Netherlands Enterprise Agency

Webinar Geotechnical and Geophysical Assessment for Hollandse Kust (noord)

Ir. F.C.W. (Frank) van Erp

Welcome

- Introduction speaker and panel
- Goal of this webinar
- Agenda

Have a successful meeting!

Hollandse Kust (noord) Wind Farm Zone – Geophysical and Geotechnical Site Investigations

Webinar, 13 June 2019, Martijn Klein (Fugro)

Contents

FUGRO

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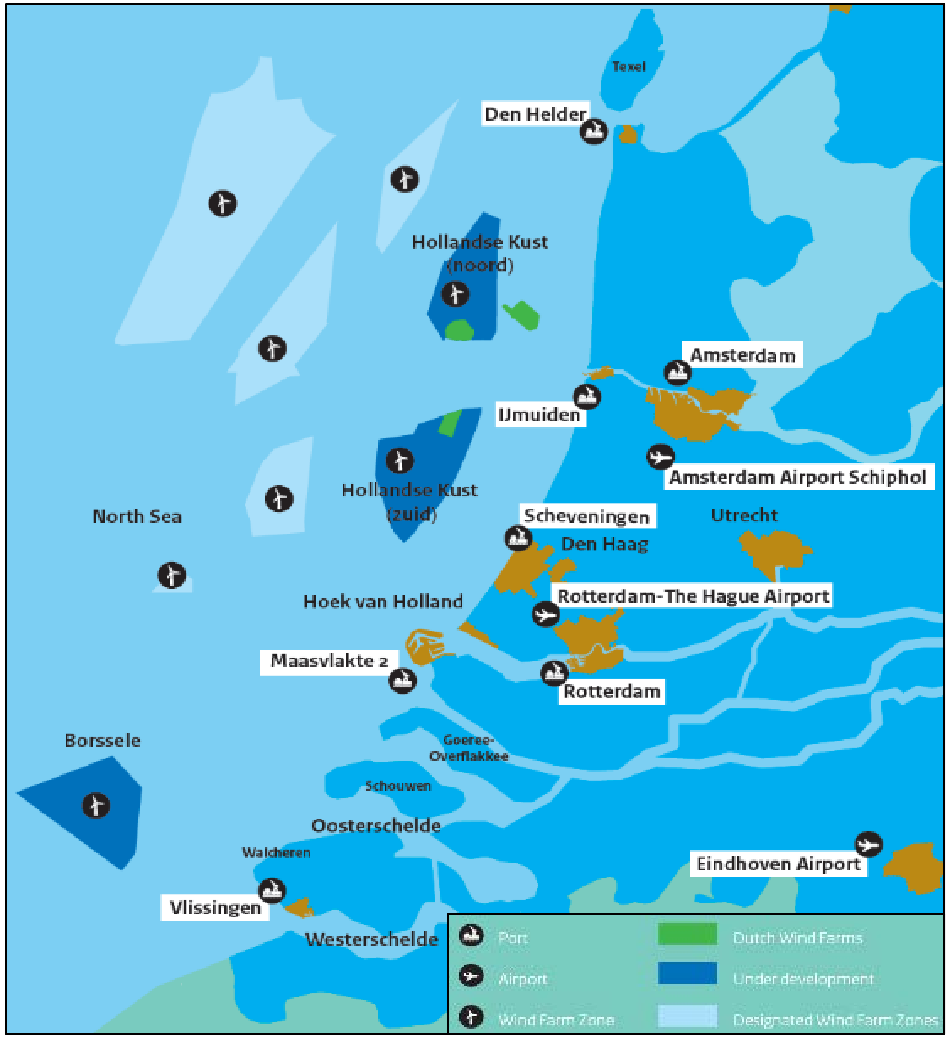
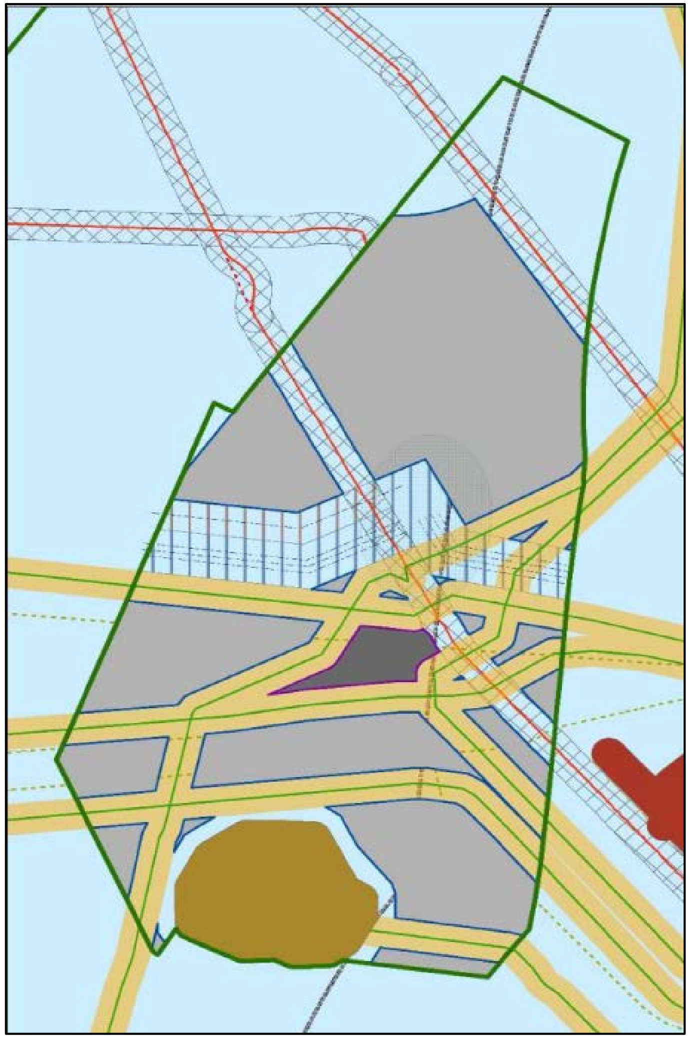
Geophysical & Geotechnical Site Investigations

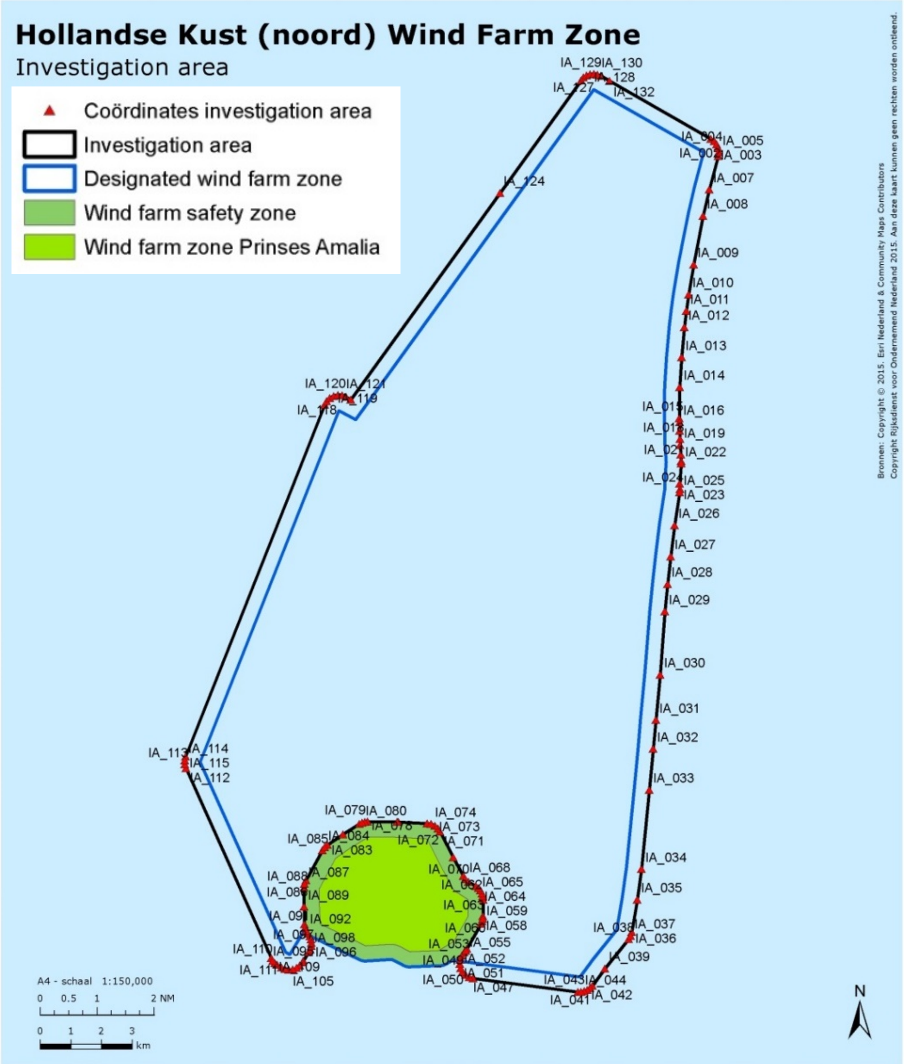
Hollandse Kust (noord) Wind Farm Zone (HKN WFZ)

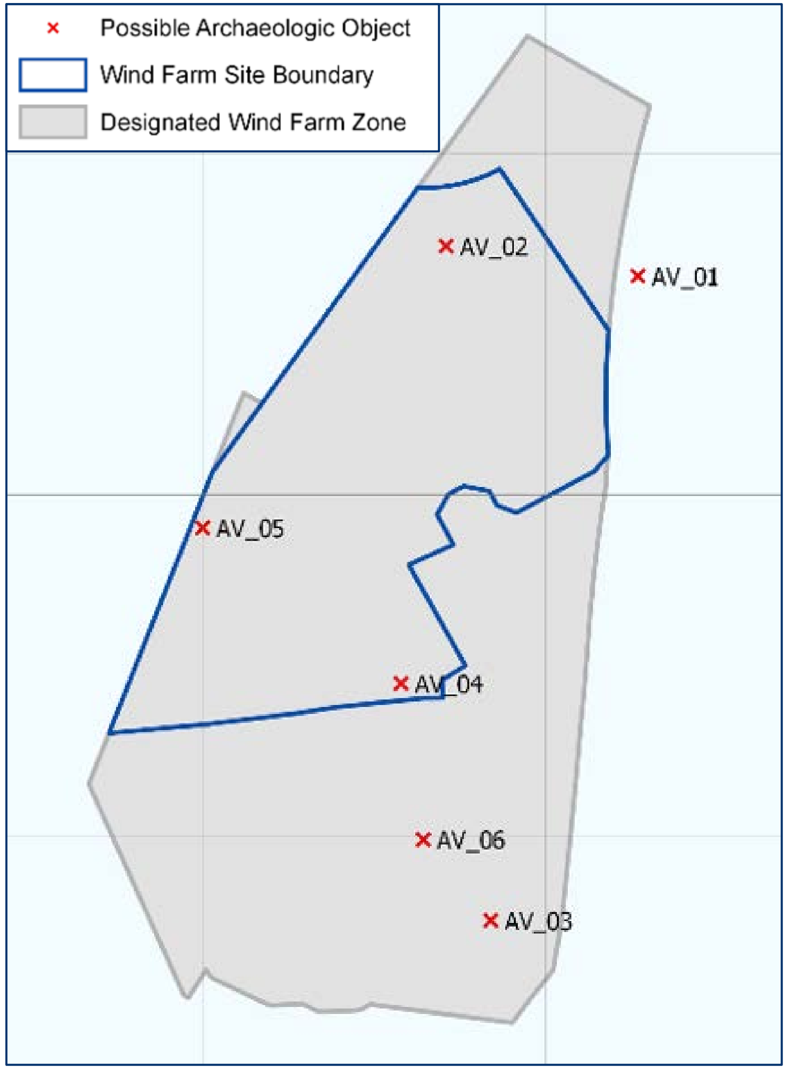




Sources: "Existing port and manufacturing infrastructure base in the Netherlands" www.offshorewind.rvo.nl and "Voorgestelde verkaveling" www.rvo.nl Note verification recommended, presented figure may have been updated.

HKN WFZ – Wind Farm Site and Investigation Area





Ref.:

Project and Site Description HKN; Appendix C, Boundaries and Coordinates - version 16 April 2019

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Starting Points for Investigation Plans

RVO Desk Studies

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Geophysical Site Phases

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Geophysical Reporting

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Geotechnical Site Phases

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Laboratory Testing

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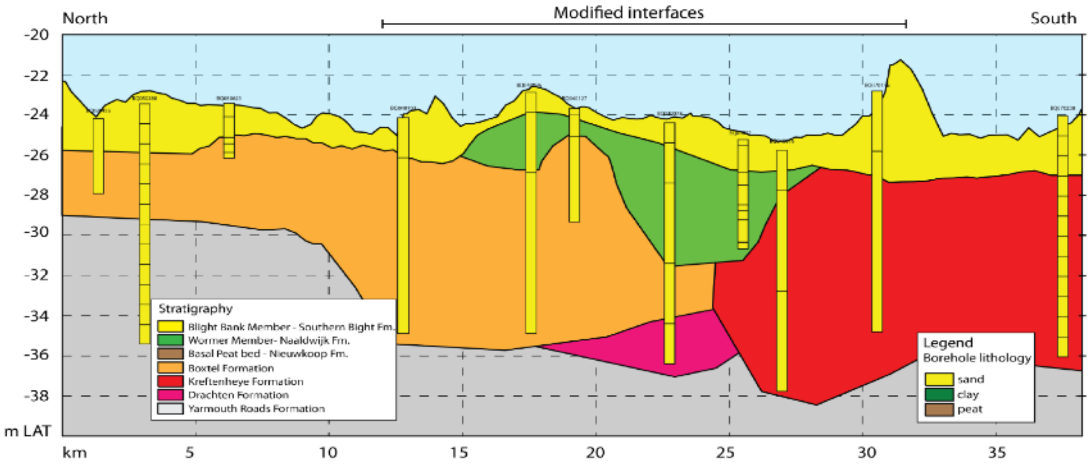
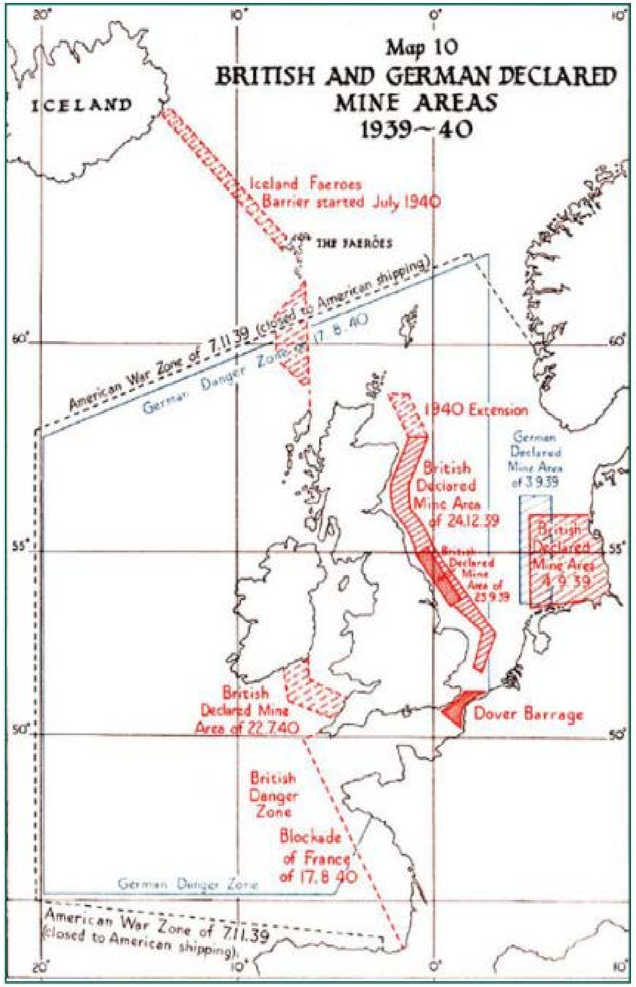
Geotechnical Reporting





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Geophysical Investigation – Site Phases

RVO Desk Studies

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Geophysical Site Phases

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Geophysical Reporting

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Geotechnical Site Phases

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Laboratory Testing

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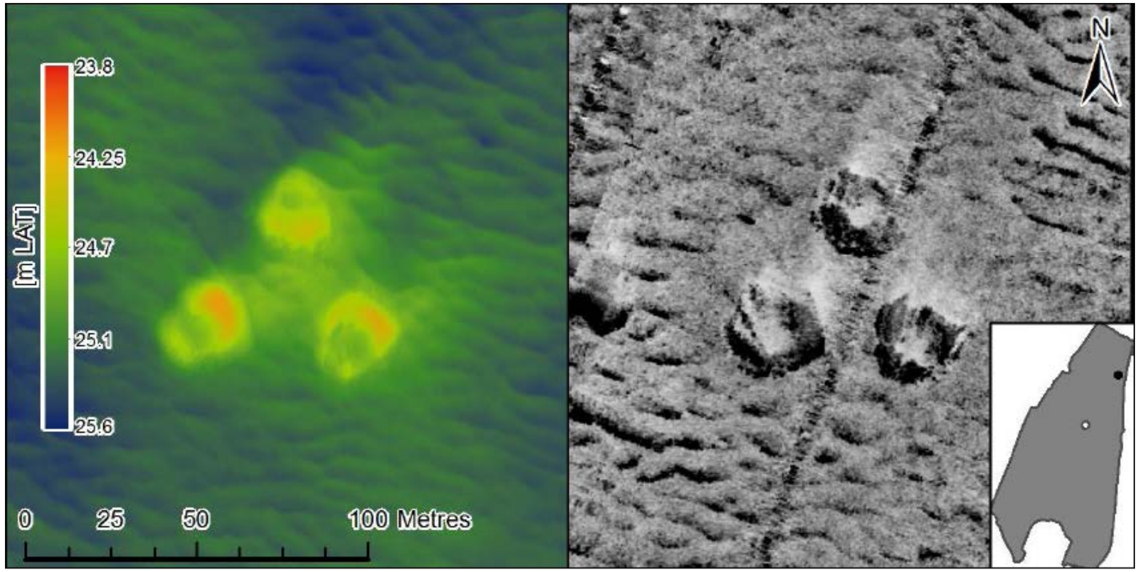
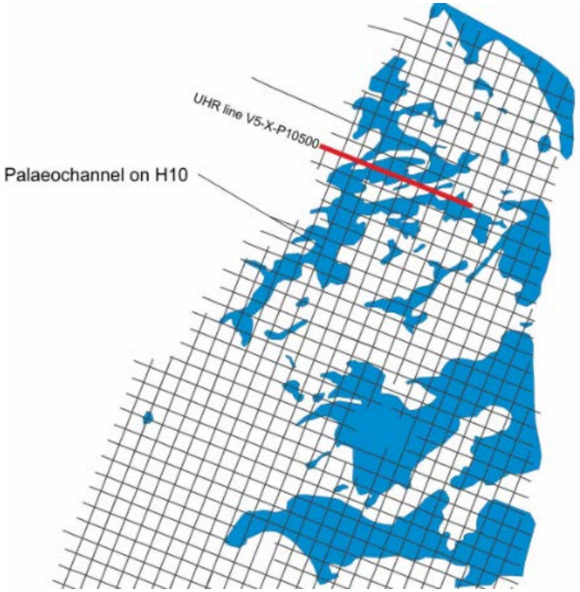
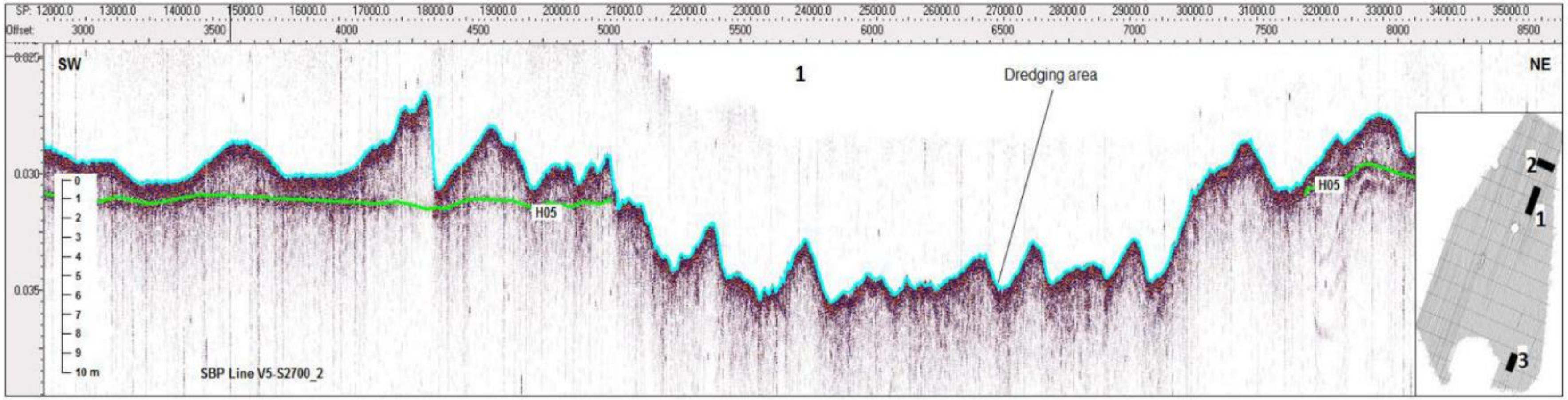
Geotechnical Reporting







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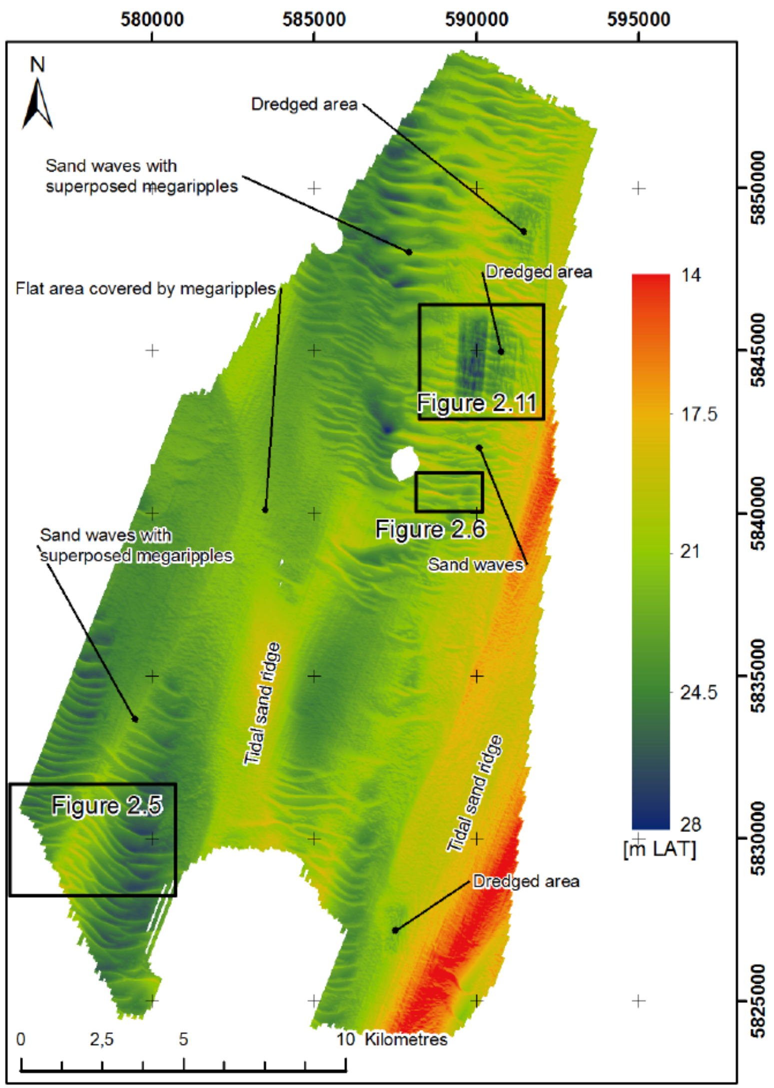
Geophysical Investigation – RVO Objectives

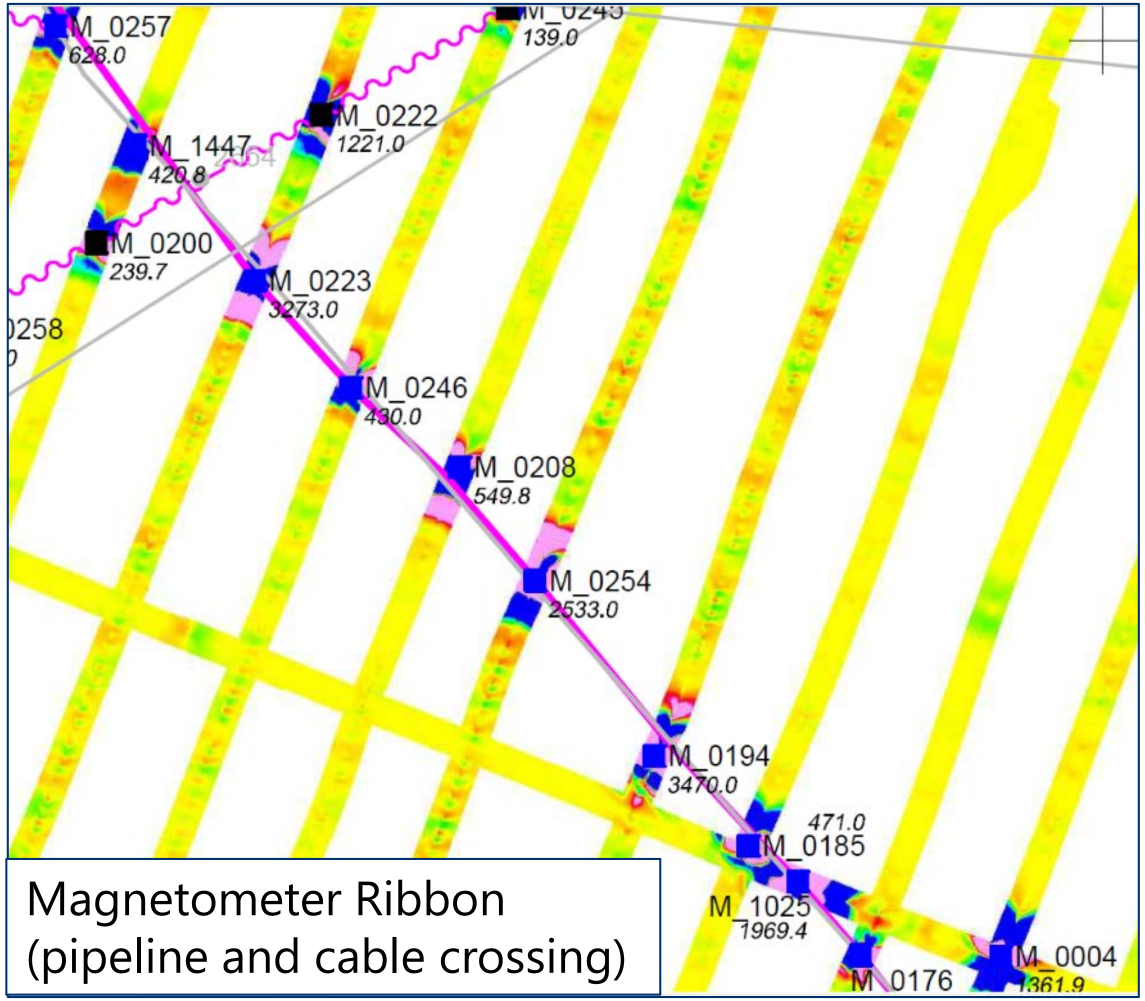
- Provide bathymetry and information on seafloor conditions
- Identify natural and man-made features, objects, obstructions
- Identify and/or confirm the positions of wrecks, pipelines, cables and other infrastructures
- Provide geophysical/geological ground model, including:
  - detailed interpretation of seismic reflection data
  - illustrate significant interfaces
  - illustrate facies changes on appropriate maps and sections
- Identify geological features, geohazards, and structural complexities in the subsurface



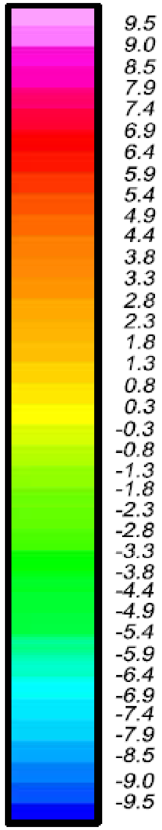
Geophysical Investigation – Site Phase

- MV Fugro Gauss (100m/ 2000m)
  - Multibeam Echo Sounder (MBES)
  - Single Beam Echo Sounder (SBES)
  - Sidescan Sonar (SSS)
  - Magnetometer (MAG)
  - Sub-Bottom Profiler (SBP)
  - Single Channel Seismic (SC-UHRS)

- MV Fugro Meridian (500m/ 500m)
  - Multichannel Seismic (MC-UHRS)



Magnetometer Ribbon (pipeline and cable crossing)



Magnetic Residual Scale Bar (in *nT*)

Geophysical Investigation – Equipment Resolution

Sensor Type	Equipment	Line spacing	Resolution
Multibeam Echo Sounder	Kongsberg EM2040 dual-head	Main 100 m Cross 2000 m	The survey was conducted in accordance with International Hydrographic Organization (IHO). The requirement was to achieve the requirements of the Order 1a standard.
Sidescan Sonar	EdgeTech 4200-FS (300/600 kHz)	Main 100 m Cross 2000 m	Heights of seabed obstructions estimated from the SSS data are considered to have an accuracy of ± 0.1 m.
Magnetometer	G-882 marine magnetometer	Main 100 m Cross 2000 m	-
Sub-bottom Profiler	SES 2000 parametric sub-bottom profiler	Main 100 m Cross 2000 m	An useful acoustic penetration up to 10 ms or approximately 8 m below seabed was generally achieved over the survey area. The vertical resolution of the data is estimated as 0.1 m
Single Channel Seismic	GSO 200-tip-sparker with 24 element streamer	Main 100 m Cross 2000 m	The vertical resolution is estimated at 0.5 m in the shallower part [-30 m LAT] (average Vp of ~1600 m/s)
Multi Channel Seismic	GSO 360-tip-sparker with GeoEel 48 channel (split) streamer	Main 500 m Cross 500 m	The vertical resolution is estimated at 0.9 m in the shallower part [-40 m LAT] (average Vp of ~1700 m/s) to 1.3 m in the deeper part [-100 m LAT] (Vp of ~1800 m/s).

