Source: RVO

Hollandse Kust (zuid) WFSI&II – Geotechnical Site Investigation

Webinar, 24 January 2017, Martijn Klein (Fugro)

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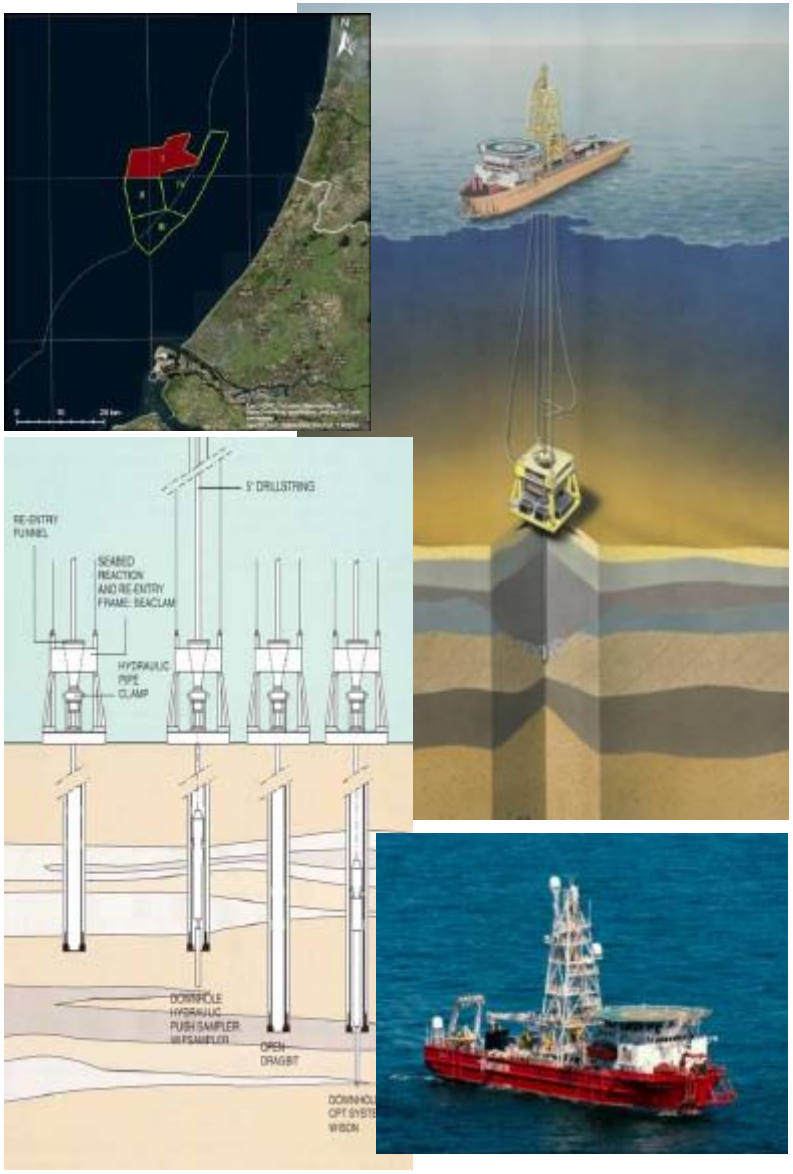
Geotechnical Site Investigation – Overview

Purpose of the Geotechnical Site Investigation:

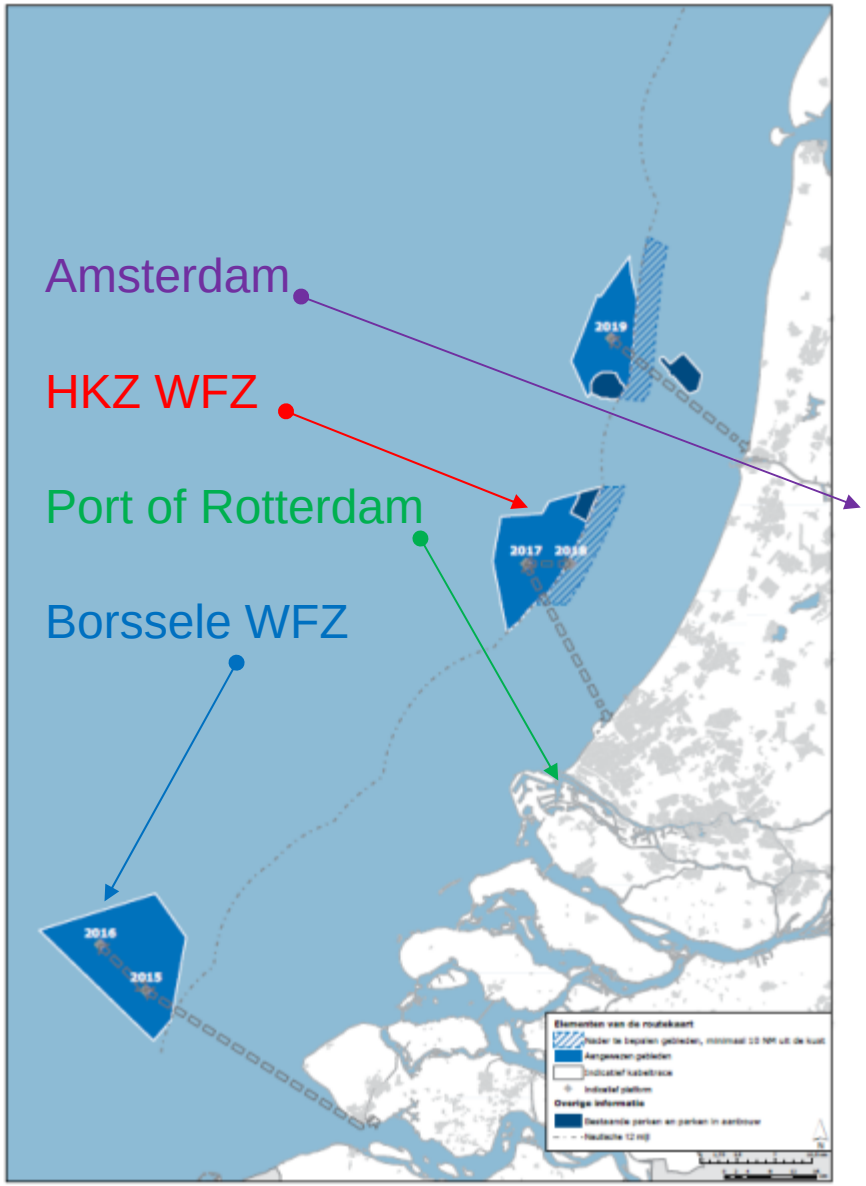
- Further develop geological/geophysical model for HKZ
- Determine vertical and lateral variation in seabed conditions
- Provide relevant geotechnical data for design, including but not limited to foundations and cables
- Update geological desk study and provide geological model
- No need for further (sampling) boreholes in future SI

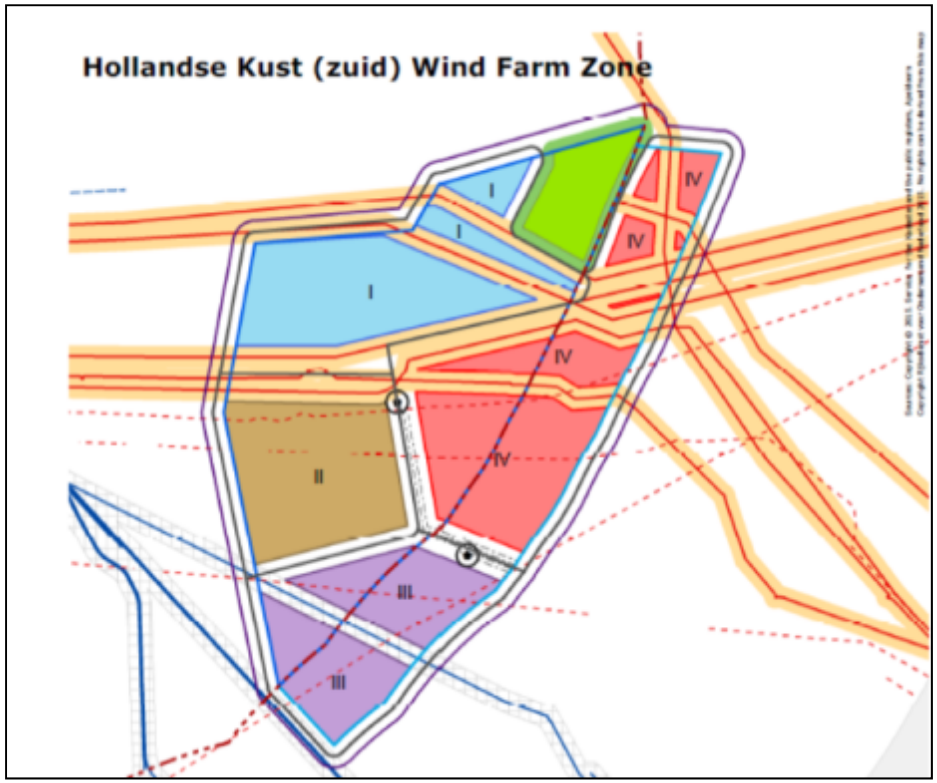
Overview of Geotechnical Site Investigation:

- According to ISO 19901-8 (2014) Marine Soil Investigations
- Fieldwork campaign from 16 June to 17 July 2016 using the geotechnical drilling vessel Bucentaur
- Geotechnical borehole drilling, downhole sampling, downhole in situ testing and seafloor in situ testing
- In-office laboratory test programme completed, including advanced static and cyclic test programme
- Investigation Data and Geological Ground Model Reports submitted as final to RVO and certified by DNV



Geotechnical Site Investigation – Overview Site Area





Nautical 12 mile
Designated windfarm zone
Additional zone

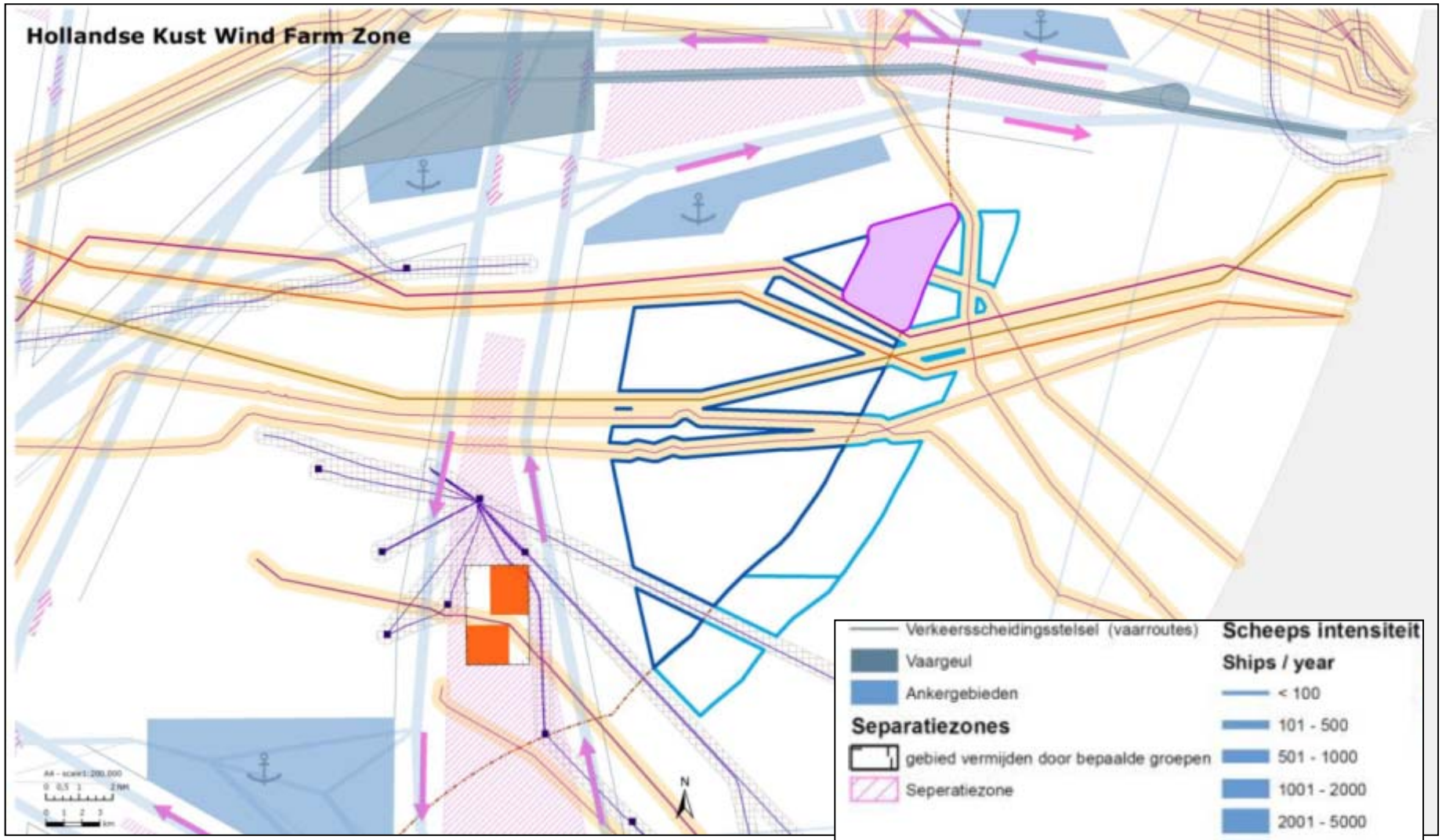
Wind farm sites

I
II
III
IV

Platform
Wind farm Luchterduinen
Wind farm safety zone
Export cable
Cables
Pipelines
Pipeline maintenance zone (500m)
Cable maintenance zone (500m)

Sources:
"Offshore wind energy in the Netherlands" and "RVO_basiskaart", www.rvo.nl.
note verification recommended, presented figure may have been updated.

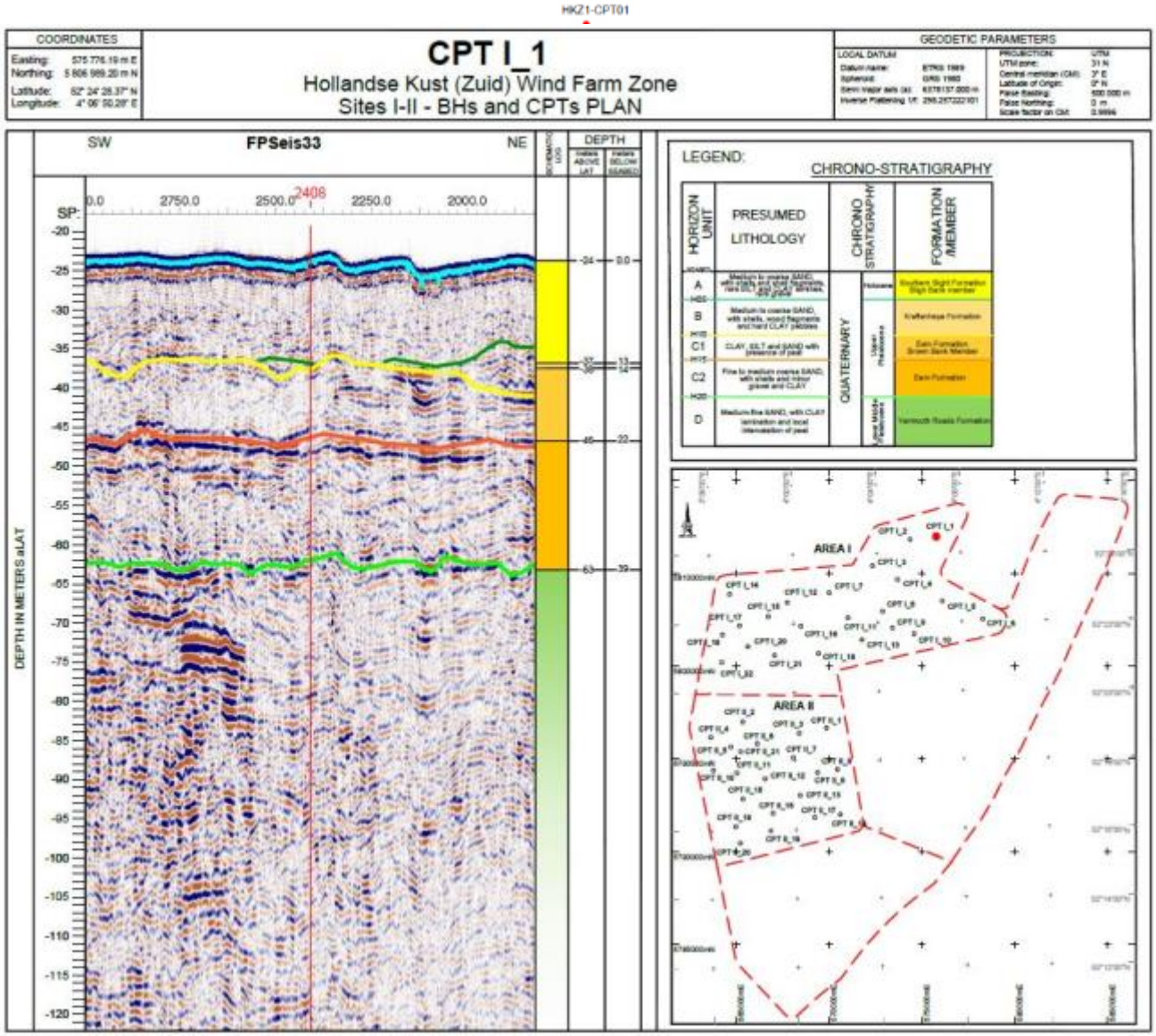
Geotechnical Site Investigation – Overview Site Area



Sources: SOW geotechnical survey HKZ - "Starting points & Assumptions – Part 1 General", note verification recommended, presented figure may have been updated.

