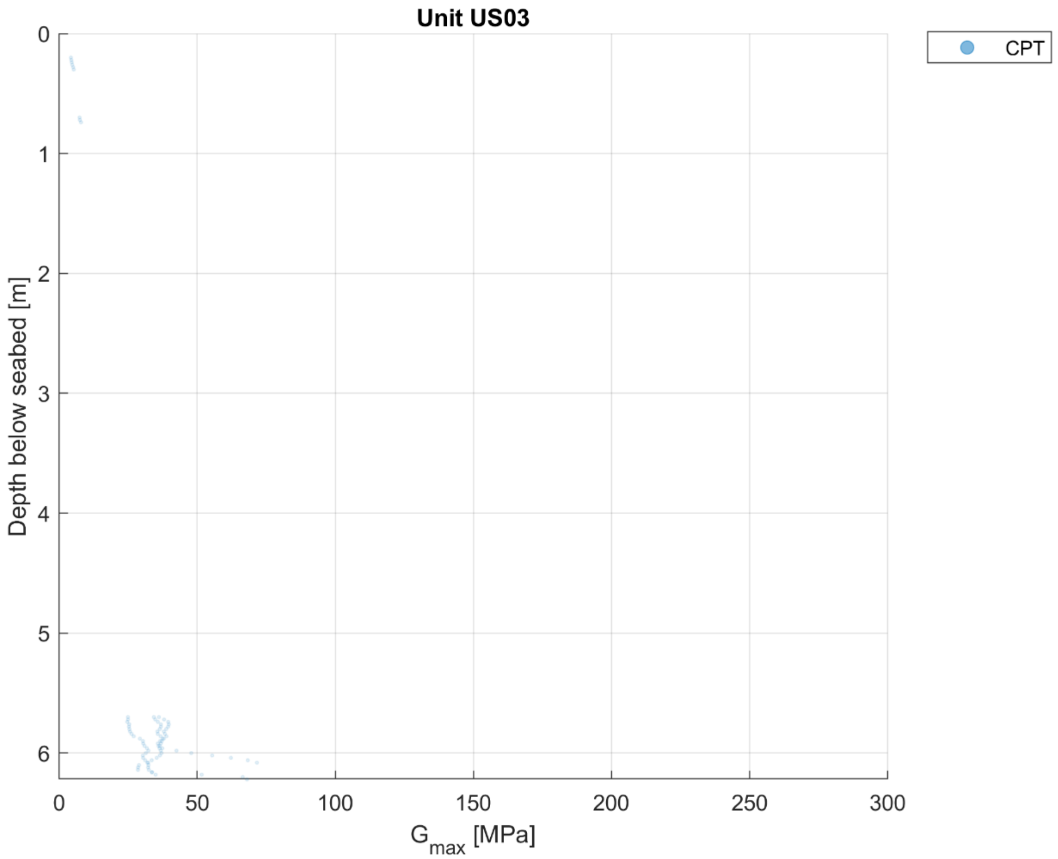
D.5 Small-strain shear modulus

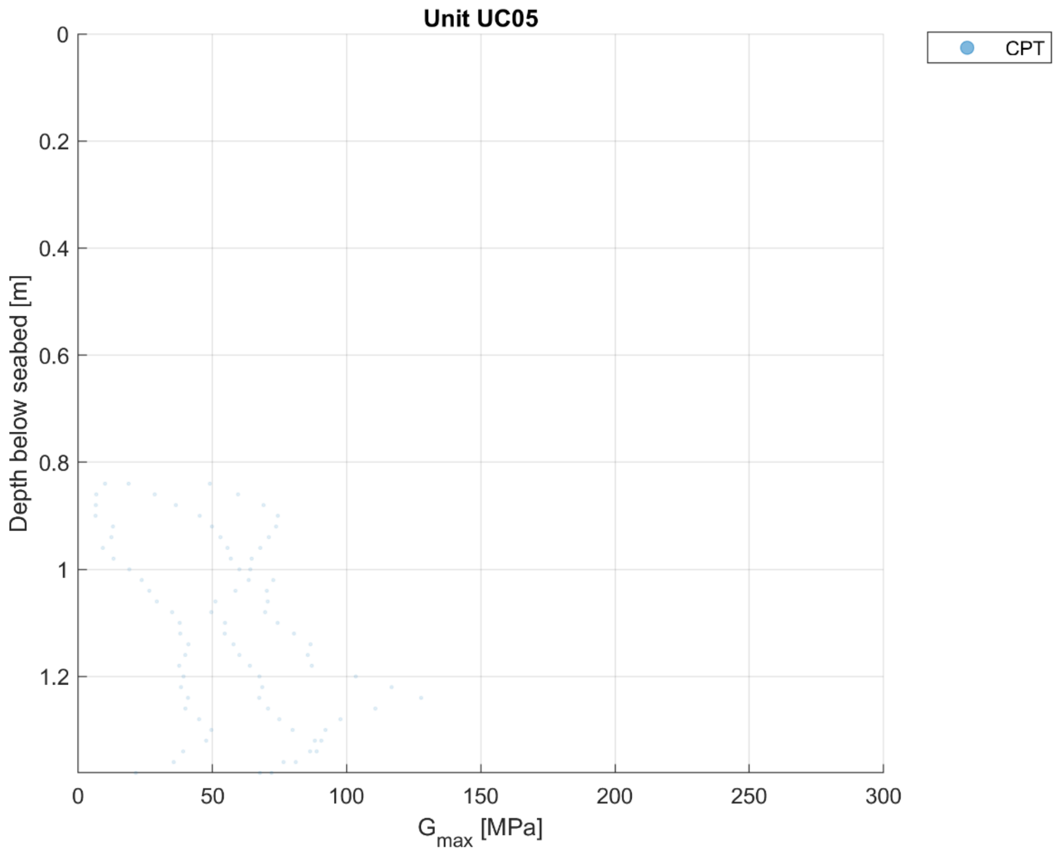


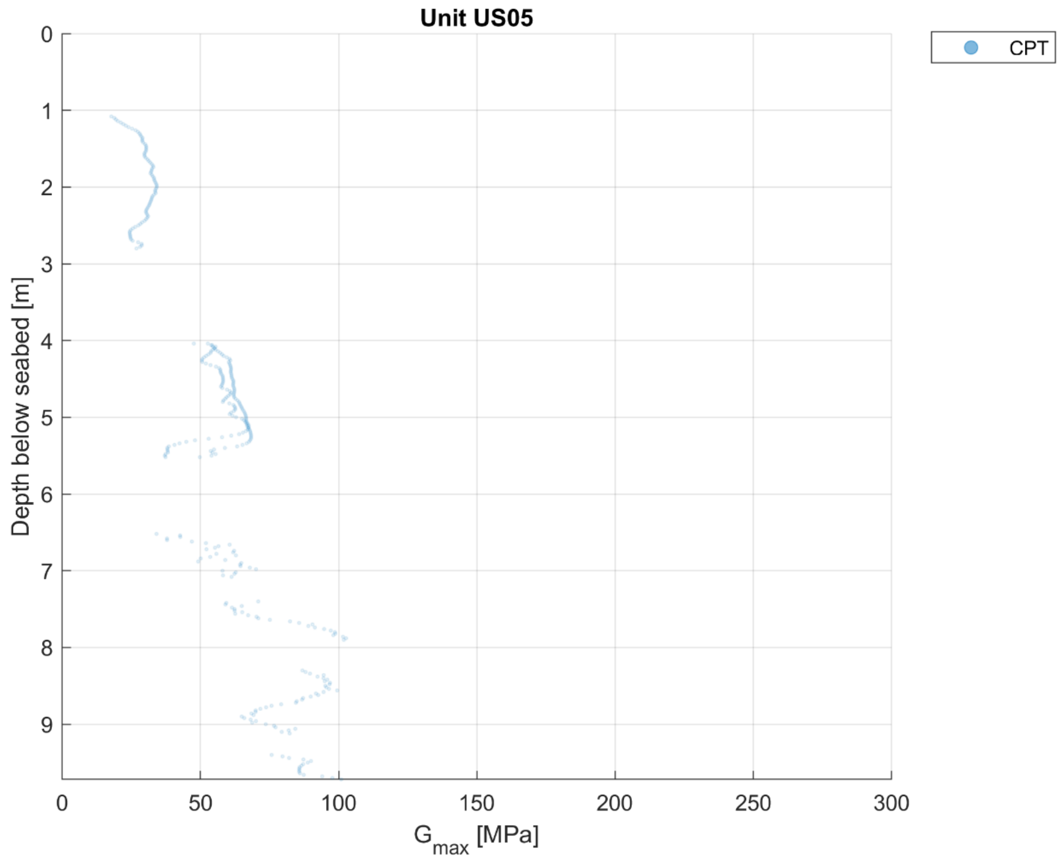