Geophysical Investigation – Ground Model Development

RVO Desk Studies

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Geophysical Site Phases

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Geophysical Reporting

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Geotechnical Site Phases

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Laboratory Testing

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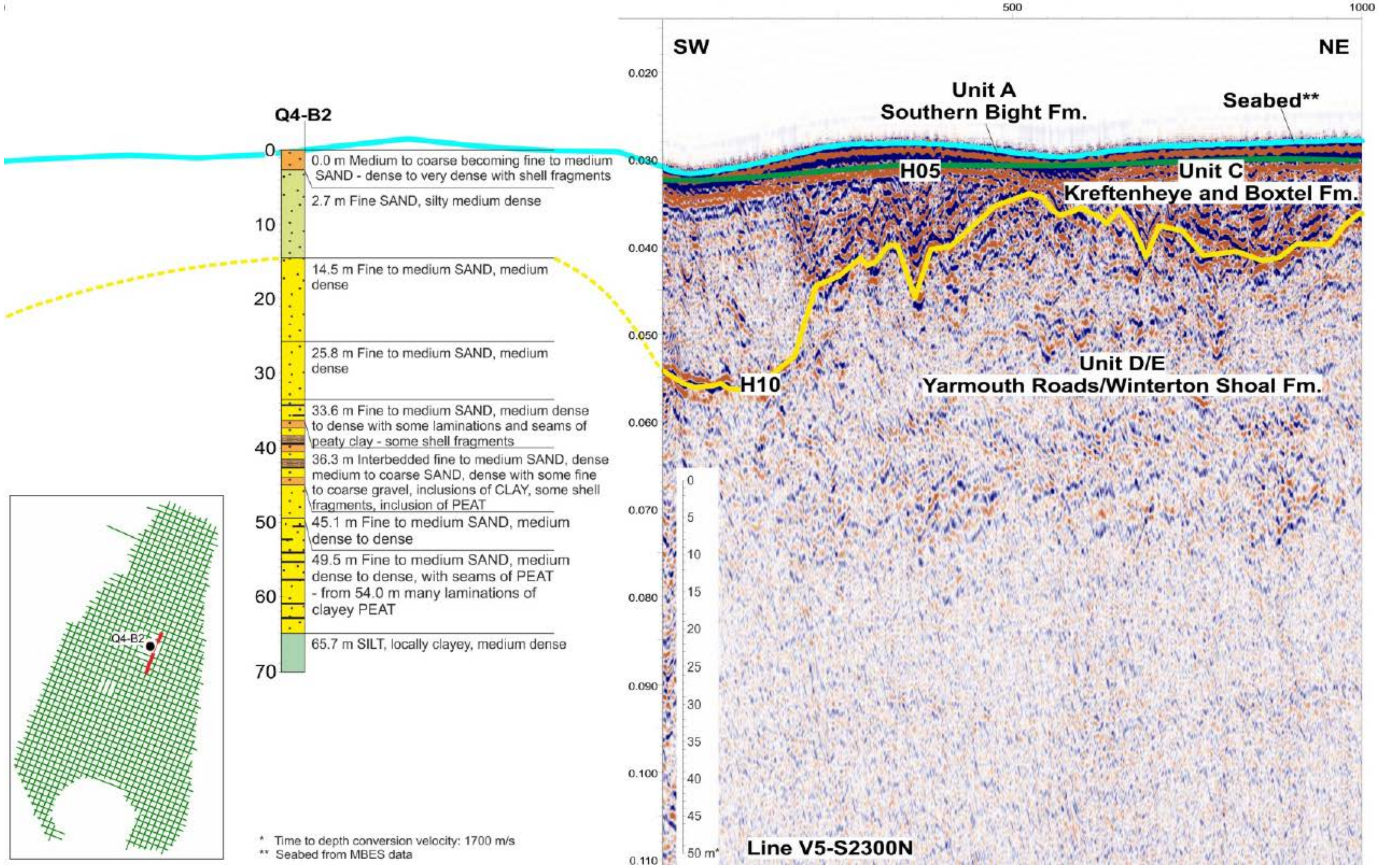
Geotechnical Reporting



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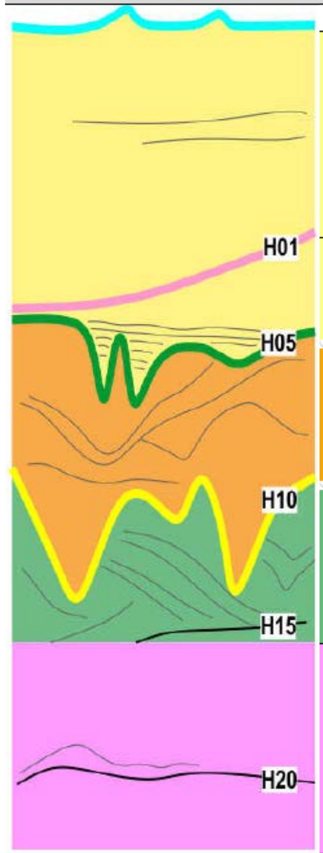
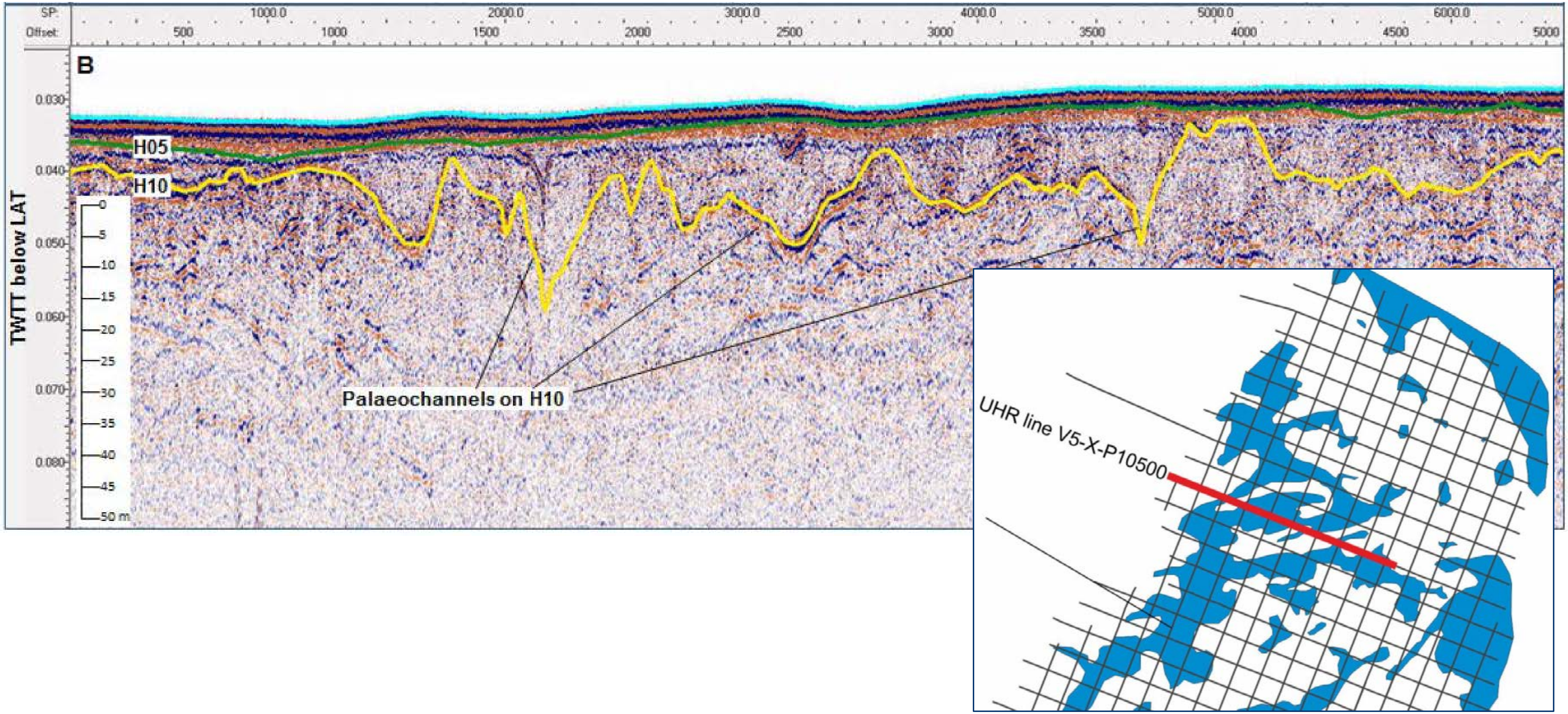
Geophysical Investigation – Ground Model (1)



Schematic Log	Seismic units	Reflectors		Base of unit min/max depth in m LAT [1]	Base of unit min/max depth in m below seabed [1]	Internal structure of the unit	Indicative lithology [2]	Depositional Environment	Formation	Age
		Top	Base							
	A	Seabed	H01 or H05	-20 to -29	0 to 12	Controlled at the top by sand dune morphology	Fine to coarse SAND with CLAY and SILT laminae, locally GRAVEL, sparse boulders	Shallow marine	Southern Bight (Bligh Bank Member)	Holocene
	B	H01	H05	-20 to -29	0 to 12	Sheet-like deposit channelled at the base	Very fine to medium SAND, locally CLAY levels and PEAT, possible boulders	Coastal plain	Naaldwijk (Wormer Member, Velsen Bed)	Holocene
	C	H05	H10	-23 to -64	4 to 38	Complex configuration channelled at the base	Fine to coarse SAND; GRAVEL and minor CLAY, possible boulders	Fluvio – peri-glacial environment	Kreftenheye and Boxtel	Upper Pleistocene
	D	H10	Not interpreted	Approx. -60 to -70	N/A	Complex configuration	Fine to coarse SAND with local CLAY and SILT, possible boulders and occasional clay/peat beds	Fluvial	Yarmouth Roads	Lower to Middle Pleistocene
	E	Not interpreted	N/A	N/A	N/A	Sheet-like deposit	Fine to coarse SAND with CLAY intercalation	Fluvio - deltaic	Winterton Shoal	Lower to Middle Pleistocene

Geophysical Investigation – Ground Model (2)



Geotechnical Investigation – Site Phases

- RVO Desk Studies
- ↓ Geophysical Site Phases
- ↓ Geophysical Reporting
- ↓ Geotechnical Site Phases
- ↓ Laboratory Testing
- ↓ Geotechnical Reporting

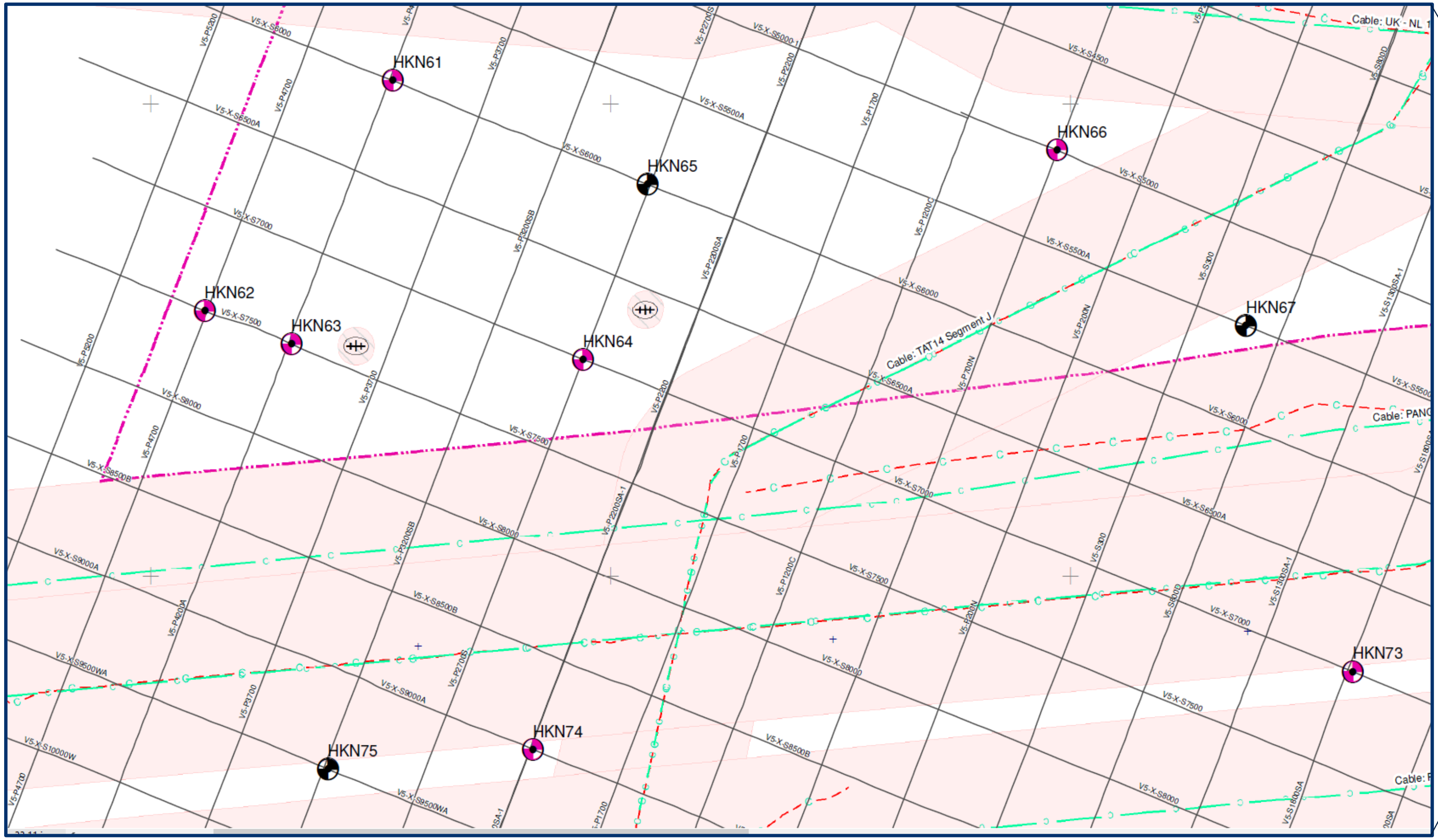
RVO objectives Geotechnical Site Investigation

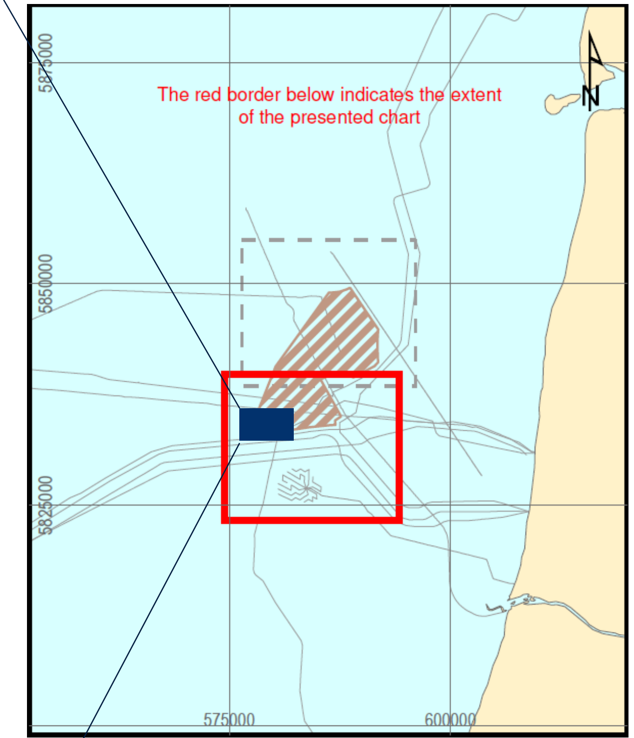
- Further develop and update the geophysical/geological ground model
- Determine the vertical and lateral variation in subsurface conditions
- Provide relevant geotechnical data for design of the wind farm

Geotechnical Investigation Strategy

- Target location to confirm and enhance current understanding
- Capture predominant soil conditions & minimize future SI needs
- Combine different investigation techniques
- Phased approach: seafloor testing → BH drilling→ laboratory testing

Geotechnical Investigation – Target Location Selection (1)



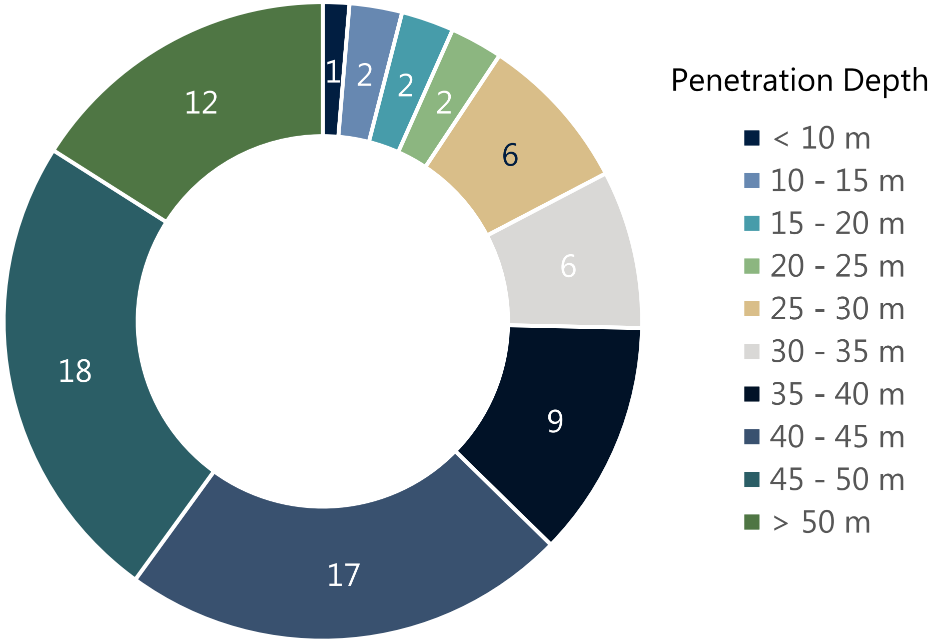


Geotechnical Investigation – Seafloor In Situ Testing

SEACALF® 20 tons MkIV Constant Drive System (CDS) unit with 1500 mm^2 piezo-cone penetrometers for (S)CPTs and PPDTs, and with 1000 mm^2 for TCPTs:

- Eighty-two (82) seafloor PCPTs at 75 distinct locations to depths of 2.1 m to 53.0 m BSF, with 72 PPDTs at 38 distinct locations;
- Twenty-eight (28) SCPTs at 21 distinct locations to depths of 2.9 m to 52.9 m BSF;
- Twenty-four (24) TCPTs at 23 distinct locations to depths of 3.0 m to 7.5 m BSF.

Overview penetration performance seafloor in situ testing (deepest test point per location)



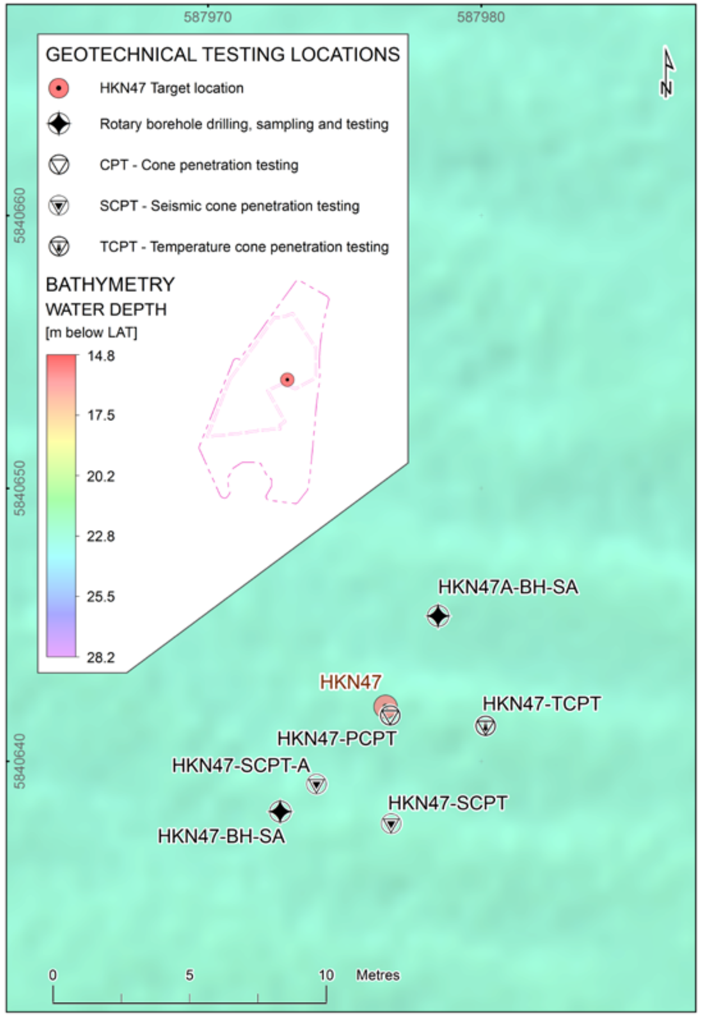
Geotechnical Investigation – Borehole Drilling (1)

The drilling, sampling and situ testing programme at 33 locations included 36 boreholes (including re-drills, i.e. additional boreholes) with a combination of drilling, downhole sampling and /or in situ testing to depths ranging between ~3 m to ~80 m BSF:

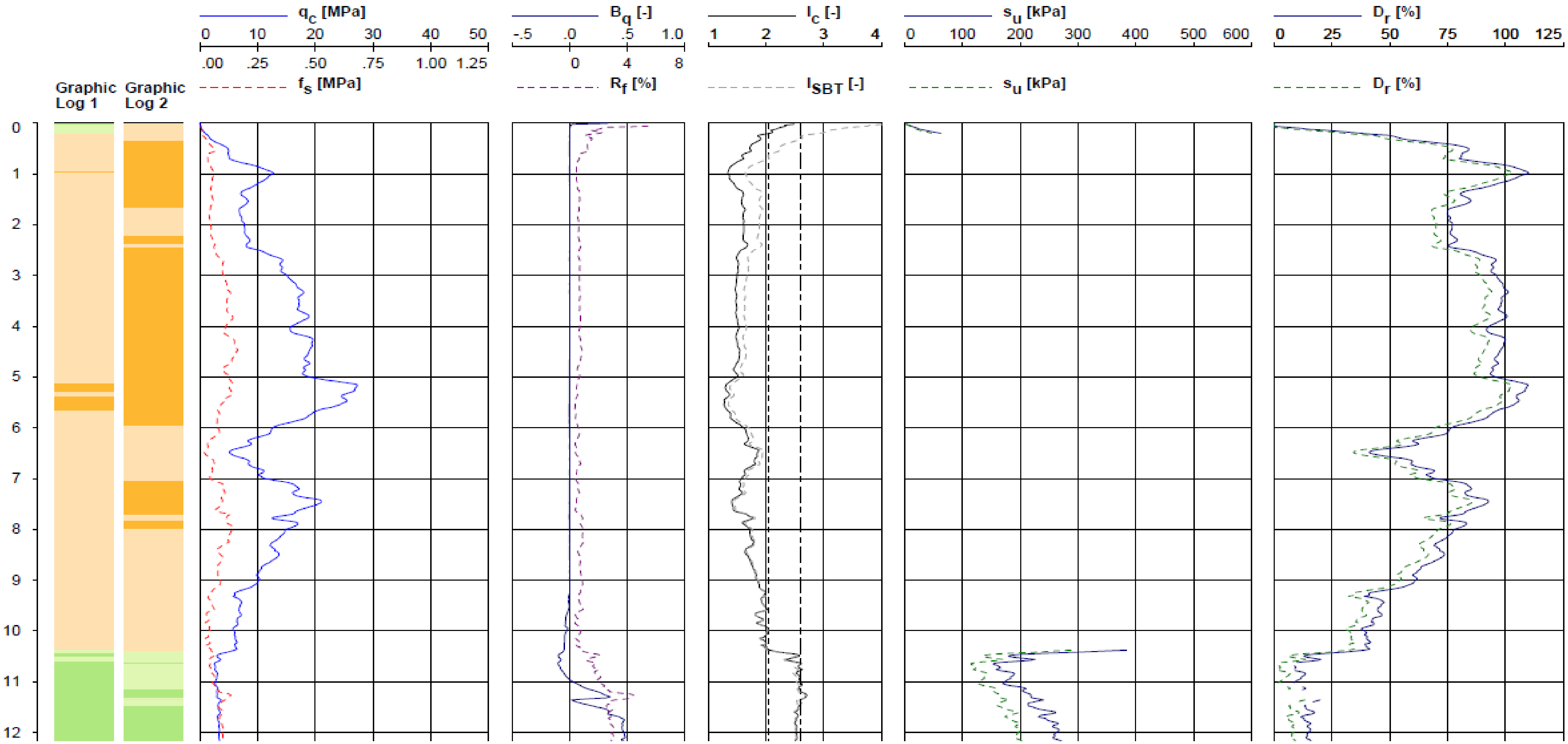
Number of Boreholes	Target Depth	Scope of work
31	~60 m to ~80 m BSF	Sampling and SCPTs (at selected locations) to approximate penetration depth of seafloor CPT, followed by CPTs with (over-)sampling
1	~60 m BSF	SCPT
4	~60 m BSF	Drill-out of approximately 52 m followed by CPT and selected oversampling

Geotechnical Investigation – Borehole Drilling (2)

- Locations within ~5 m radius from target location;
- Open-hole rotary drilling (API) with SEADEVIL™;
- WISON® downhole investigation tools cone-penetrometers 500 mm^2 & 1000 mm^2
- SCPTs with double seismic array HUSH on SBF;
- WIPSAMPLER® with Shelby tubes (2 inch/3 inch/ thin & thick walled/ core catcher/ inner liner)



Geotechnical Investigation – Cone Penetration Tests



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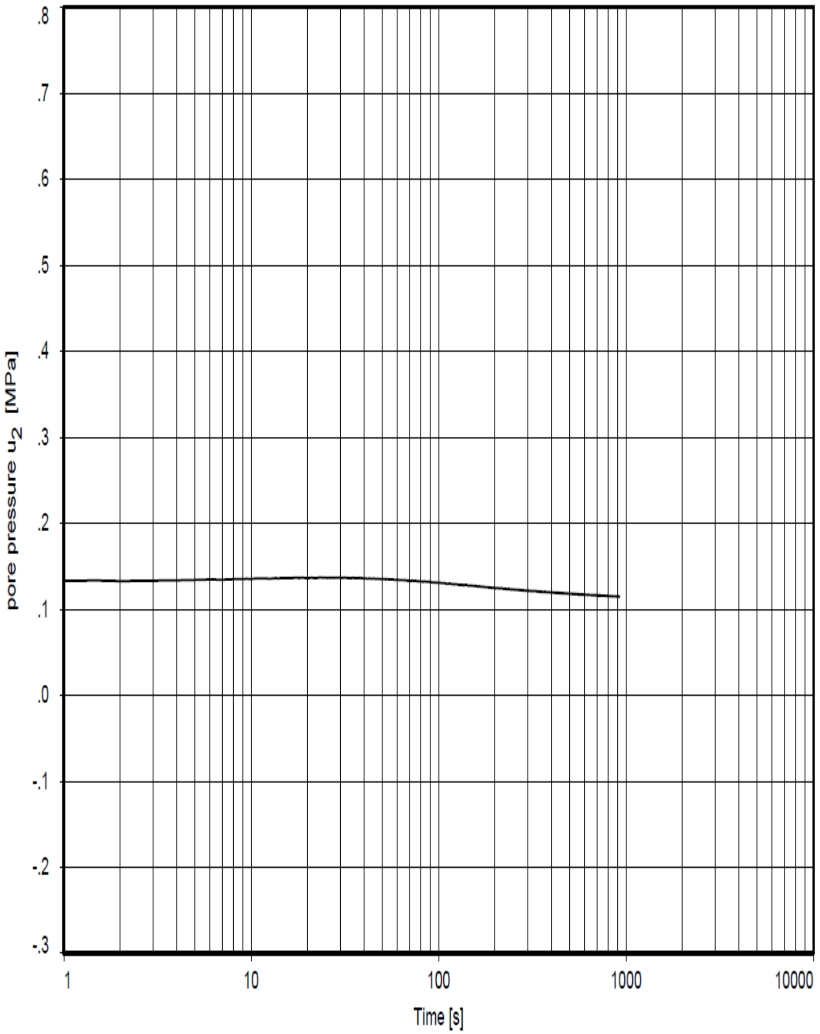
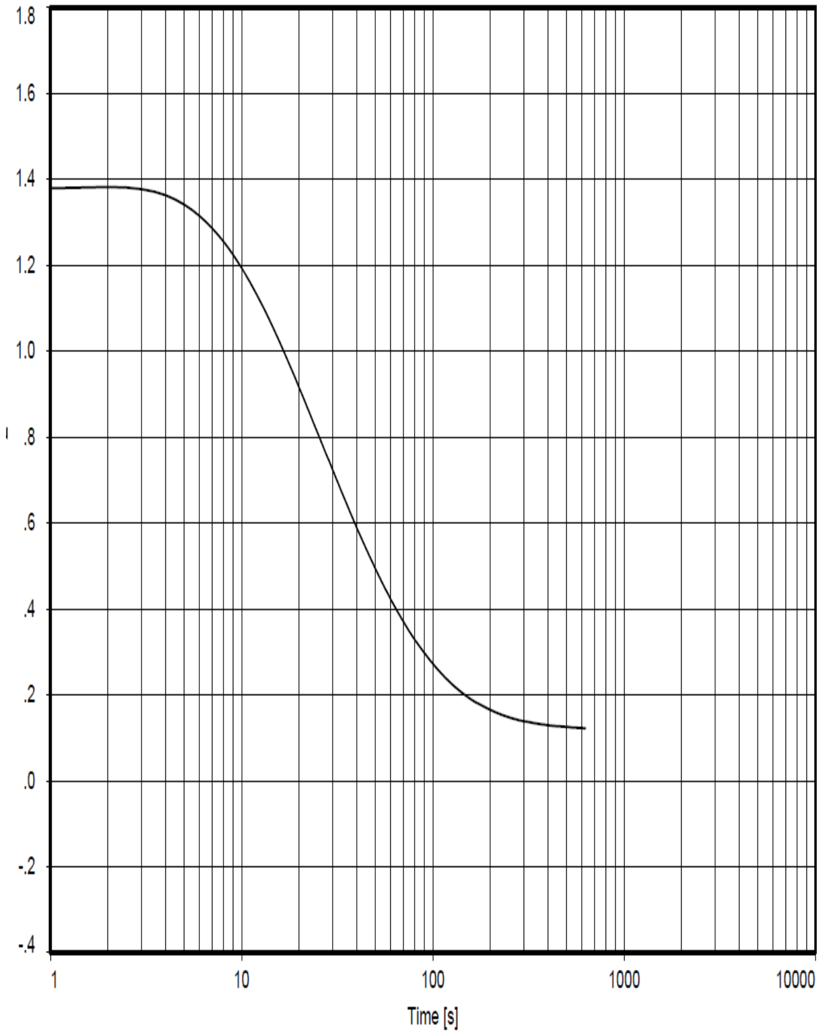
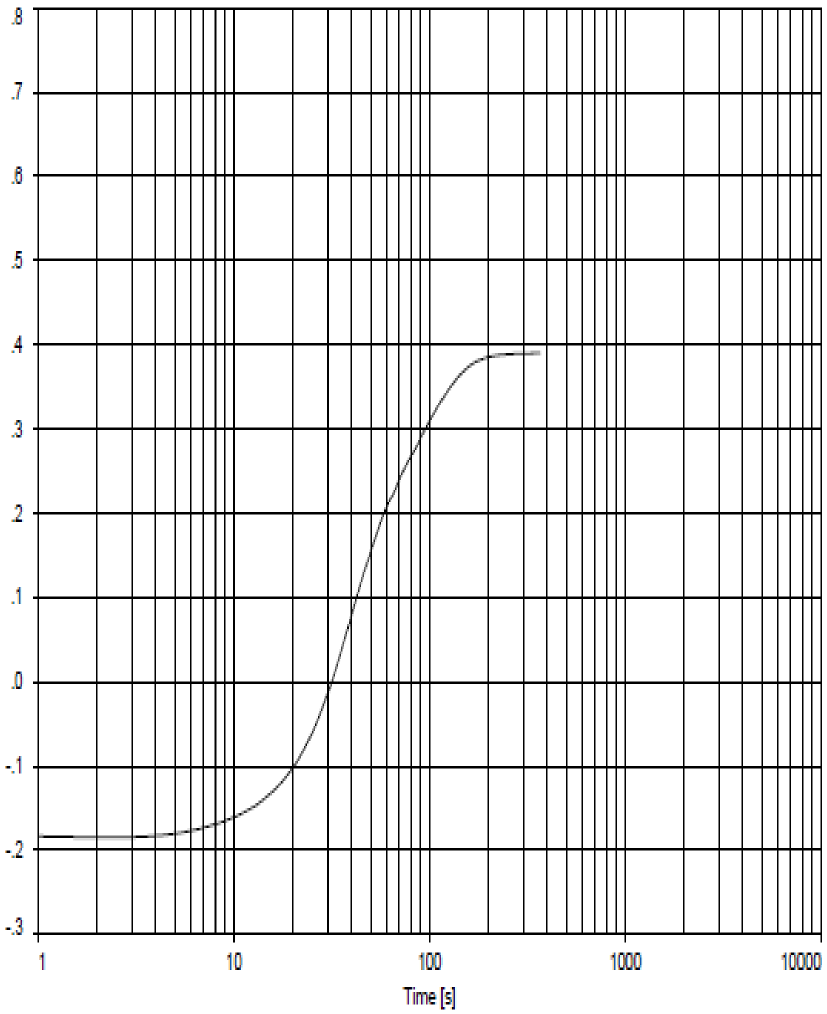
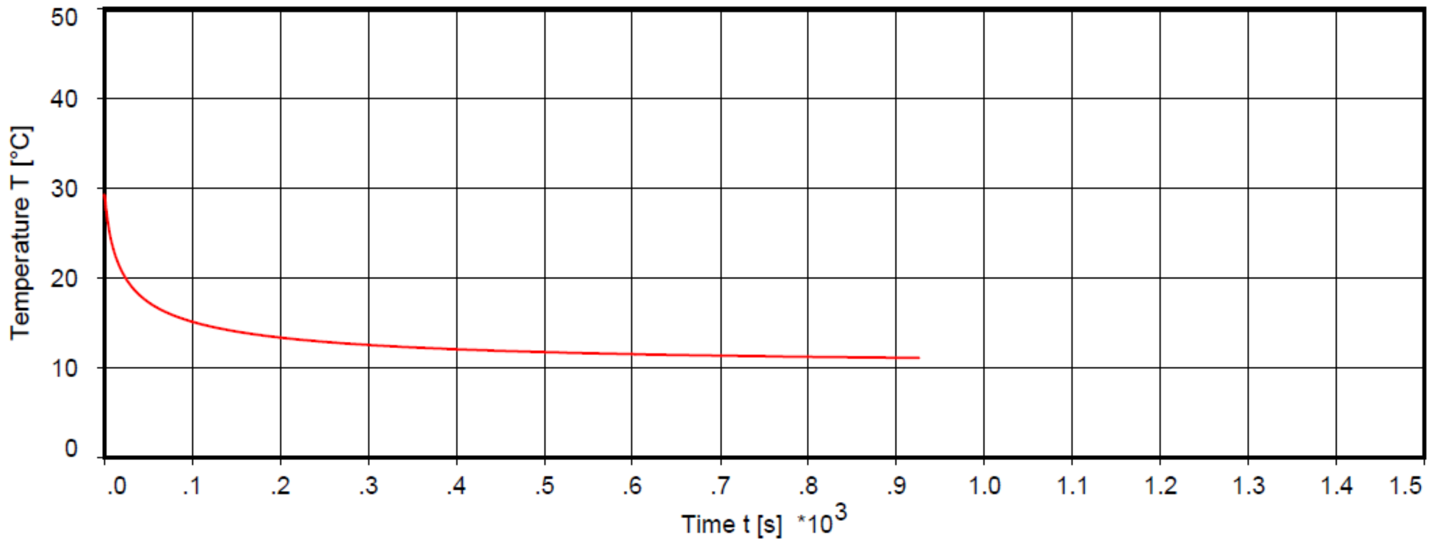
Geotechnical Investigation – Pore Pressure Dissipation Tests

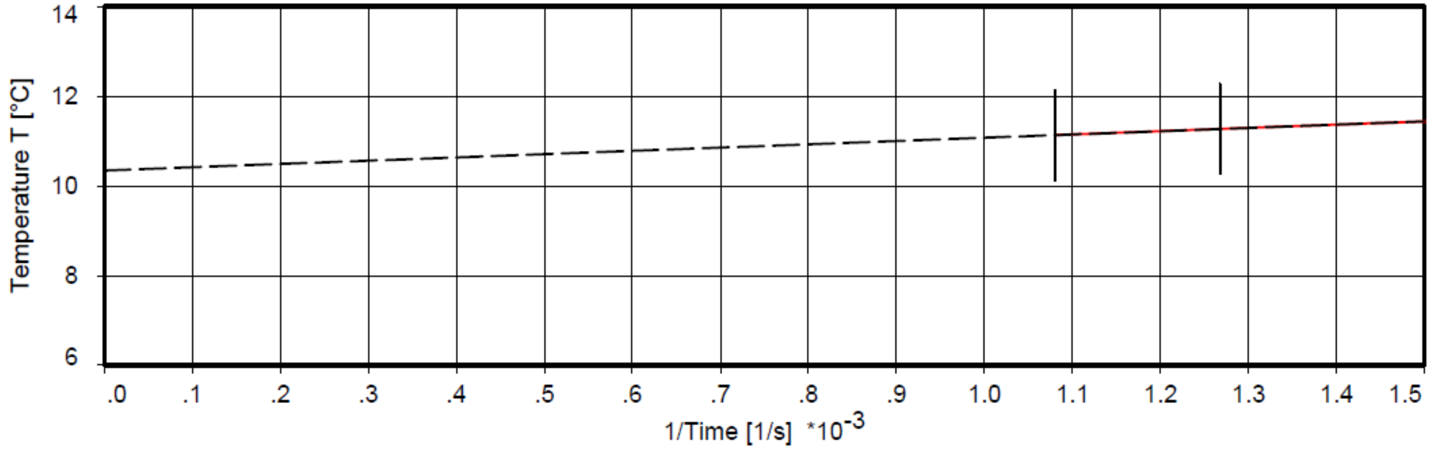


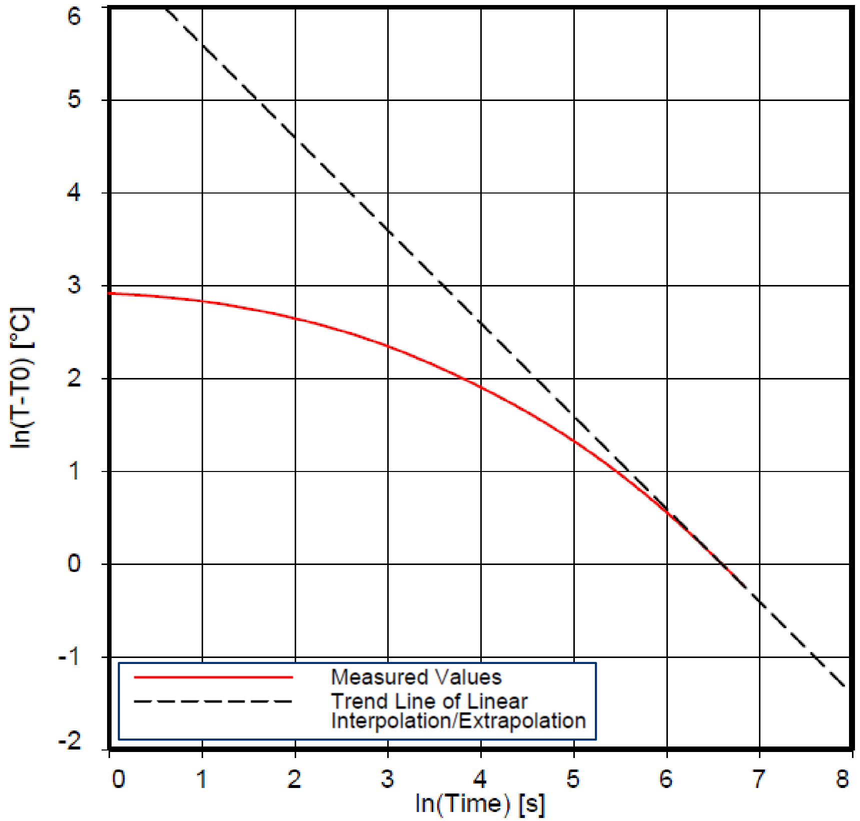




Geotechnical Investigation – Temperature Equilibrium Tests (1)