Geotechnical Site Investigation – Investigation Strategy

Geophysical data



Geotechnical Site Investigation – Investigation Strategy

Geophysical data

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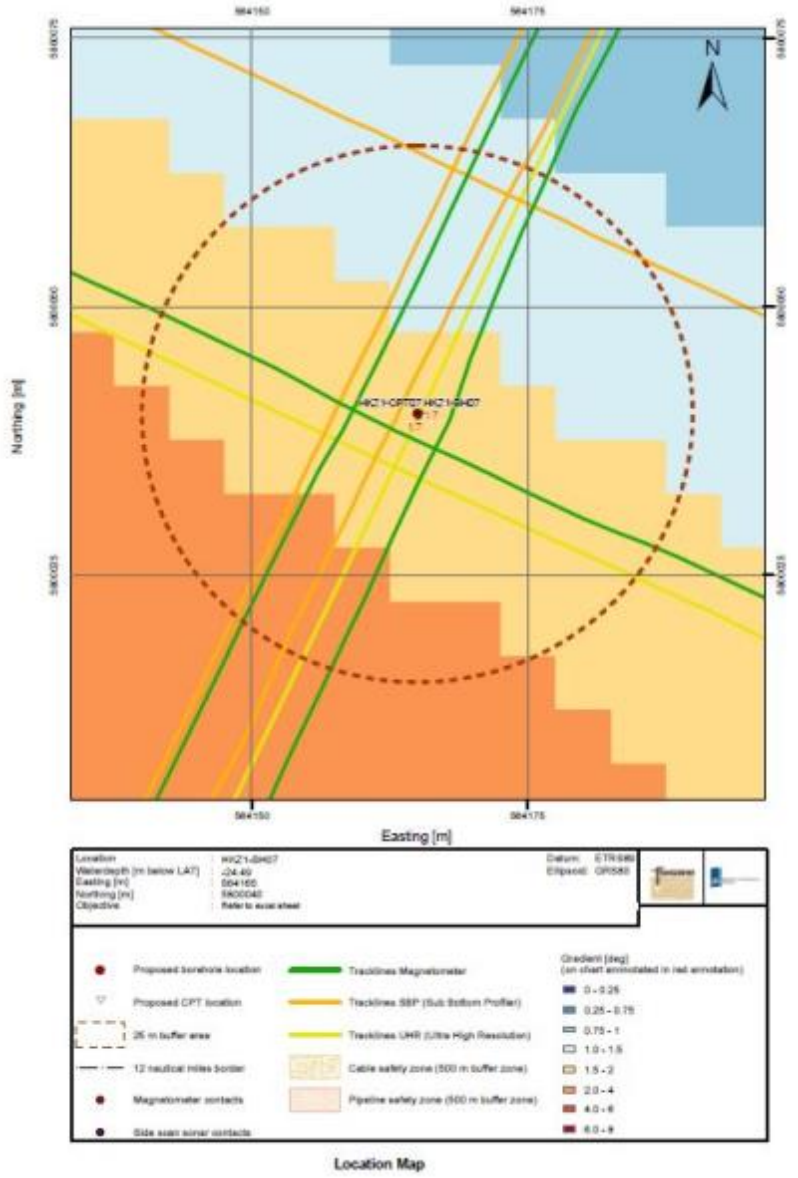
Perform Seafloor CPT



Geotechnical Site Investigation – Investigation Strategy

Geophysical data

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Perform Seafloor CPT

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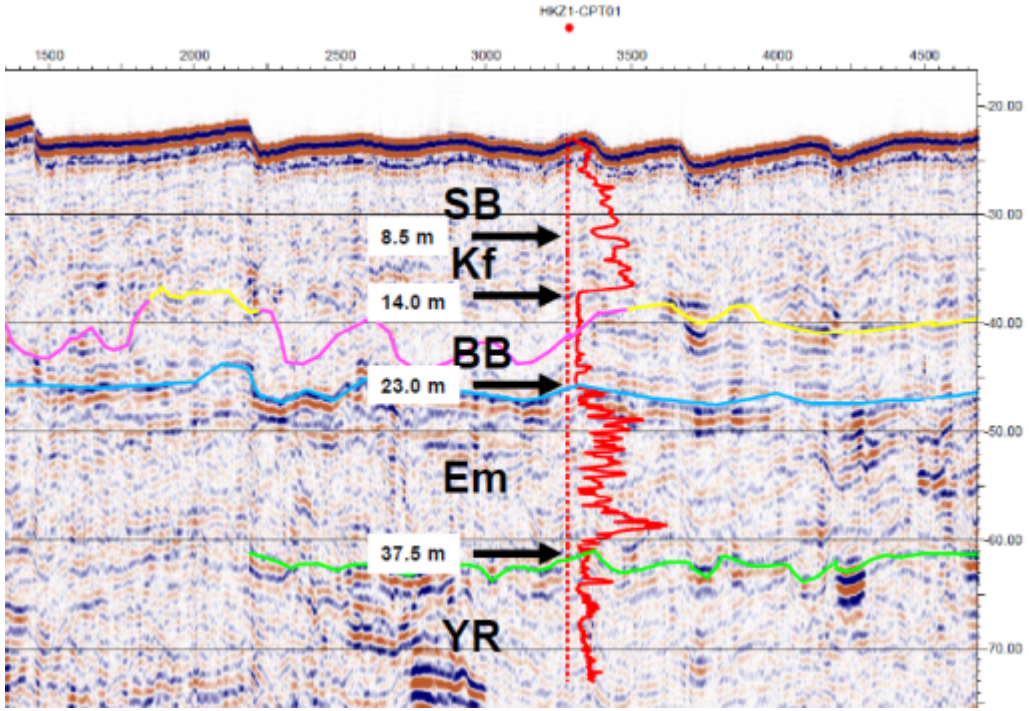
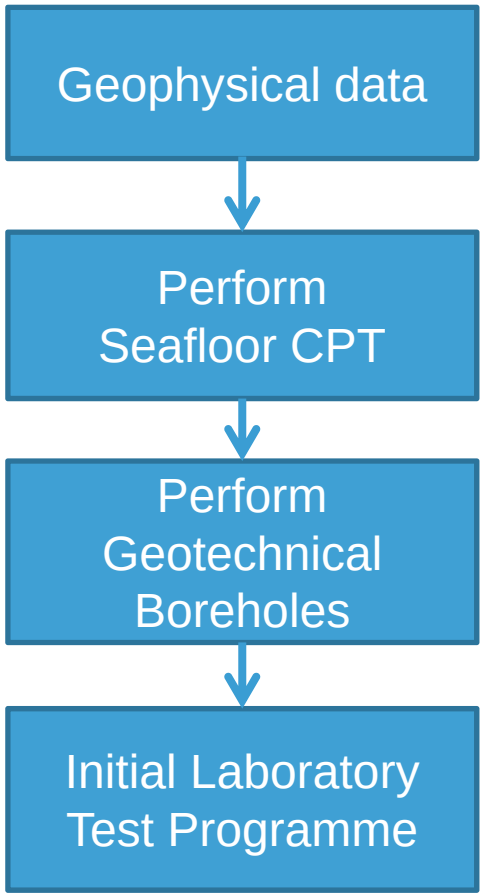
Perform Geotechnical Boreholes



Project Location Name	Associated BH/CPT	Target depth [m BSF]	Easting	Northing	Objective
BH_I_1	CPT_I_1	50	575778	5806994	Check of the stratigraphy, presence of Brown Bank Mb
BH_I_2	CPT_I_7	50	570022	5803948	Possible presence of Brown Bank Mb
BH_I_3	CPT_I_13	50	571790	5801420	Check stratigraphy, channel infill within Kreftenheye Fm
BH_I_4	CPT_I_14	50	564654	5803865	Stratigraphy info, internal reflector within Eem Fm
BH_I_5	CPT_I_17	50	565188	5802181	Check complete stratigraphy
BH_I_6	CPT_I_19	50	564265	5801665	Possible presence of GRAVEL within Eem Fm
BH_I_7	CPT_I_22	50	564236	5800194	Check stratigraphy of the southern part of the survey area, top Yarmouth Roads Fm missing
BH_I_8	CPT_I_16	50	568484	5802149	Check stratigraphy of the central part of the survey area
CPT_I_1	BH_I_1	50	575776	5806989	Assess geotechnical properties of the shallow deposits, in particular of Brown Bank Mb
CPT_I_2		50	574378	5806826	Assess geotechnical properties, presence of top Yarmouth Roads and Eem Fms
CPT_I_3		50	572360	5805398	Assess geotechnical properties within the top of Brown Bank Mb, lateral surfaces
CPT_I_4		50	573688	5804663	Assess geotechnical properties presence of Brown Bank Mb and possible base of Eem Fm
CPT_I_5	BH_I_5	50	576105	5803513	Assess geotechnical properties, presence of Brown Bank Mb and possible base of Eem Fm
CPT_I_6		50	578289	5802543	Assess geotechnical properties, top Yarmouth Roads Fm missing

Geotechnical Site Investigation – Investigation Strategy



Sample Information							Test Schedule									
Sample Location	Area	Sub-sample ID	Sub-sample Depth (top of sample)	Length [cm]	Main soil type	Geological Unit	Unconsolidated Undrained (UU) Triaxial Test (undisturbed)	Unconsolidated Undrained (UU) Triaxial Test (remoulded)	Particle Density (cohesionless)	Particle Density (cohesive)	Sieving	Sieving and hydrometer	Atterberg limits	Carbonate content	Organic content (dichromate oxidation)
							UU	UU	PD	PD	PS	PS	AT	CC	OC
HKZ2-BH01-SA	WFS2	20BagB	14.80	25.00	SAND	B1									
HKZ2-BH01-SA	WFS2	21BagA	15.50	30.00	SAND	B1									
HKZ2-BH01-SA	WFS2	21BagB	15.80	25.00	SAND	B1									
HKZ2-BH01-SA	WFS2	22BagA	16.50	30.00	SAND	B1									
HKZ2-BH01-SA	WFS2	22BagB	16.80	25.00	SAND	B1					c				
HKZ2-BH01-SA	WFS2	23BagA	17.50	30.00	SAND	B1									
HKZ2-BH01-SA	WFS2	23BagB	17.80	20.00	SAND	B1									
HKZ2-BH01-SA	WFS2	24BagA	18.50	20.00	SAND	B1									
HKZ2-BH01-SA	WFS2	24BagB	18.70	20.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	24WaxC	18.90	20.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	24BagD	19.10	25.00	CLAY	C2					c		c		
HKZ2-BH01-SA	WFS2	25BagA	19.50	15.00	CLAY	C2								c	c
HKZ2-BH01-SA	WFS2	25BagB	19.65	35.00	SAND	C2									
HKZ2-BH01-SA	WFS2	25BagC	20.00	30.00	SAND	C2									
HKZ2-BH01-SA	WFS2	26BagA	20.50	20.00	SAND	C2					c				
HKZ2-BH01-SA	WFS2	26BagB	20.70	20.00	SAND	C2									
HKZ2-BH01-SA	WFS2	26BagC	20.90	25.00	SAND	C2									
HKZ2-BH01-SA	WFS2	27BagA	21.50	20.00	SAND	C2									
HKZ2-BH01-SA	WFS2	27BagB	21.70	25.00	SAND	C2									
HKZ2-BH01-SA	WFS2	27BagC	21.95	40.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	28BagA	22.50	20.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	28BagB	22.70	20.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	28BagC	22.90	20.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	28BagD	23.10	25.00	CLAY	C2			c		c		c		
HKZ2-BH01-SA	WFS2	29BagA	23.50	5.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	29BagB	23.55	25.00	SAND	C2									
HKZ2-BH01-SA	WFS2	29BagC	23.80	50.00	SAND	C2									
HKZ2-BH01-SA	WFS2	30BagA	24.50	30.00	SAND	C2					c				
HKZ2-BH01-SA	WFS2	30BagB	24.80	20.00	SAND	C2									
HKZ2-BH01-SA	WFS2	31BagA	25.50	30.00	SAND	C2									
HKZ2-BH01-SA	WFS2	31BagB	25.80	25.00	SAND	C2									
HKZ2-BH01-SA	WFS2	32BagA	26.50	15.00	CLAY	C2									
HKZ2-BH01-SA	WFS2	32BagB	26.65	15.00	CLAY	C2					c		c		
HKZ2-BH01-SA	WFS2	32BagC	26.80	20.00	CLAY	C2									

Geotechnical Site Investigation – Investigation Strategy

Geophysical data

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Perform Seafloor CPT

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Perform Geotechnical Boreholes

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Initial Laboratory Test Programme

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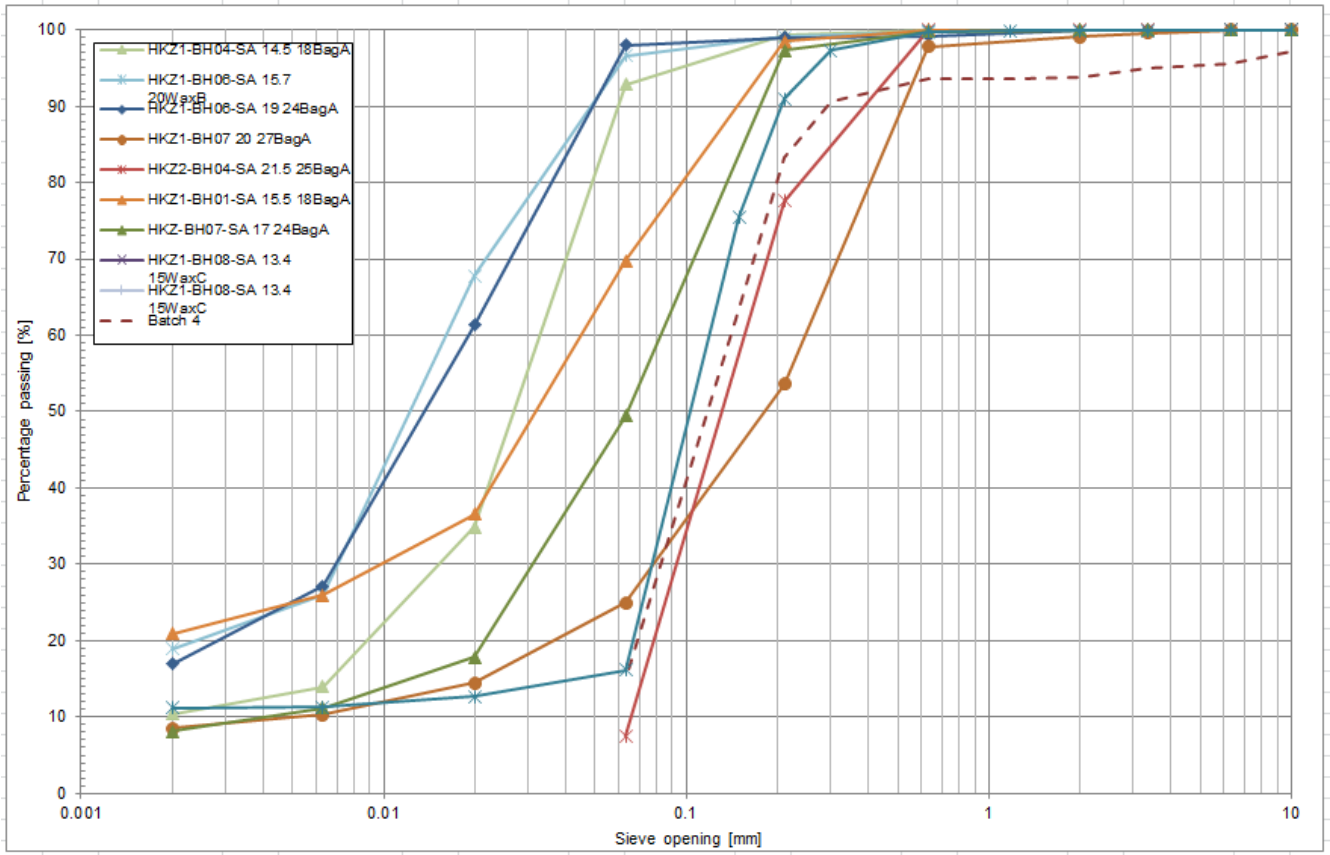
Advanced Laboratory Test Programme