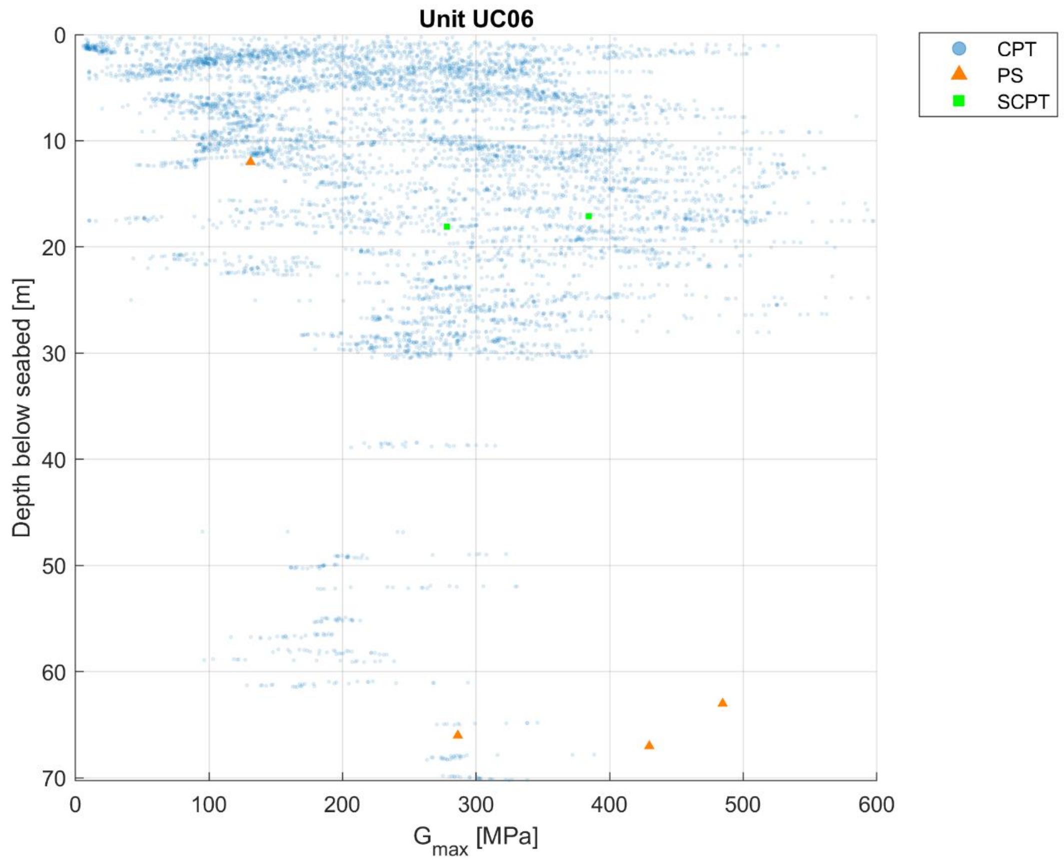

Unit UC02
CPT
Depth below seabed [m]
0
2
4
6
8
10
12
0
50
100
150
200
250
300
G_{max} [MPa]