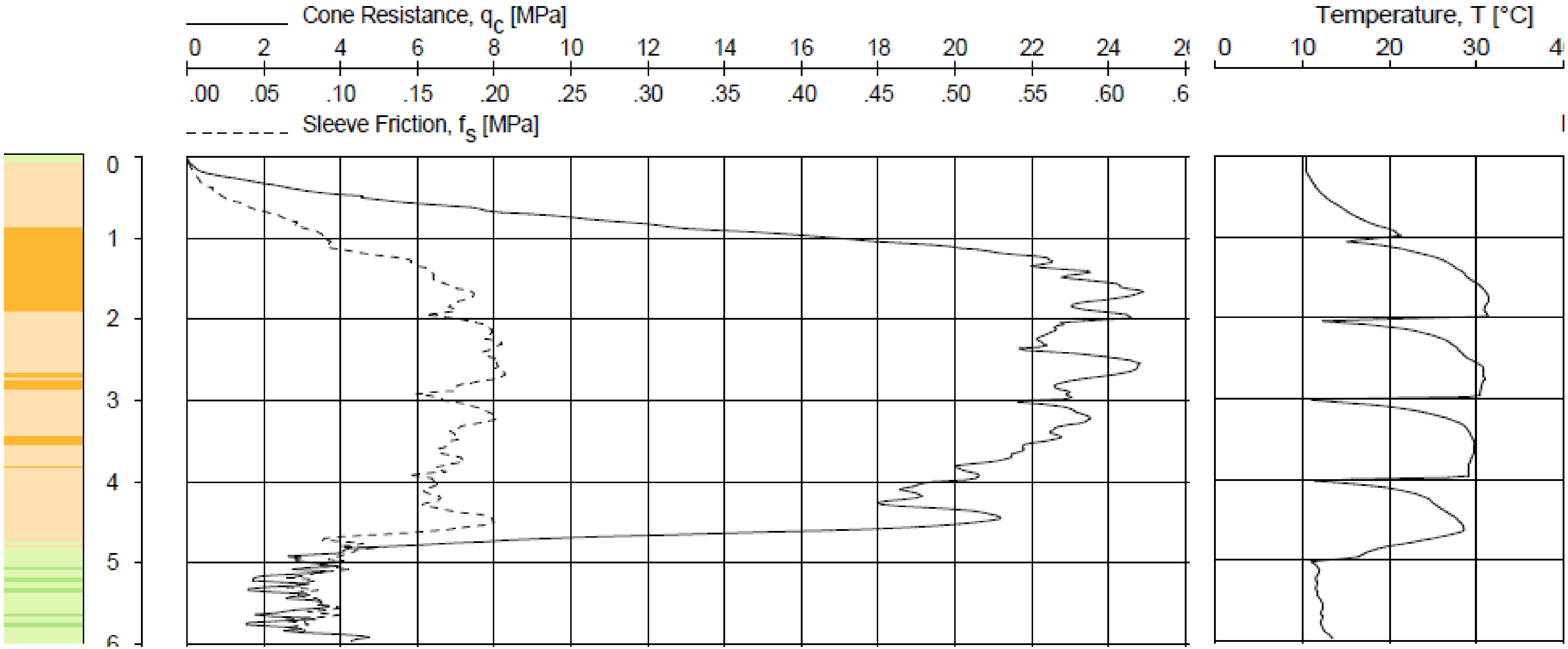




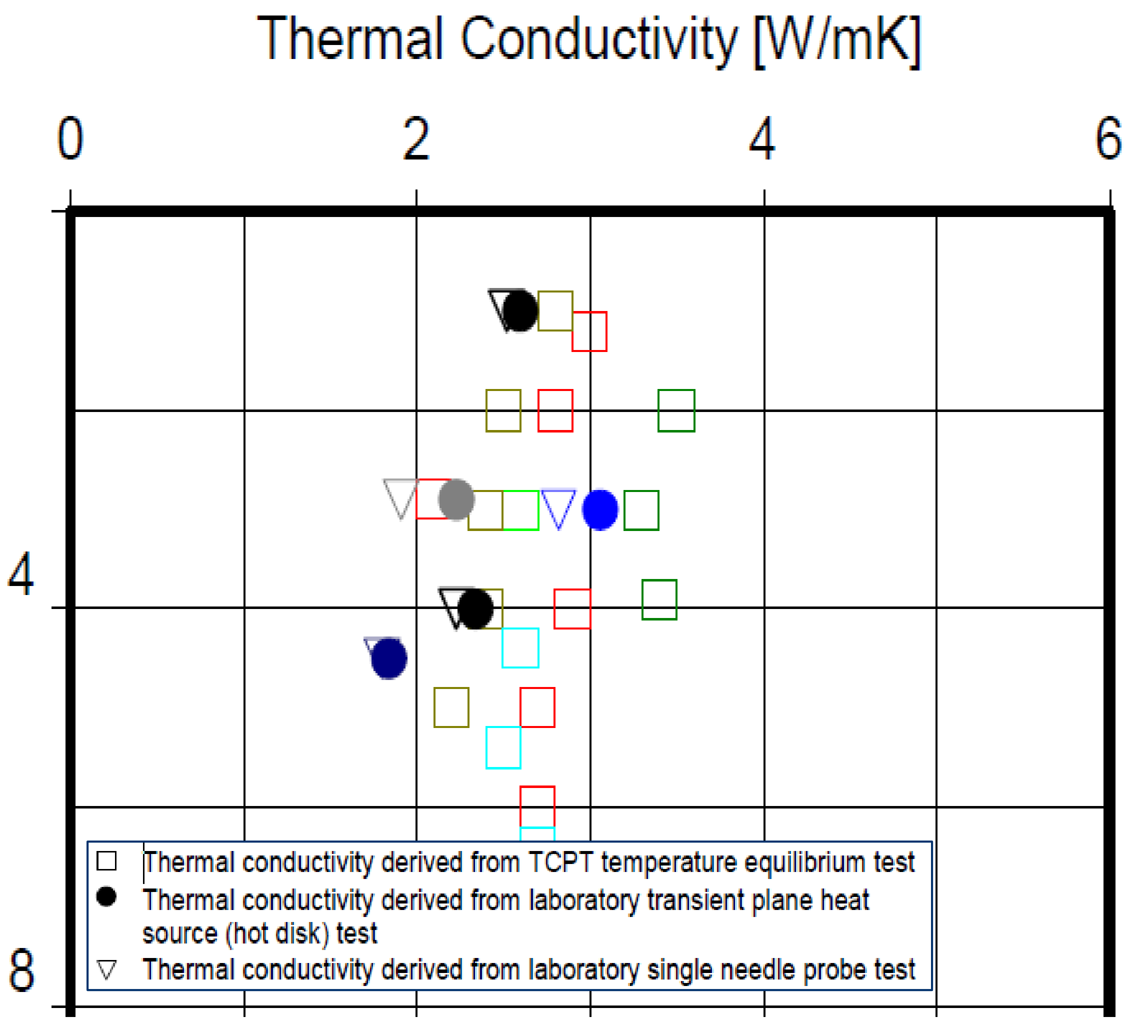


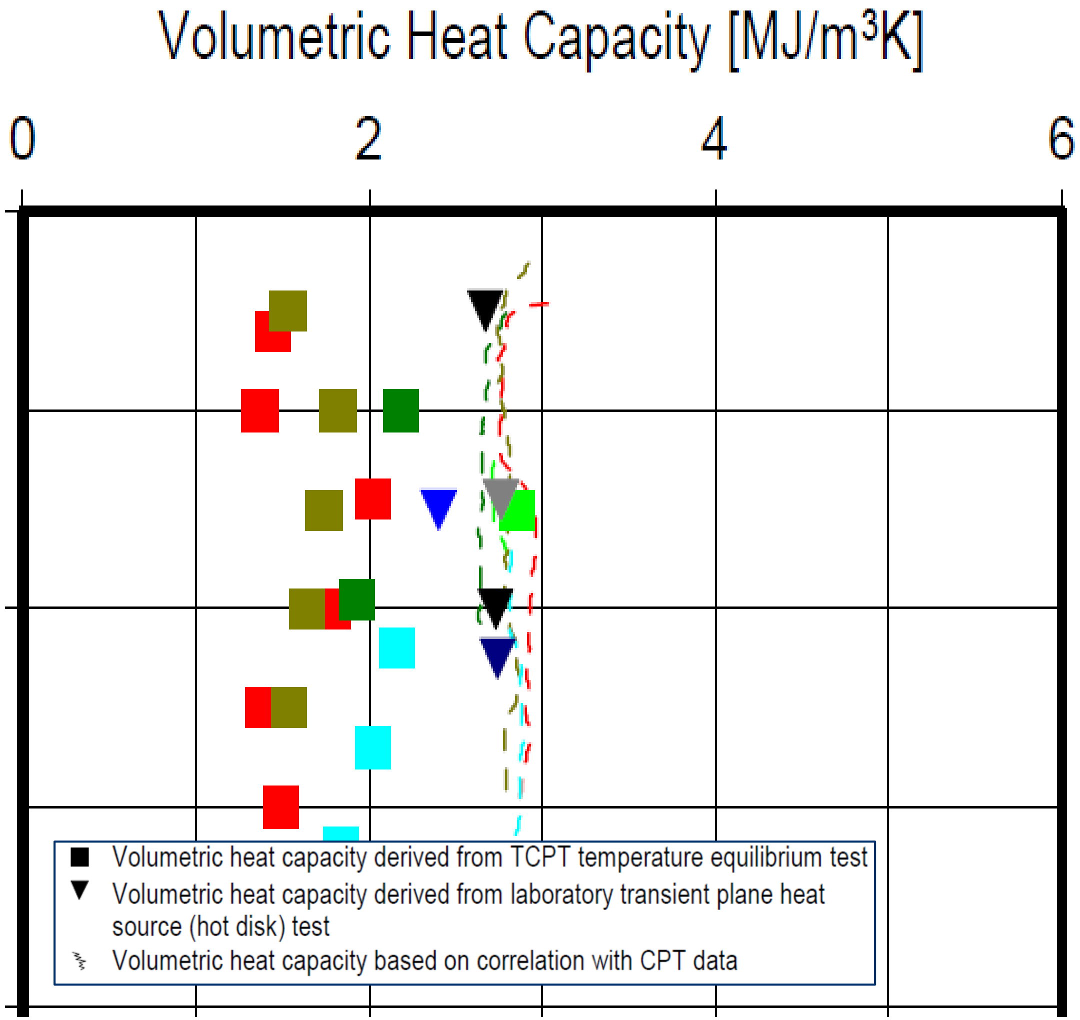
Thermal conductivity determination based on: Vardon, P.J. et al. 2018. *Interpreting and validating the thermal cone penetration test (T-CPT)*. Paper No. 17-P-214

Geotechnical Investigation – Temperature Equilibrium Tests (2)

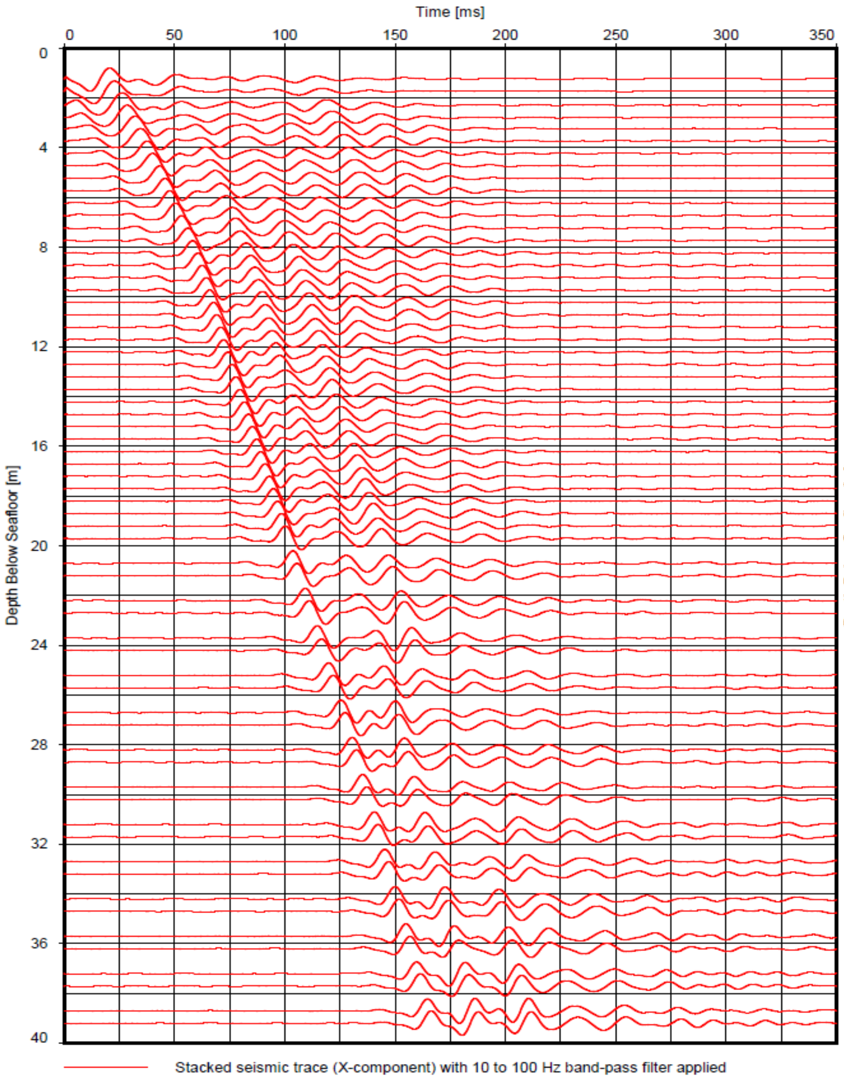


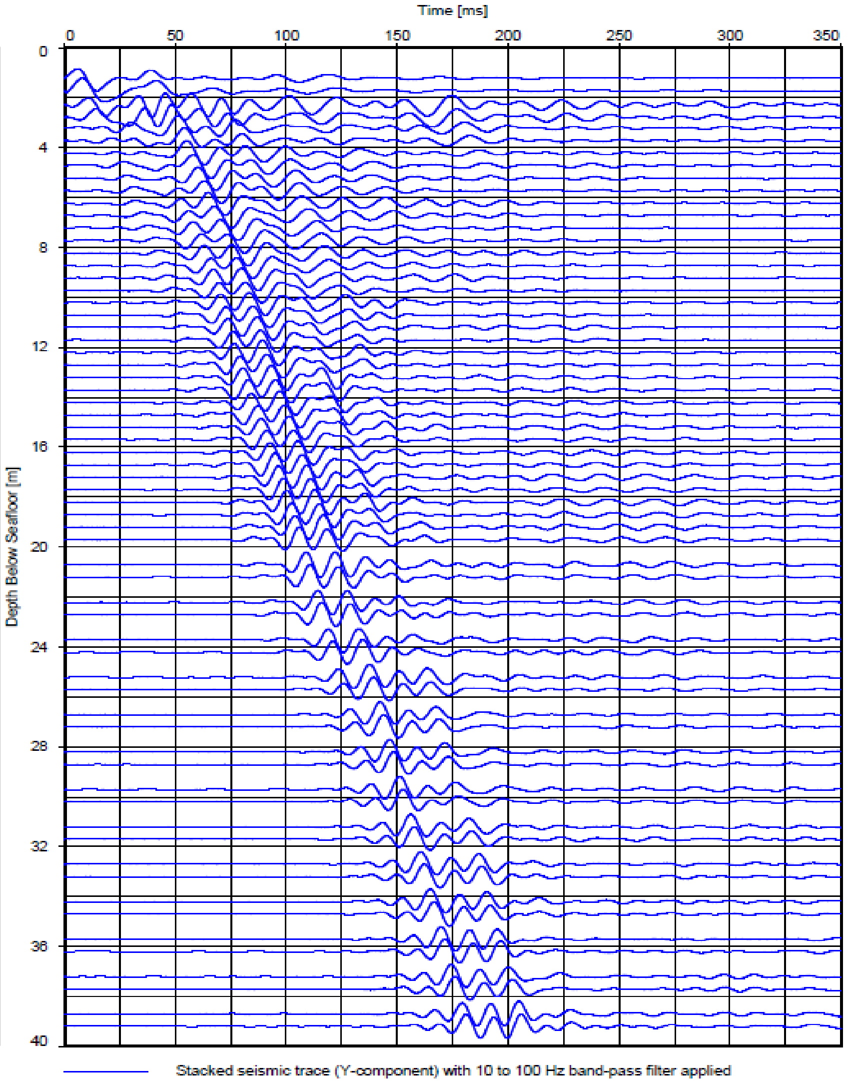
Geotechnical Investigation – Temperature Equilibrium Tests (3)

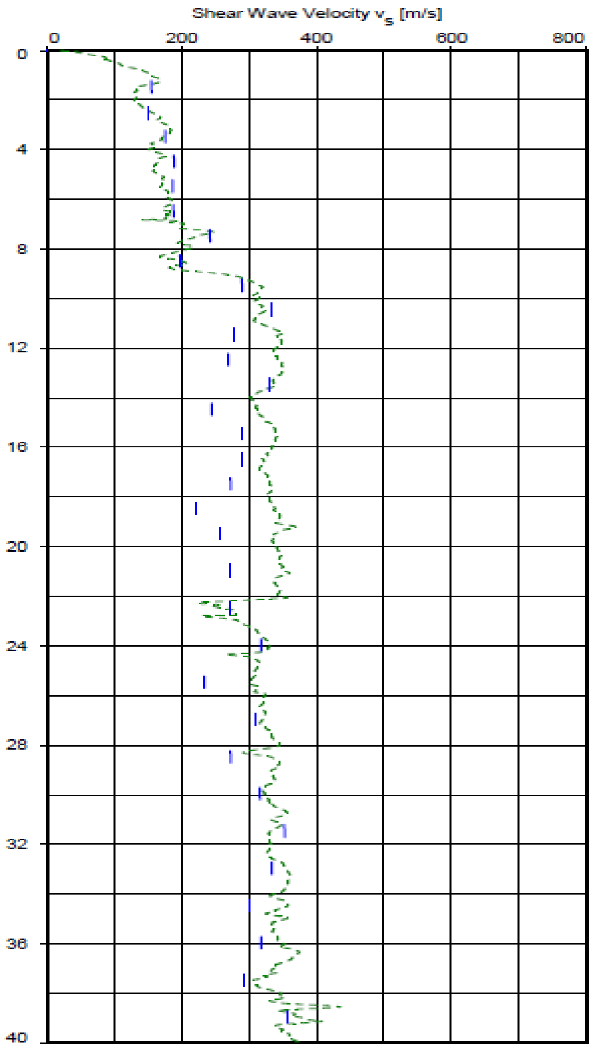




Geotechnical Investigation – SCPTs







Geotechnical Investigation – Laboratory Testing

RVO Desk Studies

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Geophysical Site Phases

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Geophysical Reporting

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Geotechnical Site Phases

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Laboratory Testing

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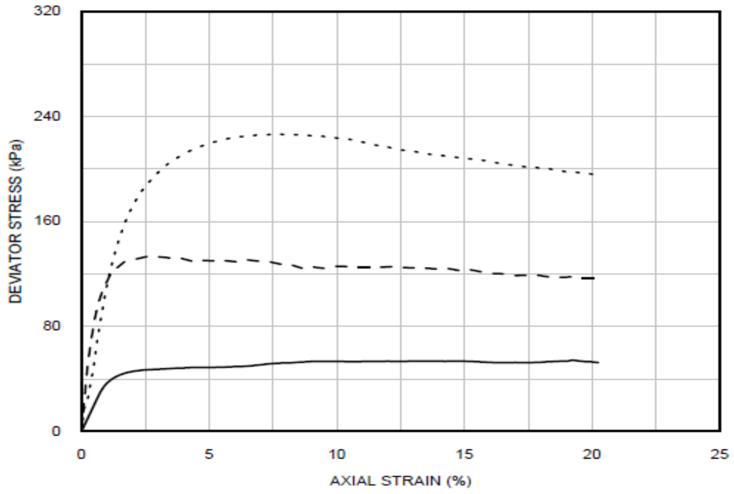
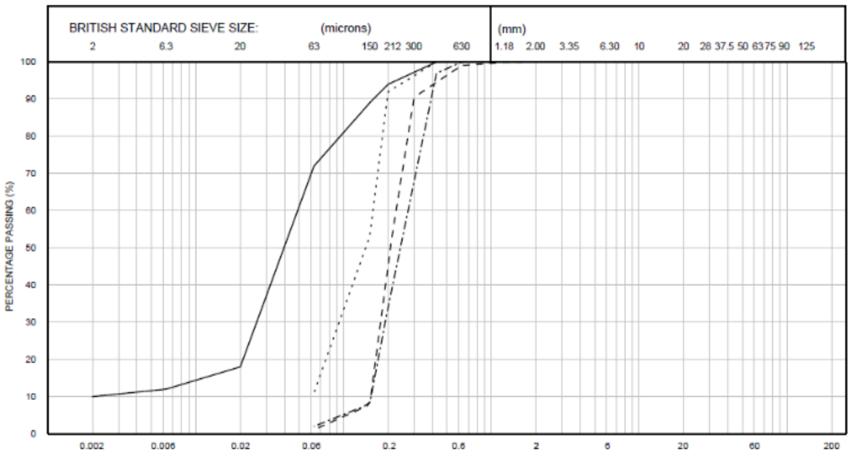
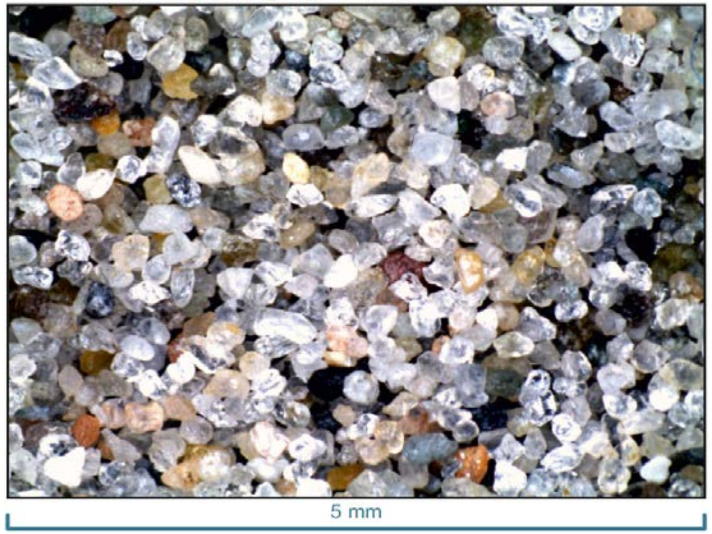
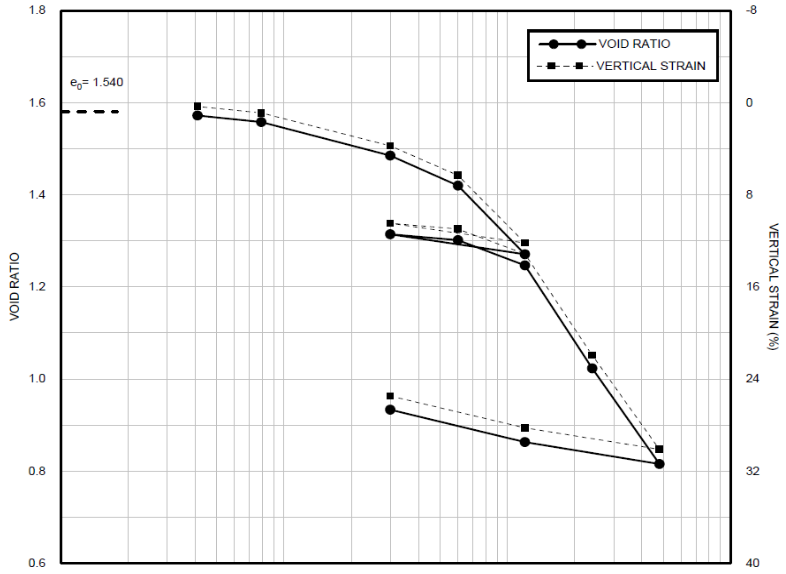
Geotechnical Reporting





Microphotographs of Washed Sample





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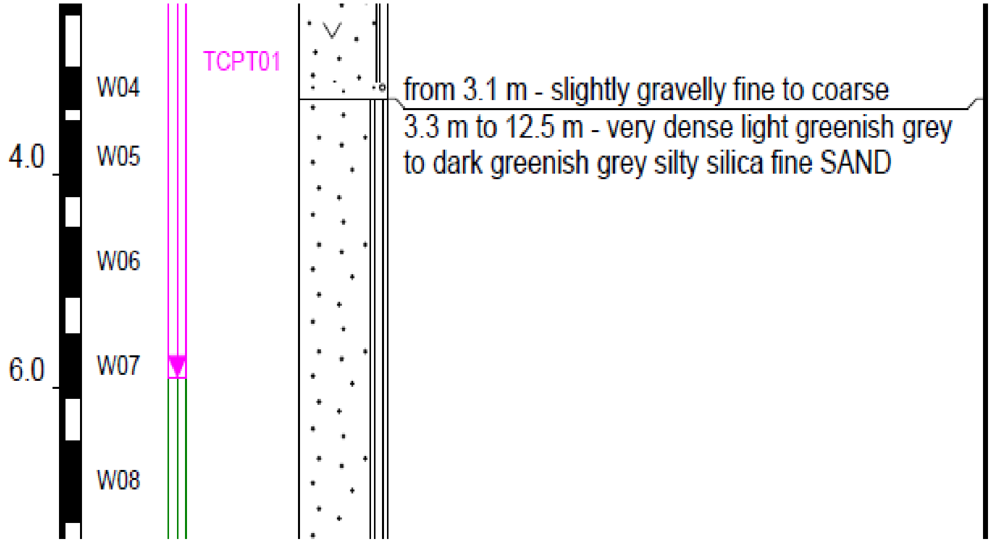
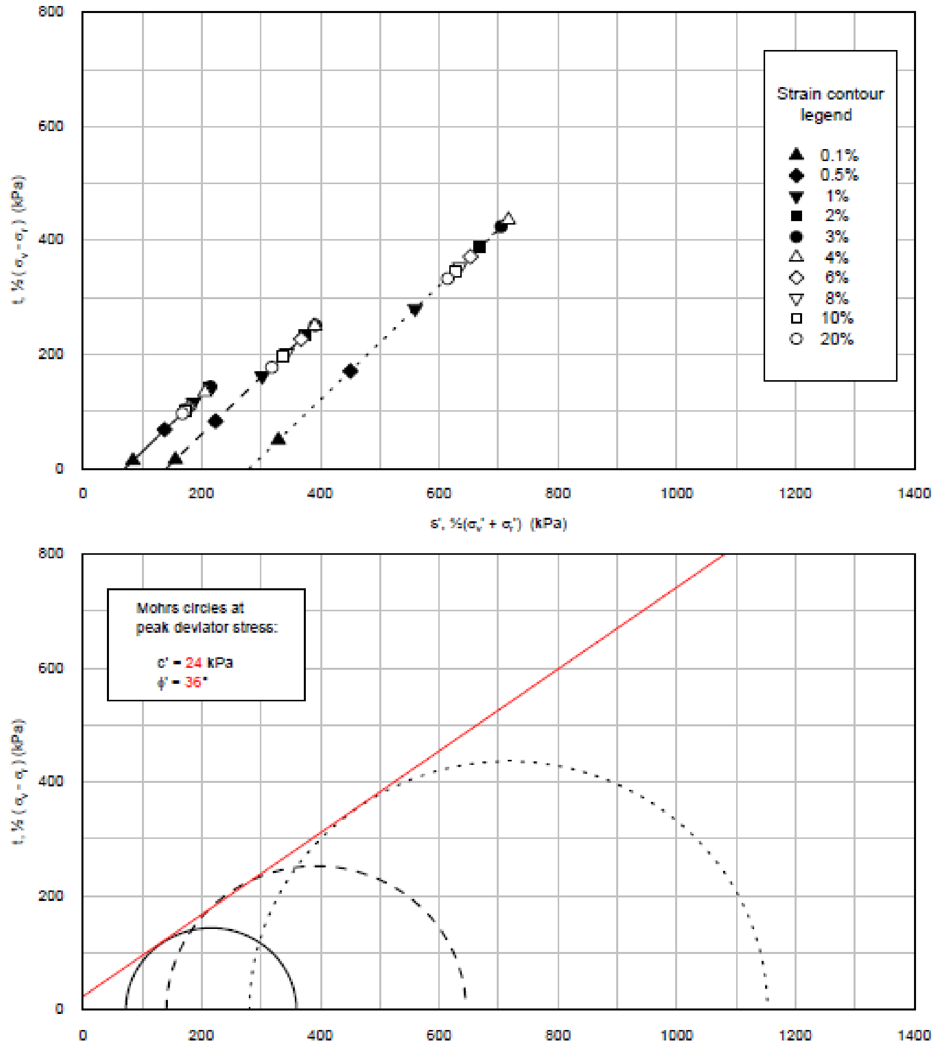
Laboratory Testing – Site Programme

- Sample description (according BS 5930:2015)
- Sample photography (intact and split)
- Geotechnical index (water content, unit weight)
- Index strength (TV, PP and UU triaxial)



Laboratory Testing – Standard Programme

- Test execution in general accordance with ISO 2014, supplemented with e.g. BS or ASTM where relevant
- Confirm and extend site findings
- Test (in principle) all major layers identified
- Allow for sufficient data points to confirm heterogeneity or homogeneity of individual layers across the sites
- Test anomalies and/or unusual soil bodies



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Laboratory Testing – Standard Programme

Test Type	Quantity
Geotechnical Index	
Density of Solid Particles (Small Pycnometer)	221
Particle Size Analysis (Sieving and Pipette)	544
Minimum and Maximum Index Dry Unit Weight	111
Atterberg Limits	94
Geochemical	
Carbonate Content	180
Organic Content (dichromate oxidation / mass loss on ignition)	193 / 59
Pore Water Salinity	27
(Index) Strength	
Unconsolidated Undrained Triaxial compression (UU) – undisturbed / remoulded	3 / 2
Anisotropically Consolidated Undrained Triaxial (CAUc) / with bender element testing	8 / 5
Isotropically Consolidated Undrained Triaxial (CIUc) / with bender element testing	1 / -
Isotropically Consolidated Drained Triaxial (CIDc) / with bender element testing	59 / 40

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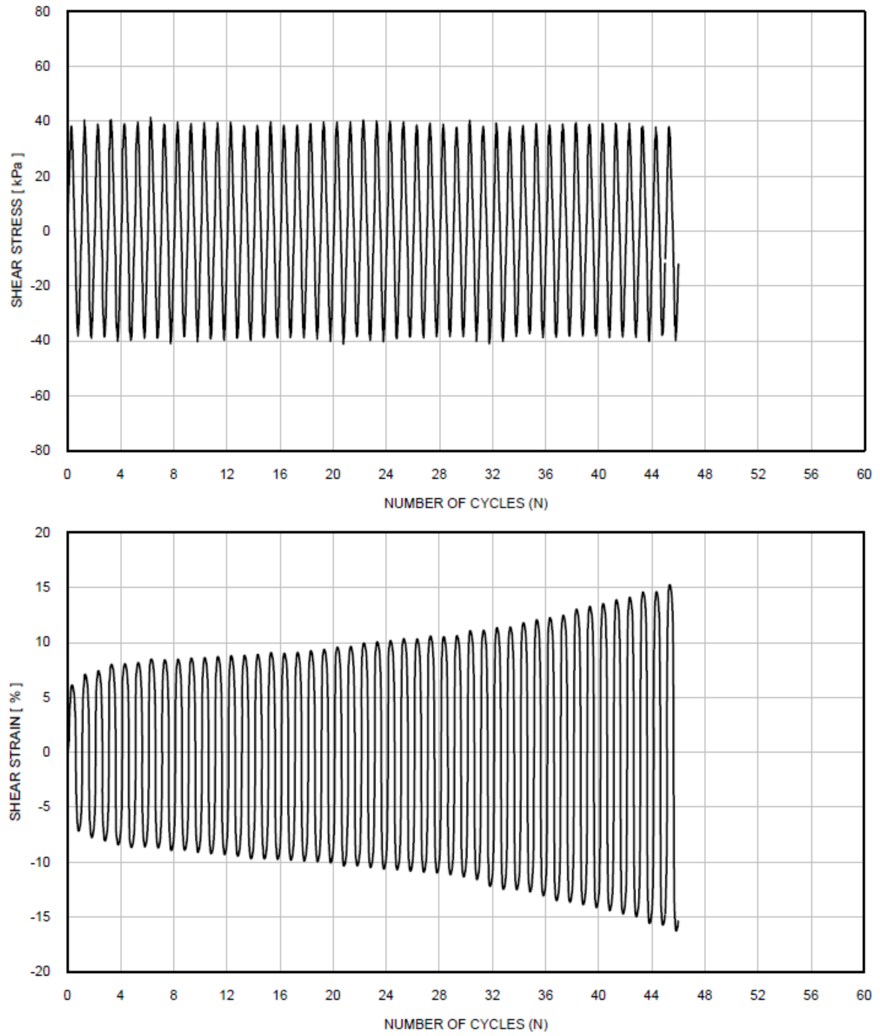
Laboratory Testing – Standard Programme

Test Type	Quantity
Interface Angle	
Ring Shear (Soil-Soil Interface / Soil-Steel Interface)	53 / 103
Compressibility	
Incremental Loading (IL) Oedometer	4
Constant Rate of Strain (CRS) Oedometer	17
Other	
Permeability Tests	69
Thermal Conductivity	27
Electrical Resistivity	27
Transient Plane Source	22
Microscopic Inspection and Photography	103

Laboratory Testing – Advanced Programme

- Build upon and extend information from the results of the standard laboratory test programme
- Provide a broad use of test results of (1) soils predominantly present across the sites, and (2) soils relevant future design
- Variety of test types, specimens conditions and loading conditions over the same depth interval
- Sample selection considers soils with different properties, (in situ) stress states and which are expected to have low, medium and high cyclic resistance
- Location-specific approach, i.e. no batching between locations



Laboratory Testing – Advanced Programme

Test Series	Location	Target Soil Unit	Batch	Target Depth [m BSF]	Selection Criteria
1	HKN25-BH-SA	Holocene	1	0.0 to 3.5	Location typical for surface conditions
2	HKN25-BH-SA	Above H10	2	6.5 to 8.8	Medium dense; fine sand; high fines content
3	HKN27-BH-SA	Above H10	3	1.5 to 3.2	Very dense; coarse sand, low fines content; at top of target soil unit
4	HKN39-BH-SA	Above H10	4	8.1 to 10.4	Dense; fine sand; intermediate fines content; at intermediate depth in target soil unit
5	HKN19-BH-SA	Above H10	5	7.0 to 10.5	Very dense; fine sand; low fines content; at base of target soil unit
6	HKN21-BH-SA	Below H10	6	19.0 to 21.3	Medium dense; fine sand; with fines content
7	HKN26-BH-SA	Below H10	7	26.5 to 29.10	Dense; fine sand; low fines content
8	HKN37-BH-SA	Below H10	8	18.0 to 20.3	Medium dense; fine sand; low fines content
9	HKN47-BH-SA	Below H10	9	17.0 to 18.5	Very dense; fine to medium sand; low fines content
10	HKN11-BH-SA/ HKN04-BH-SA	Channel Deposits	-	3.3 to 4.0	-