Concluding Remarks

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

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

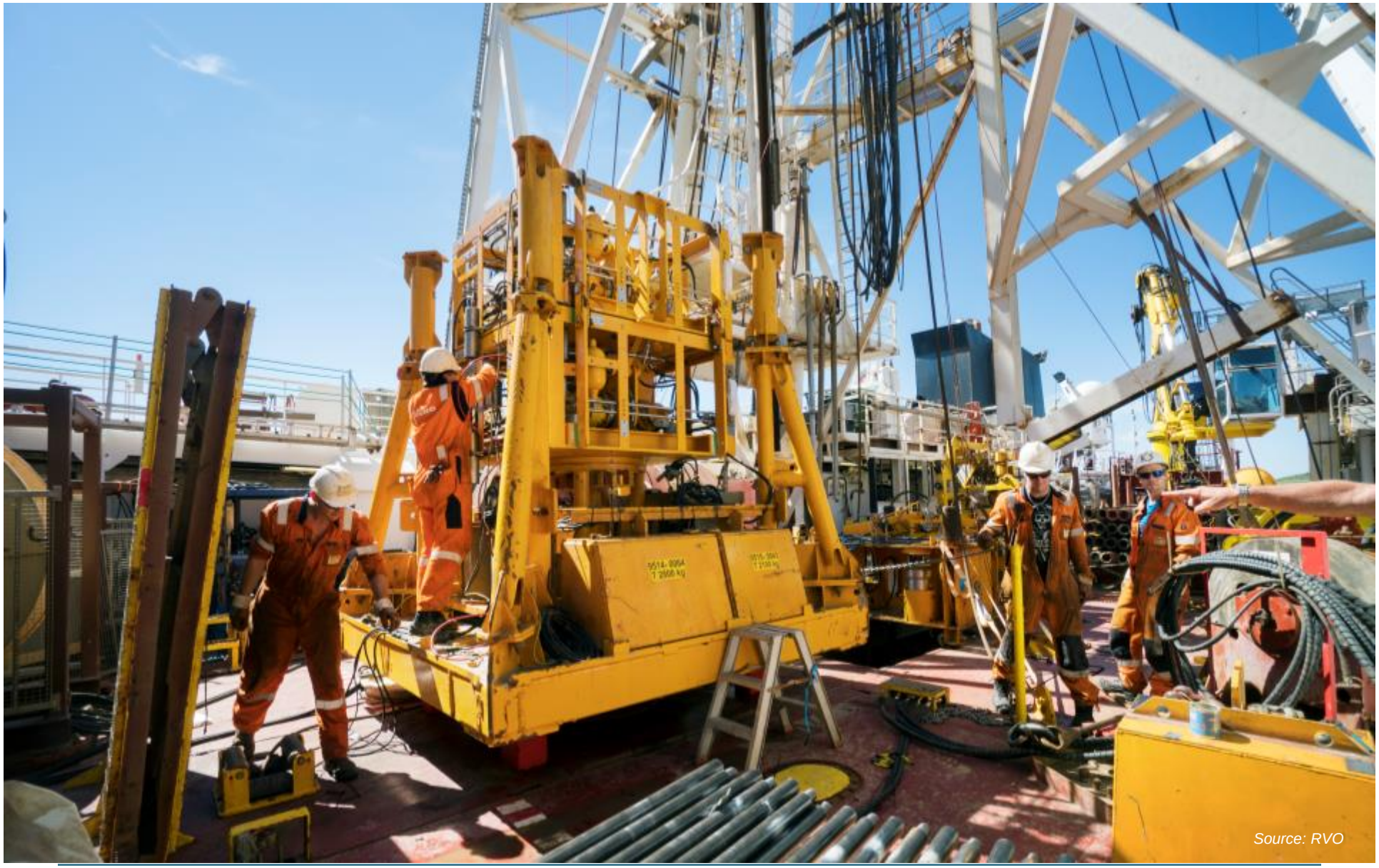
- Soil conditions at individual geotechnical locations as well as within soil units between geotechnical locations show sequences of sand, clays and intermediate soils.

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

Conclusion DNV on the site investigation and deliverables for HKZ (WFSI and II):

“This comprehensive geotechnical campaign was defined as a joint effort between multiple parties and reviewed by DNV GL with the objective to reduce the need for boreholes in later stages of development. With a proper CPT calibration and additional CPTs at each planned turbine location it is likely that additional boreholes may be omitted.”

Geotechnical Site Investigation – Fieldwork Execution



Source: RVO

Geotechnical Site Investigation – Fieldwork Execution

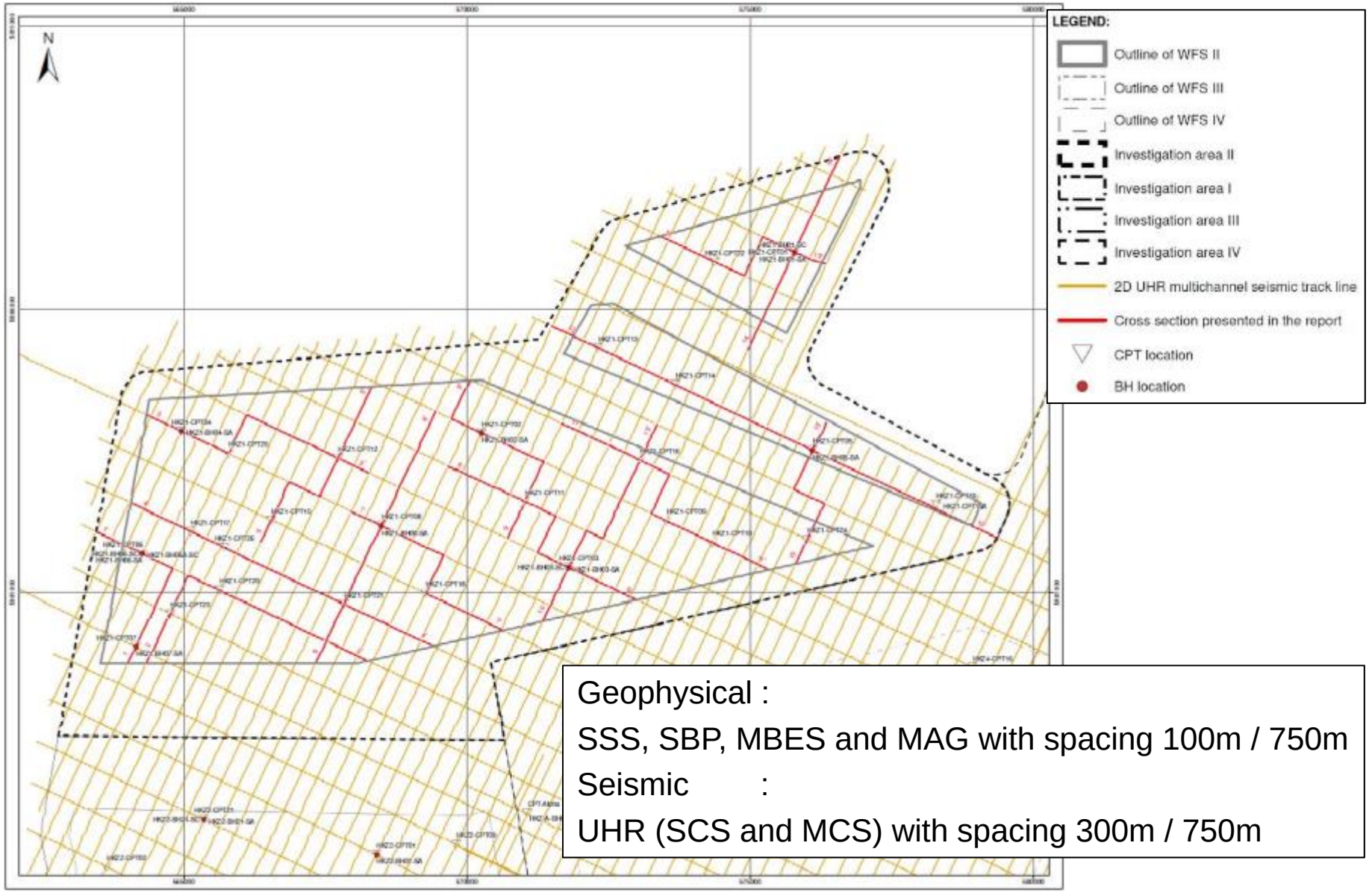
Fieldwork Objective of Geotechnical Site Investigation

- Provide high quality geotechnical information in support of Client's objectives
  Good match geophysical and geotechnical data
  Good correlation between seafloor CPT and borehole locations (profiling)
  Match between CPT and laboratory test parameters satisfactory

- No harm to people and environment
  No Recordable Incidents or Accidents
  No Lost Time Incidents or accidents
  No environmental incidents

- Execute work in safe and efficient manner
  Offshore phase executed in 31 days (total of 51 seafloor CPT and 26 geotechnical boreholes)
  Limited WOW or equipment related issues

Geotechnical Site Investigation – Investigation Points - WFSI



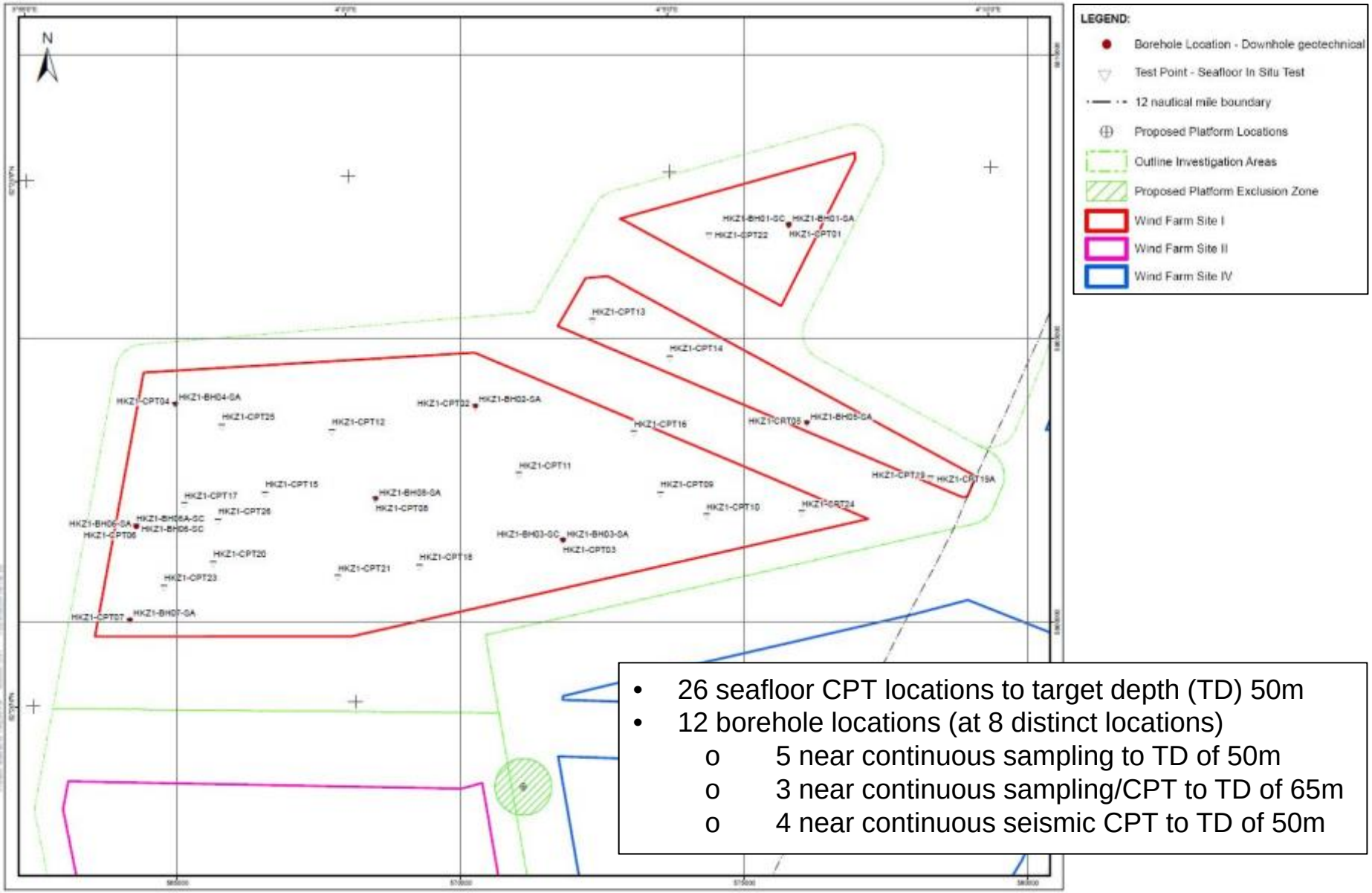
Geophysical :

SSS, SBP, MBES and MAG with spacing 100m / 750m

Seismic :

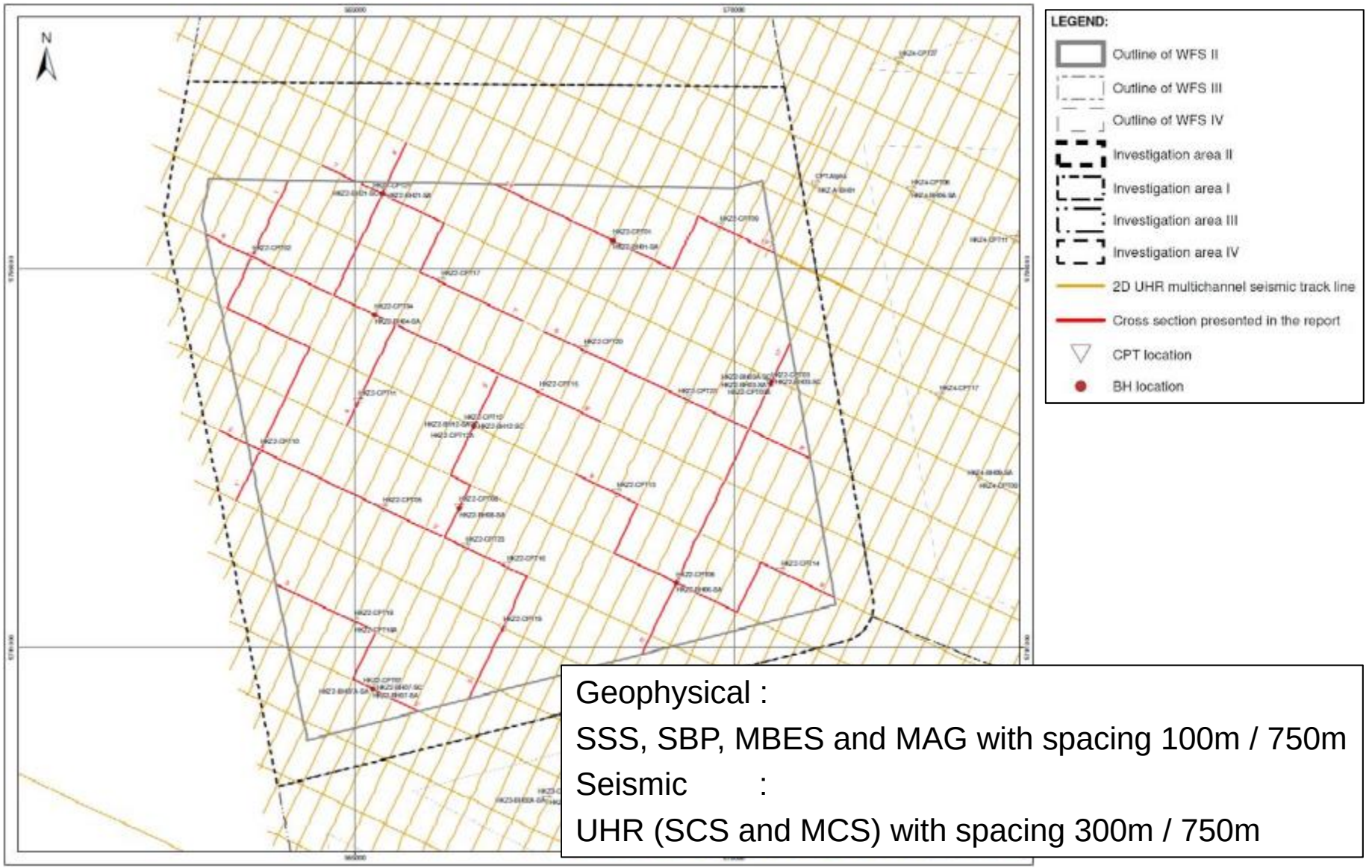
UHR (SCS and MCS) with spacing 300m / 750m

Geotechnical Site Investigation – Investigation Points - WFSI



- 26 seafloor CPT locations to target depth (TD) 50m
- 12 borehole locations (at 8 distinct locations)
  - 5 near continuous sampling to TD of 50m
  - 3 near continuous sampling/CPT to TD of 65m
  - 4 near continuous seismic CPT to TD of 50m