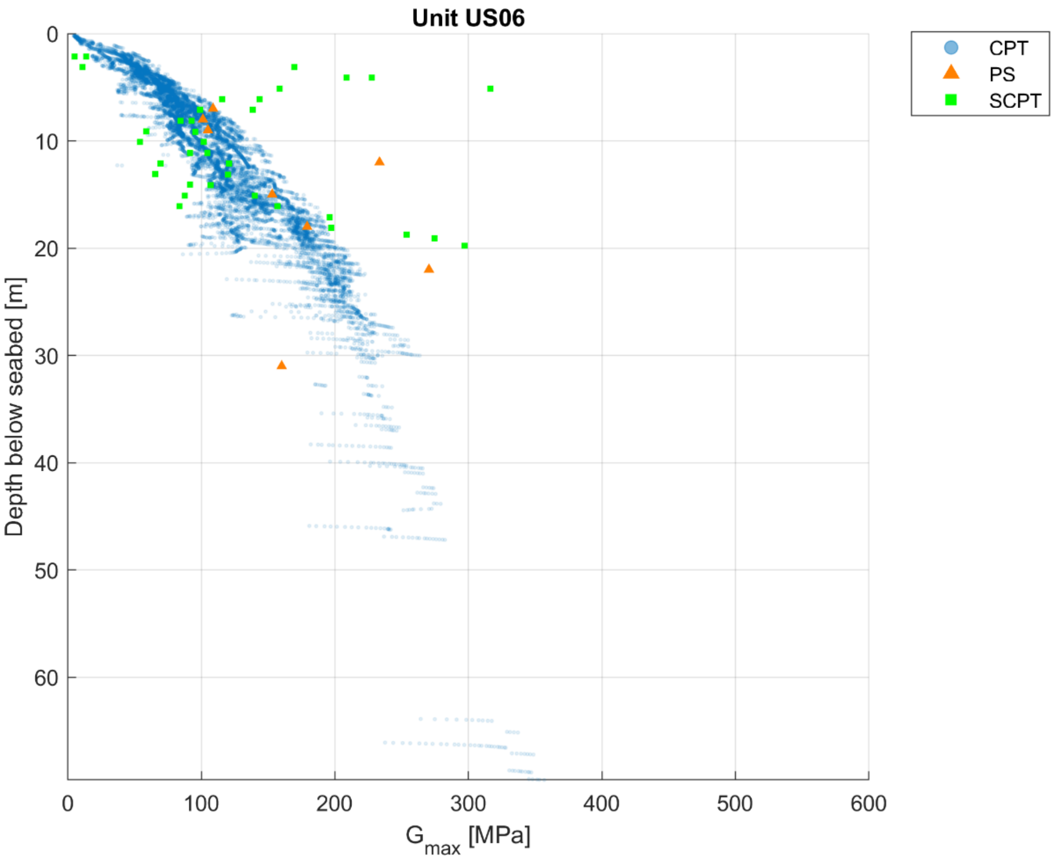

Unit UC03
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
G_{max} [MPa]

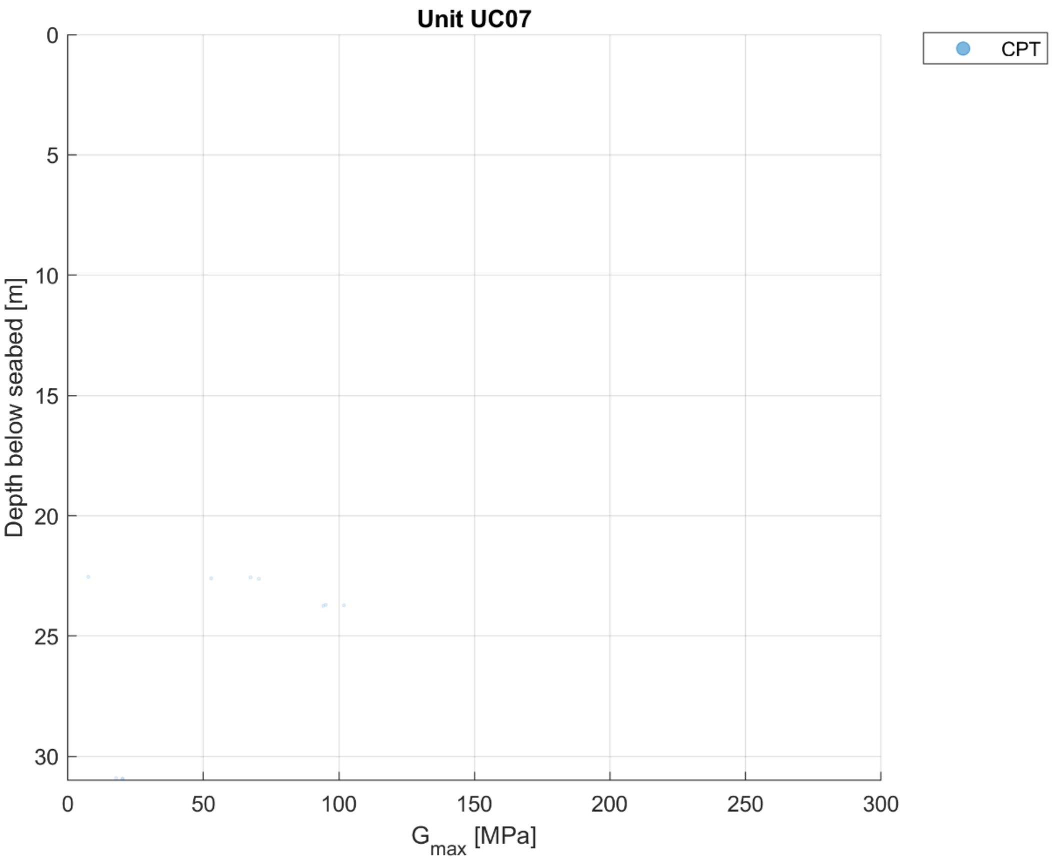

Unit US03
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
0
50
100
150
200
250
300
G max [MPa]


Unit UC05
CPT
Depth below seabed [m]
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
G max [MPa]


Unit US05
CPT
Depth below seabed [m]
0
1
2
3
4
5
6
7
8
9
0
50
100
150
200
250
300
G max [MPa]


Unit UC06
CPT
PS
SCPT
Depth below seabed [m]
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
G max [MPa]


Unit US06
Depth below seabed [m]
0
10
20
30
40
50
60
0
100
200
300
400
500
600
G max [MPa]
CPT
PS
SCPT