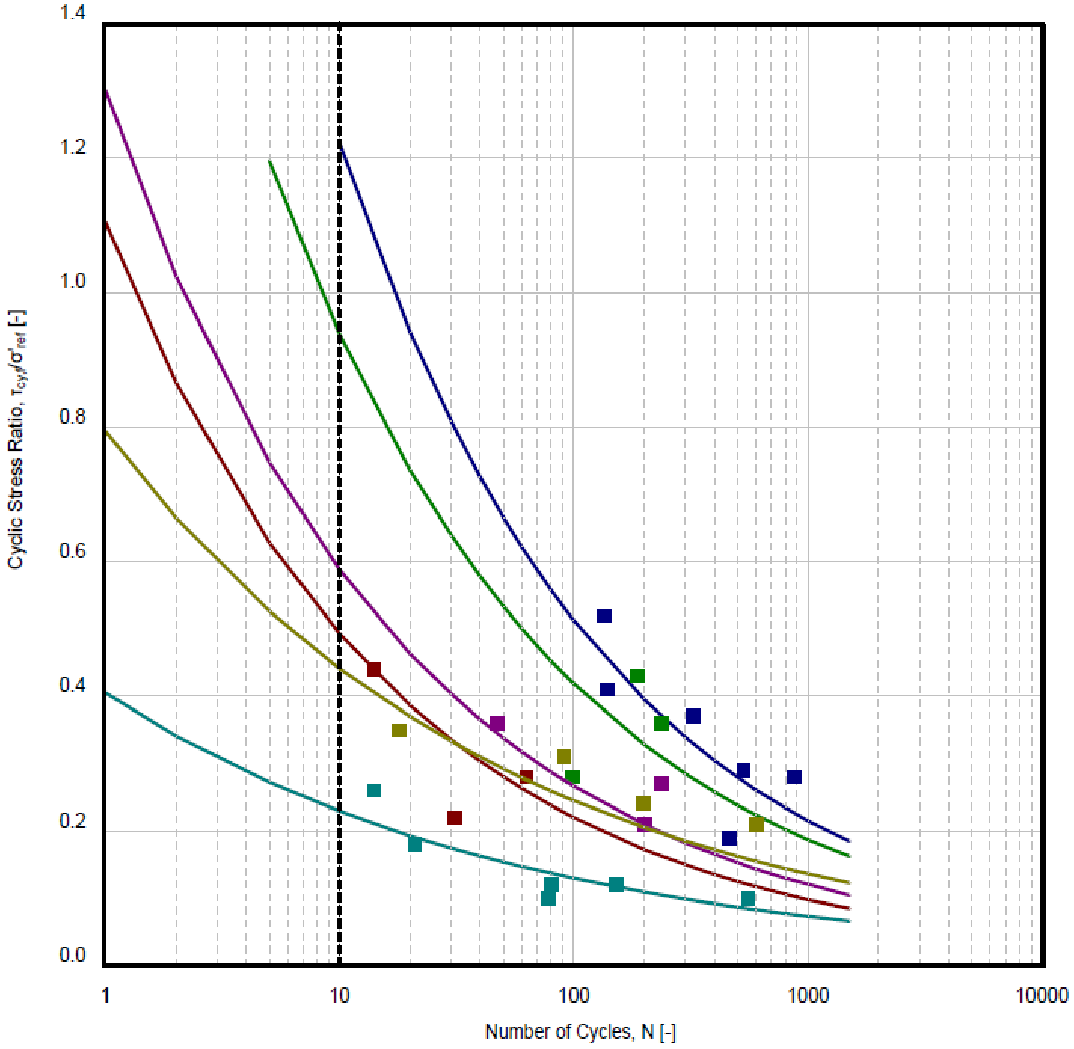
Laboratory Testing – Advanced Programme

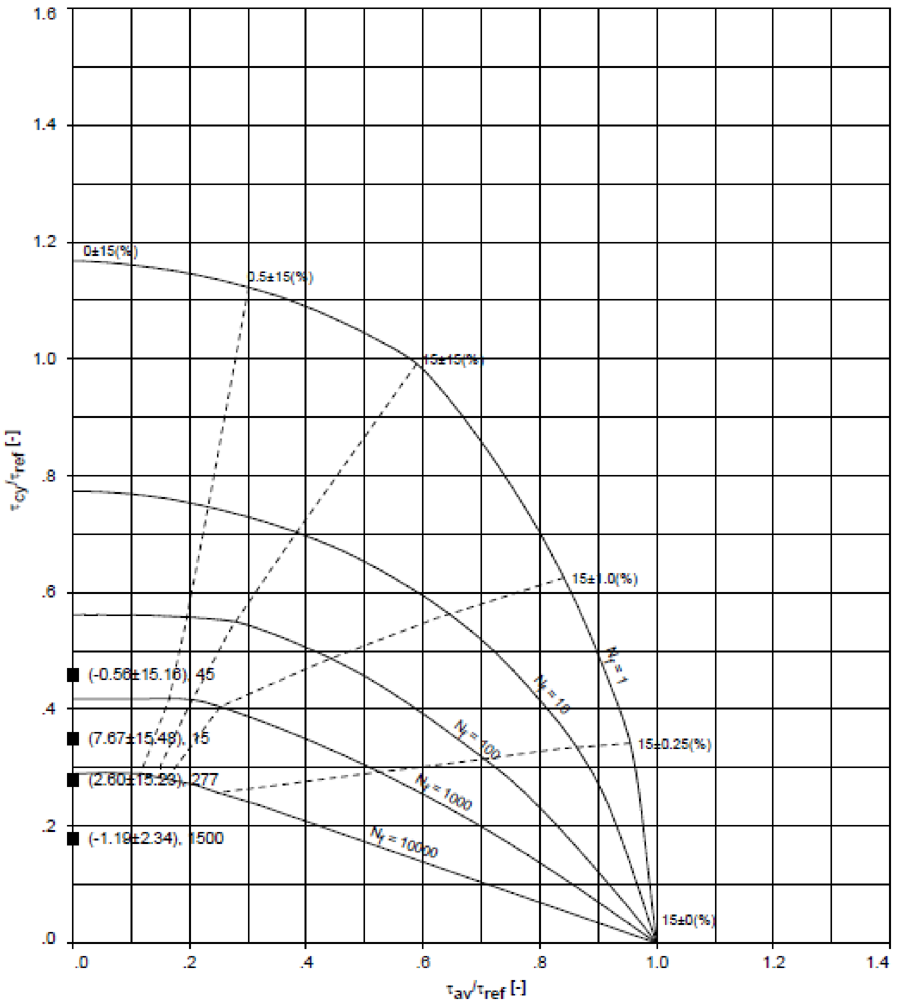
Test Type	Total	Holocene	Above H10	Below H10	Channel Deposits
Geotechnical Index					
Particle size analysis (sieving and pipette) (PSD)	**9**	1	4	4	-
Strength (Static)					
Isotropically Consolidated Undrained Triaxial in Compression (CIUc)	**9**	1	4	4	-
Isotropically Consolidated Drained Triaxial in Compression (CIDc)	**9**	1	4	4	-
Direct Simple Shear (DSS) – Constant Volume	**10**	1	4	4	1
Direct Simple Shear (DSS) – Constant Vertical Stress	**9**	1	4	4	-

Laboratory Testing – Advanced Programme

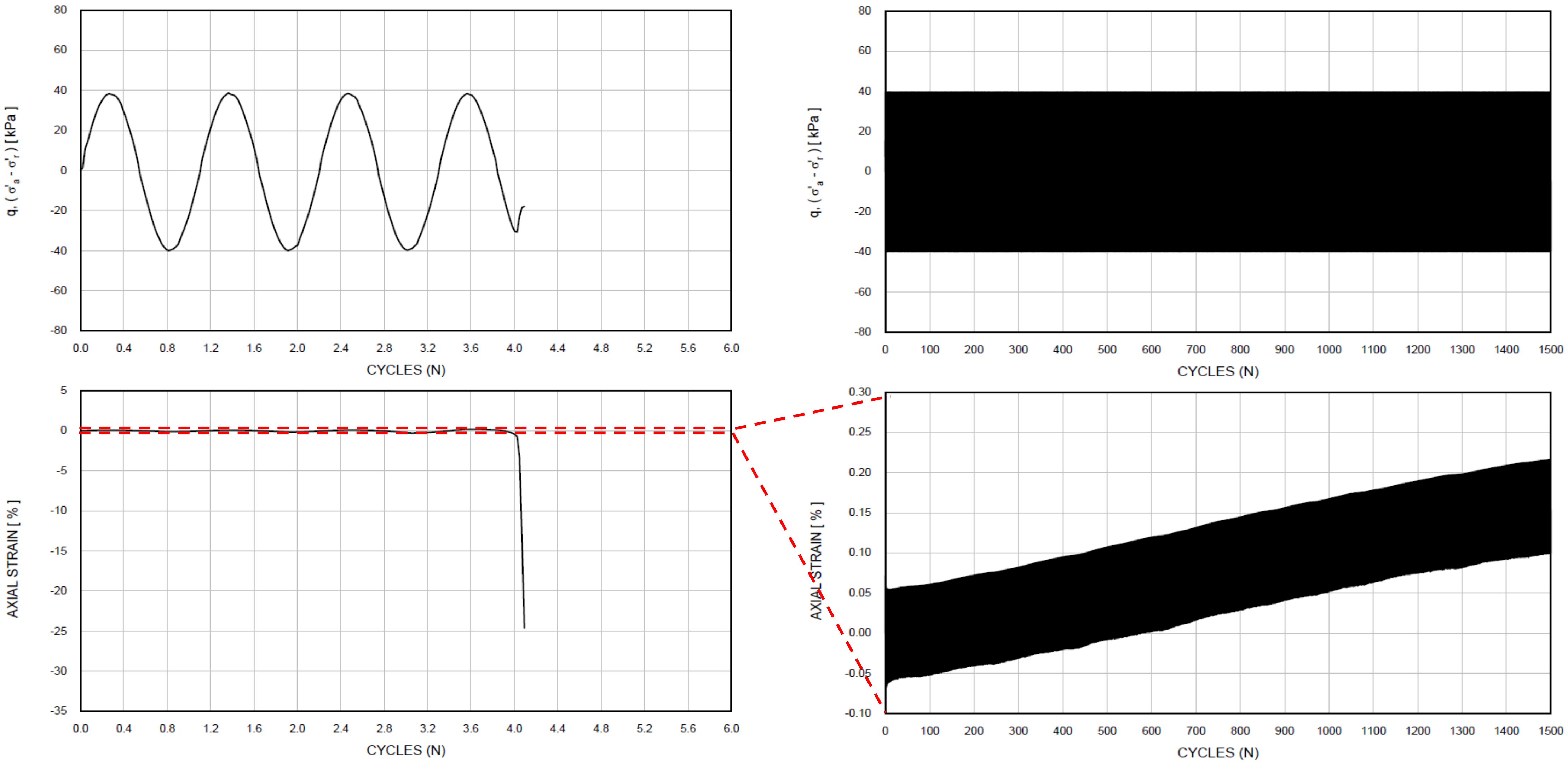
Test Type	Total	Holocene	Above H10	Below H10	Channel Deposits
Strength (Cyclic)					
Stress-controlled Anisotropically Consolidated Undrained Cyclic Triaxial (CTX)	**32**	2	15	13	2
Stress-controlled Isotropically Consolidated Drained Cyclic Triaxial (CTX)	**20**	2	9	9	-
Stress-controlled Cyclic Simple Shear (CSS)	**56**	4	23	25	4
Strain-controlled Cyclic Simple Shear (CSS)	**18**	2	8	8	-
Dynamic					
Resonant Column (RC) – Multi-stage	**10**	1	4	4	1
Resonant Column (RC) – Drained/Undrained	**2**	-	-	-	-
Other					
Sample Microscopic Photography	**9**	1	4	4	-

Laboratory Testing – Sand and Clay Specimens





Laboratory Testing – CTXL undrained/ drained



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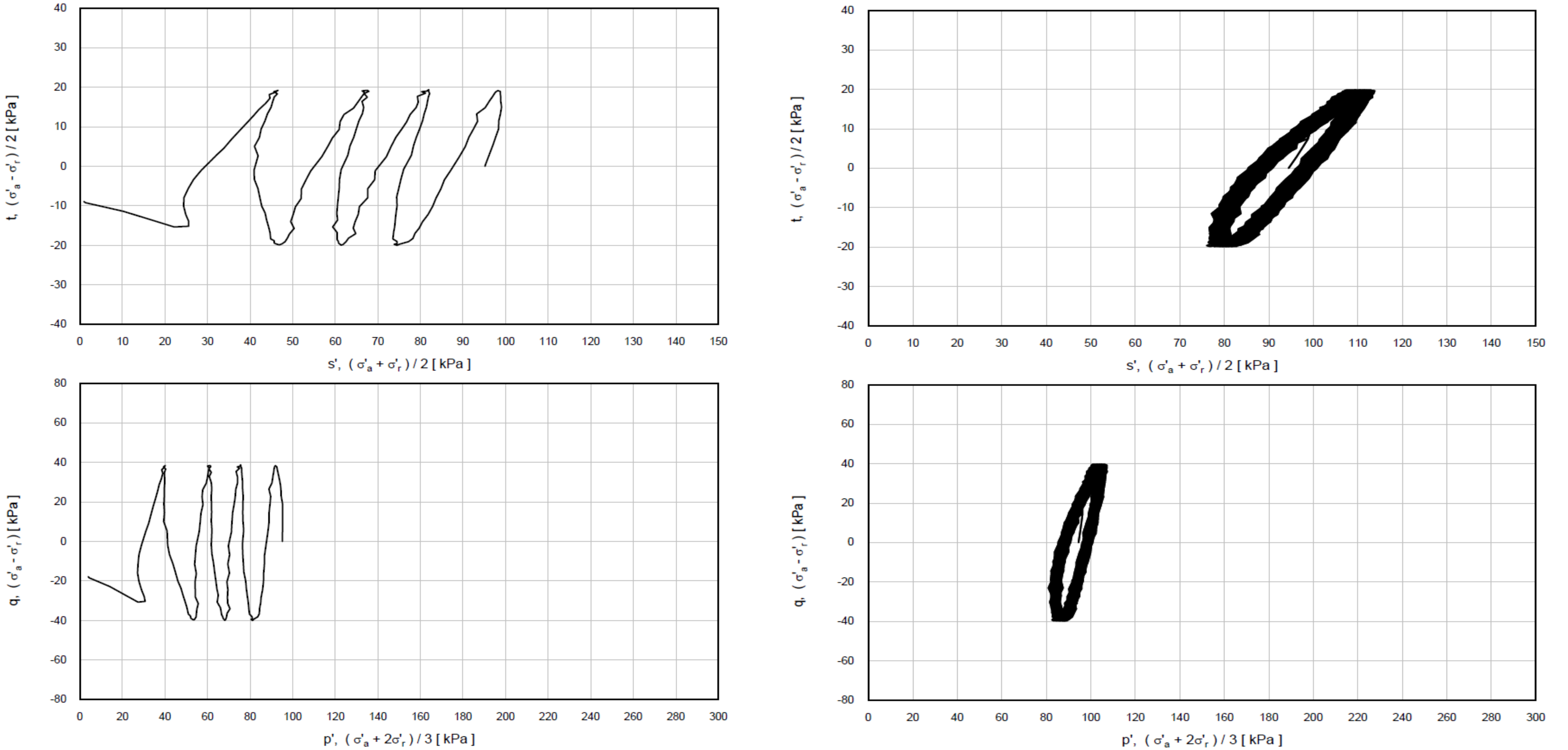
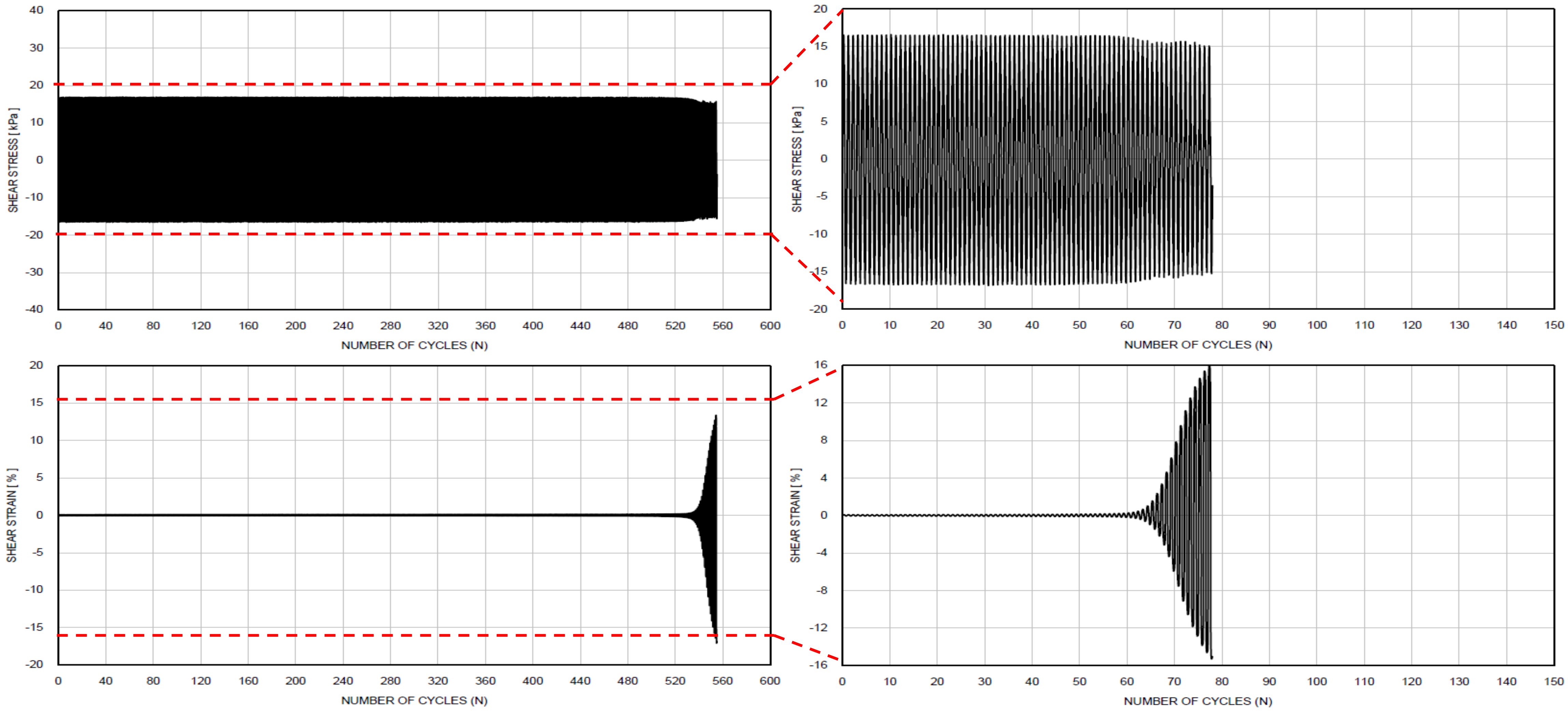
Laboratory Testing – CTXL undrained/ drained



Laboratory Testing – CSS with/without pre-shearing



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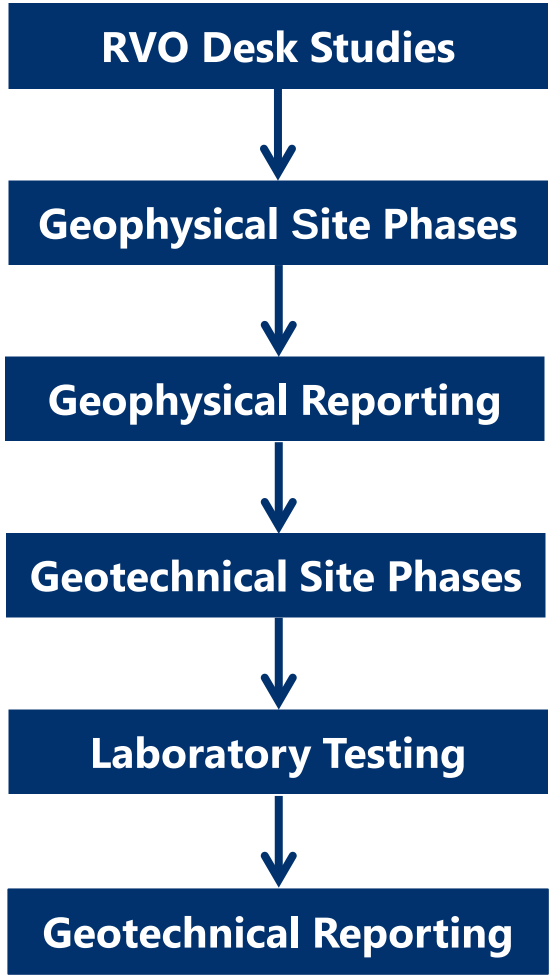
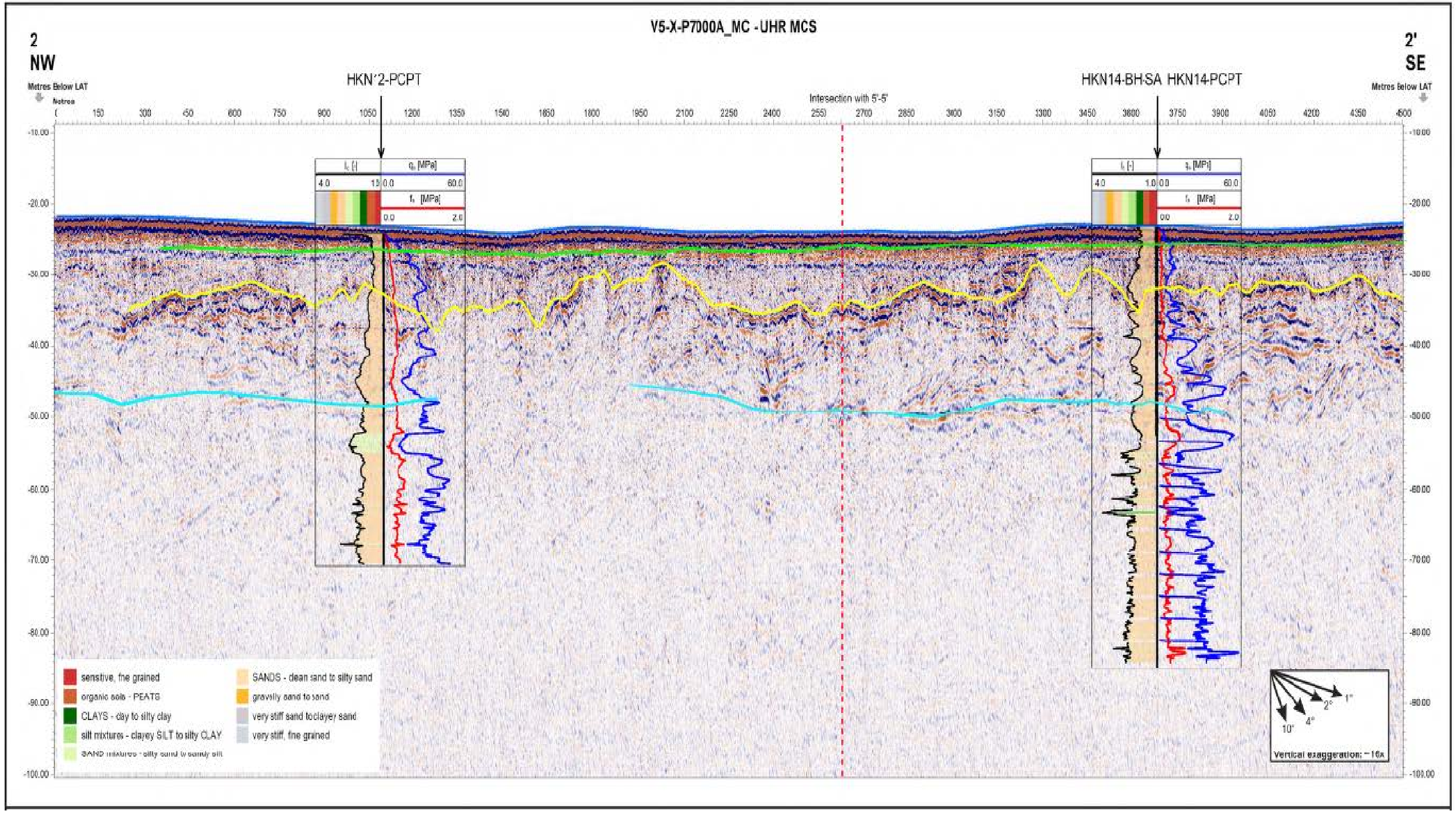
Geotechnical Investigation – Reporting





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Geophysical and Geotechnical Deliverables - Reports

Report Number	Title	Contents
GH216-R3	Geophysical Site Investigation Survey	Geophysical site survey data with accompanying charts (track plots, bathymetry, seafloor sediment classification, contacts, (geo)hazards, geological charts and profiles).
P903749/01	Investigation Data - Seafloor In Situ Test Locations	Geotechnical data including geotechnical logs, results from seafloor cone penetration tests, seafloor seismic cone penetration tests, seafloor temperature cone penetration tests (including temperature equilibrium tests) and pore pressure dissipation tests.
P903749/02	Investigation Data - Geotechnical Borehole Locations	Geotechnical data including geotechnical logs, results from downhole (seismic) cone penetration tests and results from geotechnical laboratory tests.
P903749/03	Geological Ground Model	Geological ground model including stratigraphy, lateral soil variability, geohazards, geological analyses, biostratigraphic analyses, basic geotechnical parameter values and assessment of geotechnical suitability of selected types of structures.
P903749/04	Laboratory Test Data	Results of (advanced) geotechnical laboratory tests.
P903749/05	Investigation Data – TenneT Substation	Geotechnical data including geotechnical logs, results from seafloor and downhole cone penetration tests and results from geotechnical laboratory tests.
P903749/06	Geotechnical Parameters	Results of a geotechnical parameter study.

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Geophysical and Geotechnical Deliverables – Digital Data

Project Phase	Data (Format)	
Geophysical	Raw data	▪ Multibeam echo sounder (.all, .xyz , .svp) ▪ Sidescan Sonar (.xtf) ▪ Magnetometer (.csv) ▪ Sub-bottom Profiler (.segY) ▪ 2D UHR seismic (.segD) ▪ Tidal data (.csv)
	Processed Data	▪ Multibeam echo sounder (.xyz, .xyb, GeoTiff) ▪ Sidescan sonar (.GeoTiff) ▪ Magnetometer (Oasis Montaj project) ▪ Sub-bottom profiler (Kingdom project, .segY - sections in time) ▪ 2D UHR seismic (Kingdom project, .segY - migrated sections time and depth) ▪ ArcGIS geodatabase
Geotechnical	▪ (S)CPT- data (.ags, .asc) / raw seismic shots (.asc) & stacked seismic traces (.xls) ▪ sampling/borehole/standard laboratory – data (.ags) / advanced test data (.xls)	
Ground Model	▪ Kingdom project ▪ ArcGIS geodatabase	

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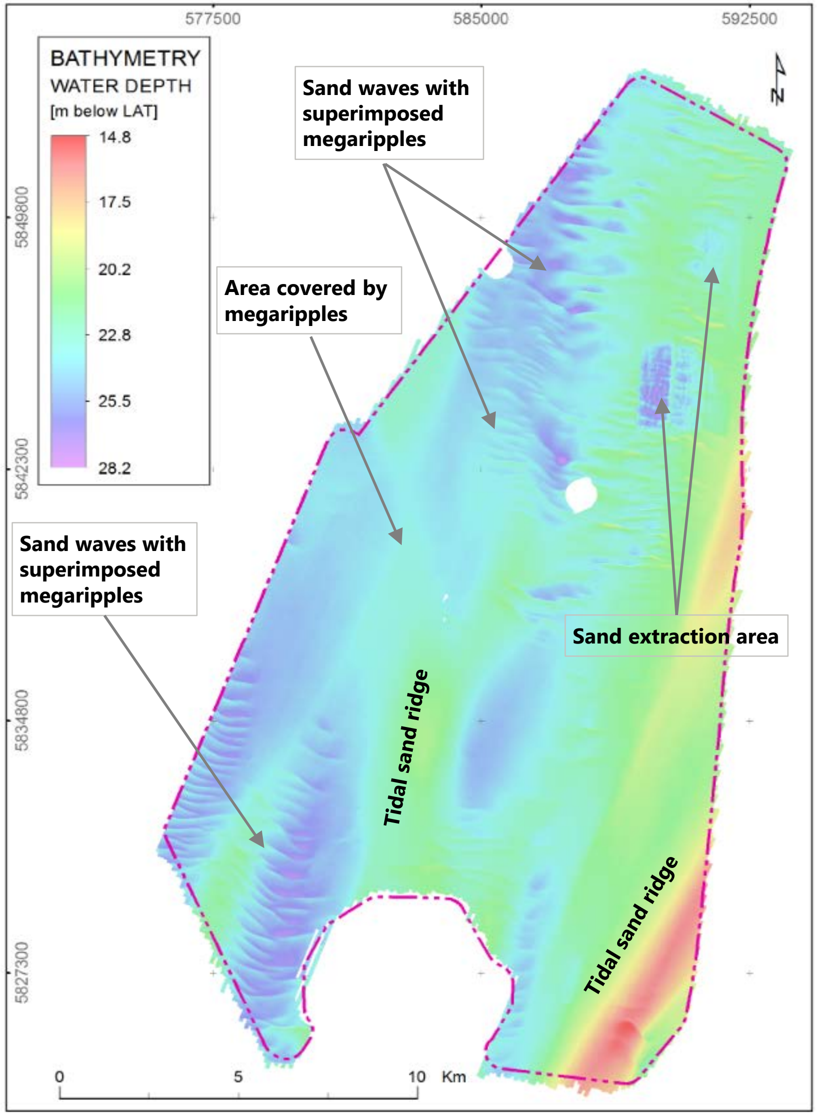
02

Geological Ground Model

Bathymetry and Bedforms

- Water depth from 15 m to 28 m LAT
- Seafloor gradient in general < 1.0°, locally higher up to 14° on the slopes of bedforms (sand waves, megaripples)
- Three type of natural bedforms:
  - Sandbanks (sand ridges): the largest bedforms, oriented NNE-SSW, present in the east and south-central part of the site
  - Sand waves: height to approximately 6 m, crest orientation WNW-ESE, predominantly present in the north and southwest
  - Megaripples: height to approximately 0,5 m, crest orientation WNW-ESE, typically superimposed on sand waves, present across the entire site



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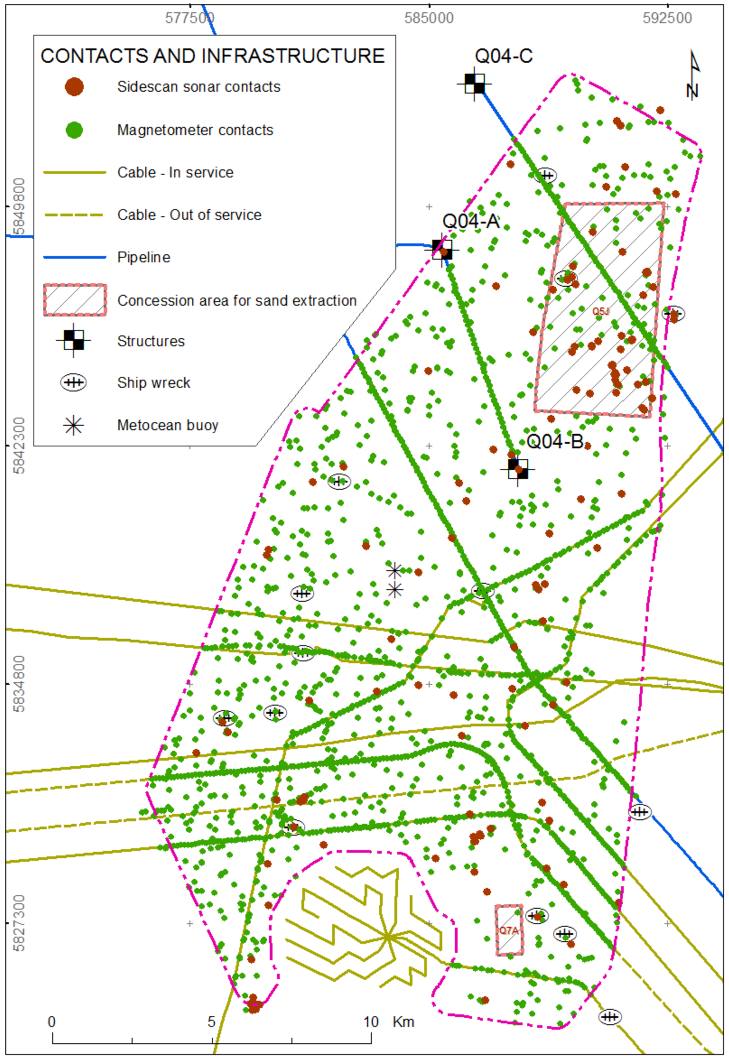
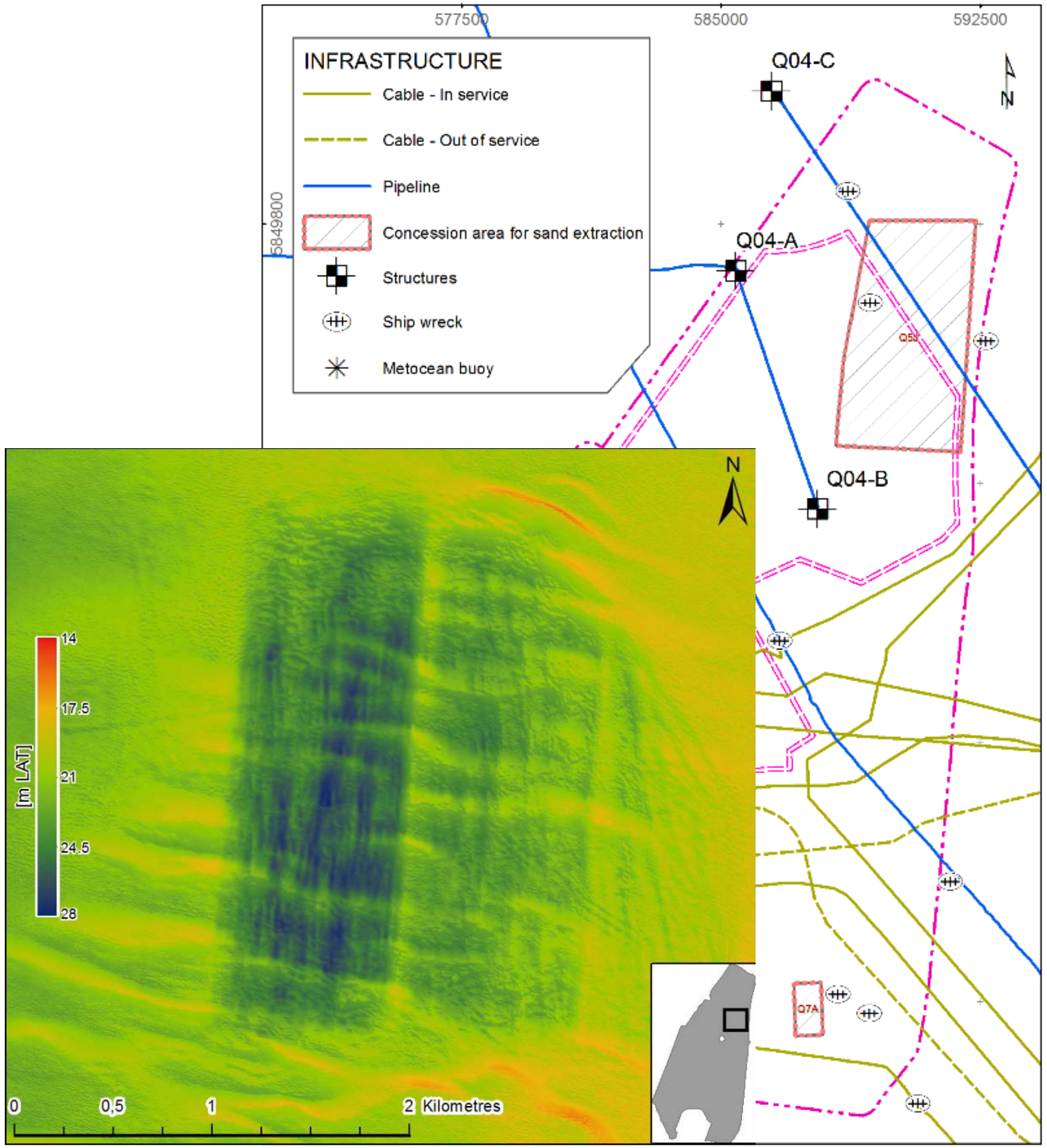
Seafloor Conditions – Infrastructure and Objects