Geotechnical Site Investigation – Investigation Points - WFSII



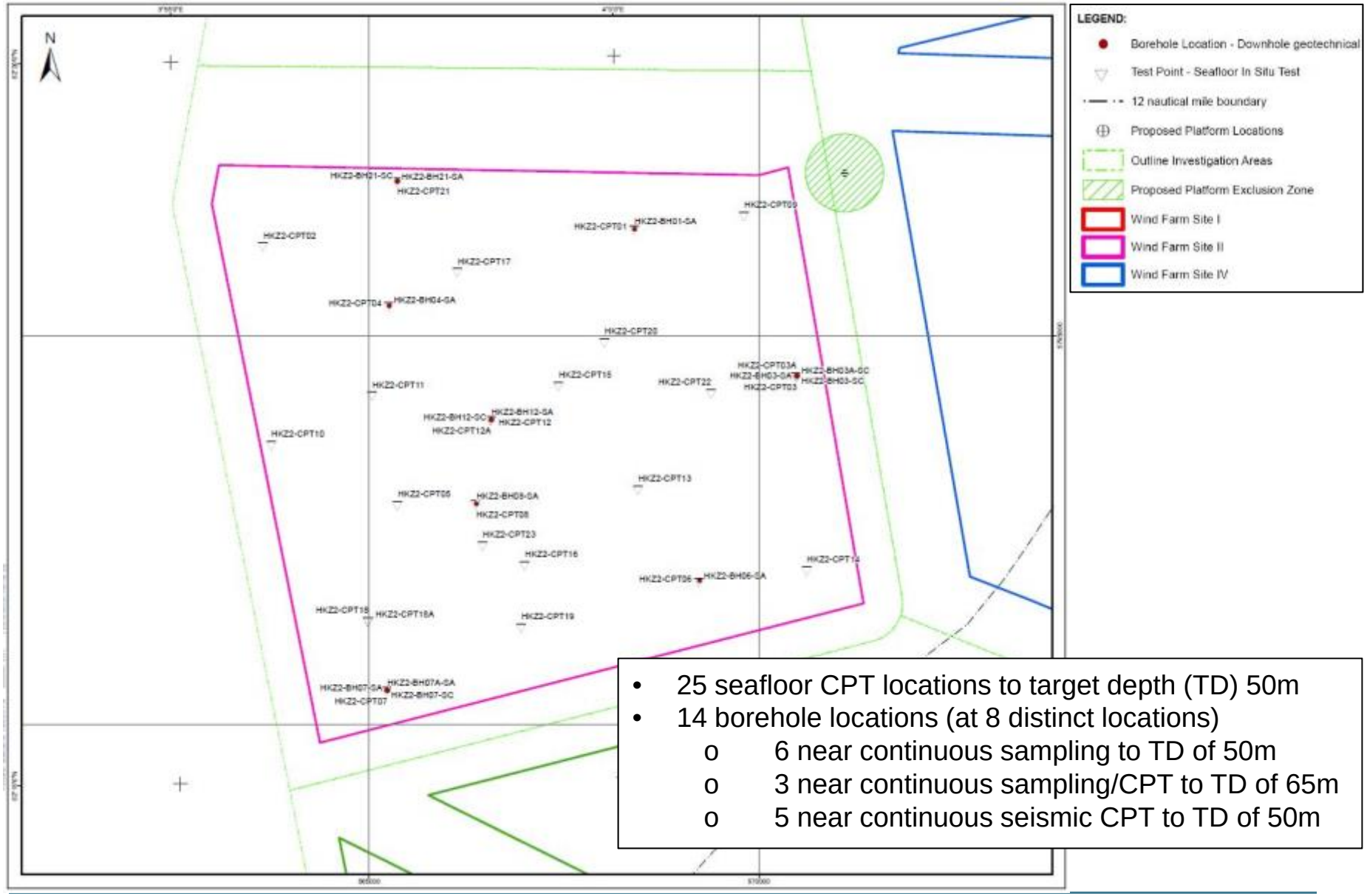
Geophysical :

SSS, SBP, MBES and MAG with spacing 100m / 750m

Seismic :

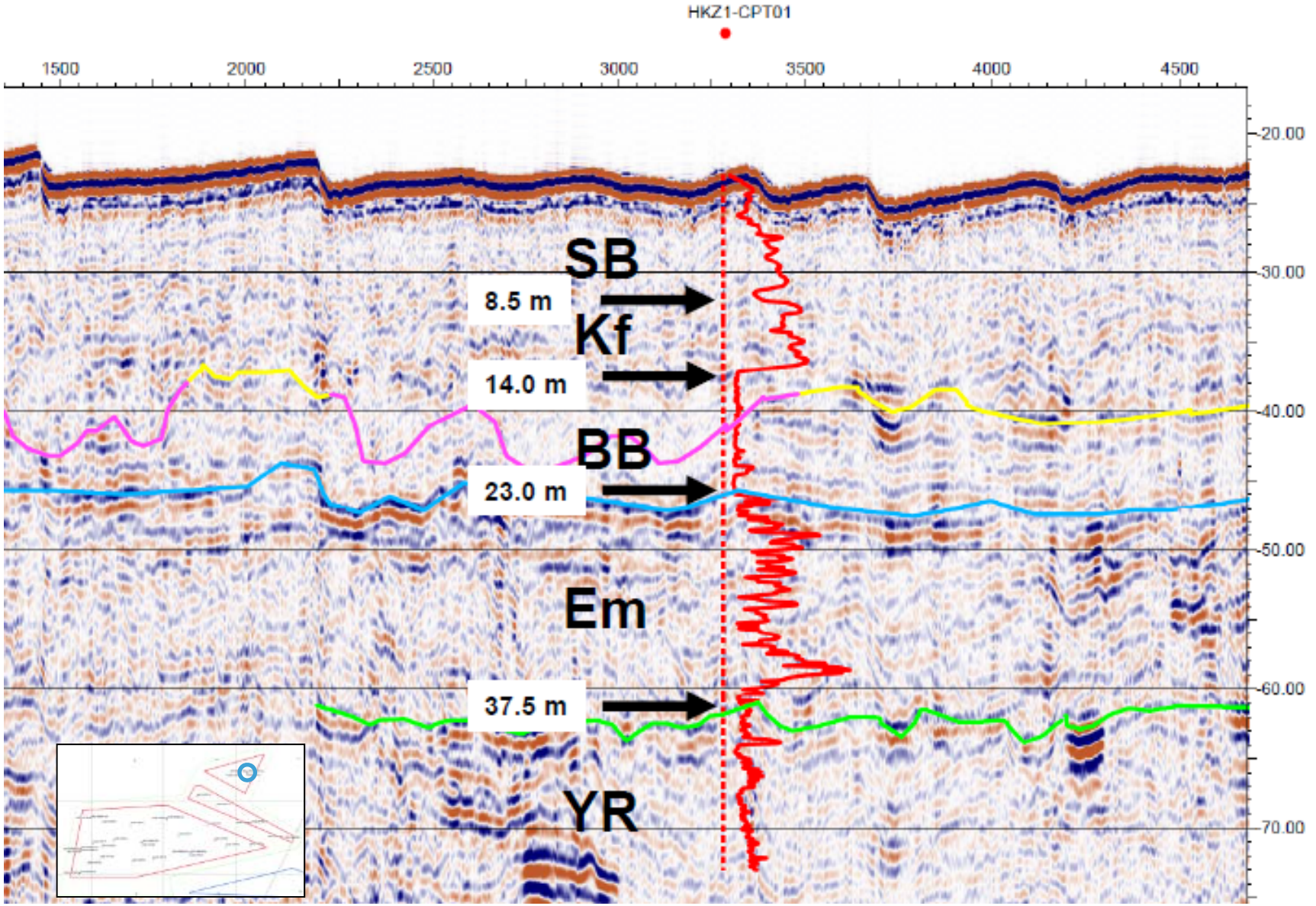
UHR (SCS and MCS) with spacing 300m / 750m

Geotechnical Site Investigation – Investigation Points - WFSII



- 25 seafloor CPT locations to target depth (TD) 50m
- 14 borehole locations (at 8 distinct locations)
  - 6 near continuous sampling to TD of 50m
  - 3 near continuous sampling/CPT to TD of 65m
  - 5 near continuous seismic CPT to TD of 50m

Geotechnical Site Investigation – Investigation Programme



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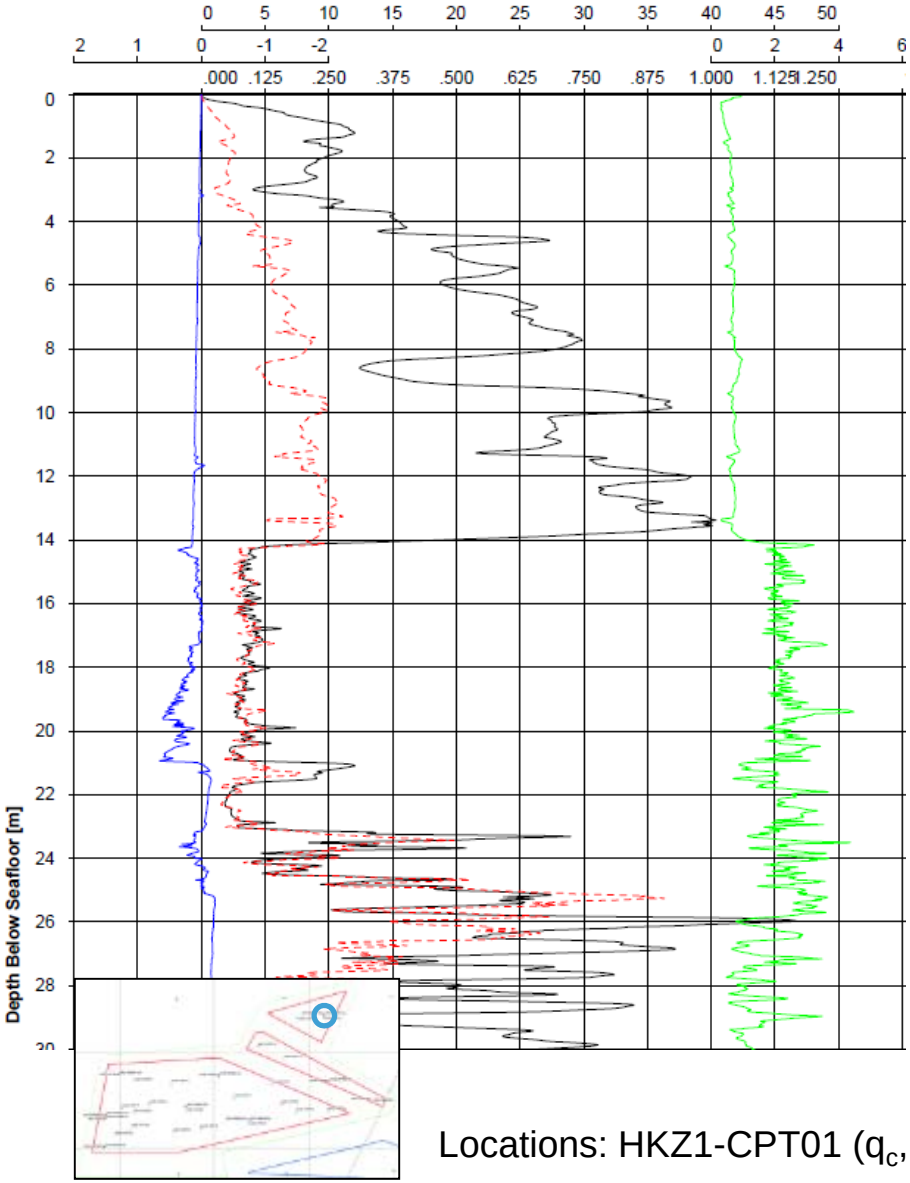
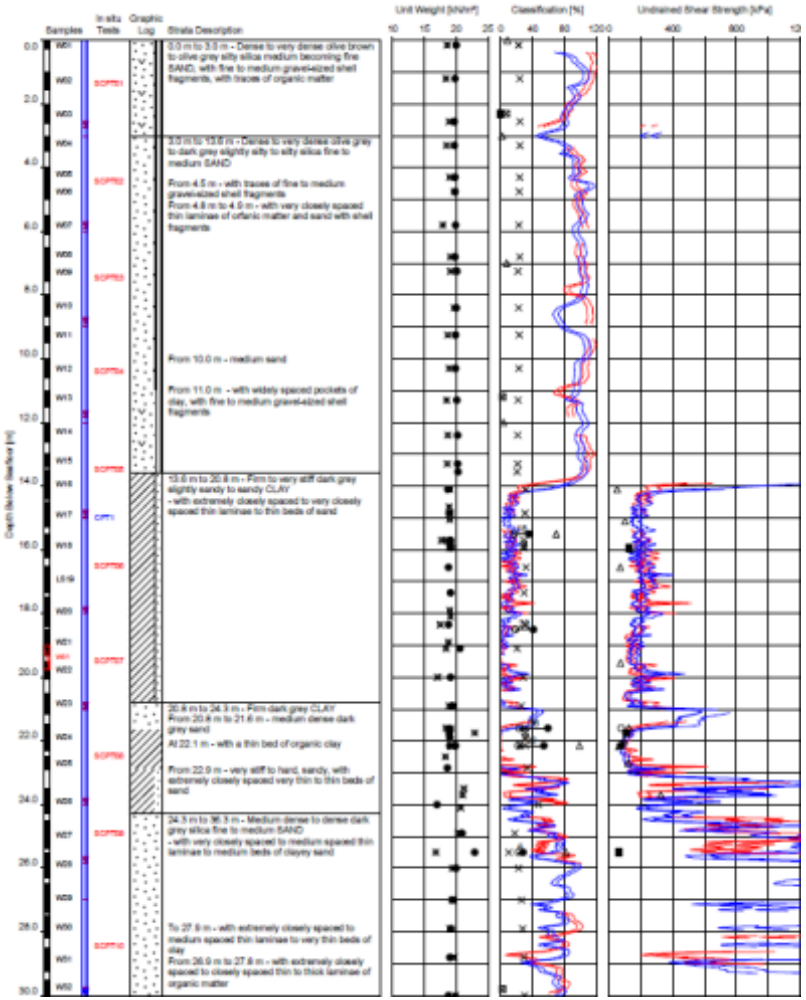
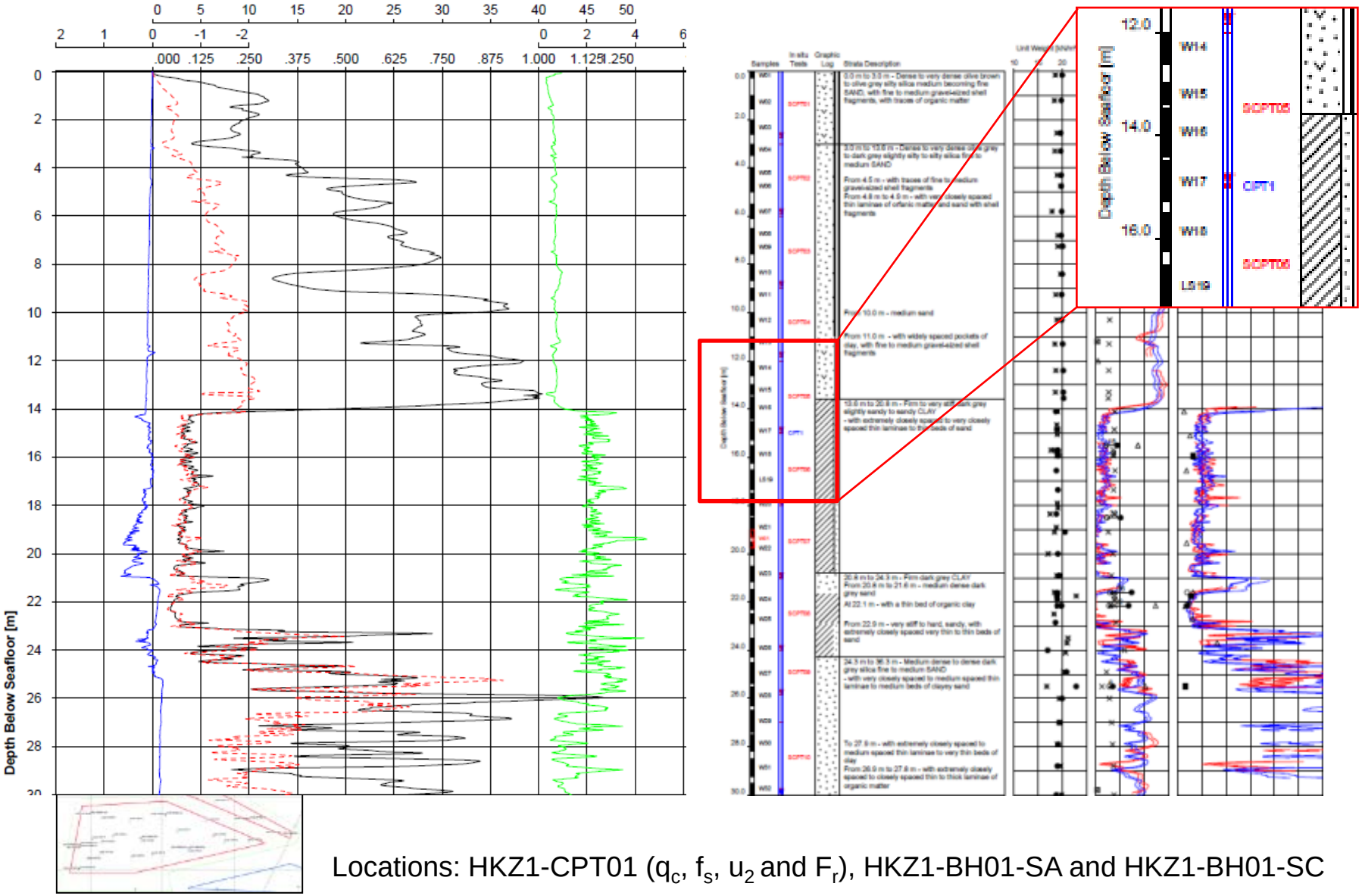