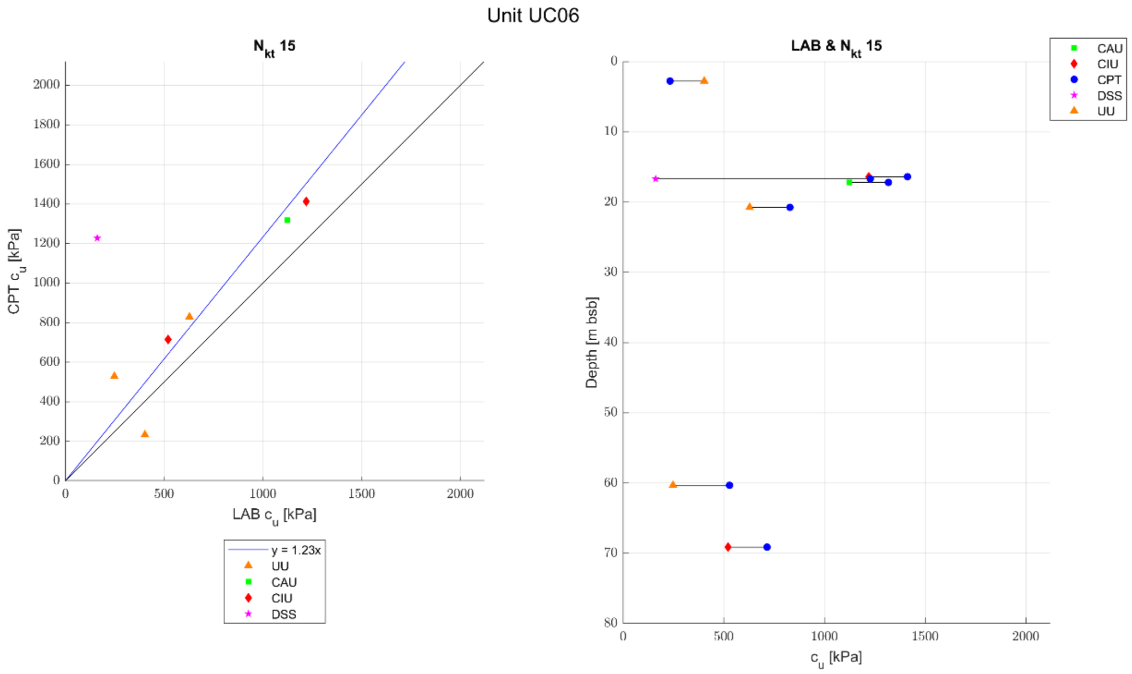

Unit UC07
Depth below seabed [m]
0
5
10
15
20
25
30
0
50
100
150
200
250
300
G max [MPa]
CPT

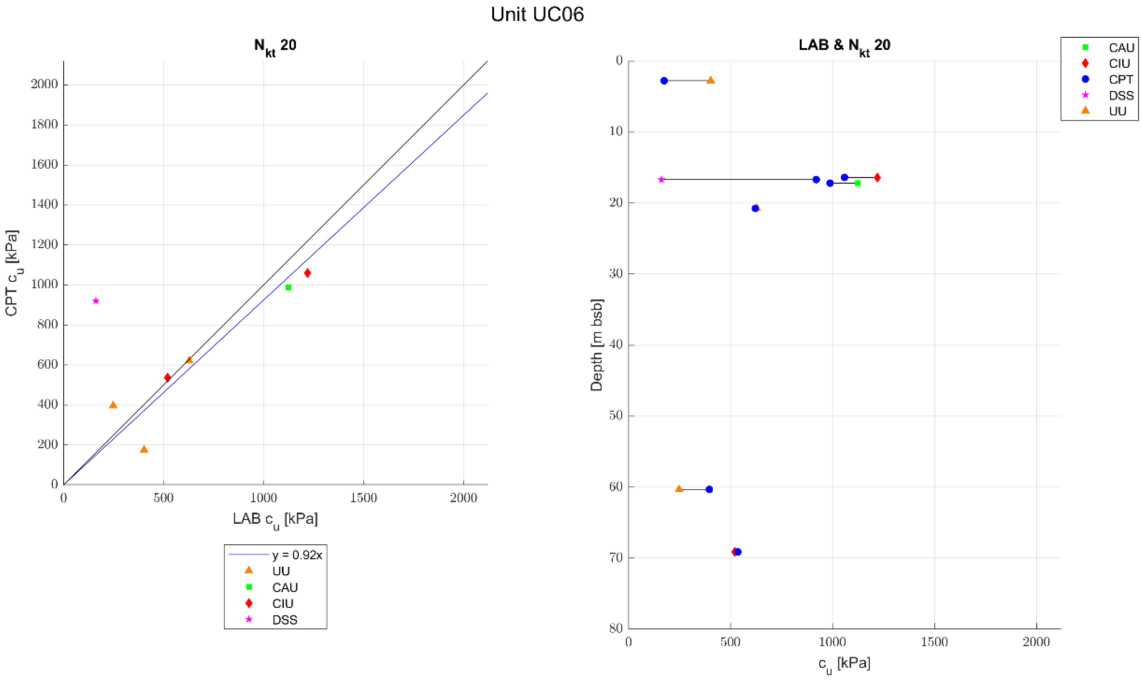
Appendix E Cone factor assessment

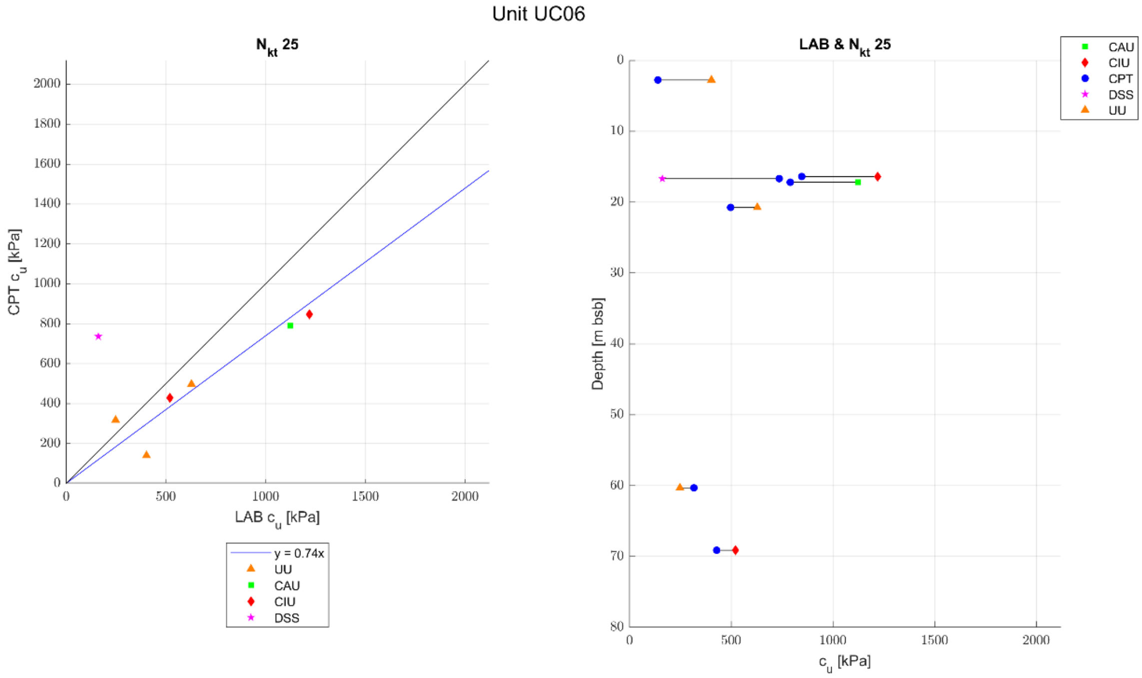
To derive undrained shear strength properties from the CPT measurements, a high-level assessment is performed to determine a cone factor, N_{kt}, to be used for correlating the CPT to undrained shear strength, where a factor of 20 is found representative.