- 4 pipelines and 9 cables
- 136 contacts on SSS data (interpreted as boulders, debris, linear debris, and other)
- 1713 MAG contacts
- 6 wrecks were identified, 7 known wrecks could not be identified
- trawl scars, especially high density in the southeastern part of the site, orientation S-N, length from 200 m to 1500 m
- 3 spudcan footprints, 2 wellheads, 1 field of metal debris



GGM – Sand Extraction Areas

- Three sand extraction zones (dredged areas)
- Reflected in seafloor topography, water depth in dredges areas was approximately 5 m lower than the surrounding seafloor
- Represents disturbed and reworked “in situ” soil and ‘back-fall’ from dredging operations
- Thickness uncertain
- Medium dense to very dense (fine to coarse SAND, with traces of fine gravel
- On seismic data: chaotic structure, no continuous reflectors



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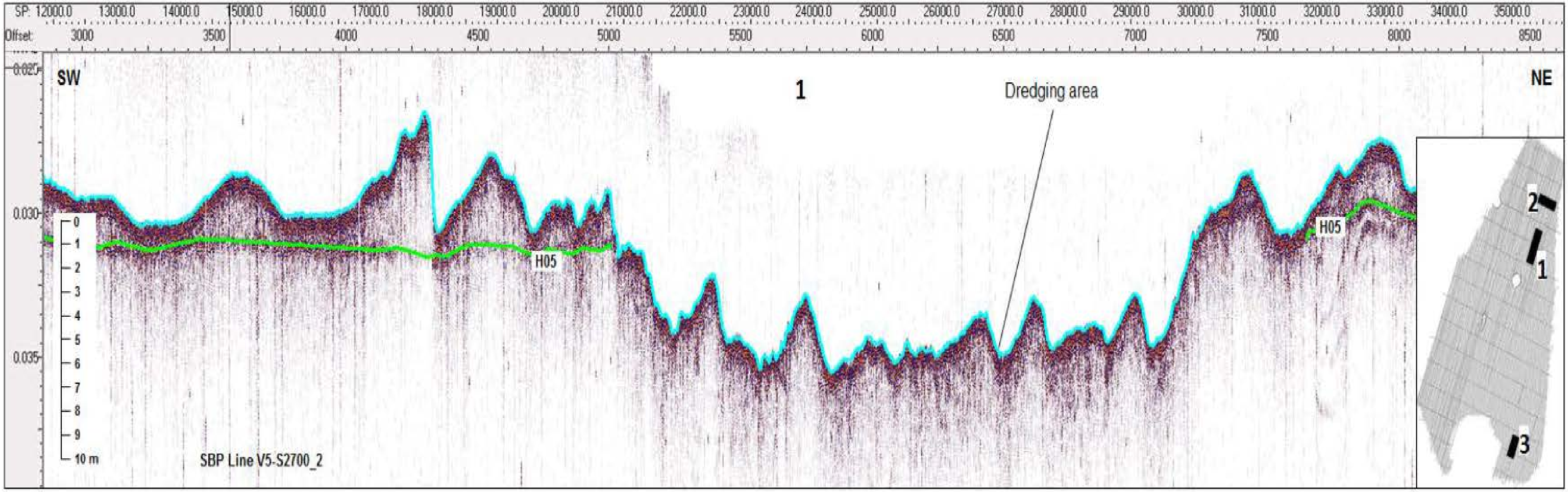
GGM – Sand Extraction Areas



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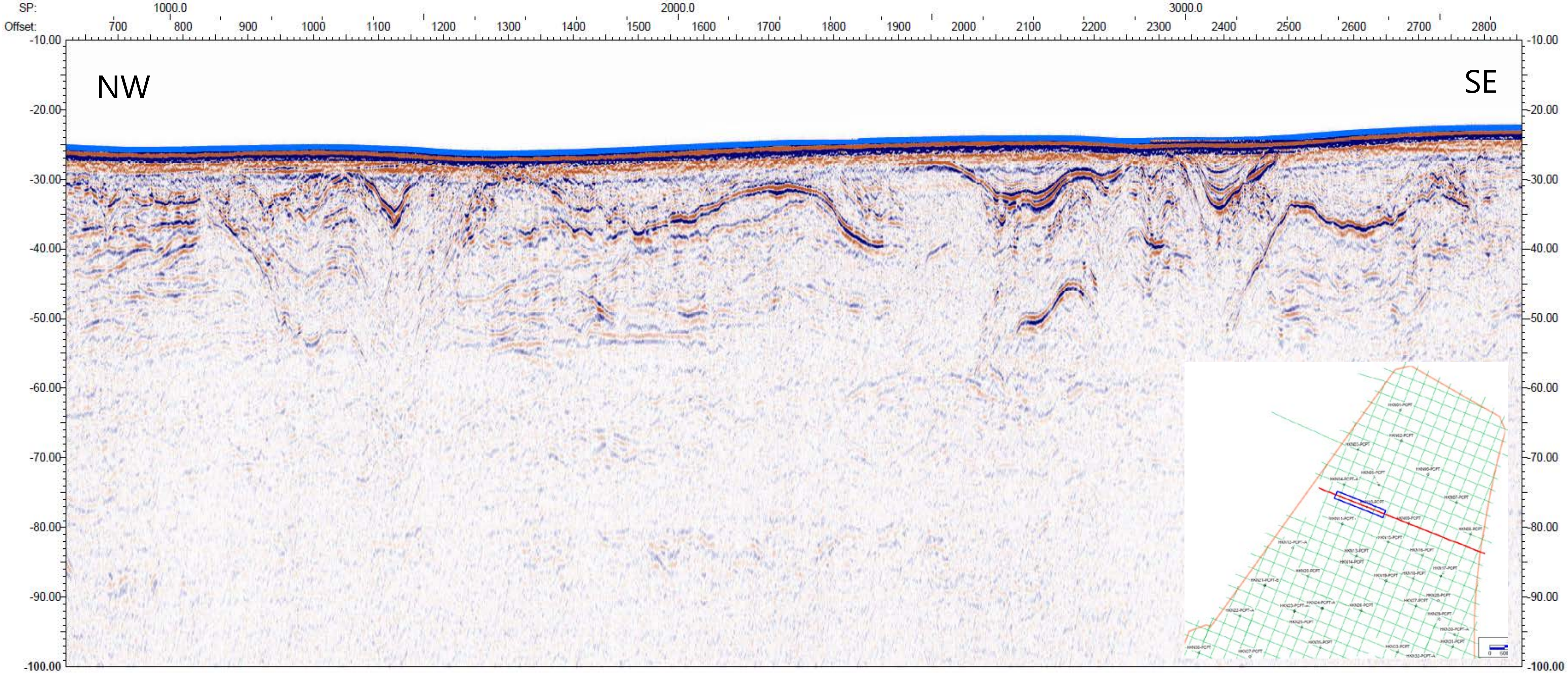
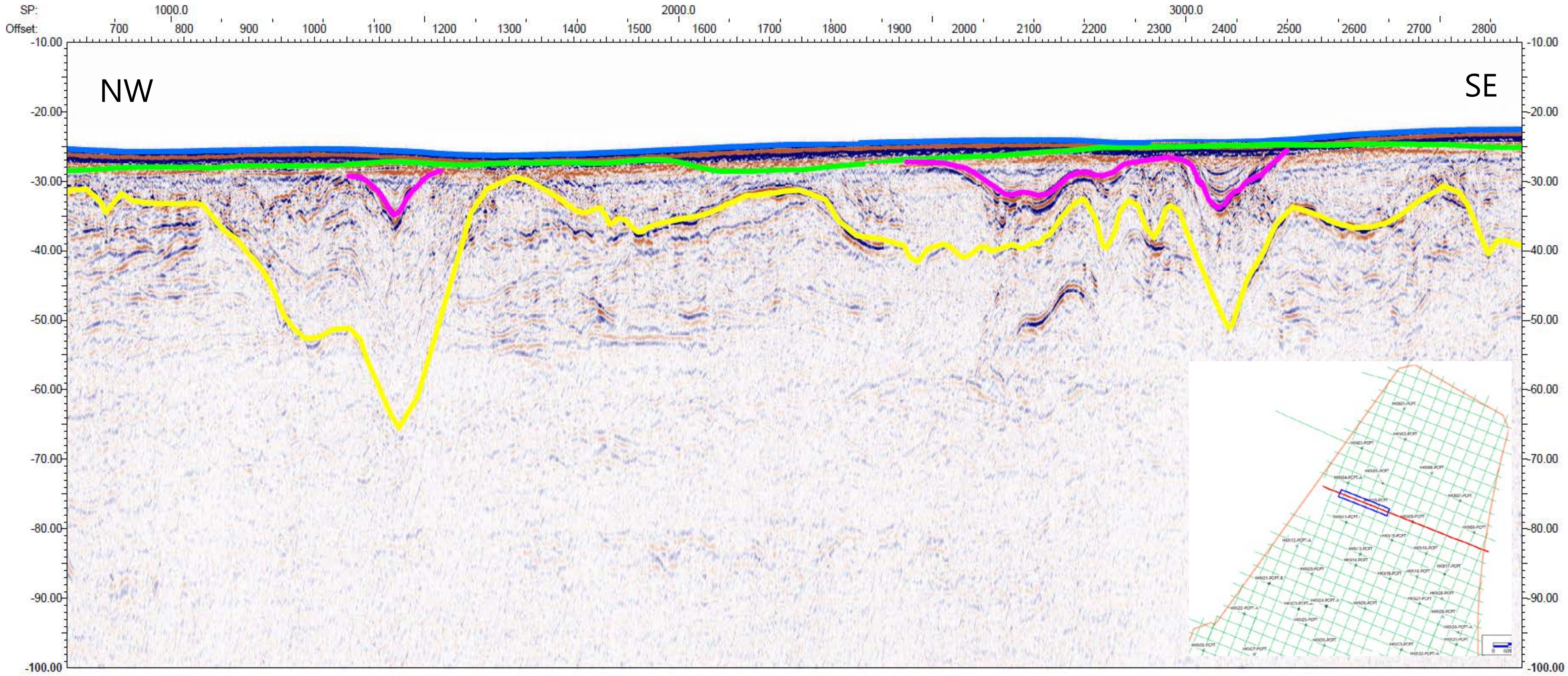
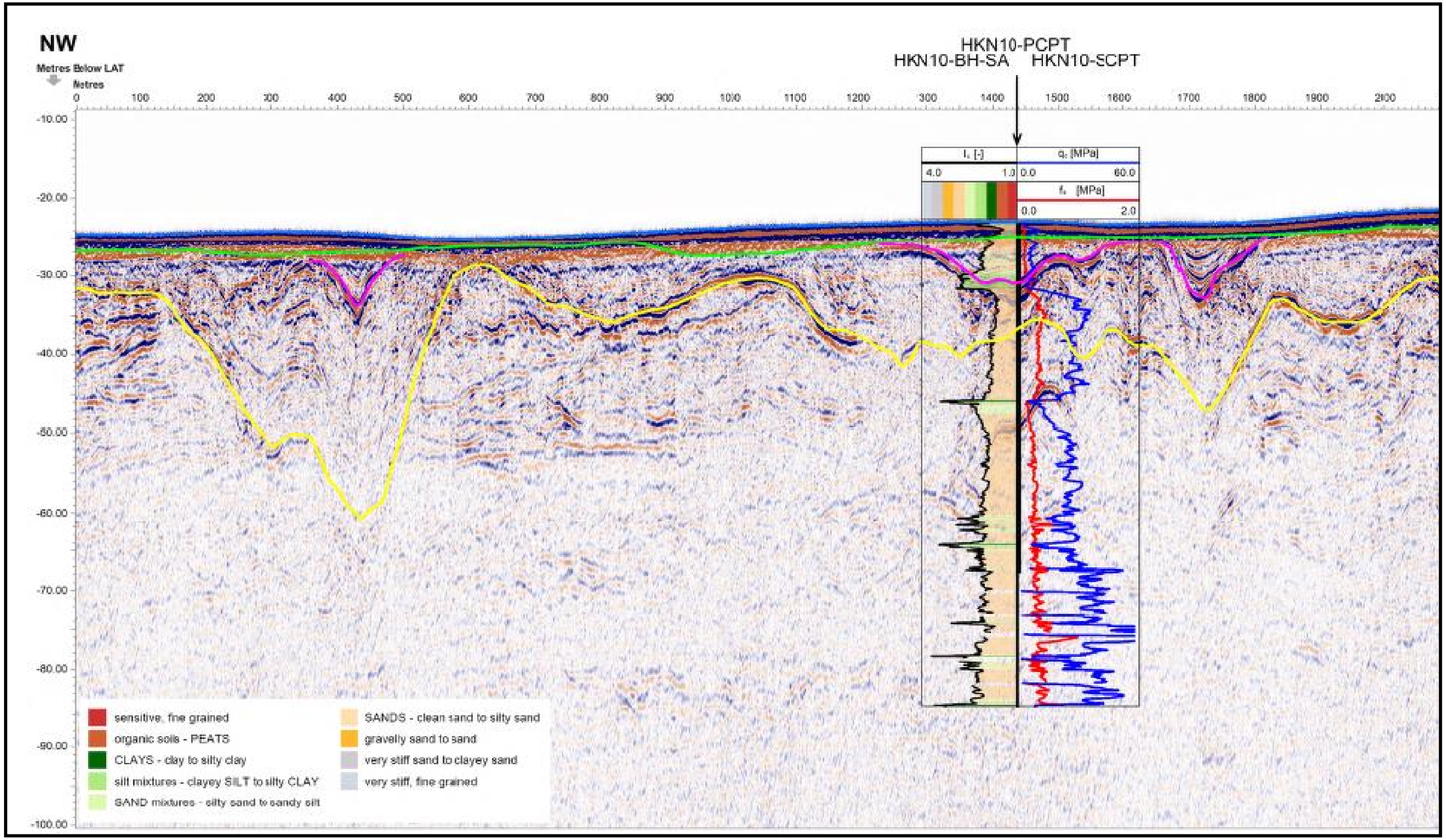
GGM – Seismic Interpretation



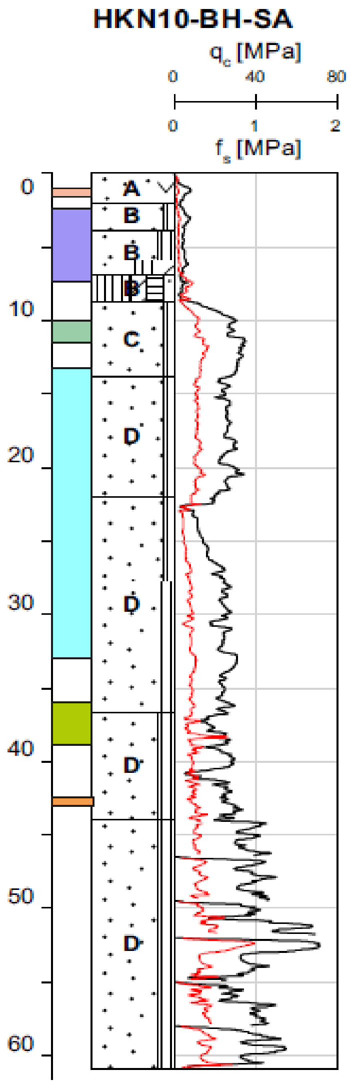
GGM – Seismic Interpretation



GGM – Data Integration



Palynology



GGM – Lithostratigraphic Framework

Unit	Fugro 2018 Seismo-stratigraphy		Rijsdijk et al. 2005		Geological Dating		
	Unit	Seismic Reflector	Formation	Member	Depositional Environment	Age	Palynology Zone
A	A	**H01** (base)	Southern Bight	Bligh Bank	marine	Holocene	HKN 1A
B	B	**H05** (base)	Naaldwijk	Wormer Velsen Bed Bergen Bed	coastal to tidal flat and lagoonal	Early Holocene	HKN 1B HKN 1C
C	C	**H10** (base)	Kreftenheye Boxtel Eem	- - Brown Bank	fluvial to fluvio-periglacial	Late Pleistocene	HKN 2 HKN 3 HKN 4
D	D E	**H15** (internal) **H20** (internal)	Egmond Ground Yarmouth Roads	- -	fluvial to fluvio-deltaic	Early to Middle Pleistocene	HKN 5 HKN 6 HKN 7 HKN 8

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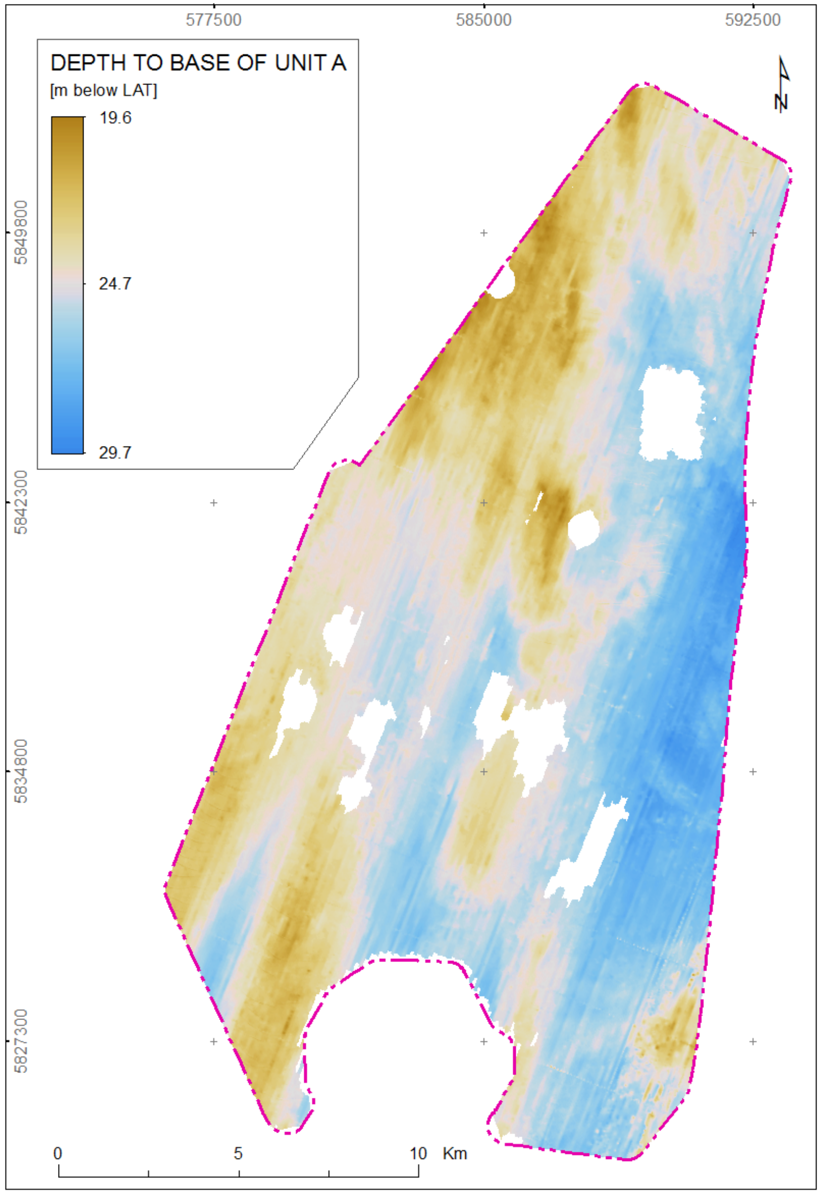
GGM – Soil Unit A

- Distribution: present across the entire site, except sand extraction areas, where can be absent; gaps on the distribution map are platform exclusion zones and areas where the base reflector was not detectable on seismic data
- Thickness: on average <1 m to 2 m, locally up to 6m at sand wave crests, and up to 13 m at the largest sandbanks
- Lithology: medium dense to very dense (fine to medium) SAND, with traces of shells and shell fragments
- Interpretation: marine setting, Holocene, Southern Bight Formation



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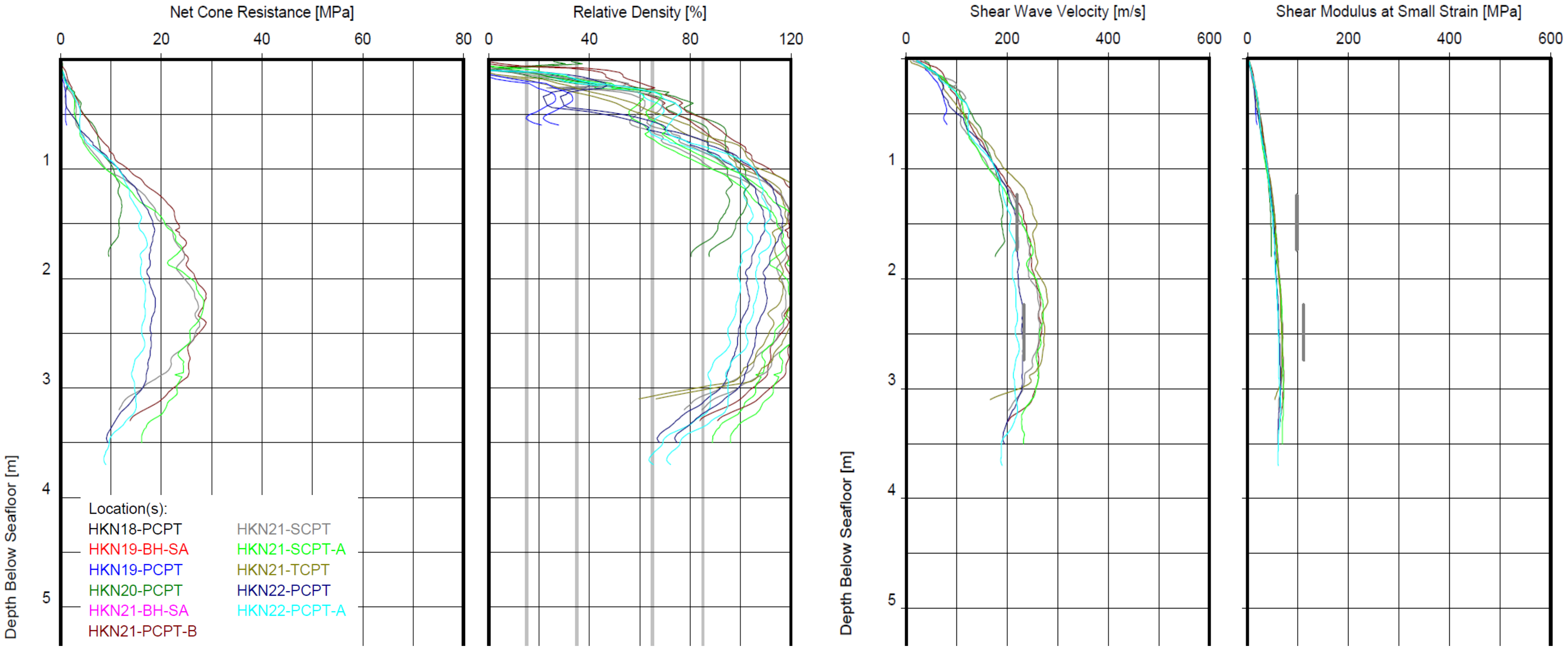
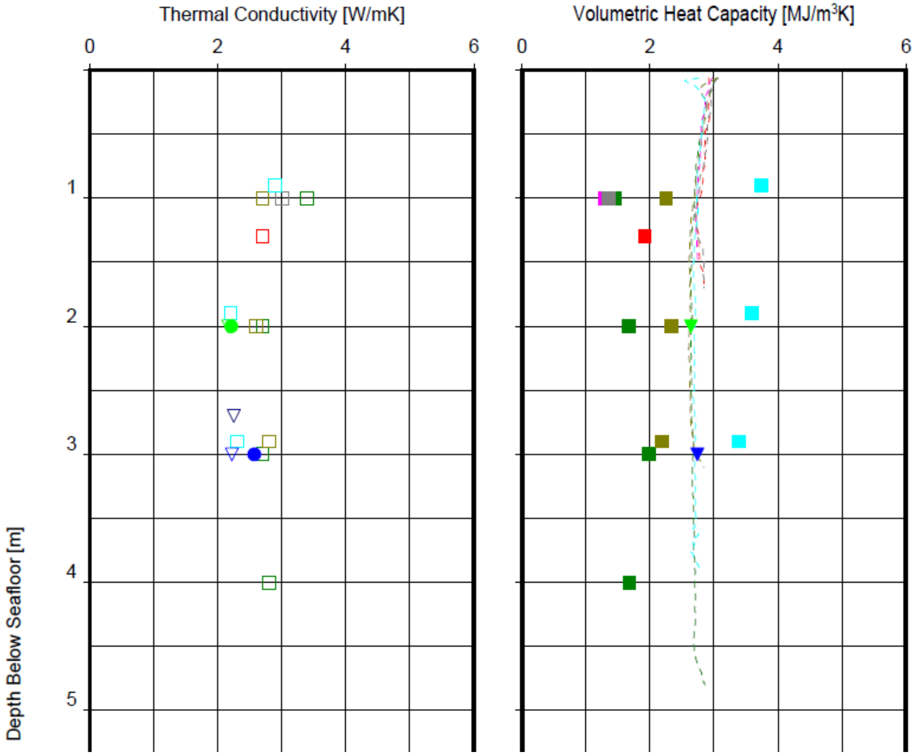
GGM – Soil Unit A – Data Example

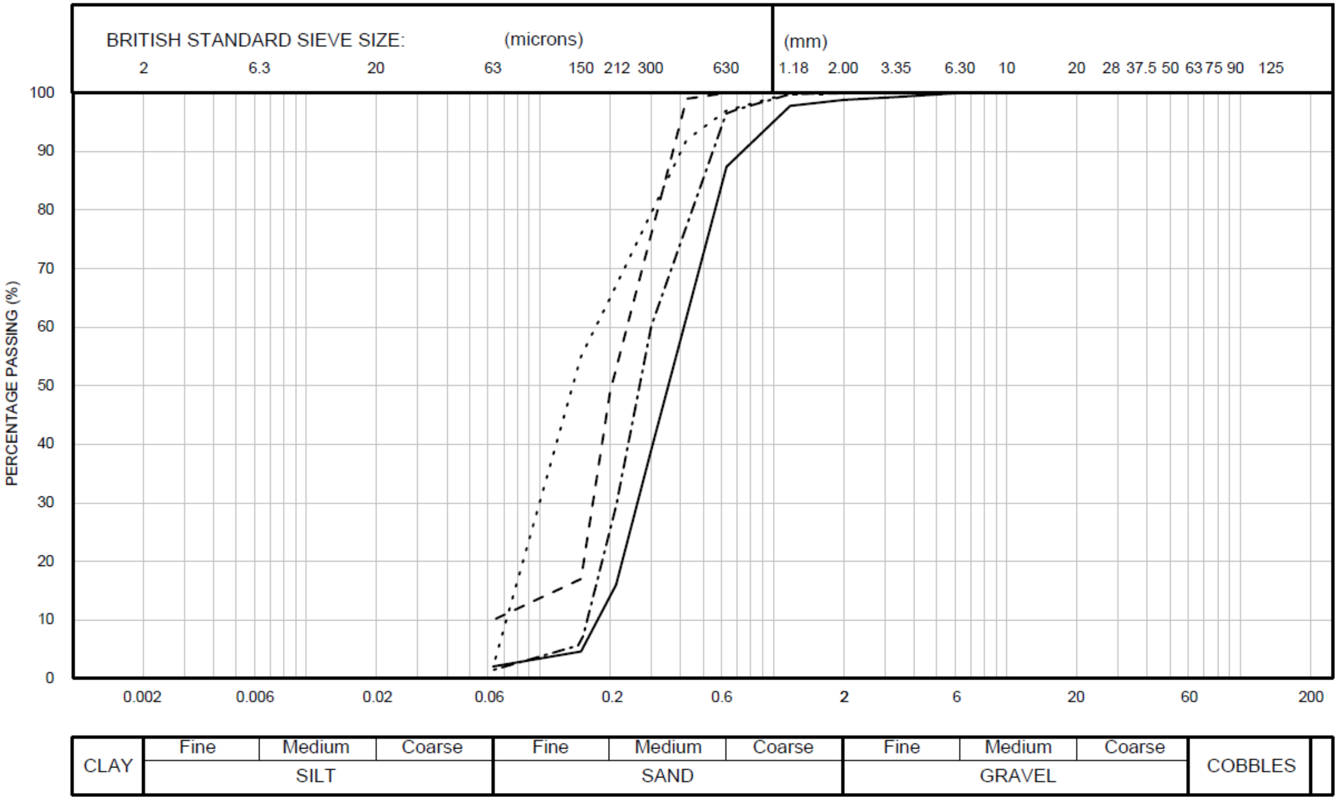


GGM – Soil Unit A – Data Example



☐ Thermal conductivity derived from TCPT temperature equilibrium test
● Thermal conductivity derived from laboratory transient plane heat source (hot disk) test
▽ Thermal conductivity derived from laboratory single needle probe test
■ Volumetric heat capacity derived from TCPT temperature equilibrium test
▼ Volumetric heat capacity derived from laboratory transient plane heat source (hot disk) test
Volumetric heat capacity based on correlation with CPT data

Location(s):
HKN02-BH-SA
HKN02-TCPT
HKN06-BH-SA
HKN06-TCPT
HKN09-TCPT
HKN10-BH-SA
HKN10-TCPT
HKN21-BH-SA
HKN21-TCPT
HKN25-BH-SA
HKN25-TCPT



Curve	Borehole	Sample	Depth (m)	BS Test * Method	Pretreatment Method	Clay	Silt†	Sand	Gravel	Cobbles
						Percentage soil types				
———	HKN06-BH-SA	01BagA	0.00	9.2	N/A	0	2	97	1	0
– – –	HKN06-BH-SA	02Liner01	1.40	9.2	N/A	0	10	90	0	0
· · · ·	HKN06-BH-SA	03Liner02	2.40	9.2	N/A	0	2	98	0	0
– · – ·	HKN06-BH-SA	04BagA	3.00	9.2	N/A	0	1	99	0	0

* Tested in accordance with the following clauses of BS 1377: Part 2: 1990:

9.2	Wet sieve
9.3	Dry sieve
9.4	Sedimentation by pipette
9.5	Sedimentation by hydrometer

† Note: Where a sedimentation test was not carried out, this figure represents total fines, i.e., particles of diameter less than 63 microns

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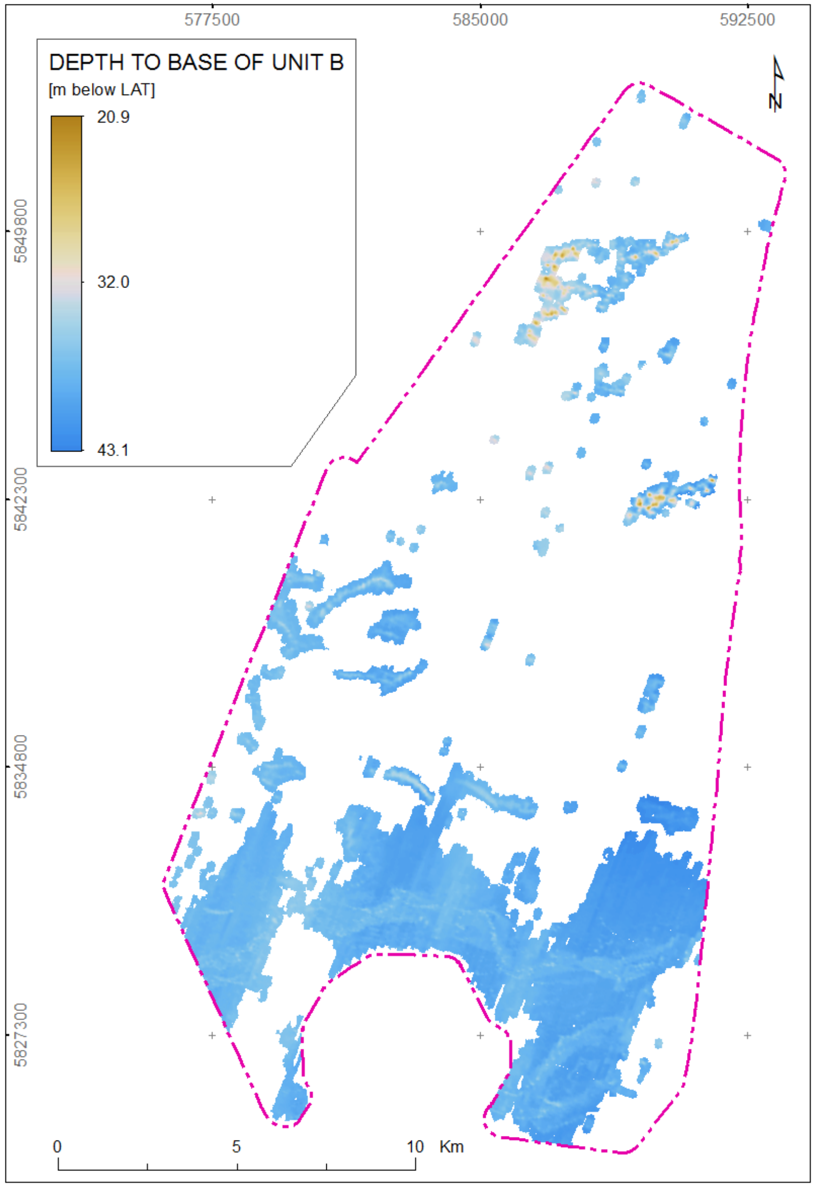
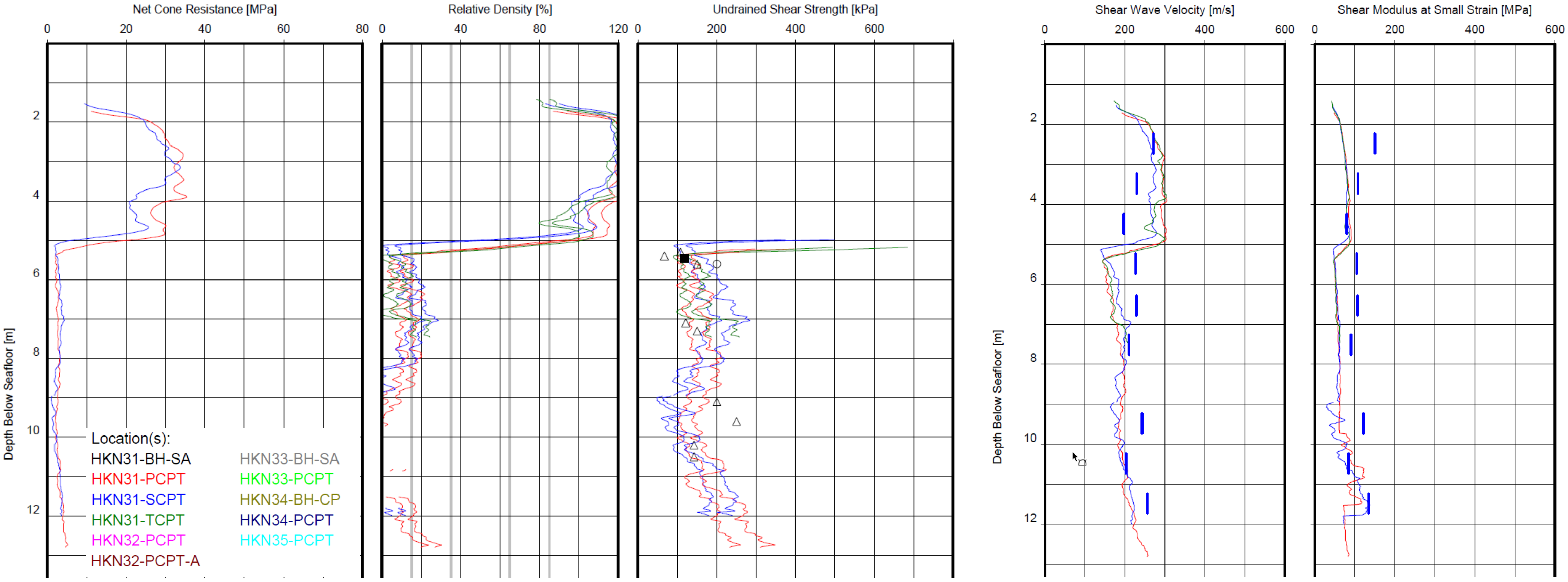
GGM – Soil Unit B