Locations: HKZ1-CPT01 (q_c, f_s, u_2 and F_r), HKZ1-BH01-SA and HKZ1-BH01-SC

Geotechnical Site Investigation – Investigation Programme



Locations: HKZ1-CPT01 (q_c, f_s, u_2 and F_r), HKZ1-BH01-SA and HKZ1-BH01-SC

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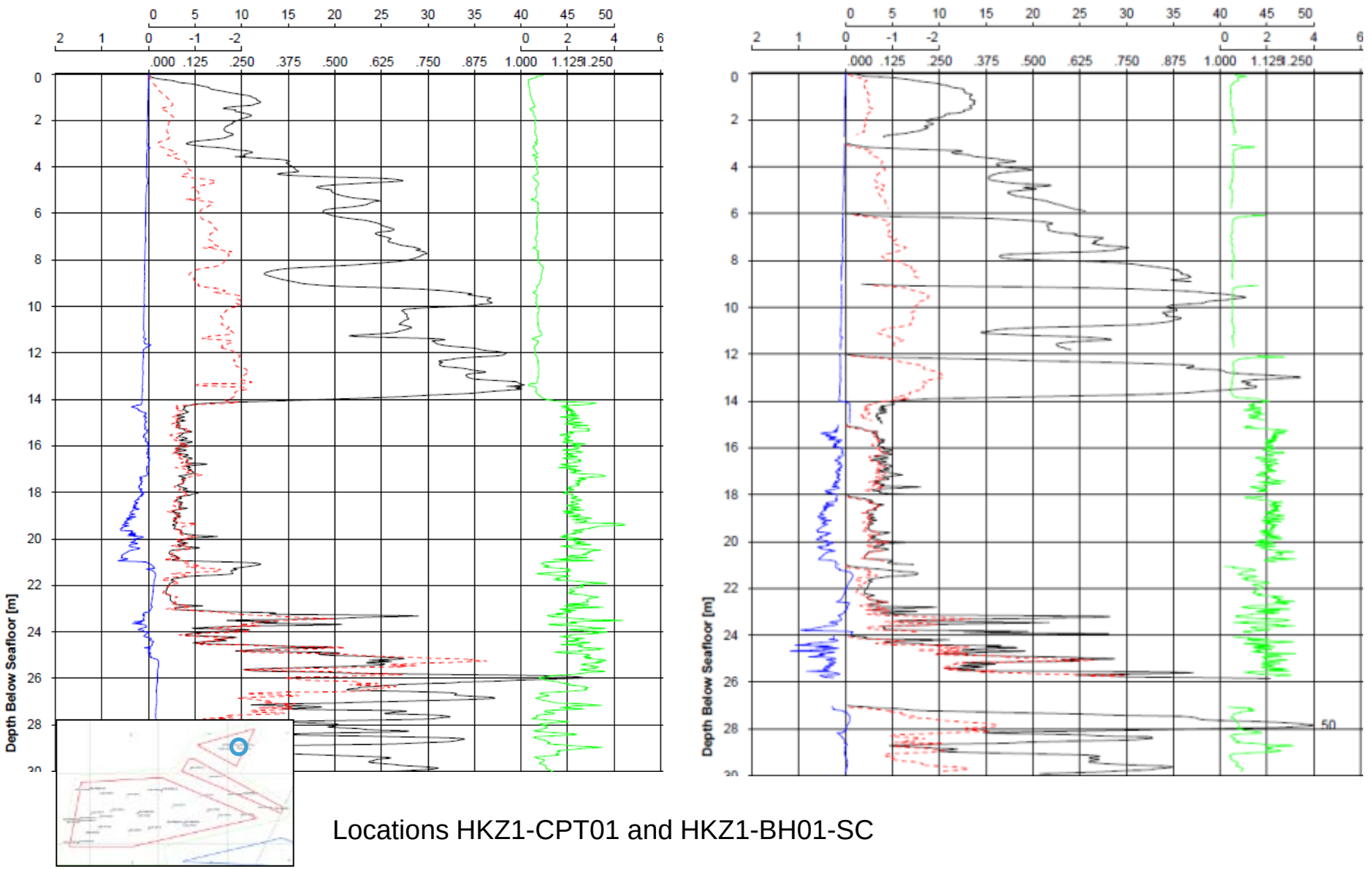
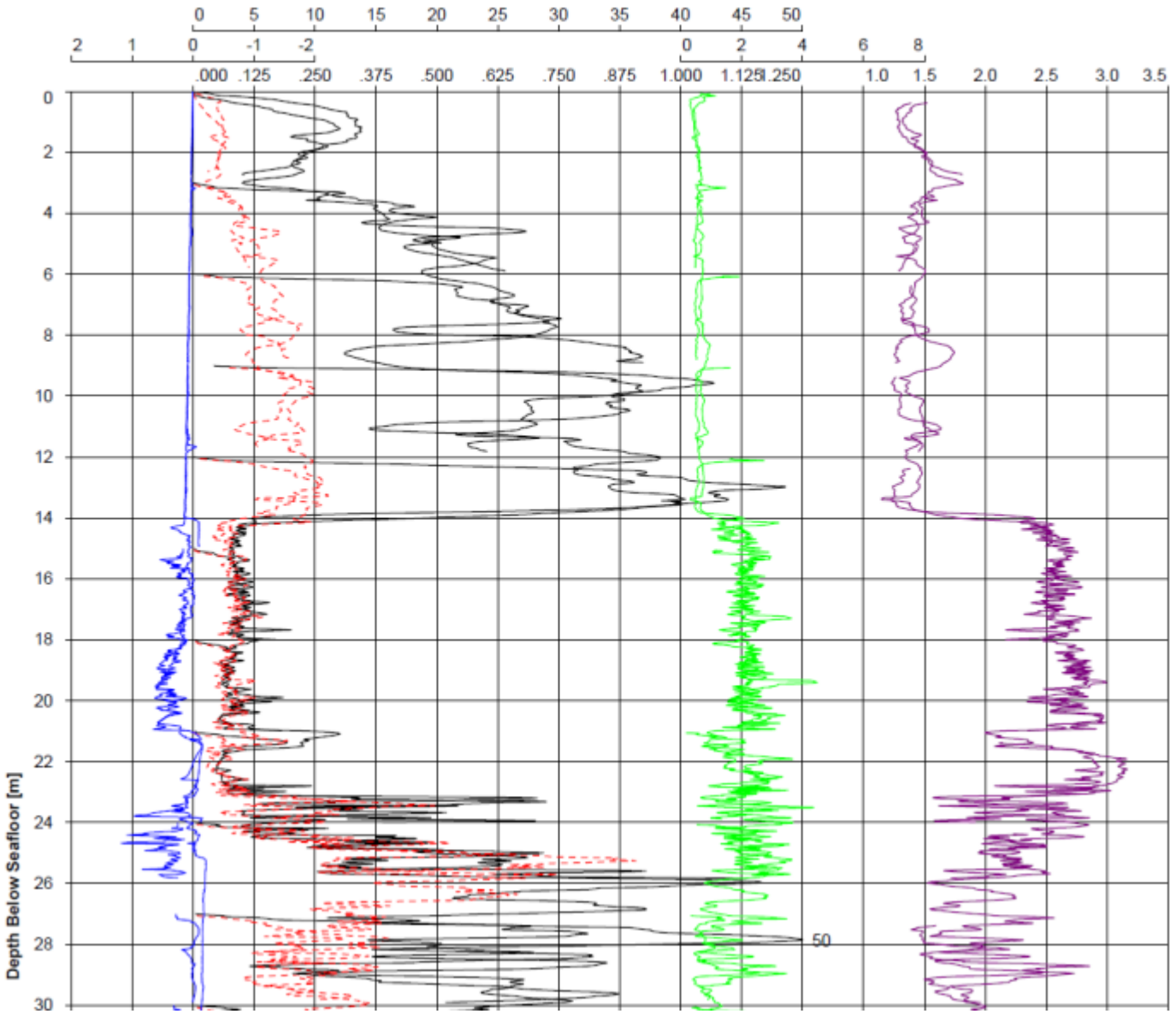


Locations HKZ1-CPT01 and HKZ1-BH01-SC

Geotechnical Site Investigation – Investigation Programme



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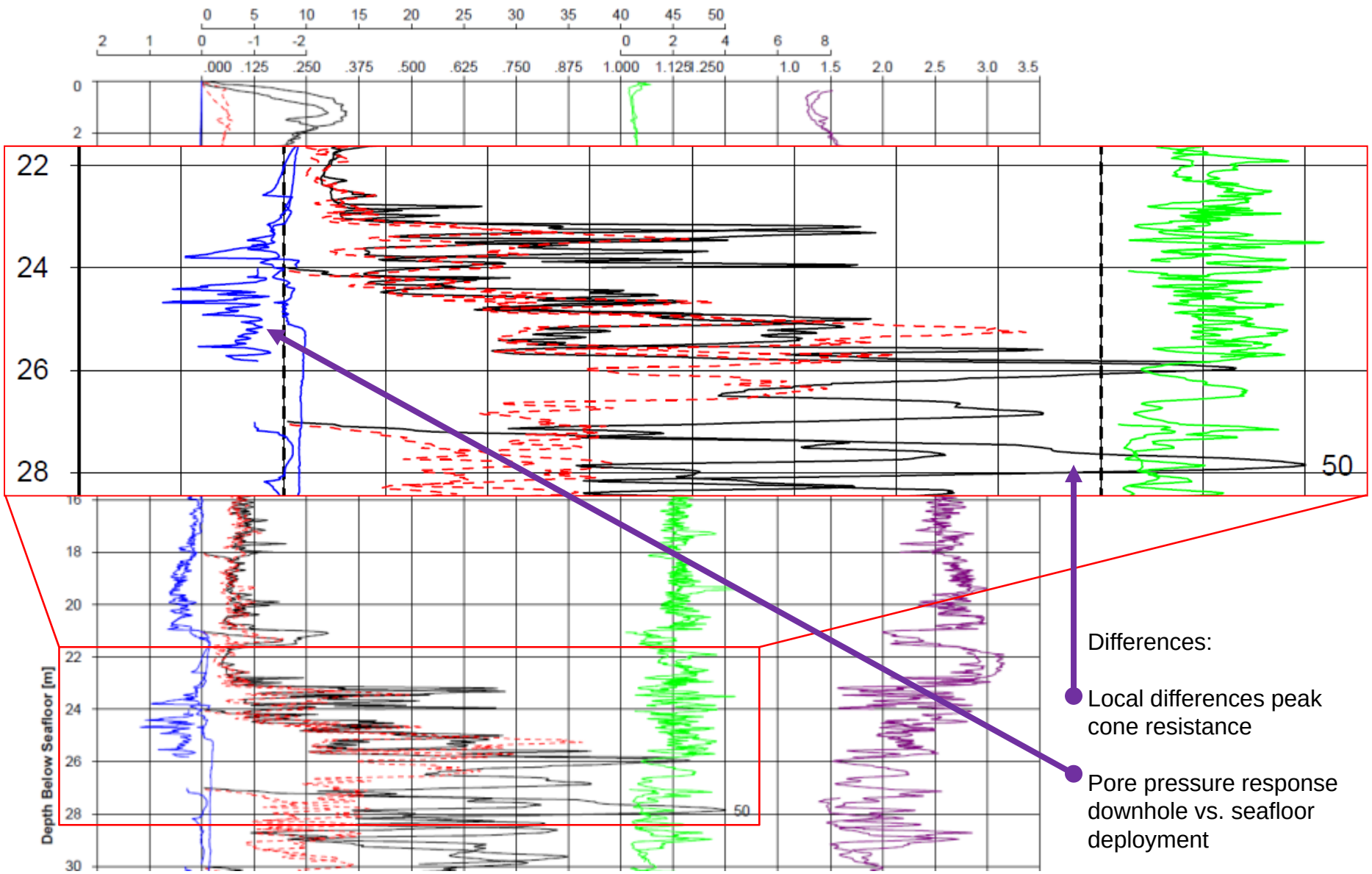

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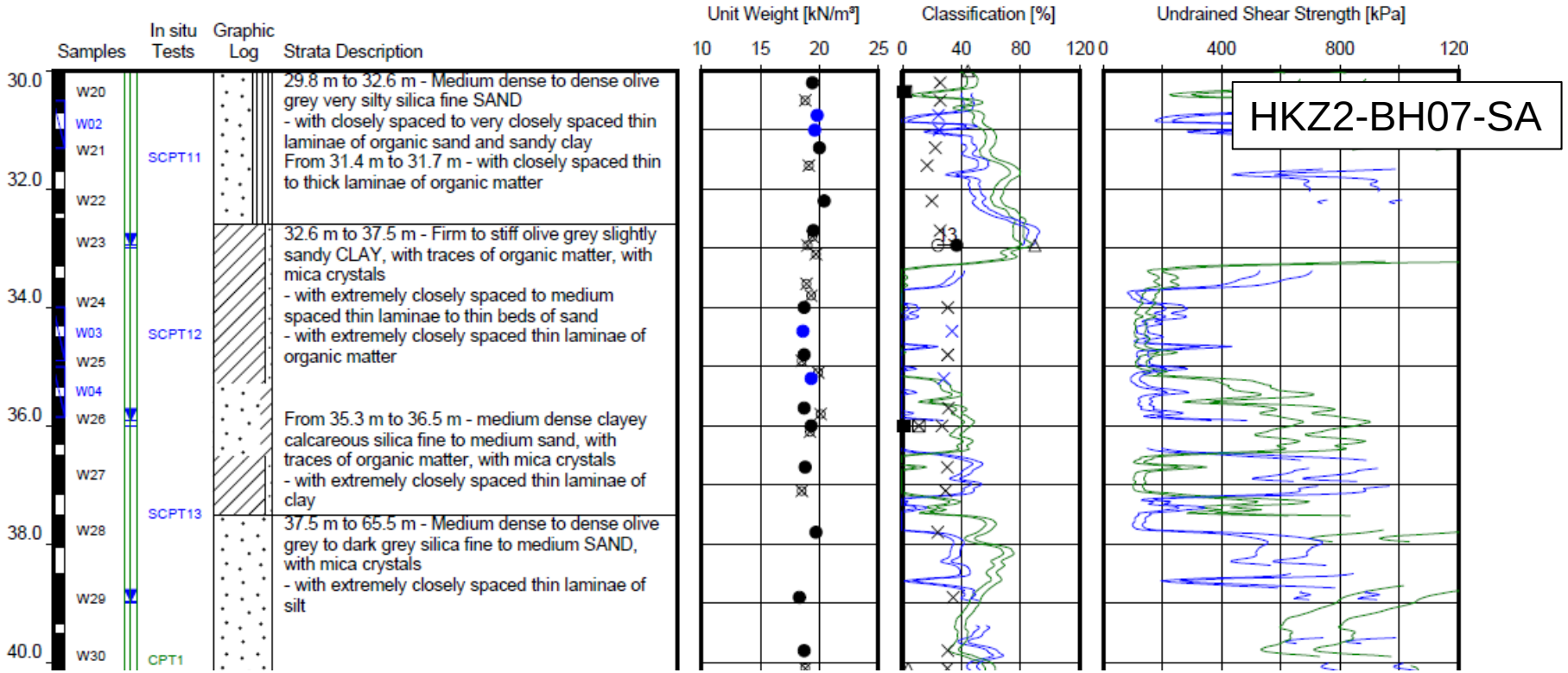
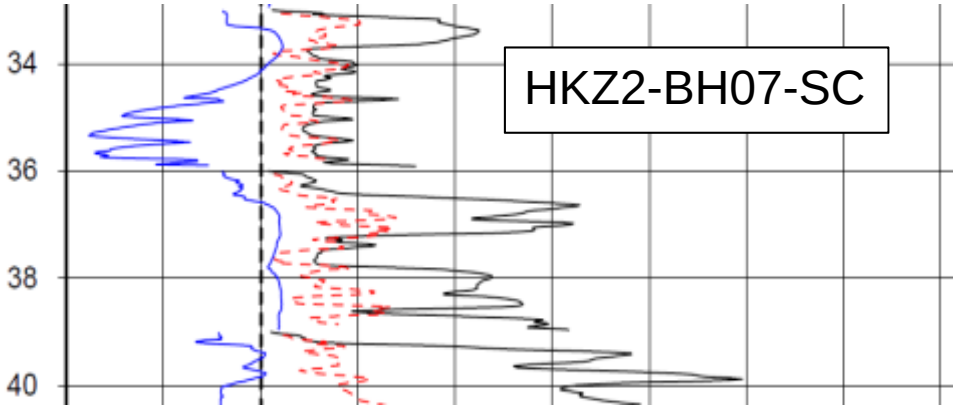
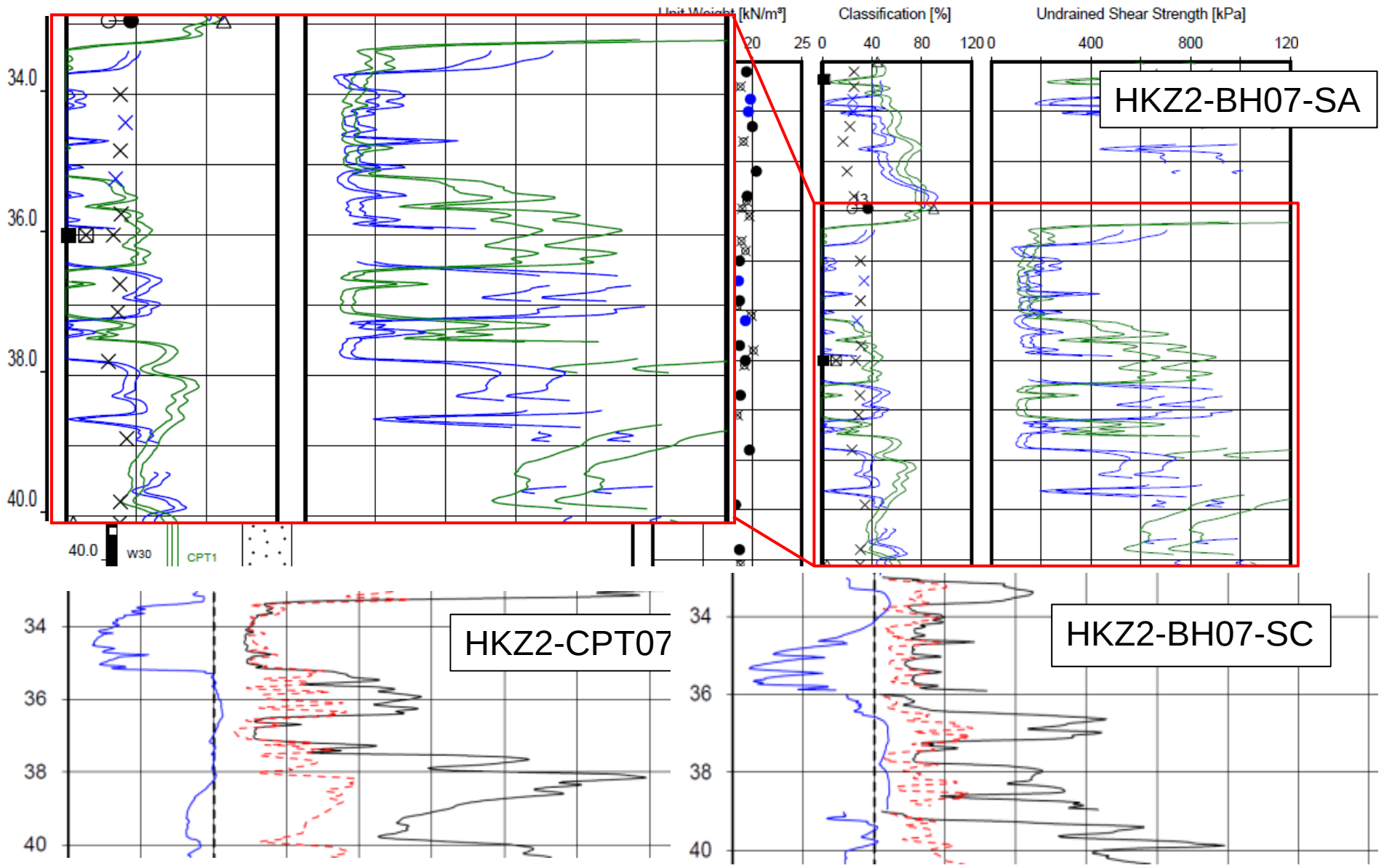