The N_{kt} factor is selected from visual inspections and engineering judgement on which value suits best for fitting the data. Below figures present the assessment for N_{kt} values of 15, 20 and 25 for unit UC06 as this is the only unit where laboratory tests being of the considered types used for calibration is available.

Below figures contain of two subplots. The left subplot shows the correlation between CPT derived values and laboratory values. The CPT values are determined with specified N_{kt} value and considering measurements within ±25 cm of the test sample depth. The blue line presents the best linear fit to the measurements, while the black line presents one-to-one values between laboratory values and CPT correlated values, hence scatter located above the line represent values determined from CPT correlation is higher than comparable test value from laboratory test, and values below the line represent values from laboratory testing results are higher than comparable values from CPT correlation. The right subplot presents the difference between laboratory tests and derived parameter from CPT correlation with respect to depth.




Unit UC06
N kt 20
CPT c u [kPa]
LAB c u [kPa]
y = 0.92x
UU
CAU
CIU
DSS
LAB & N kt 20
Depth [m bsb]
c u [kPa]
CAU
CIU
CPT
DSS
UU


Unit UC06
N kt 25
CPT c u [kPa]
LAB c u [kPa]
y = 0.74x
UU
CAU
CIU
DSS
LAB & N kt 25
Depth [m bsb]
c u [kPa]
CAU
CIU
CPT
DSS
UU

Appendix F Range of soil properties per soil unit

This appendix presents the range of soil properties per geotechnical unit. The values presented are in the format:

min / max / average / standard deviation (number of tests)

Standard deviation is calculated based on sample size formulation and is not determined when only one (1) test is available.

Table F-1 Statistical overview of the strength parameter undrained shear strength per geotechnical unit based on available laboratory tests. Note, that the geotechnical units are based on CPT measurements and geophysical data. Hence, some test results are also given for sand units (i.e., tests performed on clayey/silty specimens present within a sand unit).

Geotechnical unit	Undrained shear strength [kPa]							
	DSS	CAU	CIU	PLT	UU	UCS	PP	Vane
UC01	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	136.8/379.7/234.5/98.0 (6)	385.4/1543.8/828.2/491.4 (5)	210/1353/741.2/384.9 (14)	-/-/-/- (0)	135.6/975.6/494.9/247.2 (12)	-/-/-/- (0)	125/1000/701.4/270.5 (69)	35/35/35/0 (1)
UC07	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	110/5410/1446.7/2181.6 (6)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US01	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	133.3/1000/747.0/256.4 (21)	-/-/-/- (0)

Table F-2 Statistical overview of the friction angle and small-strain shear modulus per geotechnical unit. Note, that the geotechnical units are based on CPT measurements and geophysical data. Hence, some CID tests are also performed for clay units (i.e., tests performed on sandy specimens present within a clay unit).

	Friction angle [°]	Small-strain shear modulus [MPa]	
Geotechnical unit	CID	SCPT	P-S logging
UC01	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	38.9/38.9/38.9/0 (1)	278.1/384.2/331.2/75.0 (2)	131.1/982.0/462.8/321.1 (5)
UC07	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US01	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	34.4/44.1/39.9/4.3 (7)	5.0/316.4/130.0/77.5 (35)	101.1/270.5/163.9/62.1 (8)

Table F-3 Statistical overview of particle size distribution per geotechnical unit based on available laboratory tests.

Geotechnical unit	Gravel content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Fines content [%]
UC01	0/2/0.8/1 (4)	66/91/79/12.8 (4)	9/21/14.3/6.2 (4)	0/12/6/6.9 (4)	9/33/20.3/13 (4)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	0/25/5.2/5.7 (26)	1/62/37.1/20.5 (26)	21/52/33.5/8.3 (26)	0/67/24.2/18 (26)	32/97/57.7/22.8 (26)
UC07	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US01	9/30/19.5/14.8 (2)	49/73/61/17 (2)	14/14/14/0 (2)	4/7/5.5/2.1 (2)	18/21/19.5/2.1 (2)
US03	15/15/15/- (1)	52/52/52/- (1)	17/17/17/- (1)	16/16/16/- (1)	33/33/33/- (1)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	0/21/2.2/4.3 (32)	1/98/63.4/31.3 (32)	2/94/27.2/25 (32)	0/31/7.2/8.1 (32)	2/99/34.4/30.7 (32)

Table F-4 Statistical overview of densities from classification tests per geotechnical unit based on available laboratory tests.

Geotechnical unit	Bulk density [Mg/m^3]	Dry density [Mg/m^3]	Particle density [Mg/m^3]	Maximum dry density [Mg/m^3]	Minimum dry density [Mg/m^3]
UC01	1.87/2.12/2.01/0.08 (12)	1.45/1.73/1.63/0.08 (12)	2.59/2.61/2.6/0.01 (4)	-/-/-/- (0)	-/-/-/- (0)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	1.25/1.25/1.25/- (1)	0.45/0.45/0.45/- (1)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	1.78/2.45/2.21/0.14 (41)	1.66/2.13/1.94/0.17 (16)	2.6/2.71/2.65/0.03 (26)	-/-/-/- (0)	-/-/-/- (0)
UC07	-/-/-/- (0)	-/-/-/- (0)	2.68/2.69/2.68/0.01 (3)	-/-/-/- (0)	-/-/-/- (0)
US01	1.41/2.04/1.73/0.45 (2)	0.7/1.67/1.19/0.69 (2)	2.25/2.25/2.25/- (1)	-/-/-/- (0)	-/-/-/- (0)
US03	-/-/-/- (0)	-/-/-/- (0)	2.69/2.69/2.69/- (1)	-/-/-/- (0)	-/-/-/- (0)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	1.66/2.38/2.06/0.12 (81)	1.4/2.02/1.66/0.08 (65)	2.61/2.69/2.65/0.02 (31)	1.72/1.82/1.77/0.03 (6)	1.35/1.48/1.42/0.05 (6)

Table F-5 Statistical overview of classification properties per geotechnical unit based on available laboratory tests. Note, that the geotechnical units are based on CPT measurements and geophysical data. Hence, some test results are also given for sand units (i.e., tests performed on clayey/silty specimens present within a sand unit) even though Atterberg limits are generally only performed on silty/clayey soils.