- Distribution: present locally, more common in the south, in the north patchy distribution, as infills of buried channels
-
- Thickness: variable, typically 2 m, locally up to 19 m in the deepest channels
- Lithology: medium dense to very dense (clayey) SAND or high strength to very high strength (sandy) CLAY, with shells and shell fragments
- Interpretation: coastal plain setting, early Holocene, Naaldwijk Formation



GGM – Soil Unit B – Data Example



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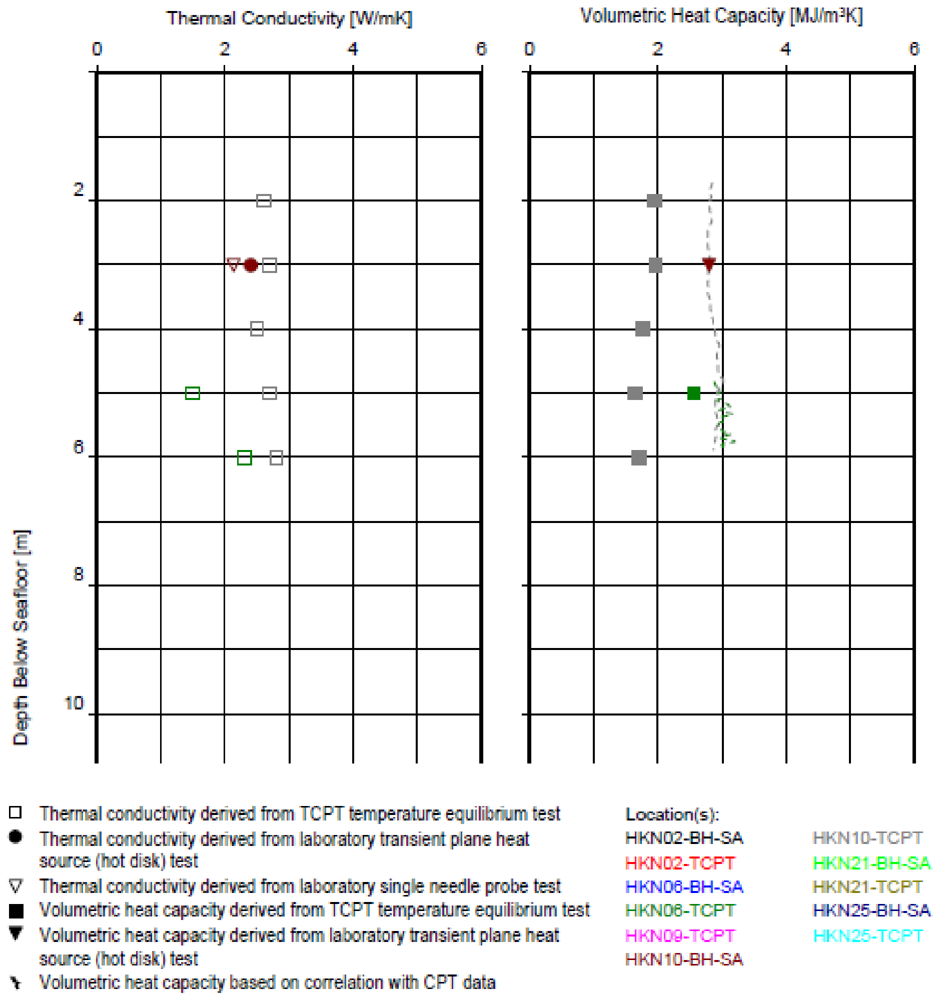
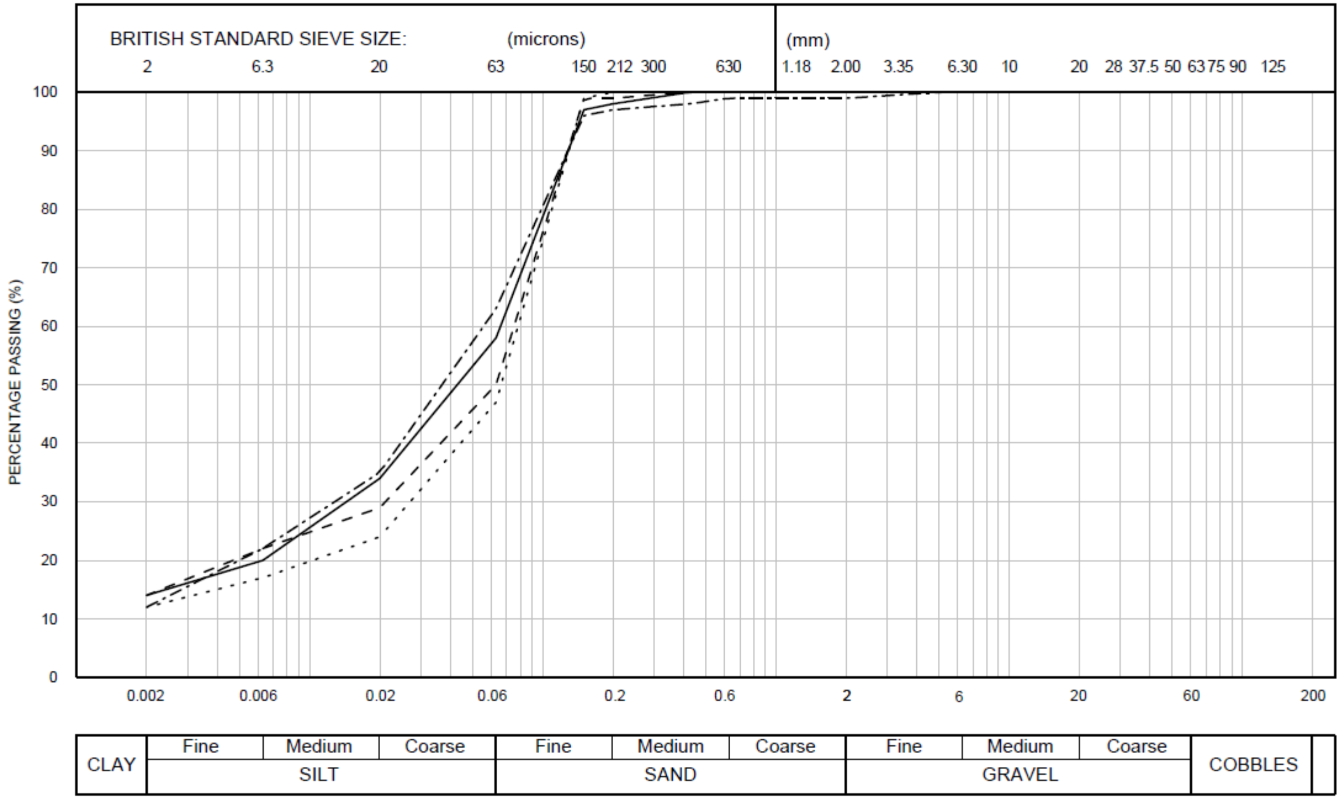
GGM – Soil Unit B – Data Example





Curve	Borehole	Sample	Depth (m)	BS Test * Method	Pretreatment Method	Percentage soil types: Clay	Silt†	Sand	Gravel	Cobbles
├──┤	HKN06-BH-SA	06BagA	5.00	9.2/9.4	N/A	14	42	44	0	0
├ – –┤	HKN06-BH-SA	07Liner03	5.50	9.2/9.4	N/A	14	34	52	0	0
├ - - -┤	HKN06-BH-SA	08BagB	6.95	9.2/9.4	N/A	12	33	55	0	0
├-·-┤	HKN06-BH-SA	10BagA	8.50	9.2/9.4	N/A	12	49	38	1	0

* Tested in accordance with the following clauses of BS 1377: Part 2: 1990:	
9.2	Wet sieve
9.3	Dry sieve
9.4	Sedimentation by pipette
9.5	Sedimentation by hydrometer

† Note: Where a sedimentation test was not carried out, this figure represents total fines, i.e., particles of diameter less than 63 microns

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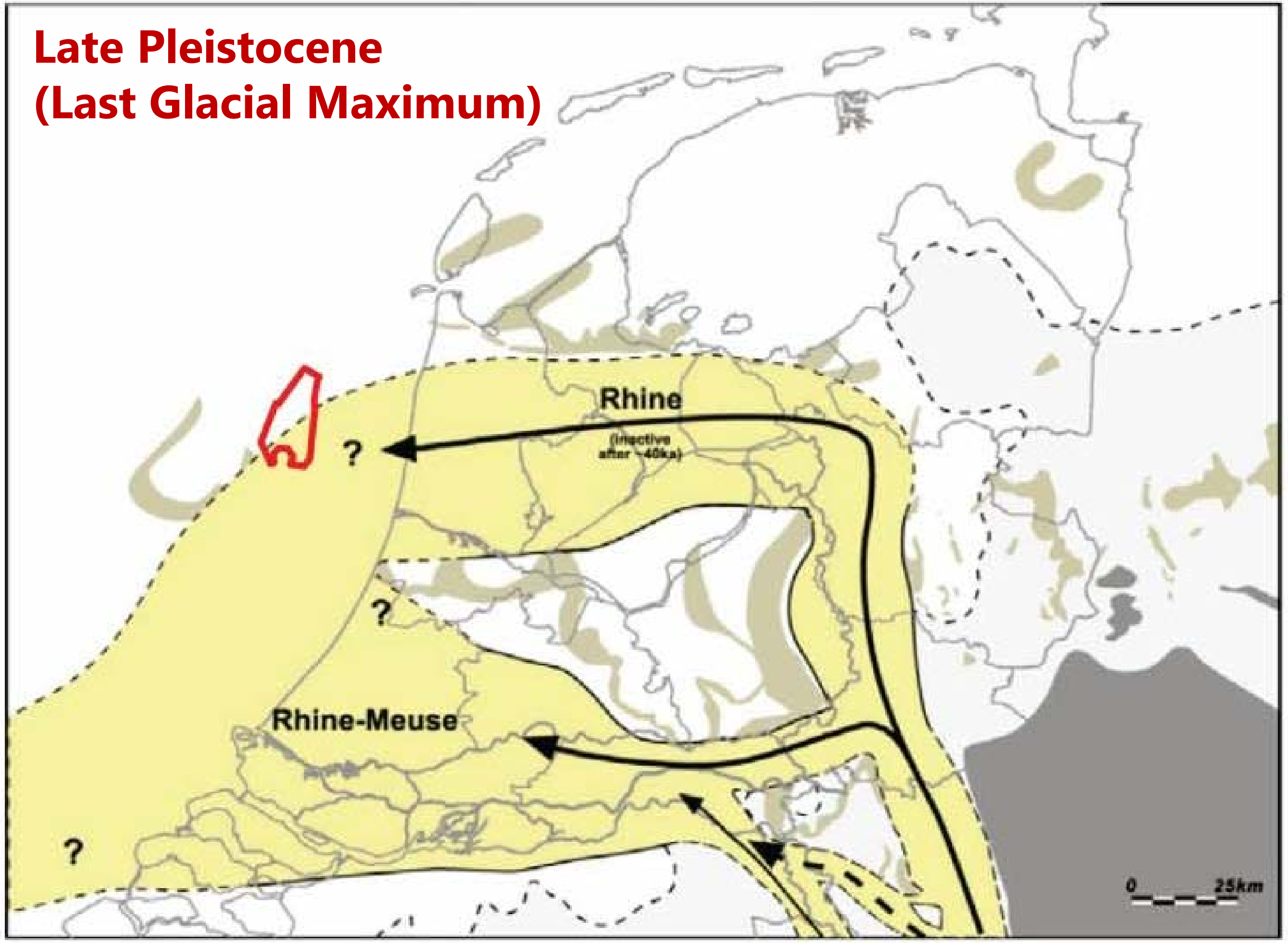
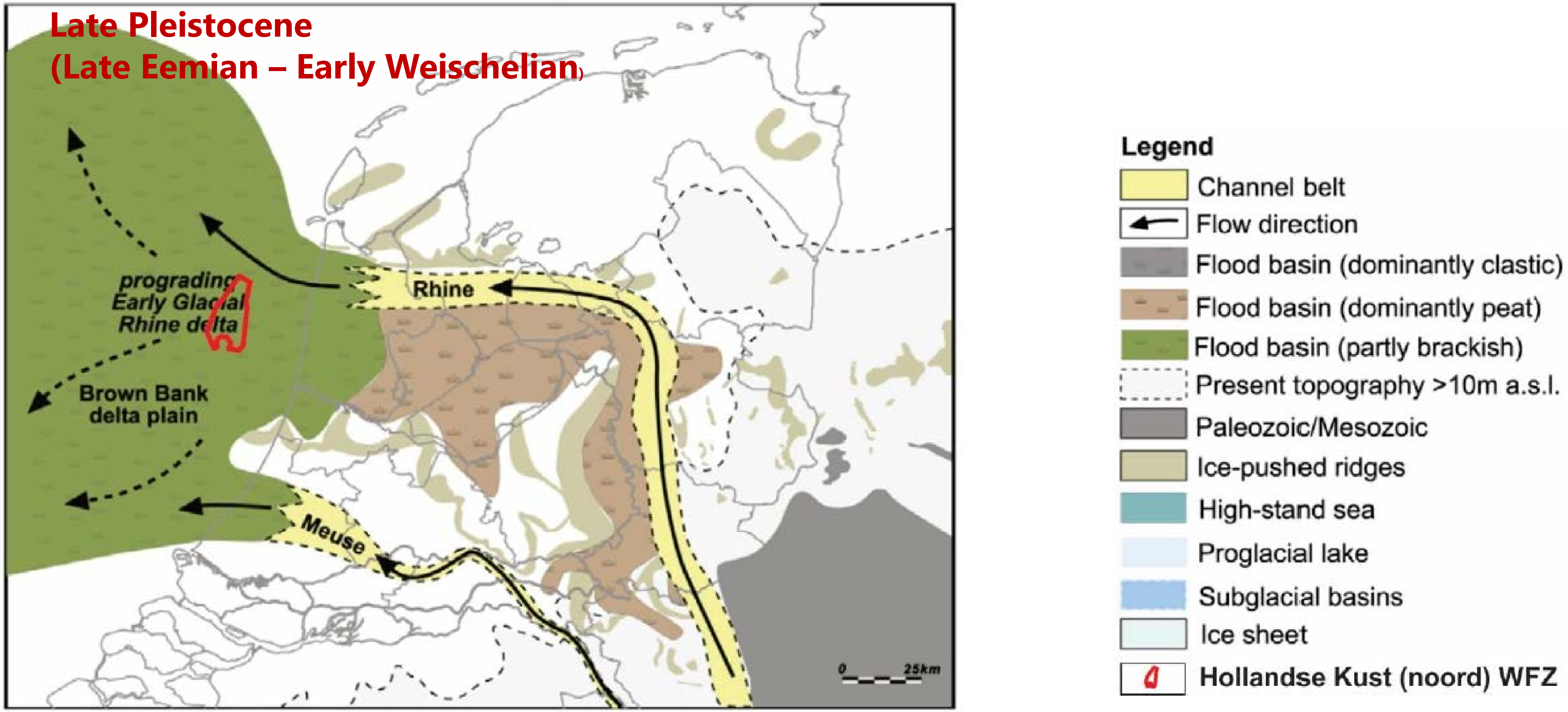
GGM – Geological Setting



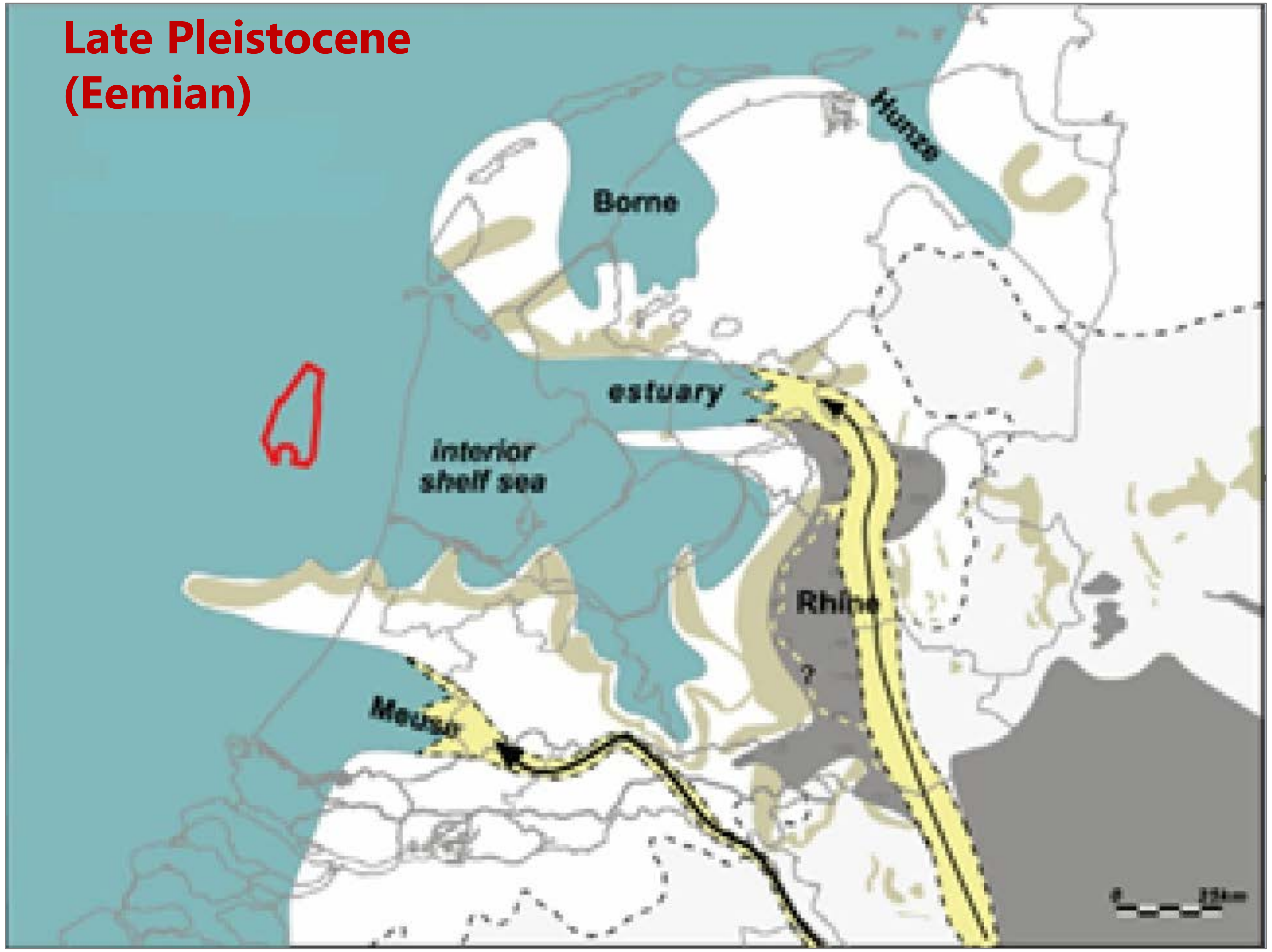
Legend

- Channel belt
- Flow direction
- Flood basin (dominantly clastic)
- Flood basin (dominantly peat)
- Flood basin (partly brackish)
- Present topography >10m a.s.l.
- Paleozoic/Mesozoic
- Ice-pushed ridges
- High-stand sea
- Proglacial lake
- Subglacial basins
- Ice sheet
- **Hollandse Kust (noord) WFZ**

GGM – Geological Setting



GGM – Geological Setting

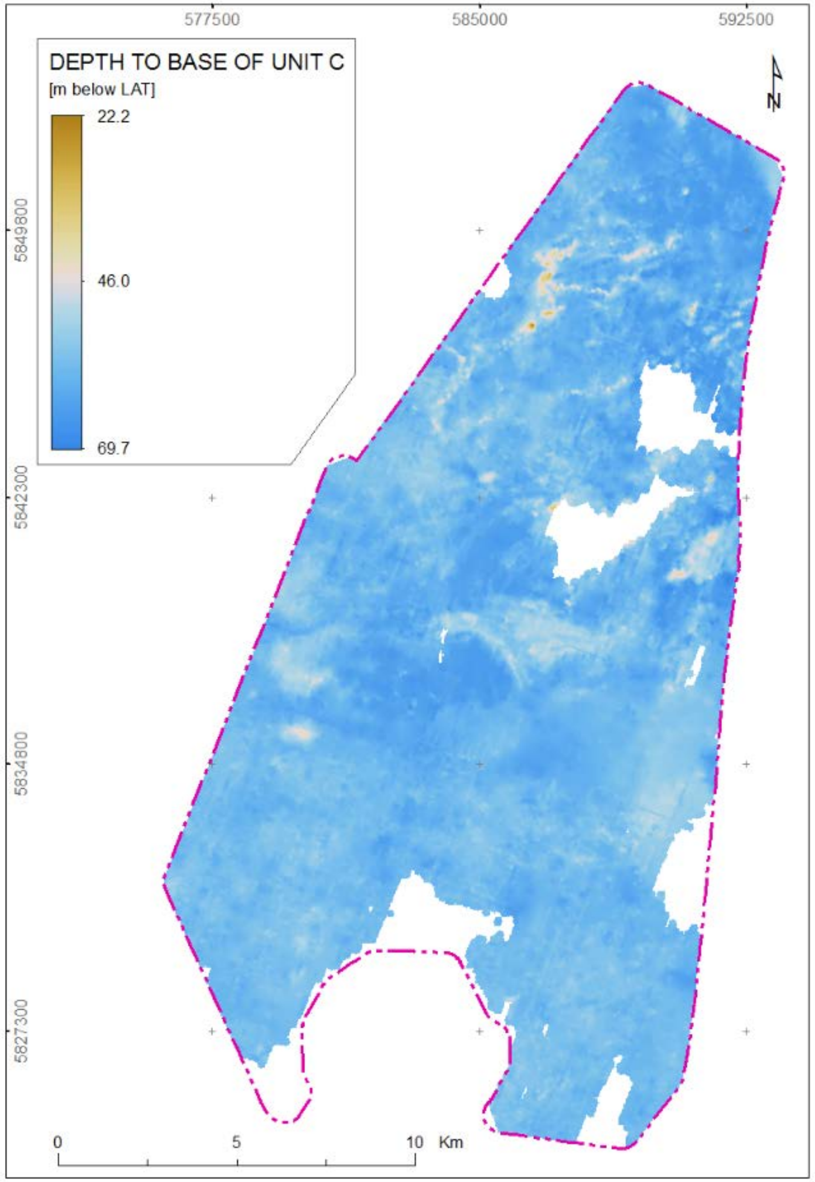


Legend

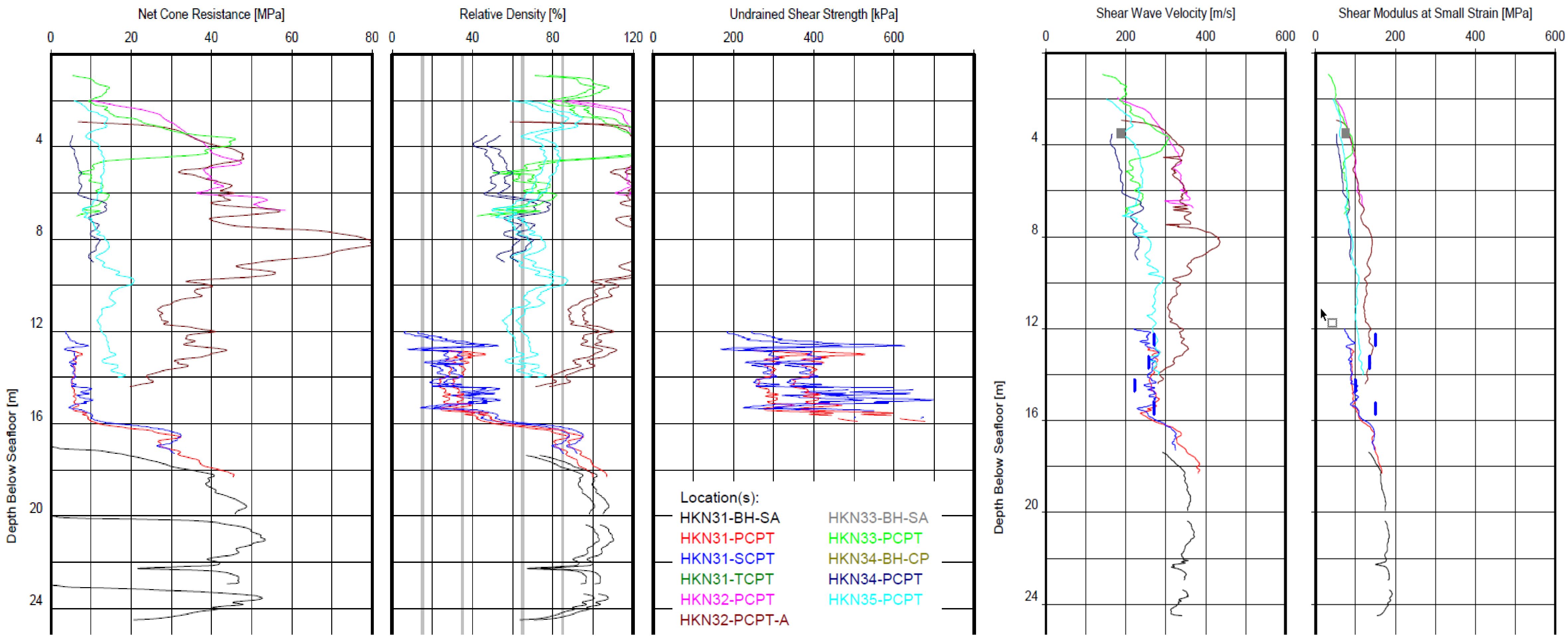
- Channel belt
- Flow direction
- Flood basin (dominantly clastic)
- Flood basin (dominantly peat)
- Flood basin (partly brackish)
- Present topography >10m a.s.l.
- Paleozoic/Mesozoic
- Ice-pushed ridges
- High-stand sea
- Proglacial lake
- Subglacial basins
- Ice sheet
- Hollandse Kust (noord) WFZ

GGM – Soil Unit C

- Distribution: present across the entire site, in sand extraction areas can be absent; gaps on the distribution map are areas where the base reflector was not detectable on seismic data
- Thickness: variable from 1 m to approximately 40 m
- Lithology: medium dense to very dense (silty, clayey, fine to medium) SAND, locally laminae to thick beds of silt or clay
- Interpretation: fluvial to fluvio-periglacial setting, locally shallow marine, Late Pleistocene, Kreftenheye and Boxtel Formations, Eem Formation



GGM – Soil Unit C – Data Example



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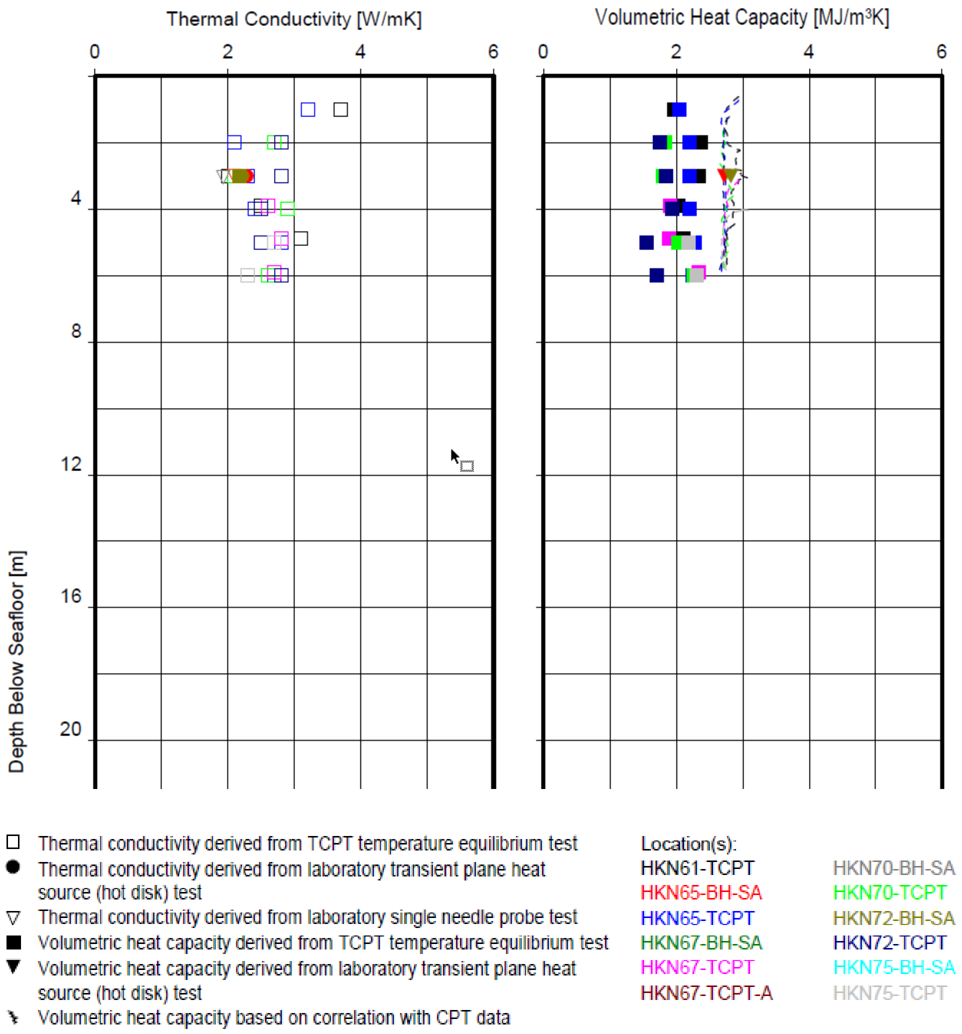
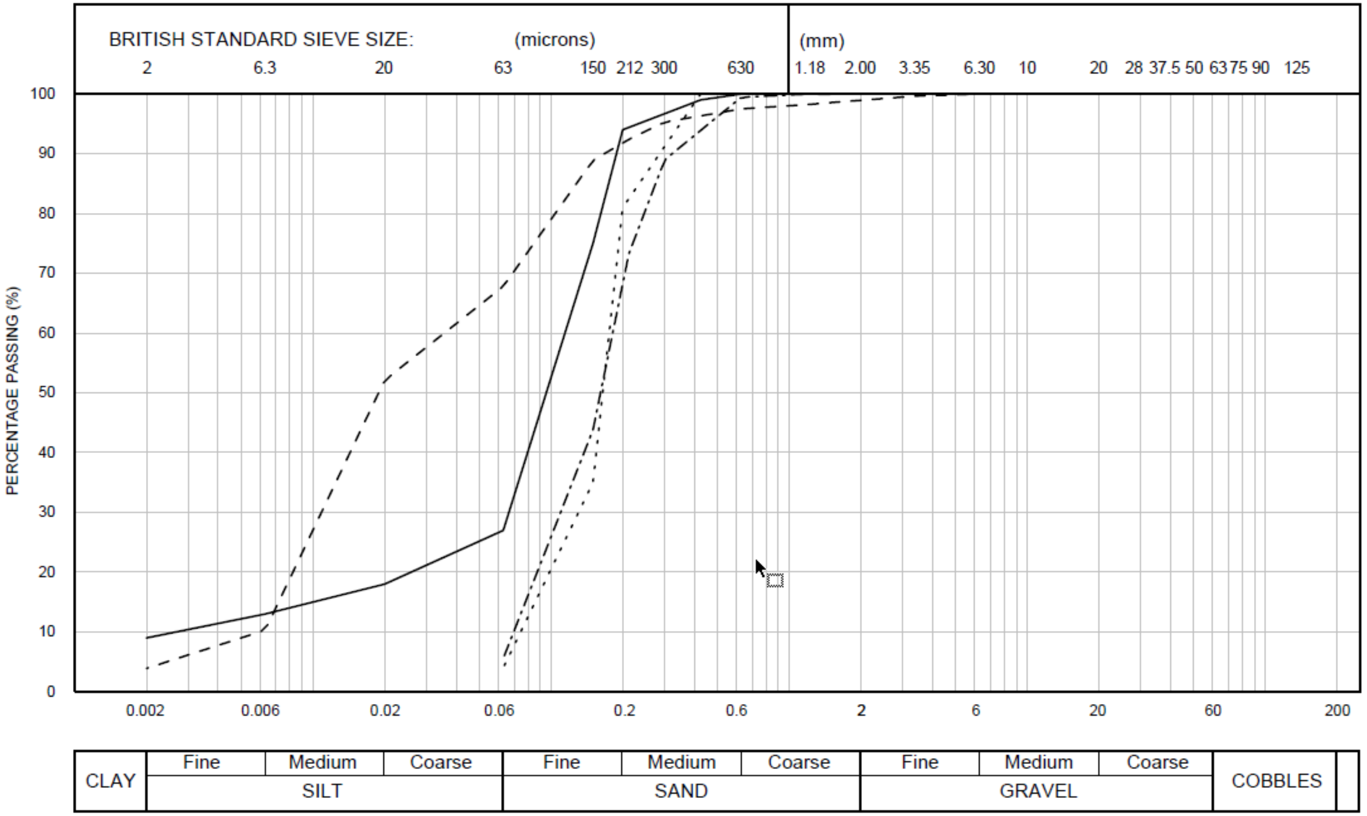
GGM – Soil Unit C – Data Example





Curve	Borehole	Sample	Depth (m)	BS Test * Method	Pretreatment Method	Percentage soil types: Clay	Silt†	Sand	Gravel	Cobbles
├──┤	HKN06-BH-SA	18BagA	15.50	9.2/9.4	N/A	9	17	74	0	0
├ ─ ─┤	HKN06-BH-SA	18BagC	16.10	9.2/9.4	N/A	4	62	33	1	0
├ · · ·┤	HKN06-BH-SA	20liner05	17.40	9.2	N/A	0	4	96	0	0
├ ─ · ─┤	HKN06-BH-SA	23BagA	19.50	9.2	N/A	0	5	95	0	0

* Tested in accordance with the following clauses of BS 1377: Part 2: 1990:

9.2	Wet sieve
9.3	Dry sieve
9.4	Sedimentation by pipette
9.5	Sedimentation by hydrometer

† Note: Where a sedimentation test was not carried out, this figure represents total fines, i.e., particles of diameter less than 63 microns

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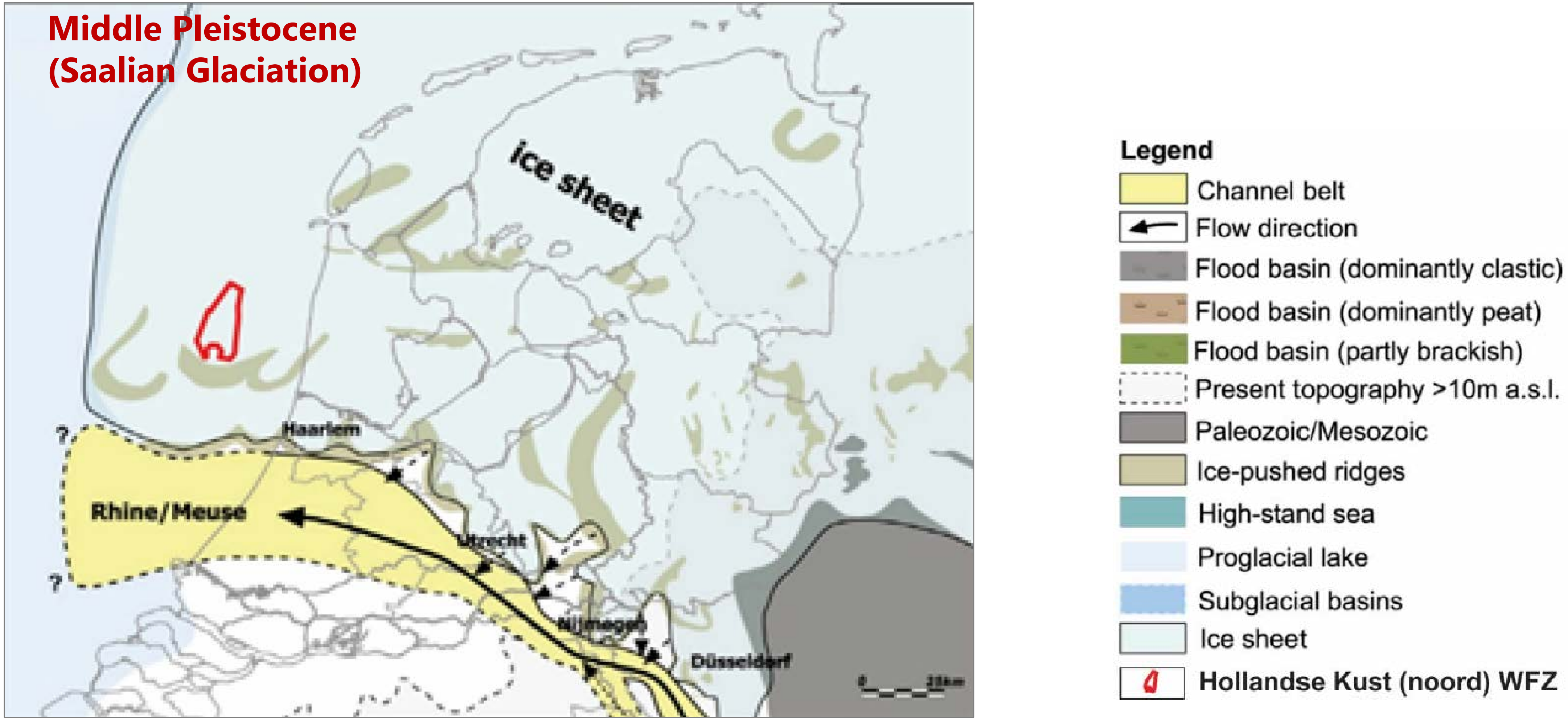
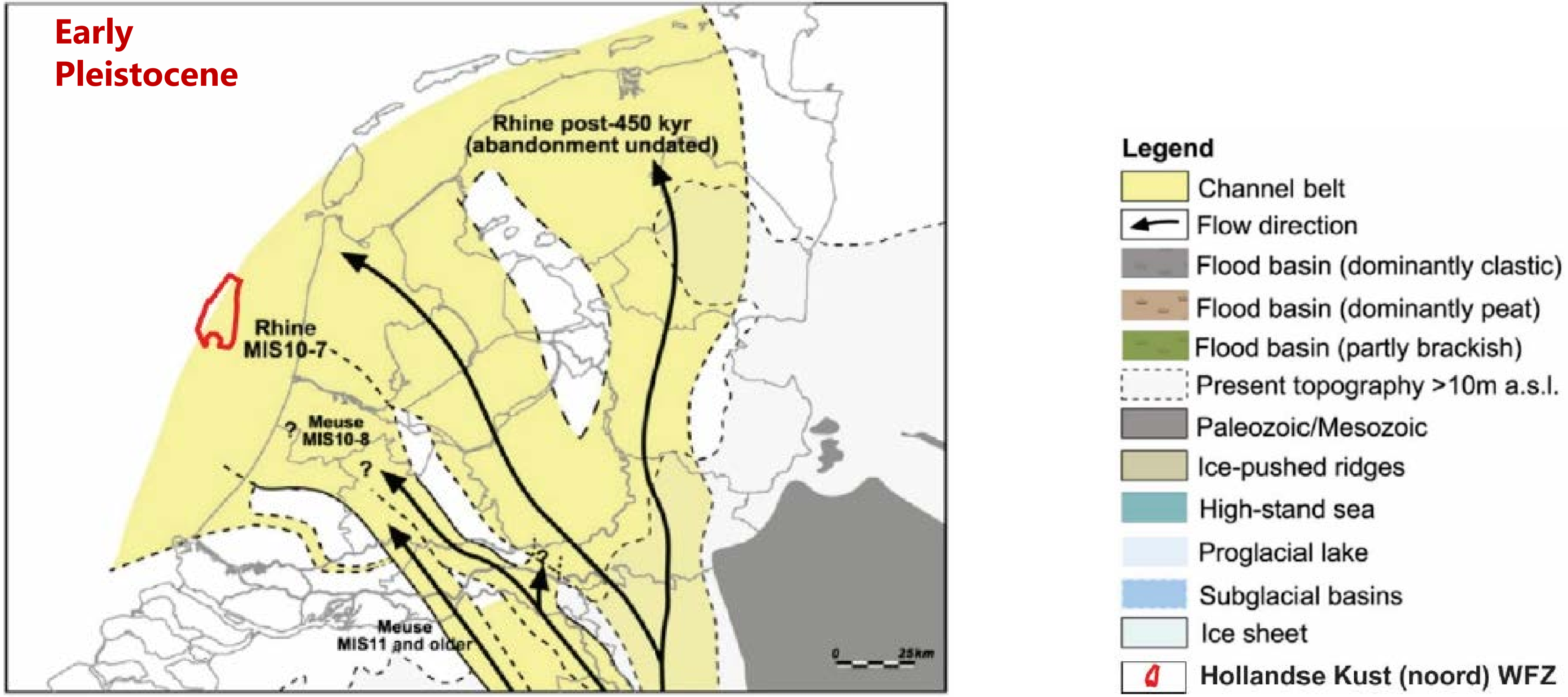
GGM – Geological Setting

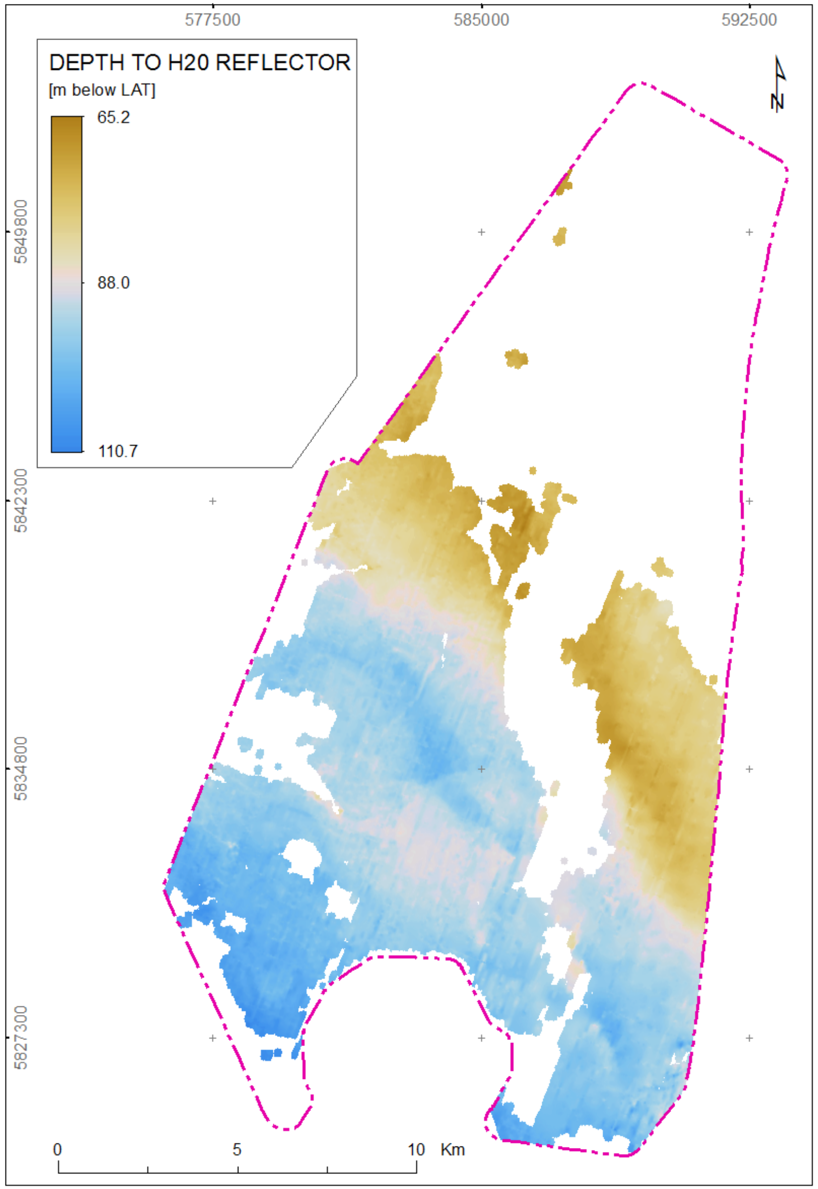


GGM – Geological Setting



GGM – Soil Unit D

- Distribution: present across the entire site; prominent internal reflector H20 dipping northwards was identified in the southern part
- Thickness: the base is below 100 m BSF (beyond the limit of geological ground model)
- Lithology: medium dense to very dense (silty) fine to medium SAND and high strength CLAY with laminae of sand
- Interpretation: fluvial to fluvio-deltaic setting, Early to Middle Pleistocene, Yarmouth Roads Formation, at top locally Urk and/or Egmond Ground Formations



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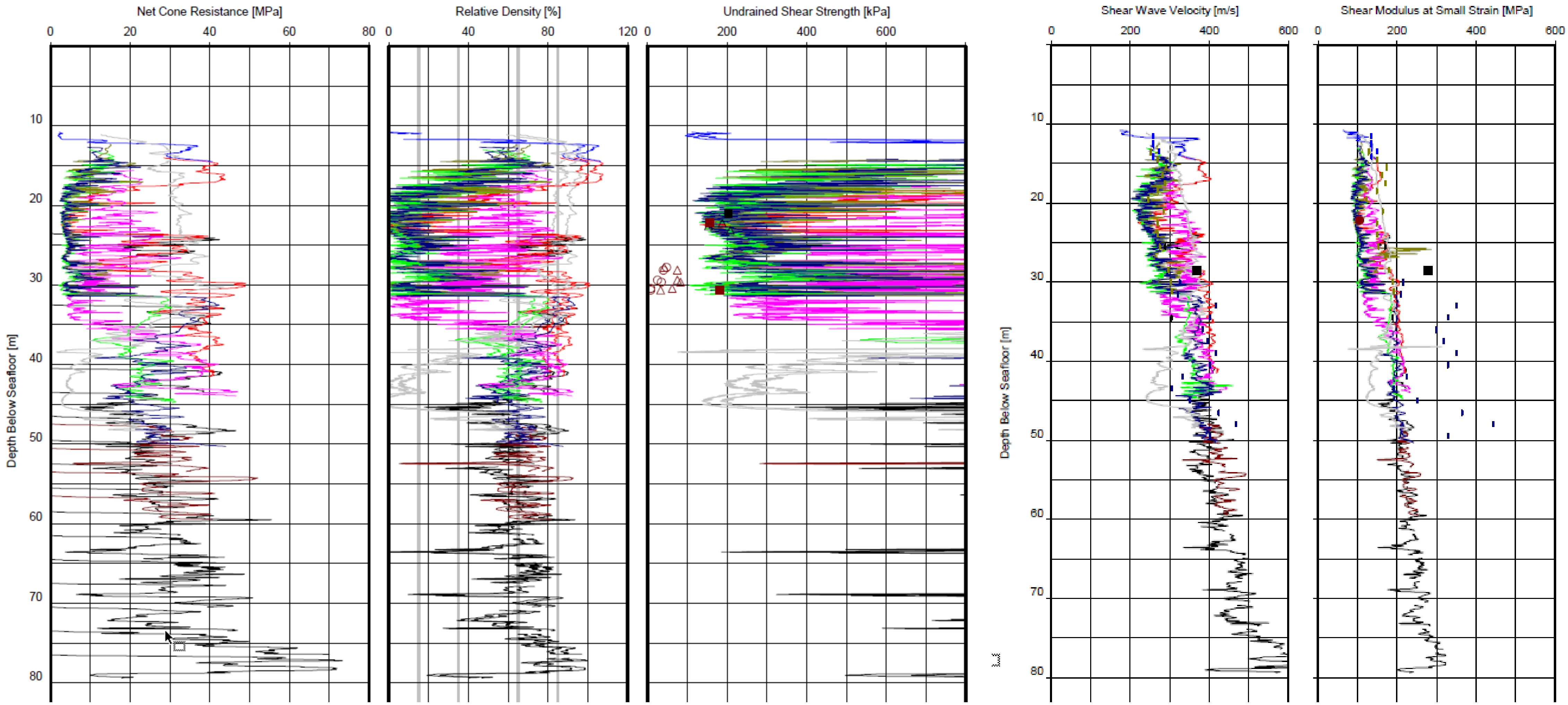
GGM – Soil Unit D – Data Example



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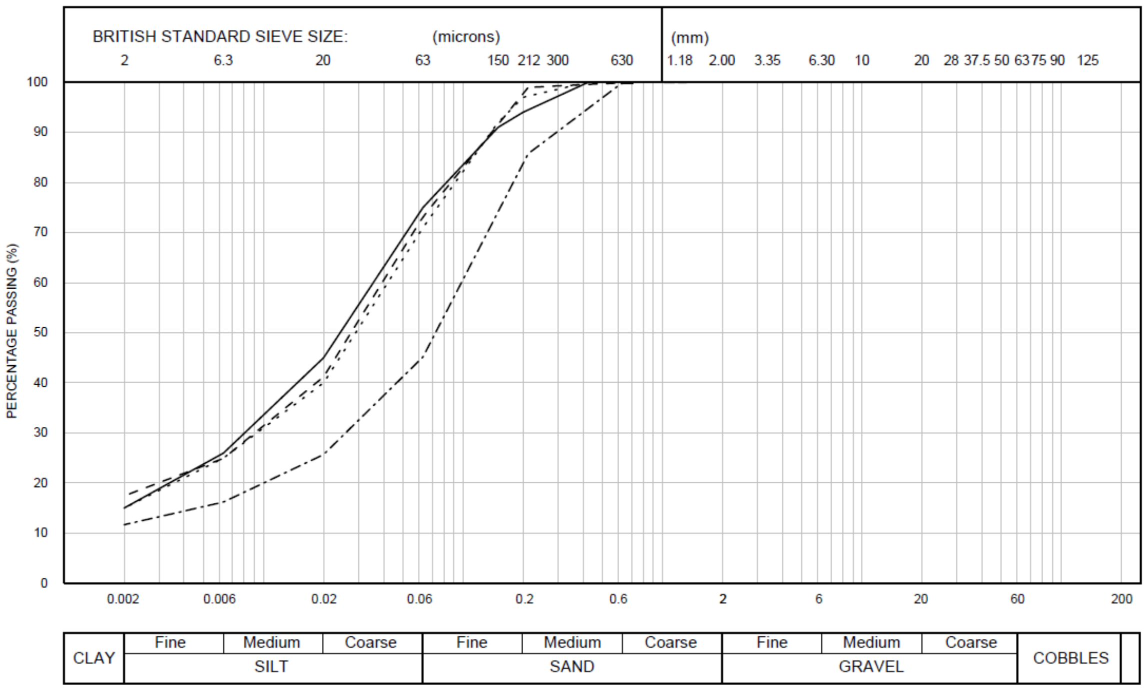
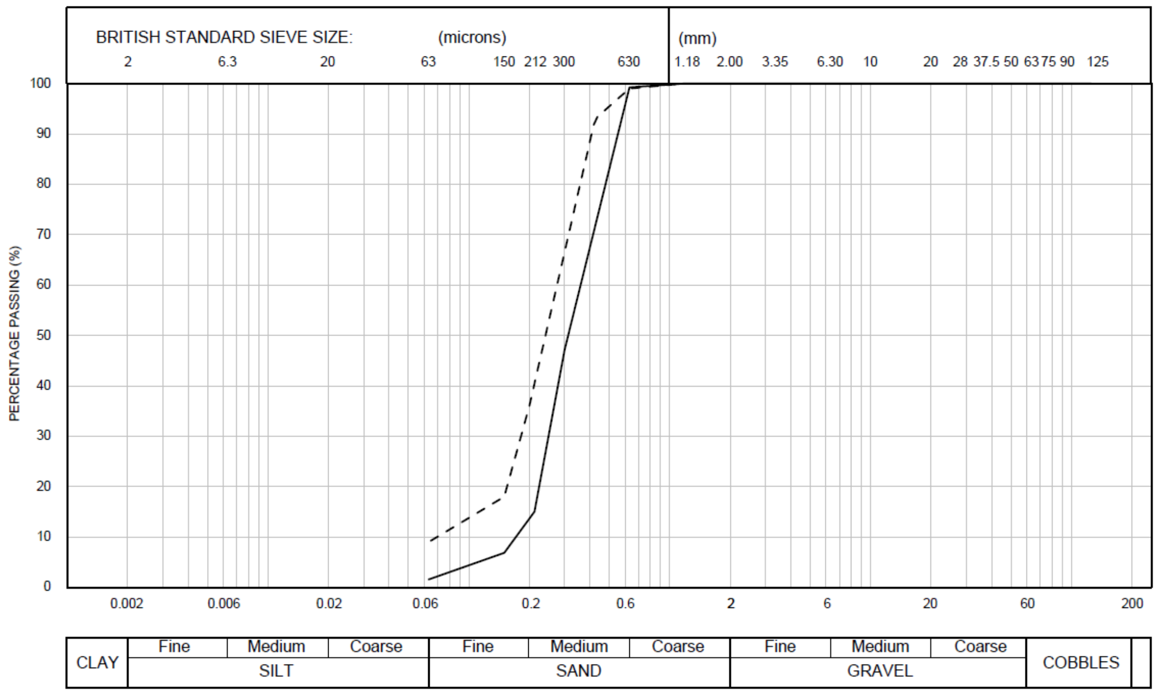
GGM – Soil Unit D – Data Example



Curve	Borehole	Sample	Depth (m)	BS Test * Method	Pretreatment Method	Percentage soil types: Clay	Silt†	Sand	Gravel	Cobbles
	HKN06-BH-SA	30BagA	45.00	9.2/9.4	N/A	15	57	28	0	0
	HKN06-BH-SA	32BagC	47.60	9.4	N/A	17	53	30	0	0
	HKN06-BH-SA	33BagB	50.30	9.2/9.4	N/A	15	53	32	0	0
	HKN06-BH-SA	34BagB	52.80	9.4	N/A	12	32	56	0	0

* Tested in accordance with the following clauses of BS 1377: Part 2: 1990:	
9.2	Wet sieve
9.3	Dry sieve
9.4	Sedimentation by pipette
9.5	Sedimentation by hydrometer

† Note: Where a sedimentation test was not carried out, this figure represents total fines, i.e., particles of diameter less than 63 microns



Curve	Borehole	Sample	Depth (m)	BS Test * Method	Pretreatment Method	Percentage soil types: Clay	Silt†	Sand	Gravel	Cobbles
	HKN06-BH-SA	35BagB	54.55	9.2	N/A	0	1	99	0	0
	HKN06-BH-SA	36BagC	57.00	9.2	N/A	0	9	91	0	0

* Tested in accordance with the following clauses of BS 1377: Part 2: 1990:	
9.2	Wet sieve
9.3	Dry sieve
9.4	Sedimentation by pipette
9.5	Sedimentation by hydrometer

† Note: Where a sedimentation test was not carried out, this figure represents total fines, i.e., particles of diameter less than 63 microns

GGM – Geological Features

Peat / organic clay accumulation

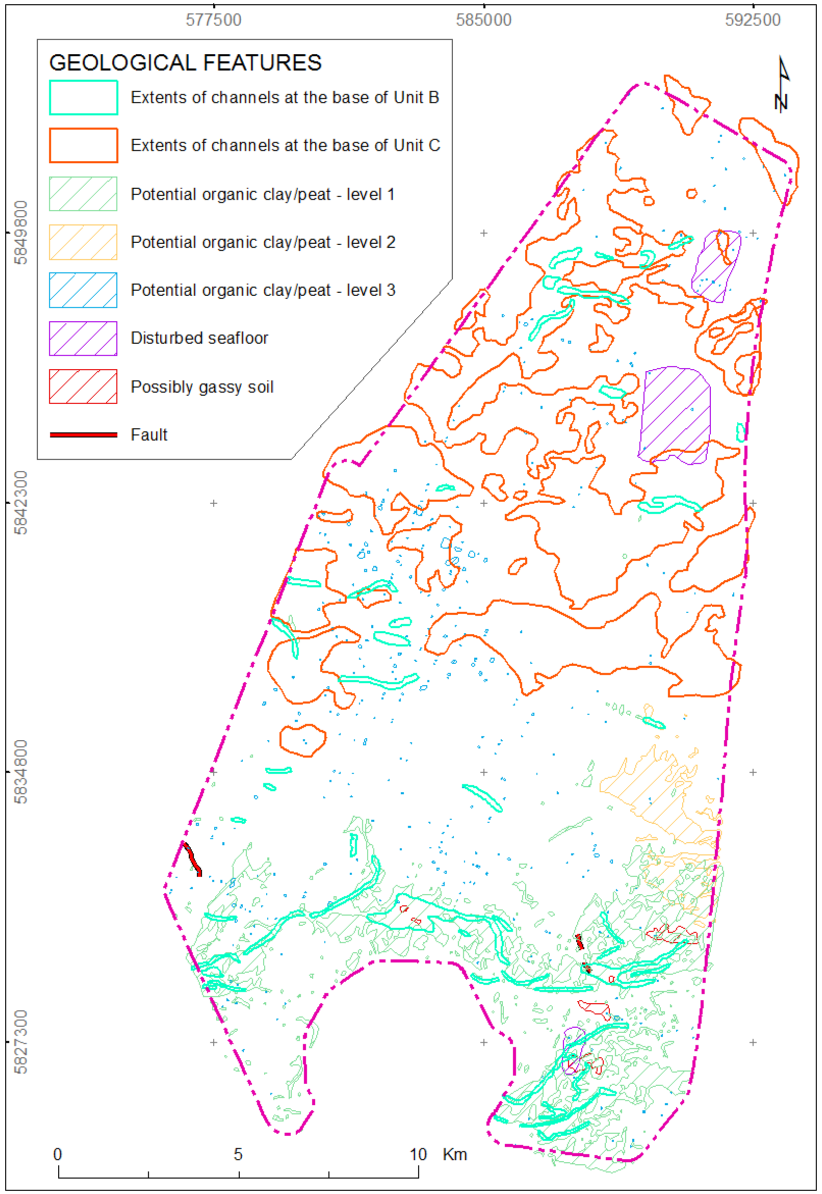
- High-amplitude, reverse polarity reflections
- At various levels below Unit A and occasionally at the base Unit A; limited lateral extent

Buried channels

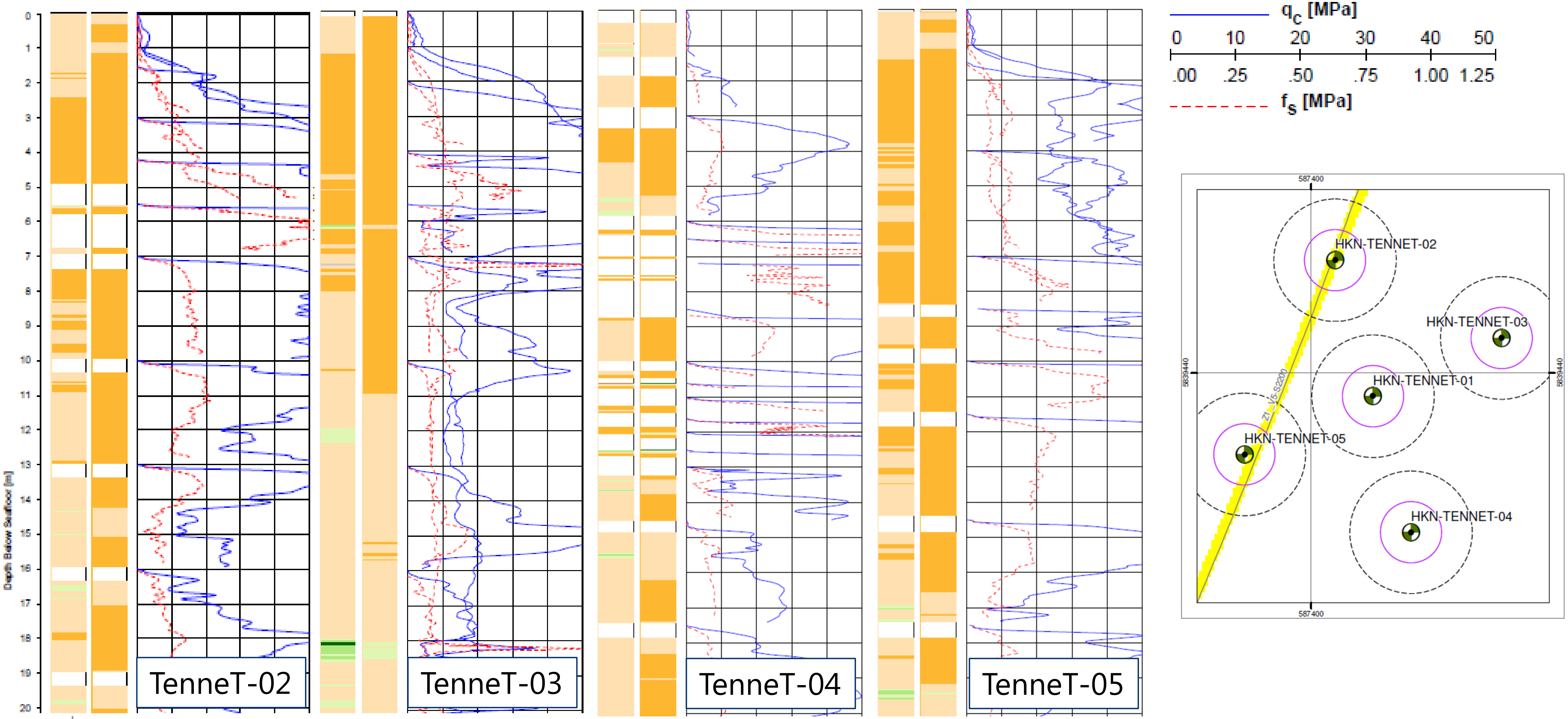
- Two main levels of channeling: at the base of Soil Unit B and the base of Unit C

Glacial deformations

- Possible glacial deformation features observed mainly in Unit D
- Unit D is affected (disturbed and deformed) by a glacier. This obscures distinction between the geological formations, especially on seismic data
- Deformations may more widespread as they are not obvious in predominantly sandy material



GGM – Soil Units – TenneT Location



03

Additional Studies

Site-Specific Hazard Assessment

Geological Feature & Hazard Type	Occurrence Area	Constraints on Structure	PL	JU	GB	SC	CB
Bedforms (sand banks, sand waves and mega ripples) / uneven seafloor	Entire HKN WFZ	▪ JU: uneven seafloor causing high and non-uniform VHM loading on legs	N (N)	L (N)	H (N)	L (N)	L (N)
Sand extraction area(s)	Refer to Section 3 of Main Text	▪ All: potentially disturbed ground compared to areas away from sand extraction area ▪ All: potential interruption in hydraulic flow regime affecting scour and soil deposition processes ▪ All: avoidance may not be practicable; mitigate by design	H (N)	L (N)	H (N)	H (N)	L (N)
Alternation of sand and clay	Infill of paleo-channels (Unit B and parts of Unit C and D)	▪ JU: possibility of leg punch-through followed by jack-up instability ▪ SC: installation might not be feasible	N (N)	L (N)	N (N)	L (N)	N (N)

Key:
PL=Pile Foundation / JU=Jack-up Platform / GB=Gravity Base Foundations / SC=Suction Caisson Foundation / CB=Cables
- Letter indicated hazard probability rating; **H = high / L = low / N = Negligible**
- Hazard probability rating in bracket considers application of relevant mitigation measures

Site-Specific Hazard Assessment

Pile Foundations:

- Pile foundation are assessed feasible;
- The assessment considers monopiles, jacket piles and piles for tripod support structures installed by impact driving;
- Where applicable, driven pile installation should be sufficiently robust for penetration of very dense sand layers and/or concentrations of gravels and cobbles in the seabed.

Jack-up Platforms:

- Use of jack-up platforms for temporary works is assessed feasible;
- Particularly, scour and soil deposition around spudcans should be allowed for.

Microbiologically Influenced Corrosion (MIC) – General

- Microbiologically influenced corrosion (MIC) is caused by the presence and activities of micro-organisms, including bacteria, archaea, and fungi;
- Extent of MIC depends on environmental setting, soil type(s), micro-organisms and the material exposed to corrosion;
- HKN scope:
  - recommendations for MIC of steel foundations embedded in marine soil at the HKN WFZ
  - intended as input for assessment of environmental action(s) for durability limit states
  - Integrated approach including:
    - review of standards, codes of practice and general public domain information;
    - assessment of general site setting, including laboratory test results;
    - review of a site-specific correlation for corrosion rates;
    - selection of values for corrosion rates, including expert review by specialists of Delft University of Technology and Deltares.

MIC – Laboratory Analyses

- Test programme covered 22 samples from 5 boreholes:
  - Endures: determination of counts of MIC-relevant micro-organisms using (1) MPN (8 targets), and (2) combination of MPN (3 targets) and qPCR;
  - Dr. Brill + Partner: (1) metabolic activity using microcalorimetry, and (2) DOC;
  - Fugro: classification tests.
- Laboratory test programme generally confirms a benign environmental setting;
- Test results show no evidence for spatial trends, such as borehole location within the HKN WFZ and depth below seafloor;
- Test results provide an indication of a microbial consortium for a sampling point at a specific time. Microbial numbers will change with time. Microbial numbers do not equal microbial rates and/or microbial activity;
- To the knowledge of Fugro, a relationship between microbial numbers and MIC has not been established in published scientific studies.

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MIC – Site-Specific Correlation

- Review of a site-specific correlation between laboratory test results and corrosion rates derived from steel coupons placed in sand of a tidal flat zone near the island of Norderney (Germany), performed by Dr. Brill + Partner;

- Correlation result is a mass loss rate for corrosion with a suggested maximum value of 0.15 mm/year between seafloor and 2 m BSF (mass loss rate = weight loss of exposed steel coupons);

- The indicated depth zone from seafloor to 2 m BSF may be compared to the upper exposure zones of a foundation (i.e. AC-B for the exterior of the foundation and ST-B for the interior).