Geotechnical Site Investigation – Investigation Programme

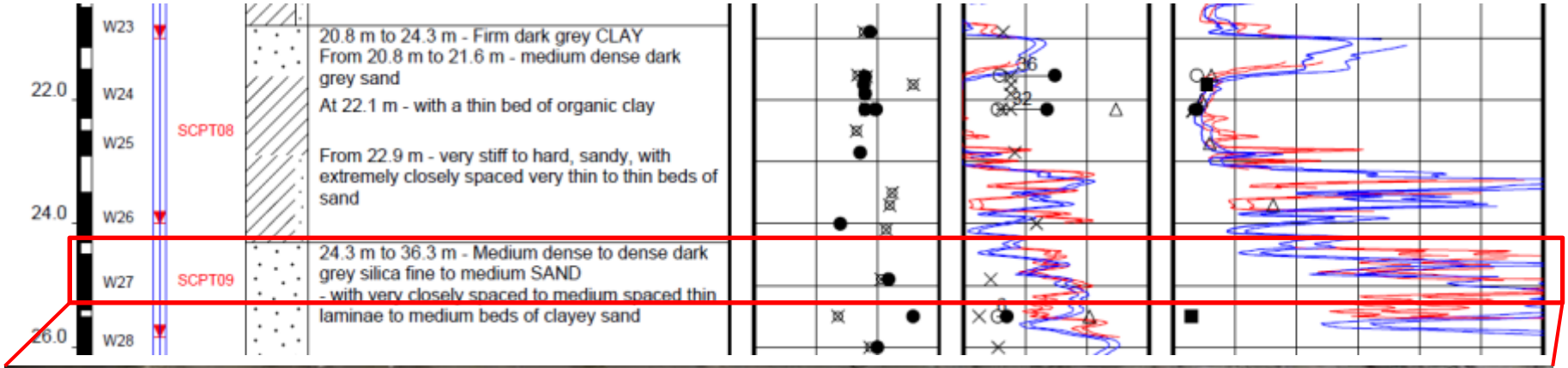


Geotechnical Site Investigation – Laboratory Test Programme

On-site laboratory test programme:

- Sample description *(according BS 5930, BSI,1999)*
- Sample photography *(intact and split)*
- Geotechnical index *(water content, unit weight)*
- Index strength *(torvane, pocket penetrometer and UU triaxial)*

BSI British Standards Institution, 1999. BS 5930 Code of Practice for Site Investigations", London: BSI.



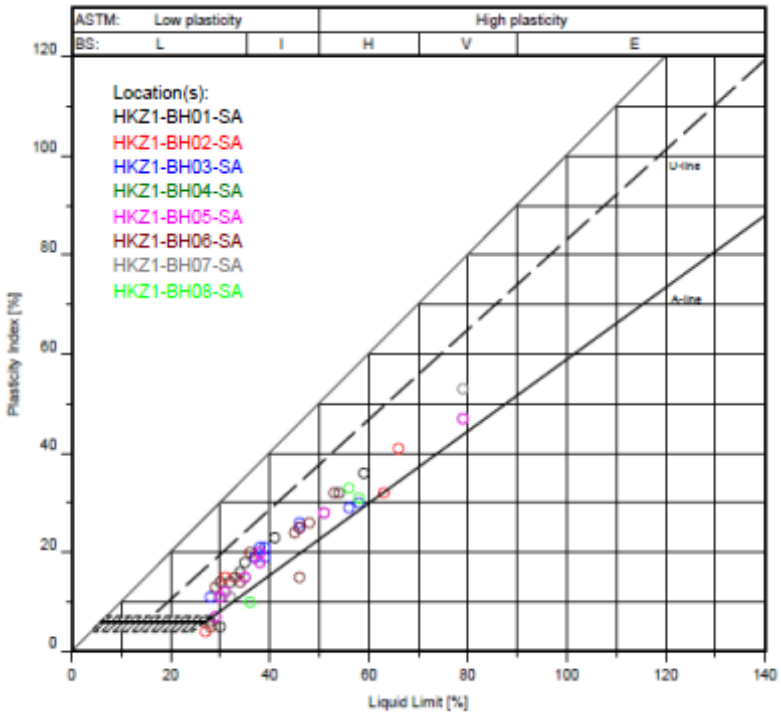
Geotechnical Site Investigation – Laboratory Test Programme

Initial office laboratory test programme premises:

- Confirm and extend site findings (classification / characteristics)
- Test (in principle) all major (>2m thickness) layers identified
- Allow for sufficient data points to confirm heterogeneity or homogeneity of individual layers
- Test (where relevant) anomalies and/or unusual soil bodies

Initial Office Laboratory Test programme consisted of:

- Geotechnical Index Testing
- Geochemical Index Testing
- (Index) Strength Testing
- Compressibility Testing
- Thermal Conductivity Testing
- Dynamic Testing
- Age Dating (*palynology*)



Geotechnical SI – Initial Laboratory Test Programme

Test Type	WFSI	WFSII
Density of Solid Particles (Small Pycnometer)	57	42
Particle Size Analysis (Sieving and Pipette)	141	121
Minimum and Maximum Index Dry Unit Weight	16	35
Atterberg Limits	55	44
Carbonate Content	28	31
Organic Content (dichromate)	30	26
Unconsolidated Undrained Triaxial compression (UU) – undisturbed / remoulded	24 / 24	14 / 14
Isotropically Consolidated Undrained Triaxial (CIUc) / with bender element testing	12 / 8	5 / 9
Isotropically Consolidated Drained Triaxial (CIDc) / with bender element testing	18 / 10	13 / 11
Ring Shear (Soil-Soil Interface / Soil-Steel Interface)	11 / 18	8 / 15
Incremental Loading (IL) Oedometer	7	6
Constant Rate of Strain (CRS)	13	10
Thermal Conductivity	10	12
Microscopic Inspection and Photography	20	29

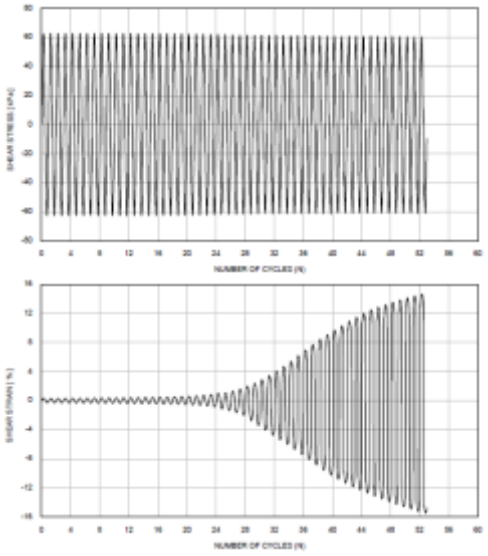
Geotechnical SI – Advanced Laboratory Test Programme

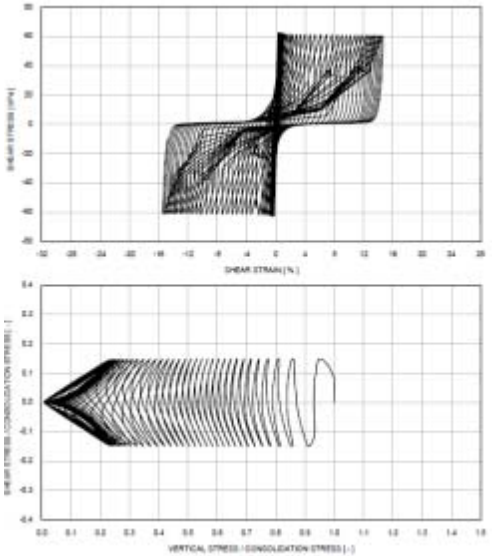
Advanced office laboratory test programme premises:

- Allow broad use of acquired test results
- Test soils predominantly present at WFS I&II
- Test soils considered relevant for probable future structure design

Comments:

- variety of test types, test specimen conditions and different loading conditions
- not every variation could be accounted for within the test programme
- selected loading conditions do not reflect a site specific design





Geotechnical SI – Advanced Laboratory Test Programme

Test Type	Total	A	B1	B2	C1	C2	D
Direct Simple Shear (DSS)	**7**	1	1	2	1	1	1
(An)Isotropically Consolidated Undrained Triaxial compression (CIUc/CAUc)	**4 / 3**	1 / -	1 / -	2 / -	- / -	- / 2	- / 1
Isotropically Consolidated Undrained Triaxial extension (CIUe)	**1**	-	-	1	-	-	-
Isotropically Consolidated Drained Triaxial compression (CIDc)	**2**	1	1	-	-	-	-
Stress-controlled Cyclic Simple Shear (CSS)	**23**	4	4	6	2	4	3
Stress-controlled Isotropically Consolidated Undrained Cyclic Triaxial (CTX)	**18**	2	1	4	1	7	3
Stress-controlled Isotropically Consolidated Drained Cyclic Triaxial (CTX)	**8**	4	4	-	-	-	-
Bender Element (BE)	**6**	1	1	1	1	1	1
Resonant Column (RC)	**9**	2	2	2	-	2	1

Geotechnical Site Investigation – Deliverables and Content

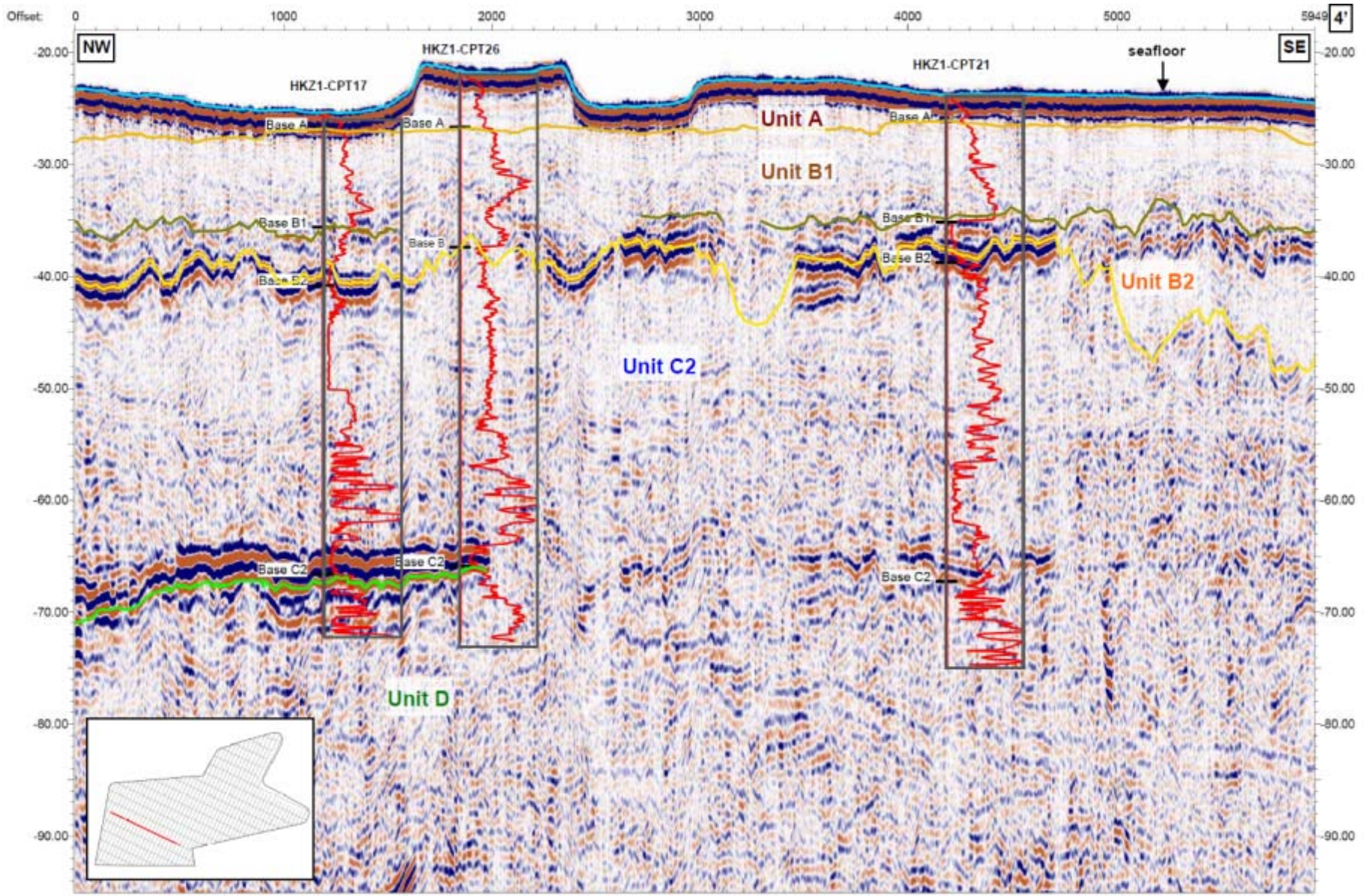
Report Type	Investigation Data	Contents
Geotechnical Reports – Investigation Data	WFSI - 12 boreholes (8 distinct locations) to depths of 6m to 67m bsf • 5 sampling (TD~50m) • 3 sampling to 50m continued by sampling & PCPT to TD~65m • 3 seismic cone penetration testing (TD~50m)	One report per site • Geotechnical logs; • Results of PCPT • Results of SCPT • Geotechnical laboratory tests results
	WFSII - 14 boreholes (8 distinct locations) to depths of 6m to 66m bsf • 6 sampling (TD~50m) • 3 sampling to 50m continued by sampling & CPT to TD~65m • 5 seismic cone penetration testing (TD~50m)	
	WFSI 26 seafloor PCPT to depths of 46m to 51m bsf, including 19 PPDT	One report per site • Interpreted PCPT logs • Results of PCPT • Results of PPDT
	WFSII 25 seafloor PCPT (at 23 distinct locations) to depths of 35m to 51m bsf, including 14 PPDT	
Geological Ground Model Reports	One report per site • Geological ground model • Geotechnical Parameter per borehole location and per unit • Assessment of suitability of selected types of structures	
Laboratory Test Report	One report combining results of advanced static and cyclic laboratory tests for WFSI&II	
Additional deliverables	• Kingdom project including WFSI and WFSII • ASCII, AGS (data from the CPT and borehole locations) and GIS (ground model)	

Key: bsf = below seafloor
PCPT = Piezo-Cone Penetration Test / SCPT = Seismic Cone Penetration Test / PPDT = Pore Pressure Dissipation Test