Geotechnical unit	Liquid limit [%]	Plastic limit [%]	Plasticity index [%]
UC01	21/21/21/0 (2)	14/14/14/0 (2)	7/7/7/0 (2)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	20/90/36/22.2 (28)	11/30/16.1/6.3 (28)	6/63/19.9/16.2 (28)
UC07	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US01	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	20/32/22.3/9.9 (8)	11/20/11.9/5.8 (8)	9/14/10.4/4.4 (8)

Table F-6 Statistical overview of classification properties per geotechnical unit based on available laboratory tests.

Geotechnical unit	Carbonate content [%]	Organic matter content [%]	Water soluble chloride [g/l]	Total acid sulphate [%]	Thermal conductivity [W/(mK)]
UC01	1.5/3.3/2.4/1.27 (2)	0.9/0.9/0.9/- (1)	1.7/1.8/1.8/0.1 (2)	0.1/0.2/0.1/0.1 (2)	2.35/2.35/2.35/- (1)
UC02	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC05	-/-/-/- (0)	15/15/15/- (1)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
UC06	4.6/4.6/1.15/1.99 (4)	8.9/8.9/8.9/- (1)	0.5/1.3/0.8/0.4 (4)	0.1/0.3/0.2/0.1 (4)	1.93/1.93/1.93/- (1)
UC07	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US01	1.2/1.5/1.35/0.21 (2)	2.2/2.2/2.2/- (1)	2.2/8.1/5.2/4.2 (2)	0.1/1.1/0.6/0.7 (2)	-/-/-/- (0)
US03	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US05	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)	-/-/-/- (0)
US06	1.5/25/9.16/8.86 (7)	0.5/2.3/1.1/0.8 (4)	0.6/2.2/1.4/0.6 (7)	0/0.1/0.1/0 (7)	2.31/2.31/2.31/- (1)

Appendix G Conceptual Geological Model

Larger versions of Figure 5-1 and Figure 5-2.

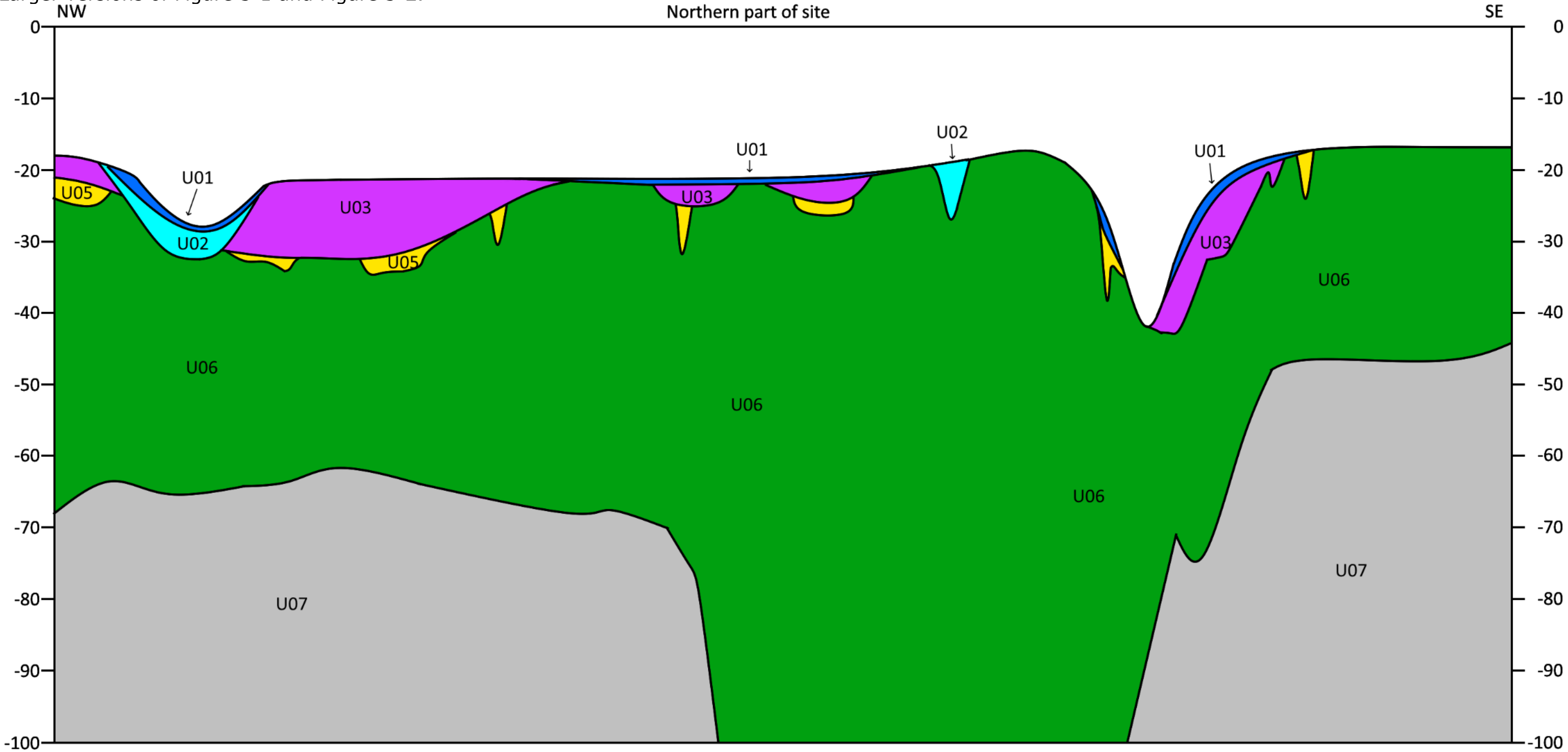


Figure G-1 Conceptual model cross section oriented from north-west to south-east through the northern part of the OWF project site.