MIC – Recommended Values

Exterior of Foundation					
Exposure Zone	**Depth [m BSF]**	**Overall Corrosion Rate [mm/year]**		**Concentrated (Pitting) Corrosion Rate [mm/year]**	
		LE	**HE**	**LE**	**HE**
AC-B (active, benign)	0 to 2	0.02	0.12	0.05	0.2
SA-B (semi-active, benign)	2 to 10	0.012	0.02	0.03	0.05
ST-B (static, benign)	< 10	0	0.012	0	0.03
ST-A (static, adverse)	< 10	0.02	0.06	0.3	0.4
Interior of Foundation					
ST-B (static, benign)	0 to 1	0.012	0.12	0.03	0.2
ST-B (static, benign)	< 1	0	0.012	0	0.03
ST-A (static, adverse)	< 0	0.02	0.06	0.3	0.4

Notes:
BSF : below seafloor, which is the upper surface of scour protection for the exterior of the foundation
LE : low estimate
HE : high estimate

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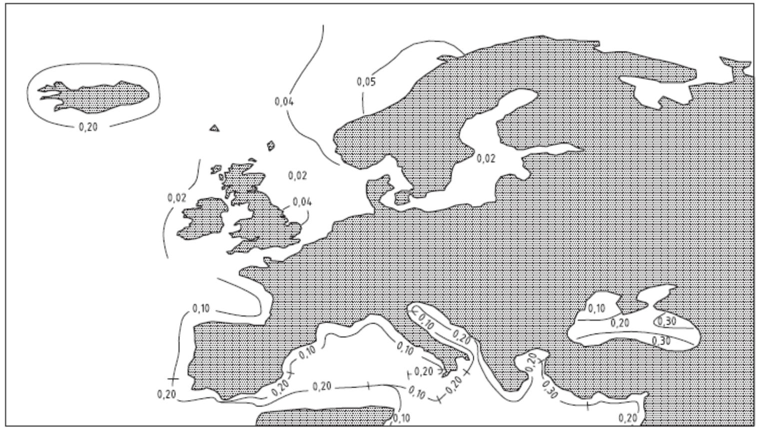
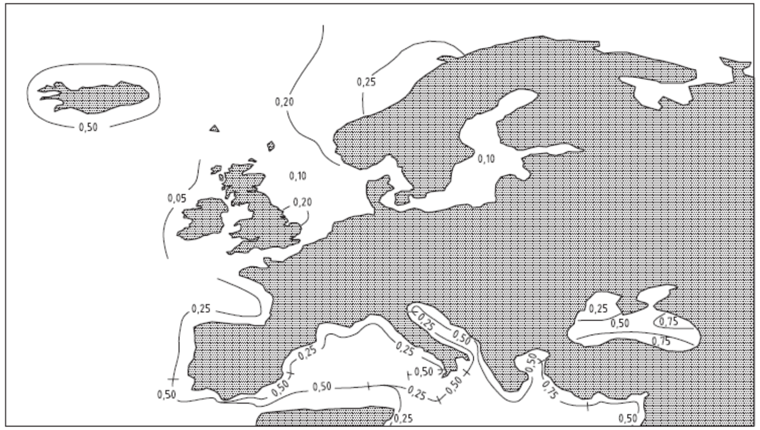
Seismic Hazard Assessment – General



a) 1,0 s oscillator periods



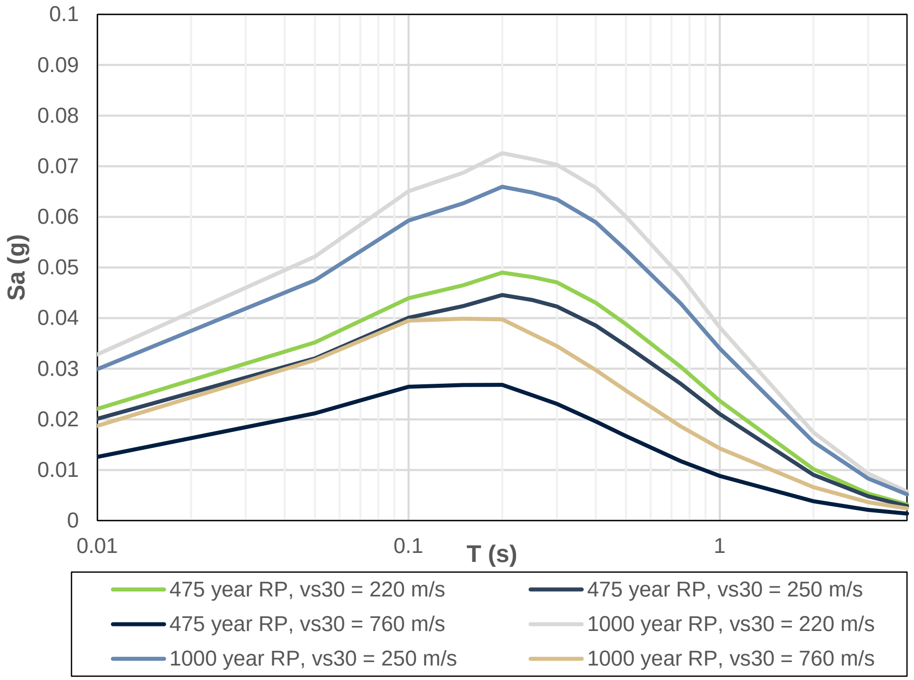
b) 0,2 s oscillator periods

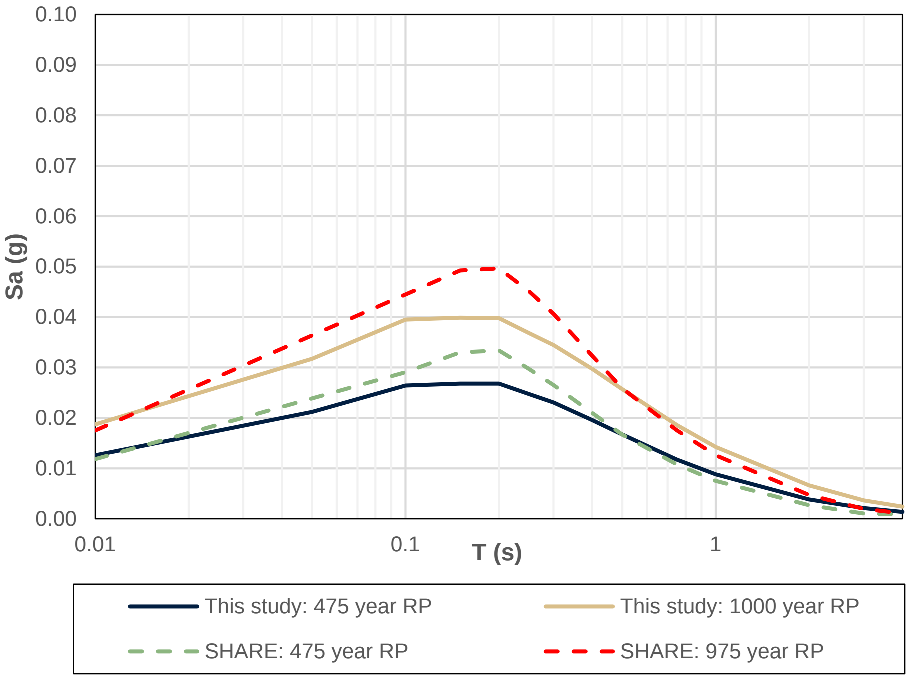
Figure B.8 — 5 % damped spectral response accelerations for offshore Europe

- Performed probabilistic seismic hazard assessment (PSHA) for the HKN WFZ provides a seismic risk setting for design of offshore structures at the site, in accordance with ISO 19901-2 (ISO, 2017) and Eurocode 8 (CEN, 2004);
- Seismic risk setting is presented by means of design horizontal acceleration response spectra for return periods of 475 and 1000 years for typical soil conditions and for bedrock conditions;
- Values for ‘average of representative shear wave velocity in a 30 m effective seabed’ (v_{s30}) of 220 m/s and 250 m/s for soil, and of 760 m/s for bedrock conditions were used. The v_{s30} values are for structures supported on driven piles, considering a 30 m deep effective seabed.

Seismic Hazard Assessment – Results

- Results: Site Class D, with some locations classified as Site Class F; Seismic Zone 0 (ISO, 2017)
- The estimates for ground motions are based on a regional-level PSHA. Results do not necessarily represent location-specific ground motions and do not cover the full range of site conditions applicable to the HKN WFZ.





5 % damped uniform hazard acceleration spectra for return periods of 475 and 1000 year, and for soil conditions (v_{s30} = 220 m/s; 250 m/s) and bedrock conditions (v_{s30} = 760 m/s)

$S_{a,map}$ (1.0) ~ 0.02 g (1000 year return period; v_{s30} = 760 m/s)

$S_{a,PSHA}$ (1.0) ~ 0.014 g (1000 year return period; v_{s30} = 760 m/s)

$S_{a,SHARE}$ (1.0) ~ 0.014 g (975 year return period; v_{s30} = 800 m/s)

Geotechnical Parameter Report (GPR) – RVO objectives

- RVO seeks to reduce design time and risks for wind farm tenderers when preparing their bids for the HKN WFZ;
- RVO intends to provide guidance on selection of characteristic values for geotechnical design of pile foundations with the aim to reduce duplication of efforts and potentially shorten the schedule for tendering and tender evaluation.

Note that different codes use different definitions for “Characteristic Value”, for example:

Eurocode 7 (CEN, 2004) considers “characteristic value”,a value of a material property having a prescribed probability of not being attained in a hypothetical unlimited test series.

DNV GL (2017) considers “characteristic value” a representative value of a load or resistance variable, generally a low but measurable value with a prescribed probability of being favourably exceeded; sub-groups are “mean value”, “lower bound” and “upper bound”.

GPR – Scope Overview

- Geotechnical ground model focusing on monopile foundations;
- Methodology for selecting characteristic values of geotechnical parameters for use in calculation models;
- Indicative ranges for selecting characteristic values, where applicable, including supporting summaries of derived values of geotechnical parameters;
- Conclusions and recommendations, with focus on data gap analysis for geotechnical information;
- Geotechnical ground model applies to the WFS and extends from 2 m BSF to 40 m BSF.

GPR – Definitions

Derived value

A value of a geotechnical parameter obtained by theory, correlation or empiricism from test results.

Indicative value

An initial, preliminary estimate of the in situ value of a specified geotechnical parameter.

Characteristic value

A value of a material property that represents a cautious estimate of the value affecting the occurrence of a limit state.

Note: This report considered “characteristic value” as defined by Eurocode 7 (CEN, 2004).

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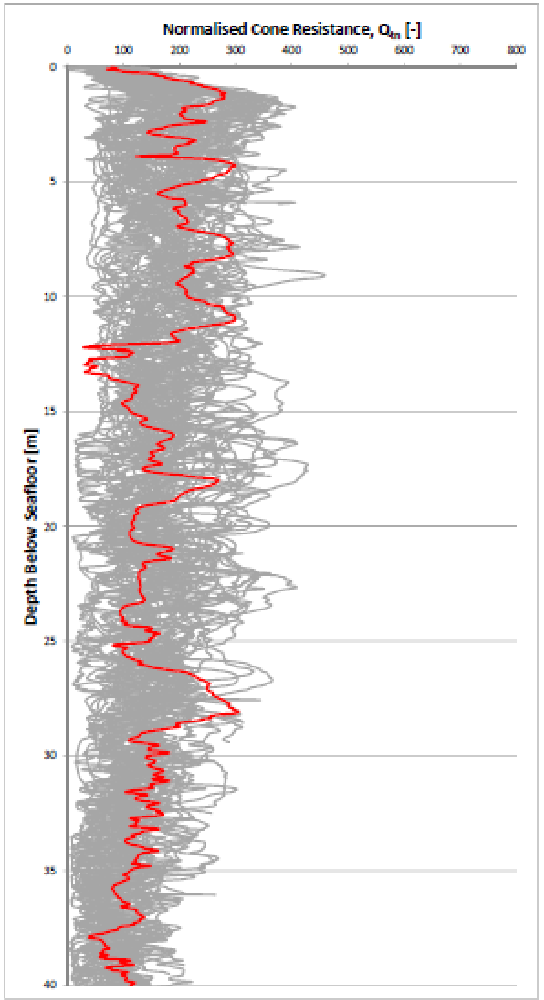
GPR – Parameters Scoping

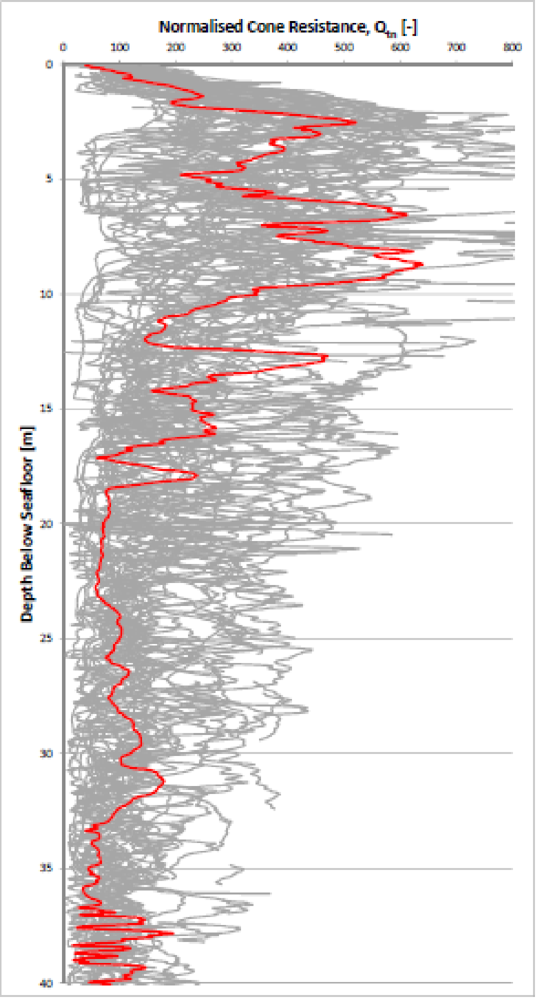
Parameter	Symbol	Sand	Clay
Soil unit weight	γ	√	√
Net cone resistance	q_n	√	√
Coefficient of earth pressure at rest	K_0	√	√
Minimum and maximum index void ratios	e_{min}, e_{max}	√	
Relative density	D_r	√	
Undrained shear strength - triaxial compression	$s_{u,TXC}$		√
Undrained shear strength – direct simple shear	$s_{u,DSS}$		√
External axial strain at half the maximum deviator stress	ε_{50}		√
Critical state line	-	√	
Effective angle of internal friction at large strain	φ'_{cv}	√	
Peak effective angle of internal friction	φ'	√	
Angle of interface friction – steel / soil	δ	√	
Constrained modulus	M		√
Coefficient of permeability	k	√	
Shear modulus at small strain	G_{max}	√	√
Normalised shear modulus	G/G_{max}	√	√
Cyclic strength	-	√	√

GPR – Location Grouping

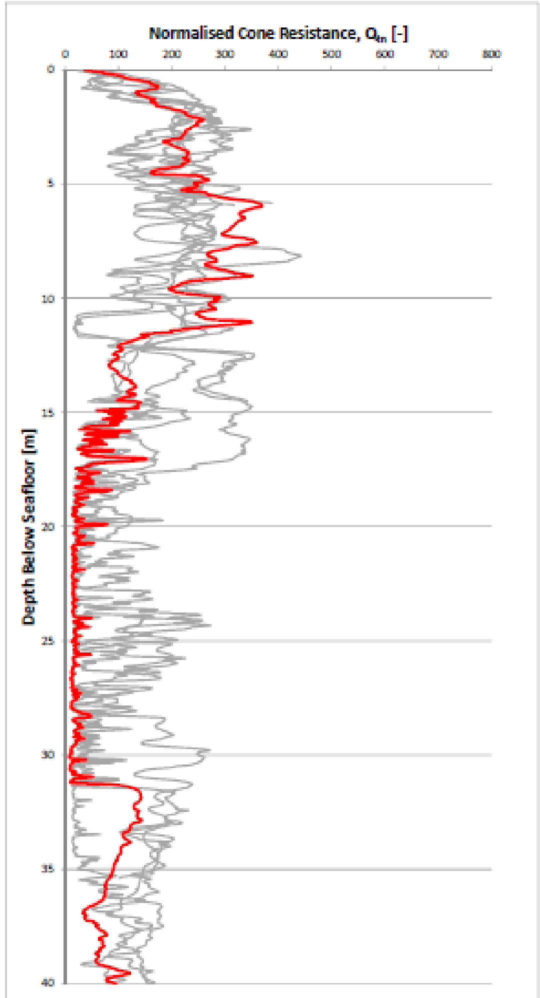
Group G1



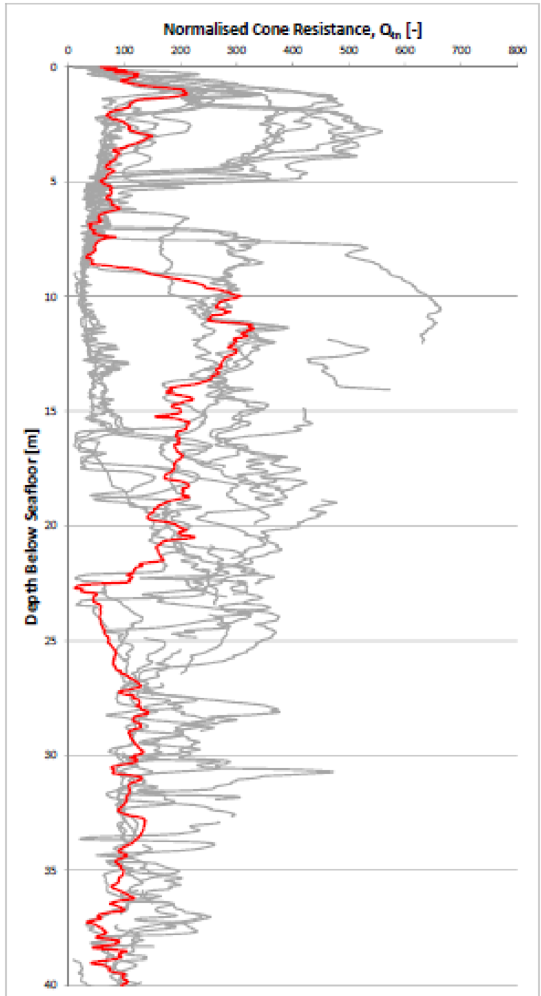
Group G2



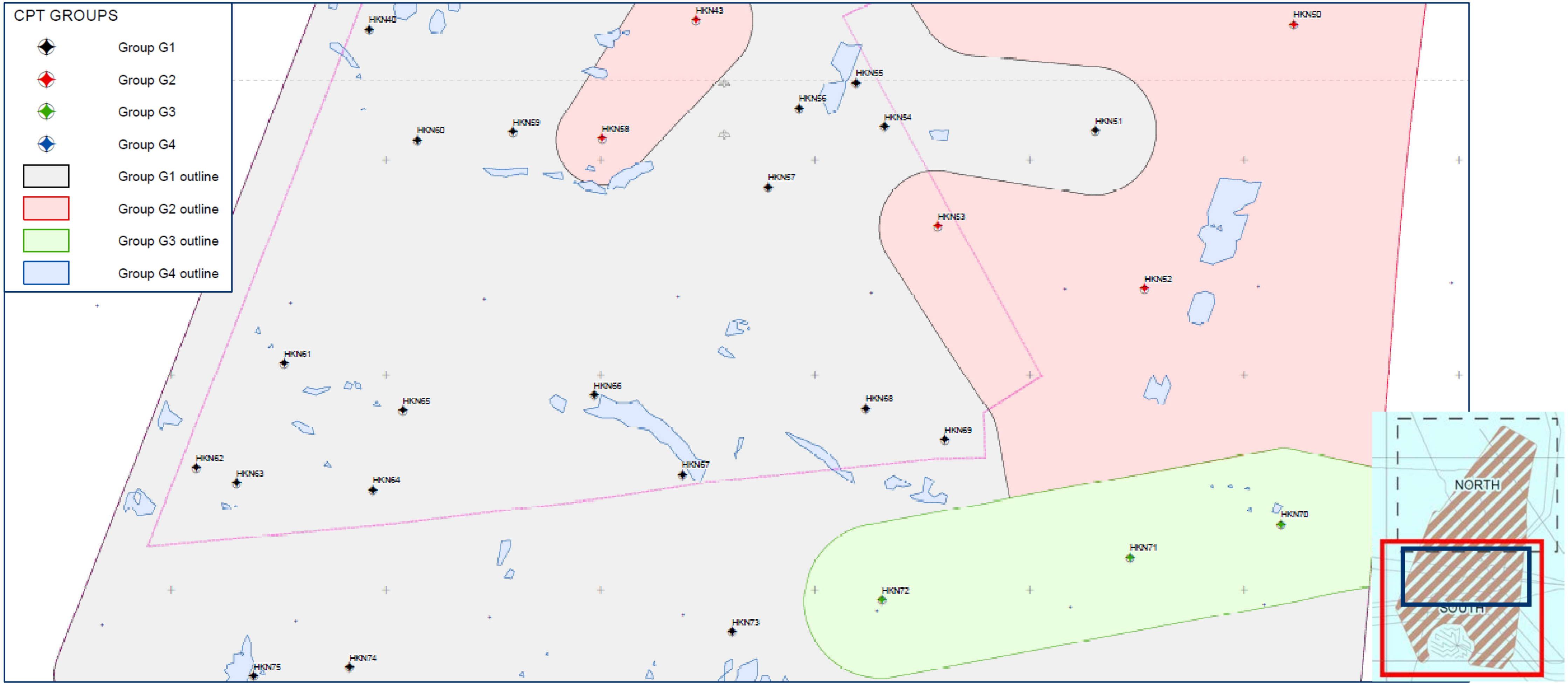
Group G3



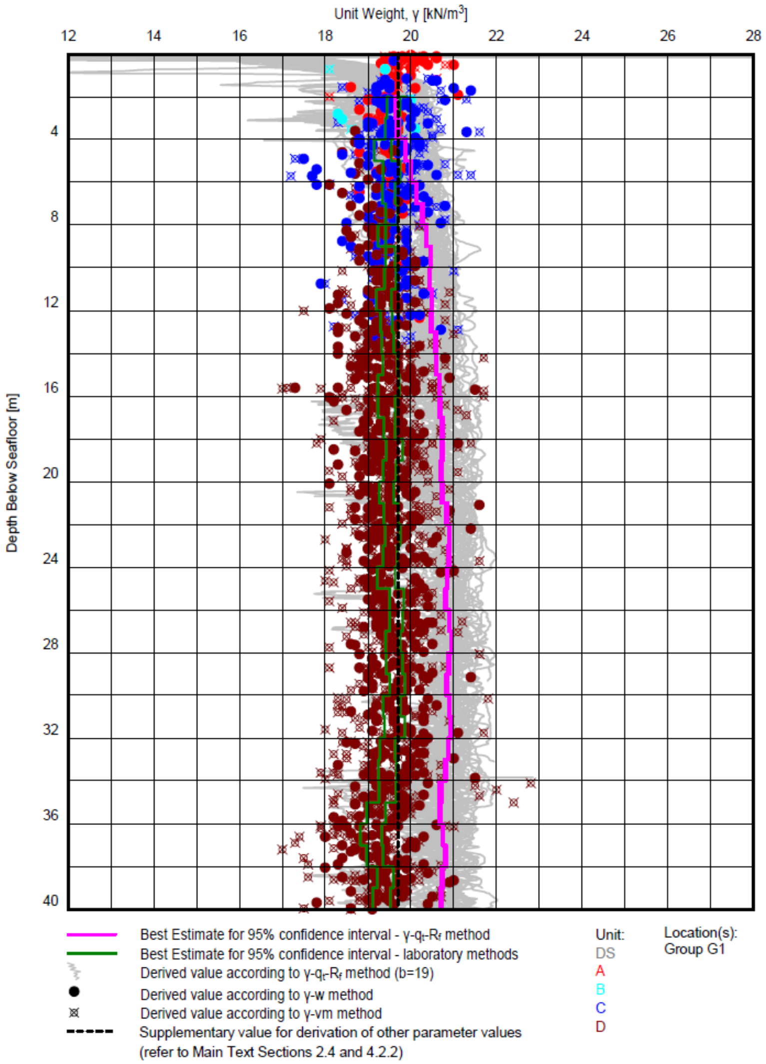
Group G4

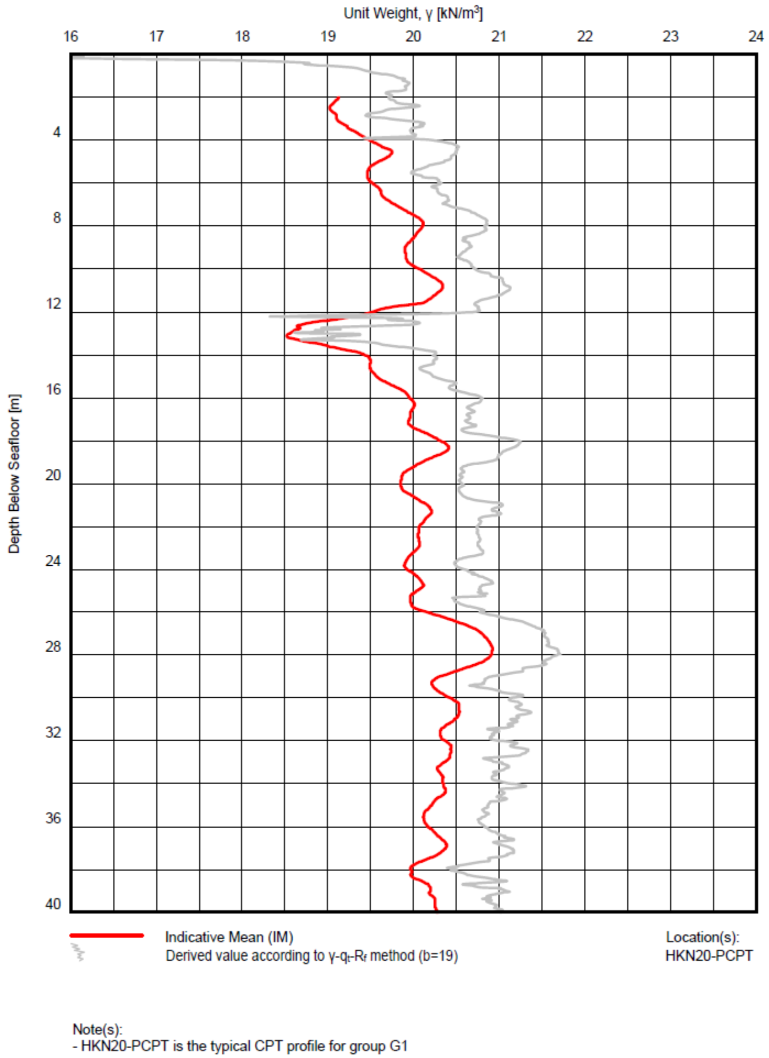


GPR – Location Grouping

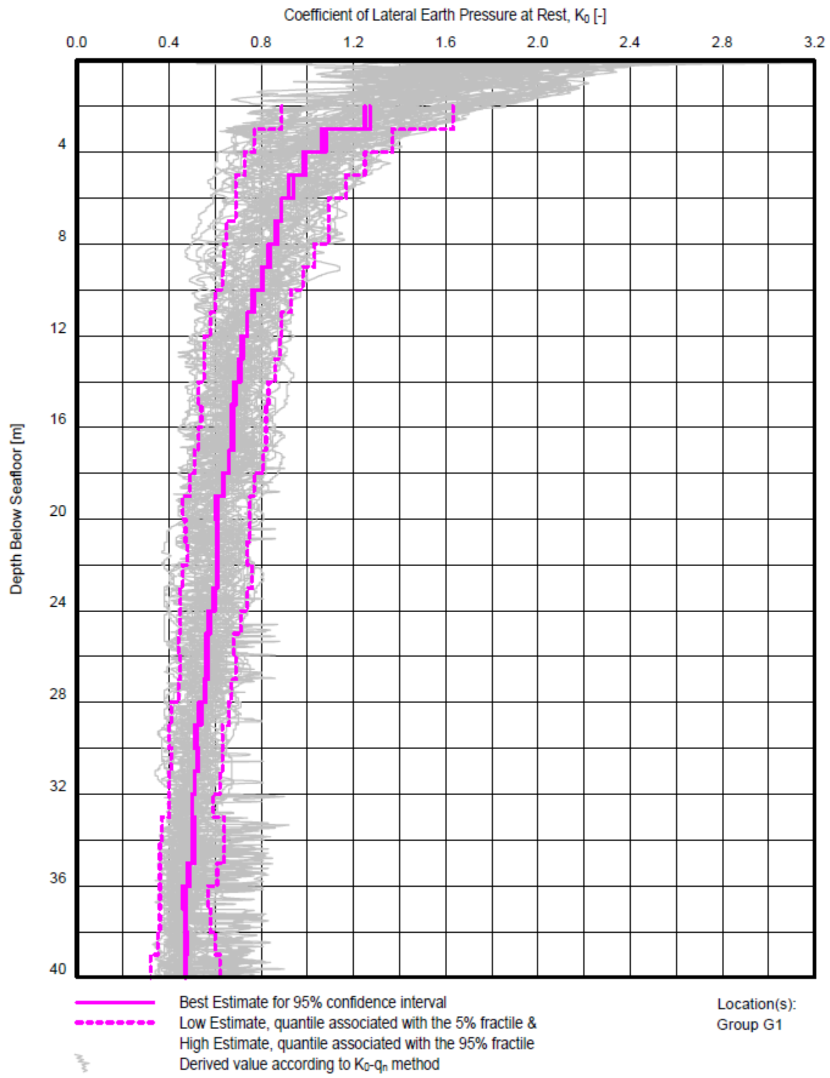


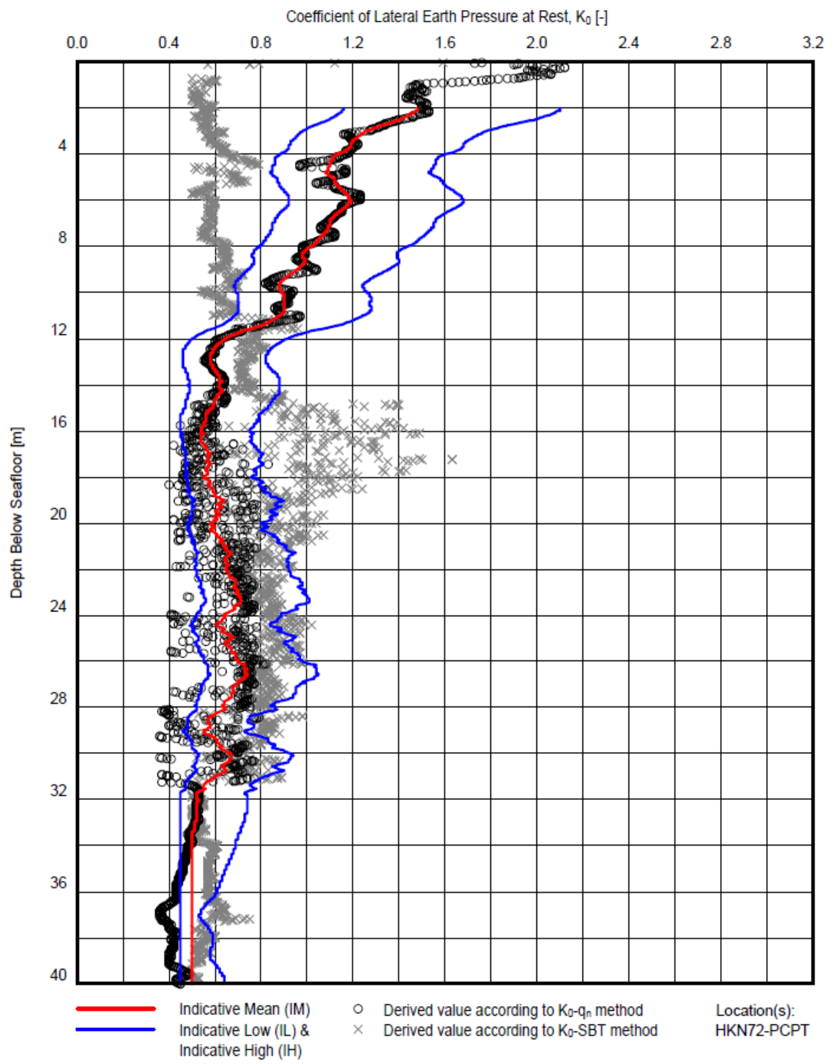
GPR – Soil Unit Weight (γ)



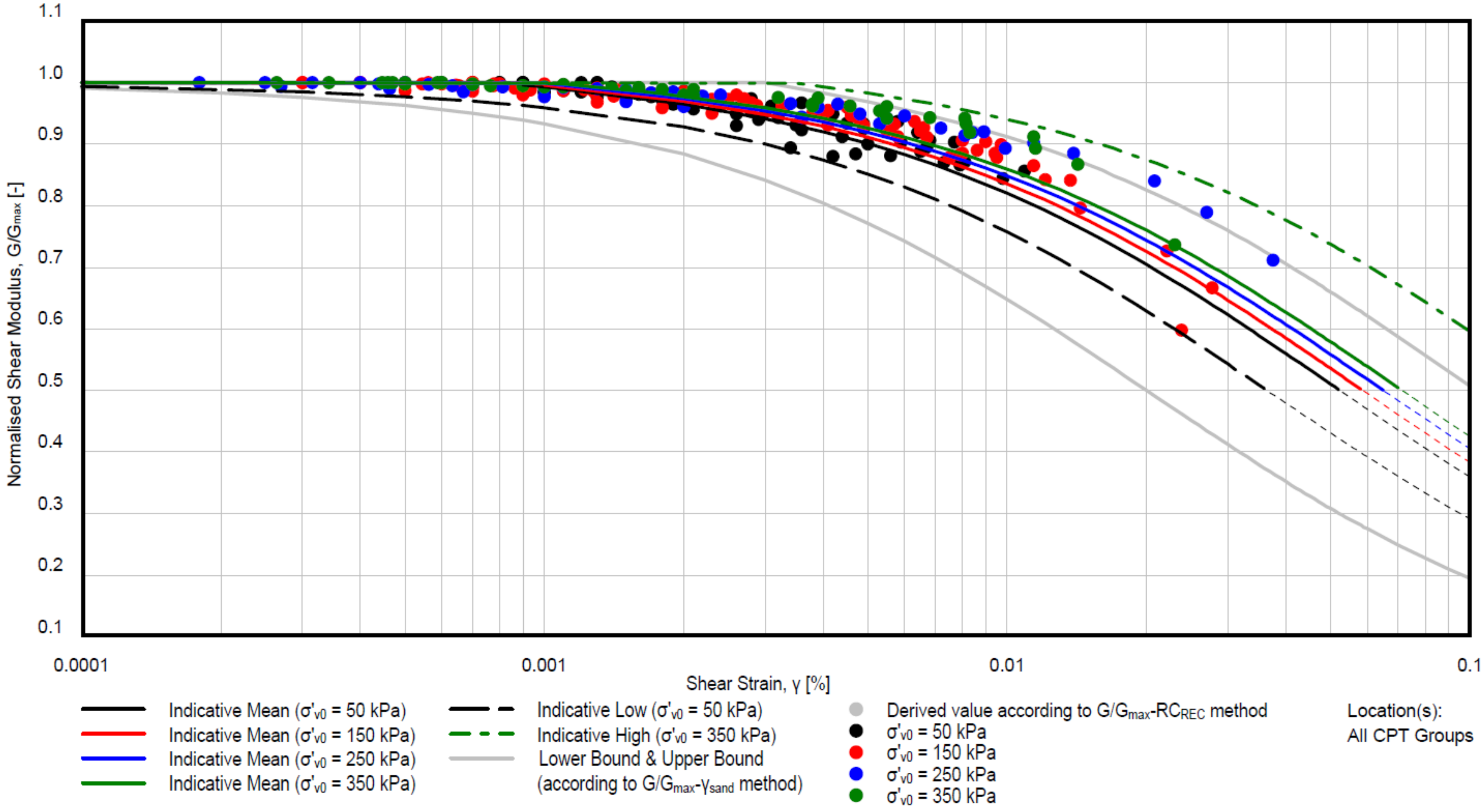


GPR – Coefficient of Lateral Earth Pressure at Rest (K_0)





GPR – Normalised Shear Modulus (G/G_{max}) - Sand



04

Concluding Remarks

Concluding Remarks

- Soil conditions at individual geotechnical locations as well as within soil units between geotechnical locations show predominantly sands, locally clay, sandy clay layers are present;

- The investigation area is characterized by limited lateral correlation of soil properties. Variations in soil conditions are evident from presented geotechnical parameters;

- The available geotechnical and geophysical data align reasonable well. They provide a good basis for the geological ground model.

- Geotechnical assessment of suitability of possible foundation elements indicates that the more commonly used types are feasible, particularly multiple pile and monopile foundations.

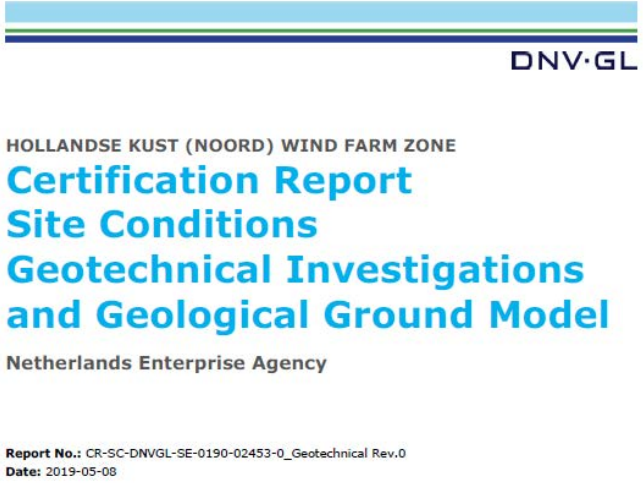
Concluding Remarks

Conclusion DNV GL on the site investigation and deliverables for HKN WFZ:

“The comprehensive geotechnical campaign and the advanced laboratory test program were defined as a joint effort between multiple parties and reviewed by DNV GL with the objective to avoid the need for additional boreholes and reduce the need for additional laboratory tests in later stages of development. With a proper CPT calibration and additional CPTs at planned turbine locations it is likely that additional boreholes may be omitted.”

“The geotechnical investigation reports and the geological ground model can be used to support the (preliminary) design of future offshore wind farms in the project area. The data presented in those reports can be used for establishing a Design Basis”

Ref.: CR-SC-DNVGL-SE-0190-02453-0_Geotechnical (noord)


DNV·GL

HOLLANDSE KUST (NOORD) WIND FARM ZONE

Certification Report
Site Conditions
Geotechnical Investigations and Geological Ground Model

Netherlands Enterprise Agency

Report No.: CR-SC-DNVGL-SE-0190-02453-0_Geotechnical Rev.0
Date: 2019-05-08

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Thank you

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Closing

- Questionnaire
- Lessons learned
- Availability panel
- Communications
  - https://offshorewind.rvo.nl
  - woz@rvo.nl

Thank you very much!