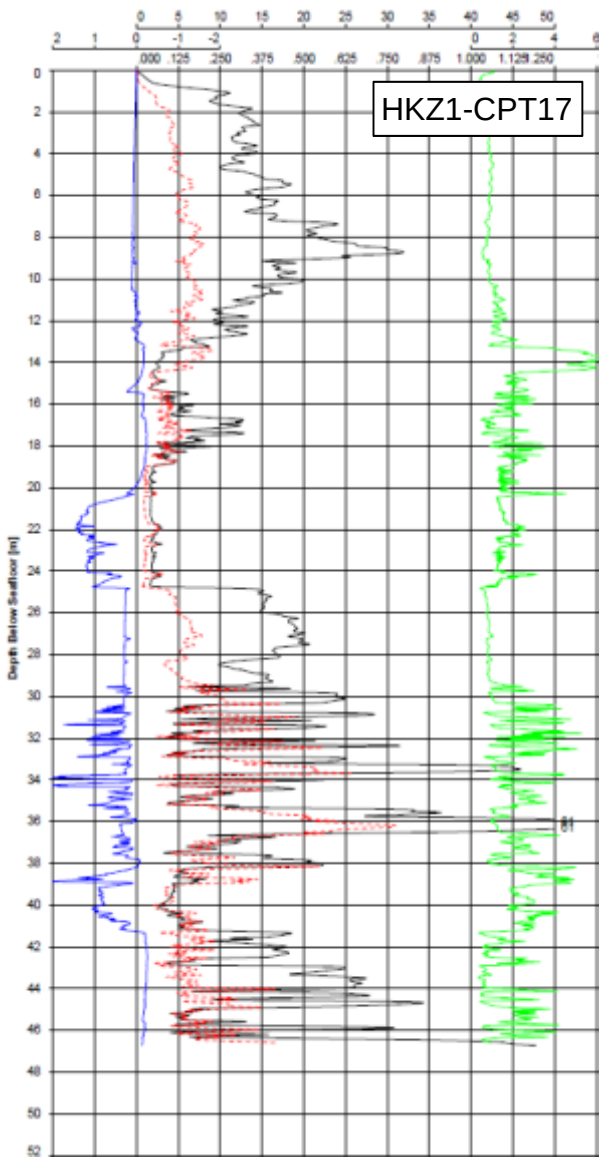
Geotechnical Site Investigation – Deliverables and Content

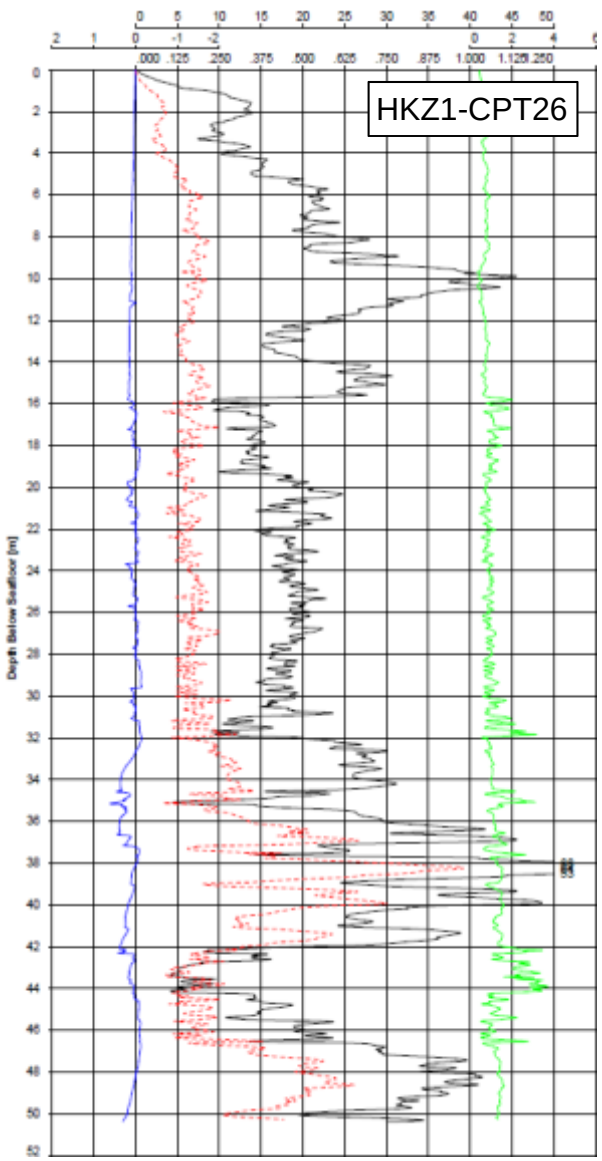
Report Number	Title	Contents
N6196/01	Geotechnical Report - Investigation Data - Geotechnical Borehole Locations Wind Farm Site I	Geotechnical data including geotechnical logs, results from downhole (seismic) cone penetration tests and results from geotechnical laboratory tests.
N6196/02	Geotechnical Report - Investigation Data - Seafloor In Situ Test Locations Wind Farm Site I	Geotechnical data including geotechnical logs, results from seafloor cone penetration tests and pore pressure dissipation tests.
N6196/03	Geotechnical Report - Investigation Data - Geotechnical Borehole Locations Wind Farm Site II	Geotechnical data including geotechnical logs, results from downhole (seismic) cone penetration tests and results from geotechnical laboratory tests.
N6196/04	Geotechnical Report - Investigation Data - Seafloor In Situ Test Locations Wind Farm Site II	Geotechnical data including geotechnical logs, results from seafloor cone penetration tests and pore pressure dissipation tests.
N6196/09	Geological Ground Model Wind Farm Site I	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.
N6196/10	Geological Ground Model Wind Farm Site II	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.
N6196/13	Geotechnical Report - Laboratory Test Data Wind Farm Sites I & II	Results of advanced static and cyclic laboratory tests.

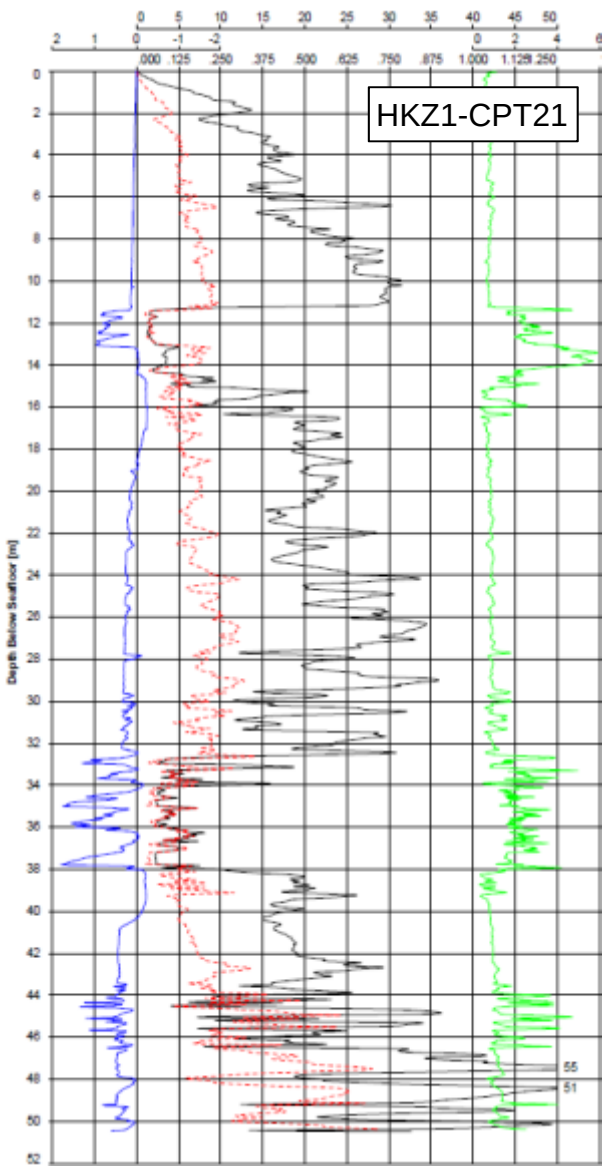
Geological Site Investigation – Data Interpretation



Geological Site Investigation – Data Interpretation







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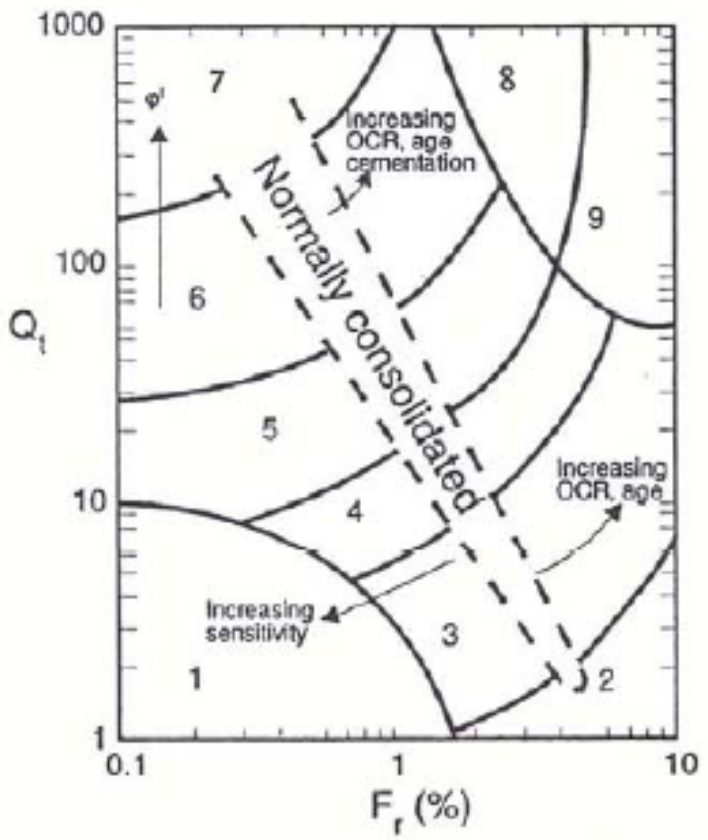
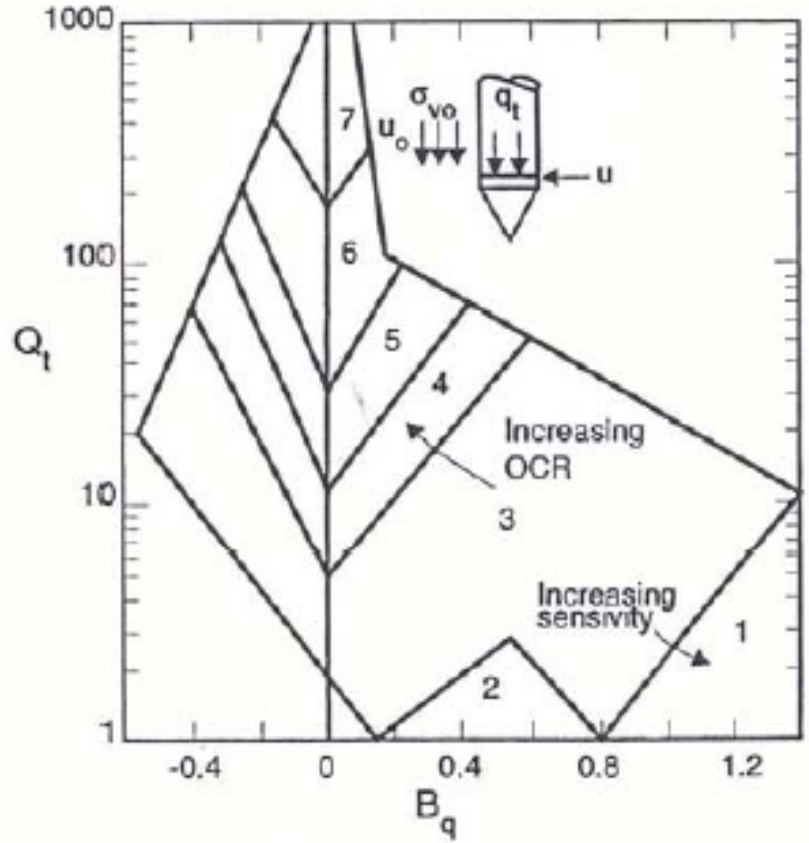
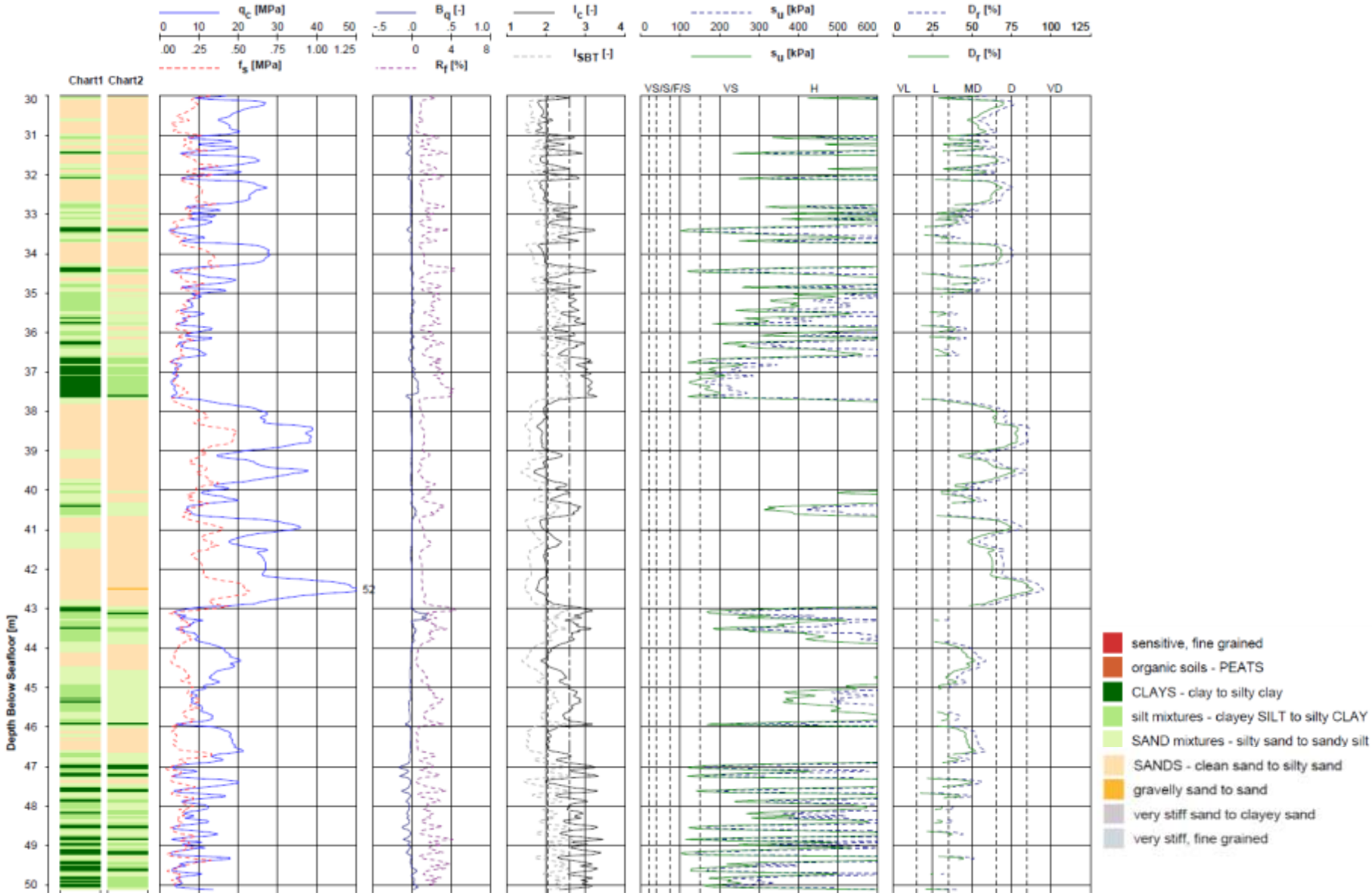




$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \qquad B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}} \qquad F_r = \frac{f_s}{q_t - \sigma_{vo}} \times 100\%$$