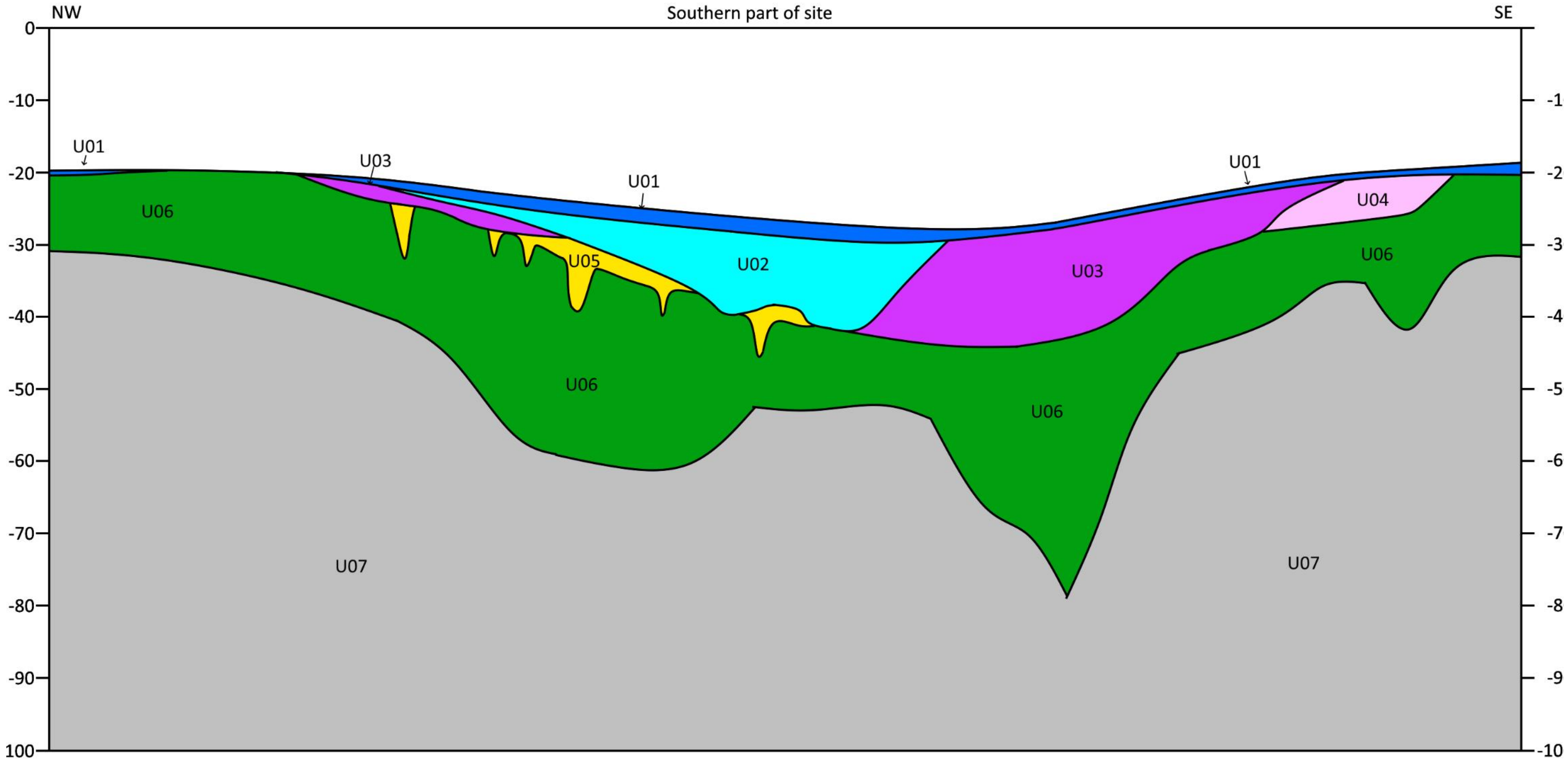


Figure G-2 Conceptual model cross section oriented from north-west to south-east through the southern part of the OWF project site.

Appendix H Soil profiles for LPA assessment

As stated in section 11.3, constant strength parameters are required as input for the high-level LPA assessment per geotechnical location. For estimating the required strength parameters for the different layers, the following procedure is used:

- For clay layers, the undrained shear strength, c_u, is estimated for each individual layer by disregarding the highest and lowest 10% of the data. This is done to remove potential smaller outliers from the considered data sample from the layer. Hereafter the average value from the remaining 80% of the measurements are determined and used as representative value for the layer.

- For sand layers, the undrained friction angle is estimated for each individual layer by disregarding the highest and lowest 10% of the data. This is done to remove potential smaller outliers from the considered data sample from the layer. After, the average value from the remaining 80% of the measurements are determined and used as representative value for the layer.

- For all types of layers, in case a startup of new CPT push is present in the layer, the first 20 cm (10 measurements) from the CPT push are removed for the strength value to not be wrongly reduced due to the effect from the new startup.

Table H-1 Soil stratigraphy per geotechnical location considered for the analyses.

Location	Unit	Top [m]	Bottom [m]	Material	Undrained shear strength [kPa]	Friction angle [°]
KG_01	US01	0	1.07	SAND	-	36
KG_01	US05	1.07	2.81	SAND	-	38.8
KG_01	UC06	2.81	6.74	CLAY	80.7	-
KG_01	UC06	6.74	11.41	CLAY	419.1	-
KG_01	US06	11.41	11.66	SAND	-	42.4
KG_02	UC01	0	6.89	CLAY	28.2	-
KG_02	UC02	6.89	7.57	CLAY	33.4	-
KG_02	US06	7.57	10.44	SAND	-	37.2
KG_02	UC06	10.44	16.23	CLAY	290.4	-
KG_02	US06	16.23	44.46	SAND	-	40.6
KG_02	UC06	44.46	70.3	CLAY	591.2	-
KG_04	UC06	0	1.88	CLAY	546.5	-
KG_04	US06	1.88	9.03	SAND	-	45.1
KG_04	UC06	9.03	11.87	CLAY	909.7	-
KG_04	US06	11.87	23.28	SAND	-	42.5
KG_05	US01	0	0.16	SAND	-	0
KG_05	UC01	0.16	1.87	CLAY	35.5	-
KG_05	UC03	1.87	4.03	CLAY	53.7	-

Location	Unit	Top [m]	Bottom [m]	Material	Undrained shear strength [kPa]	Friction angle [°]
KG_05	US05	4.03	5.54	SAND	-	40.6
KG_05	UC06	5.54	12.7	CLAY	97.2	-
KG_06	UC03	0	1.61	CLAY	43	-
KG_06	UC06	1.61	7.52	CLAY	322.1	-
KG_06	US06	7.52	9.61	SAND	-	40.3
KG_06	UC06	9.61	11.3	CLAY	188.1	-
KG_06	US06	11.3	20.33	SAND	-	41.5
KG_06	US06	20.33	30.06	SAND	-	42.6
KG_07	US03	0	0.75	SAND	-	29.5
KG_07	UC03	0.75	1.17	CLAY	19.1	-
KG_07	UC06	1.17	17.21	CLAY	327.6	-
KG_07	US06	17.21	37.21	SAND	-	40.5
KG_07	UC06	37.21	41.34	CLAY	826.3	-
KG_09	US06	0	0.97	SAND	-	31.2
KG_09	UC06	0.97	5.05	CLAY	155.1	-
KG_09	UC06	5.05	6.33	CLAY	718.8	-
KG_09	US06	6.33	18.84	SAND	-	43.7
KG_09	US06	18.84	30.32	SAND	-	42.9
KG_10	US01	0	0.46	SAND	-	30.1
KG_10	UC03	0.46	0.96	CLAY	54.5	-
KG_10	US06	0.96	7.5	SAND	-	42.5
KG_10	UC06	7.5	26.18	CLAY	698.2	-
KG_10	UC06	26.18	29.73	CLAY	411	-
KG_10	US06	29.73	30.32	SAND	-	40.9
KG_11	US01	0	1.35	SAND	-	30.1
KG_11	UC02	1.35	2.19	CLAY	41.4	-
KG_11	US06	2.19	10.98	SAND	-	43.3
KG_12	UC01	0	2.06	CLAY	87.7	-
KG_12	US06	2.06	3.51	SAND	-	35.2
KG_12	US06	3.51	4.76	SAND	-	40.2
KG_12	US06	4.76	5.63	SAND	-	34.7
KG_12	US06	5.63	18.86	SAND	-	39.9
KG_12	US06	18.86	24.47	SAND	-	43.8
KG_12	UC06	24.47	25.3	CLAY	742.5	-
KG_12	US06	25.3	28.8	SAND	-	41.4
KG_12	UC07	28.8	31.02	CLAY	2637.3	-
KG_13	UC01	0	3.02	CLAY	5.6	-
KG_13	UC02	3.02	6.52	CLAY	7.9	-
KG_13	US05	6.52	9.74	SAND	-	38.2
KG_13	UC06	9.74	13.54	CLAY	734.7	-
KG_13	US06	13.54	30.04	SAND	-	43.2
KG_14	UC03	0	0.92	CLAY	40.9	-
KG_14	UC06	0.92	4.16	CLAY	358	-
KG_14	US06	4.16	12.03	SAND	-	44.1
KG_14	UC06	12.03	17.93	CLAY	906.7	-
KG_14	US06	17.93	23.96	SAND	-	42.9
KG_14	UC06	23.96	30.58	CLAY	569.6	-

Location	Unit	Top [m]	Bottom [m]	Material	Undrained shear strength [kPa]	Friction angle [°]
KG_15	UC06	0	1.21	CLAY	37.9	-
KG_15	US06	1.21	13.61	SAND	-	43.1
KG_15	UC06	13.61	37.23	CLAY	2046.6	-
KG_15	US06	37.23	41.5	SAND	-	40.1
KG_15	UC06	41.5	44.26	CLAY	0	-
KG_15	US06	44.26	47.7	SAND	-	38.4
KG_15	UC06	47.7	63.86	CLAY	453.1	-
KG_15	US06	63.86	69.6	SAND	-	39.1
KG_17	US06	0	0.75	SAND	-	34
KG_17	UC06	0.75	2.78	CLAY	348	-
KG_17	US06	2.78	6.11	SAND	-	42.3
KG_17	US06	6.11	19.18	SAND	-	45.3
KG_17	UC06	19.18	21.43	CLAY	824.3	-
KG_17	US06	21.43	25.44	SAND	-	42.6
KG_19	UC01	0	1.34	CLAY	29.3	-
KG_19	UC03	1.34	7.17	CLAY	61.5	-
KG_19	US06	7.17	26.02	SAND	-	42.2
KG_20	UC01	0	1.31	CLAY	17.6	-
KG_20	UC06	1.31	6.62	CLAY	297.3	-
KG_20	US06	6.62	8.84	SAND	-	41
KG_20	UC06	8.84	11.61	CLAY	205.2	-
KG_20	UC06	11.61	15.68	CLAY	815.9	-
KG_20	US06	15.68	16.83	SAND	-	42.3
KG_20	UC06	16.83	18.6	CLAY	406.6	-
KG_20	UC06	18.6	21.06	CLAY	1482.2	-
KG_20	US06	21.06	23.53	SAND	-	44
KG_20	UC06	23.53	30.66	CLAY	291.6	-
KG_21	US01	0	0.89	SAND	-	30.2
KG_21	UC06	0.89	4.22	CLAY	177.2	-
KG_21	US06	4.22	11.62	SAND	-	43.8
KG_21	UC06	11.62	21.95	CLAY	1008.9	-
KG_21	UC07	21.95	27.04	CLAY	2608.6	-
KG_22	US01	0	0.89	SAND	-	30.3
KG_22	US06	0.89	1.26	SAND	-	36.9
KG_22	UC06	1.26	7.78	CLAY	332.4	-
KG_22	US06	7.78	22.76	SAND	-	44
KG_22	UC07	22.76	25.06	CLAY	2438.3	-
KG_23	US01	0	1.2	SAND	-	29.8
KG_23	UC03	1.2	5.7	CLAY	18.4	-
KG_23	US03	5.7	6.23	SAND	-	29.1
KG_23	US06	6.23	9.48	SAND	-	40
KG_23	UC06	9.48	15	CLAY	537.6	-
KG_23	US06	15	16.62	SAND	-	41.3
KG_23	UC06	16.62	30.28	CLAY	840.5	-
KG_24	UC01	0	1.75	CLAY	6.1	-
KG_24	UC02	1.75	12.28	CLAY	11.4	-
KG_24	US06	12.28	14.29	SAND	-	40.6

Location	Unit	Top [m]	Bottom [m]	Material	Undrained shear strength [kPa]	Friction angle [°]
KG_24	UC06	14.29	15.2	CLAY	0	-
KG_25	US01	0	0.84	SAND	-	30.9
KG_25	UC05	0.84	1.4	CLAY	33.3	-
KG_25	US06	1.4	16.31	SAND	-	41.6
KG_25	UC06	16.31	18.25	CLAY	1058.2	-
KG_25	US06	18.25	25.1	SAND	-	40
KG_25	UC07	25.1	26.36	CLAY	0	-
KG_26	US01	0	0.76	SAND	-	31.4
KG_26	US06	0.76	11.47	SAND	-	39.5
KG_26	UC06	11.47	13.19	CLAY	299.7	-
KG_26	US06	13.19	15.24	SAND	-	38.7
KG_26	UC06	15.24	16.13	CLAY	335.2	-
KG_26	US06	16.13	17.84	SAND	-	38.2
KG_26	US06	17.84	20.6	SAND	-	36.7
KG_26	UC06	20.6	22.85	CLAY	97	-