Source: Robertson 1990

Geological Site Investigation – Data Interpretation



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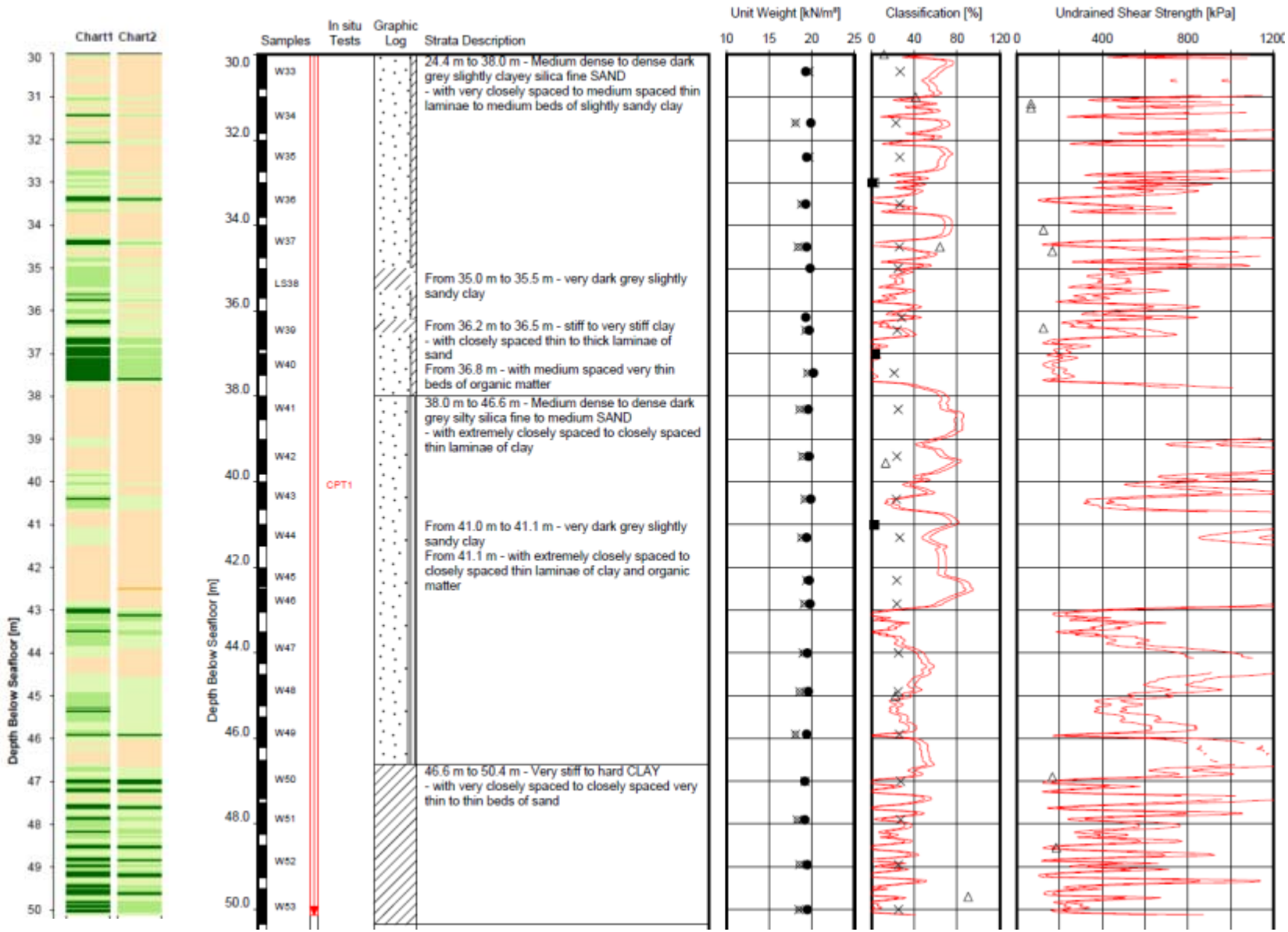

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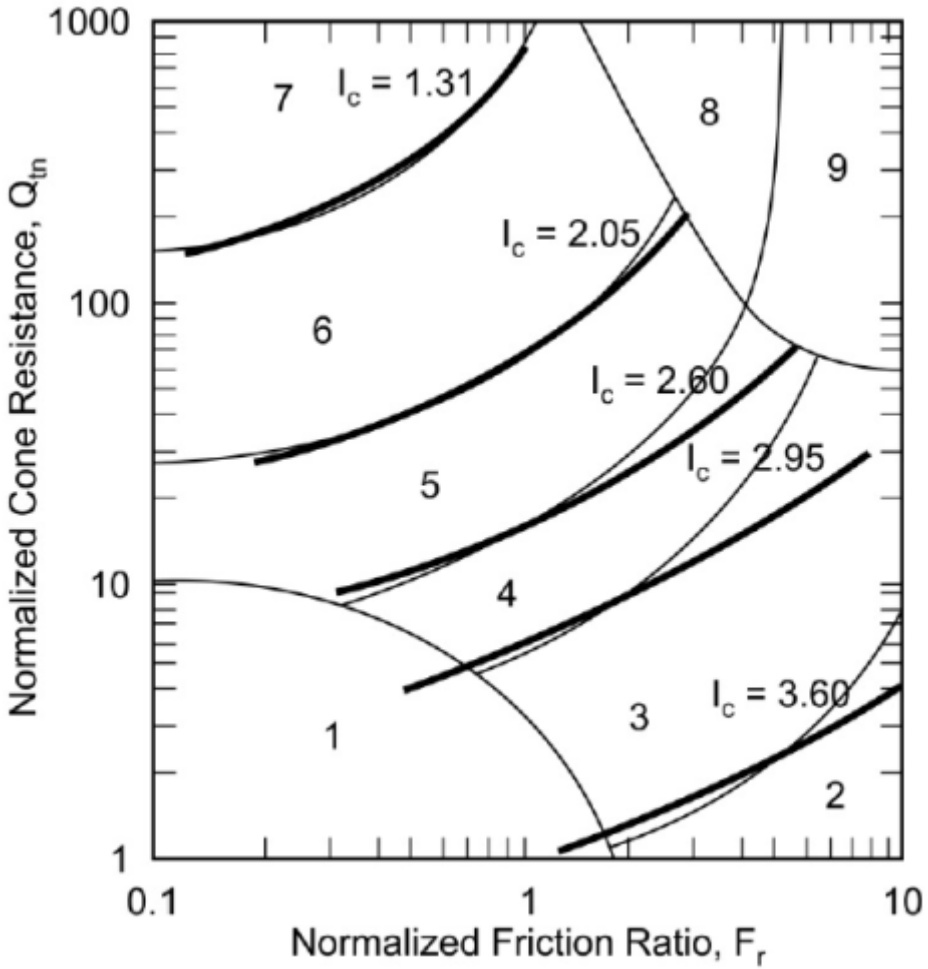
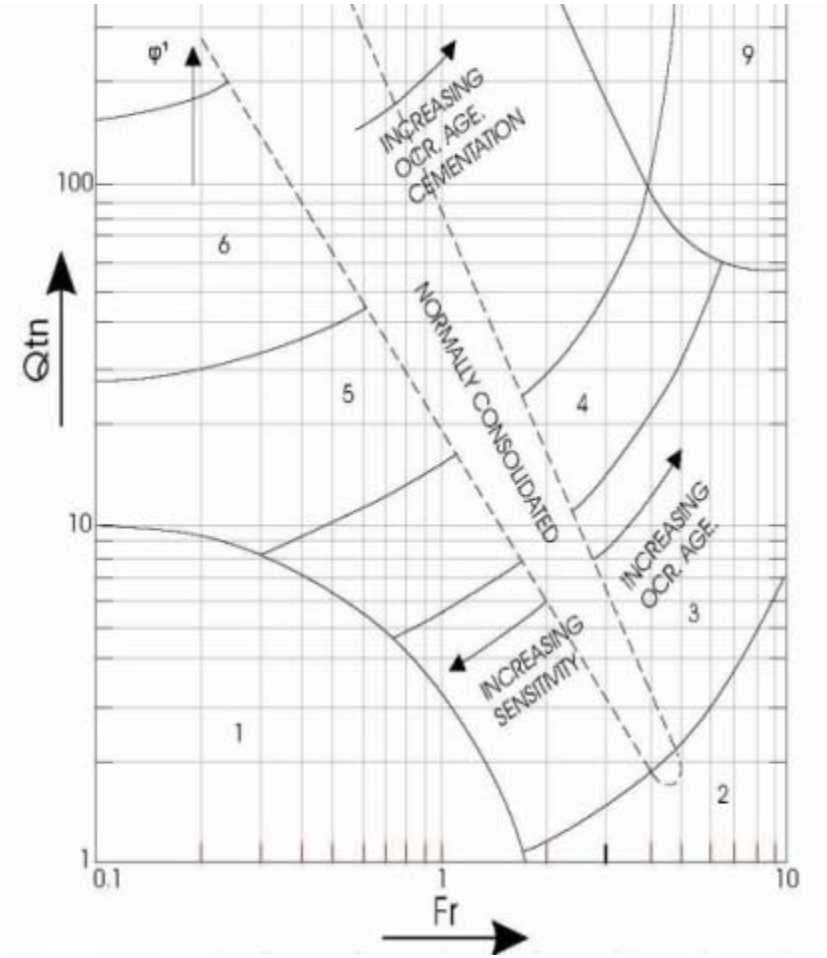
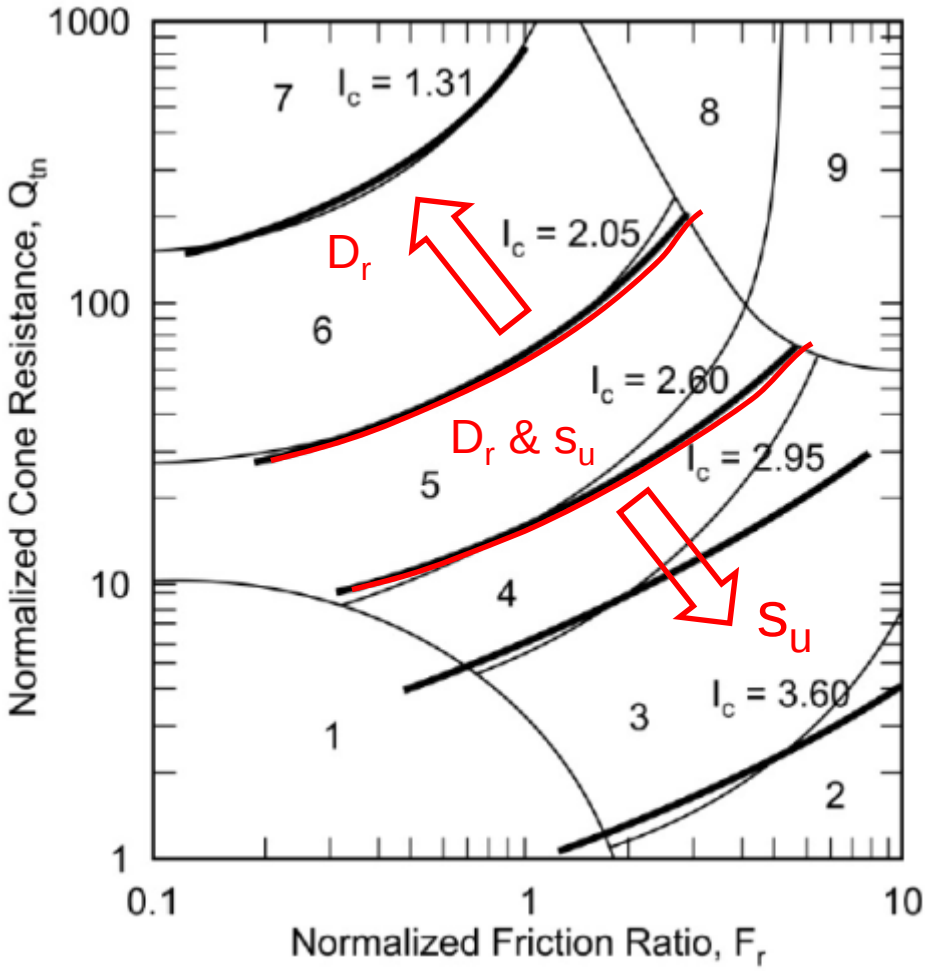




$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$$

Source: Robertson 1990, 2009 and 2010

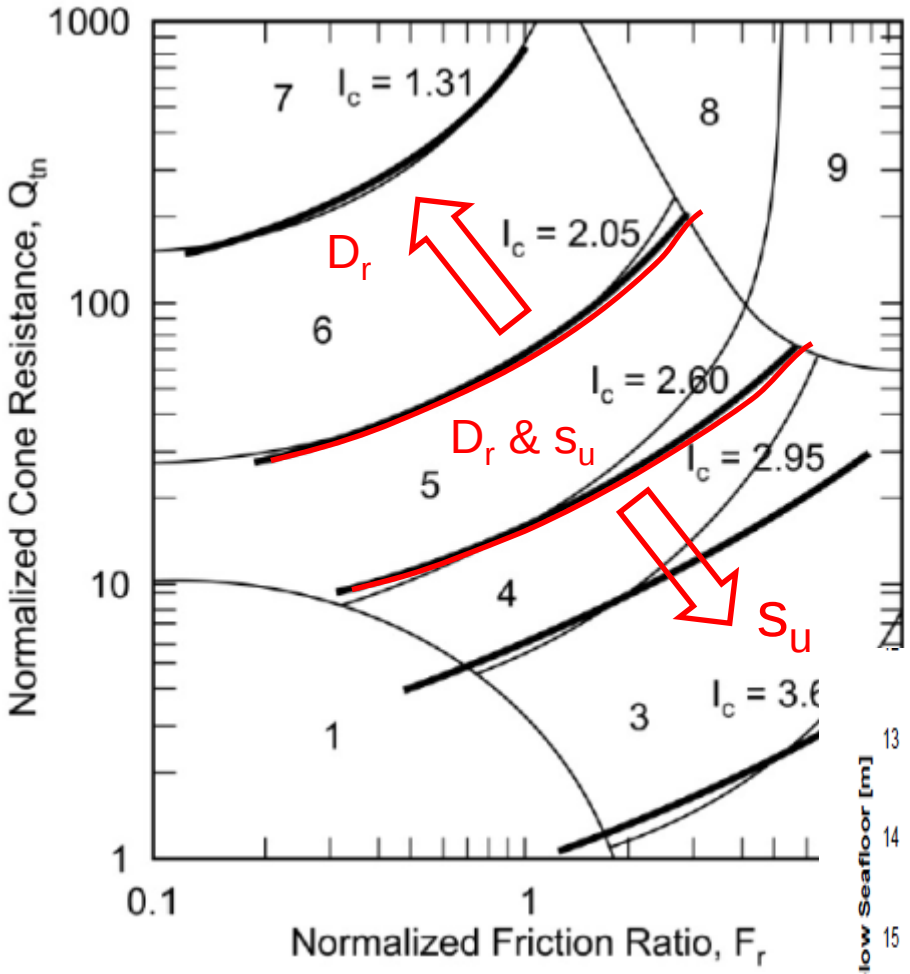
Geological Site Investigation – Data Interpretation



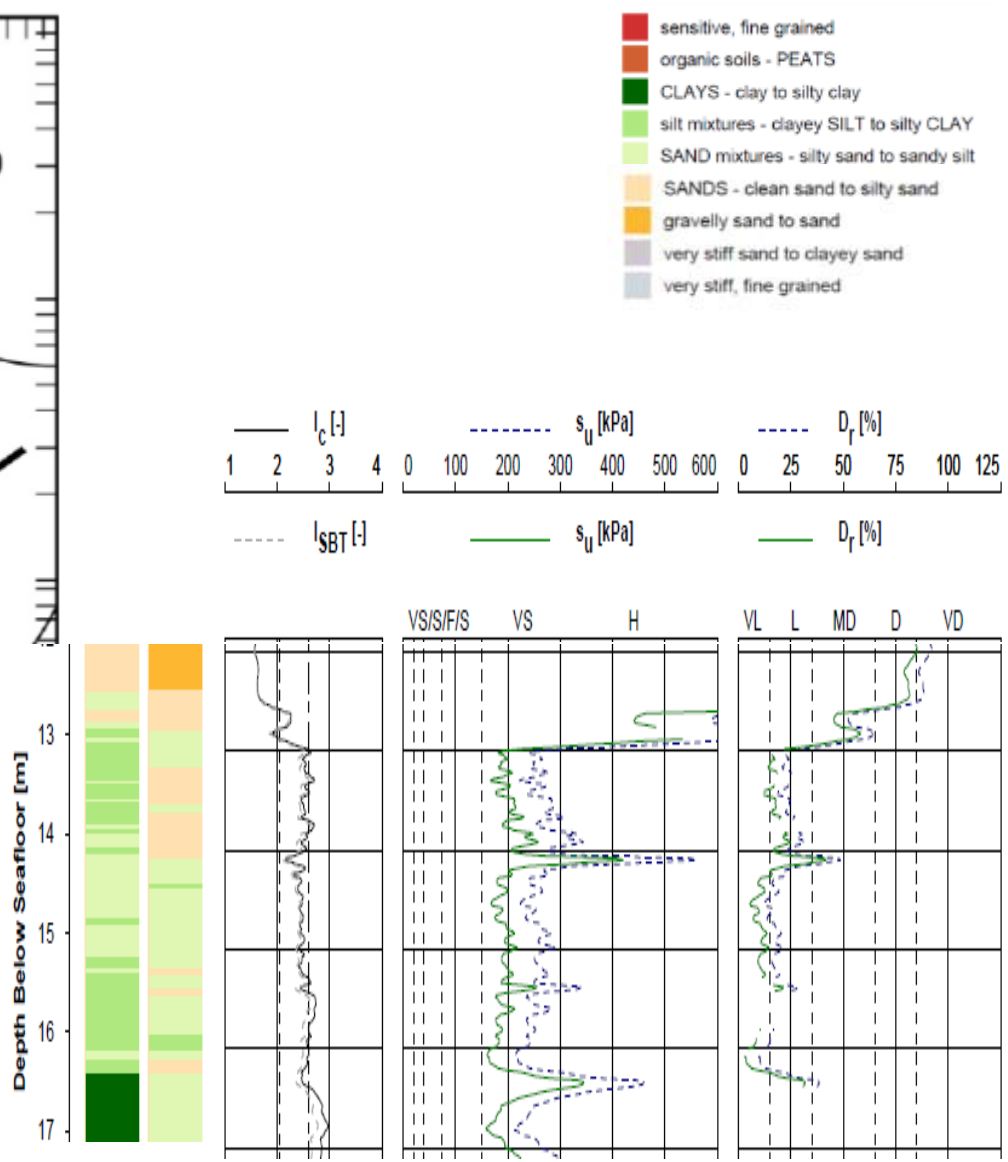
$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$$

Source: Robertson 1990, 2009 and 2010

Geological Site Investigation – Data Interpretation

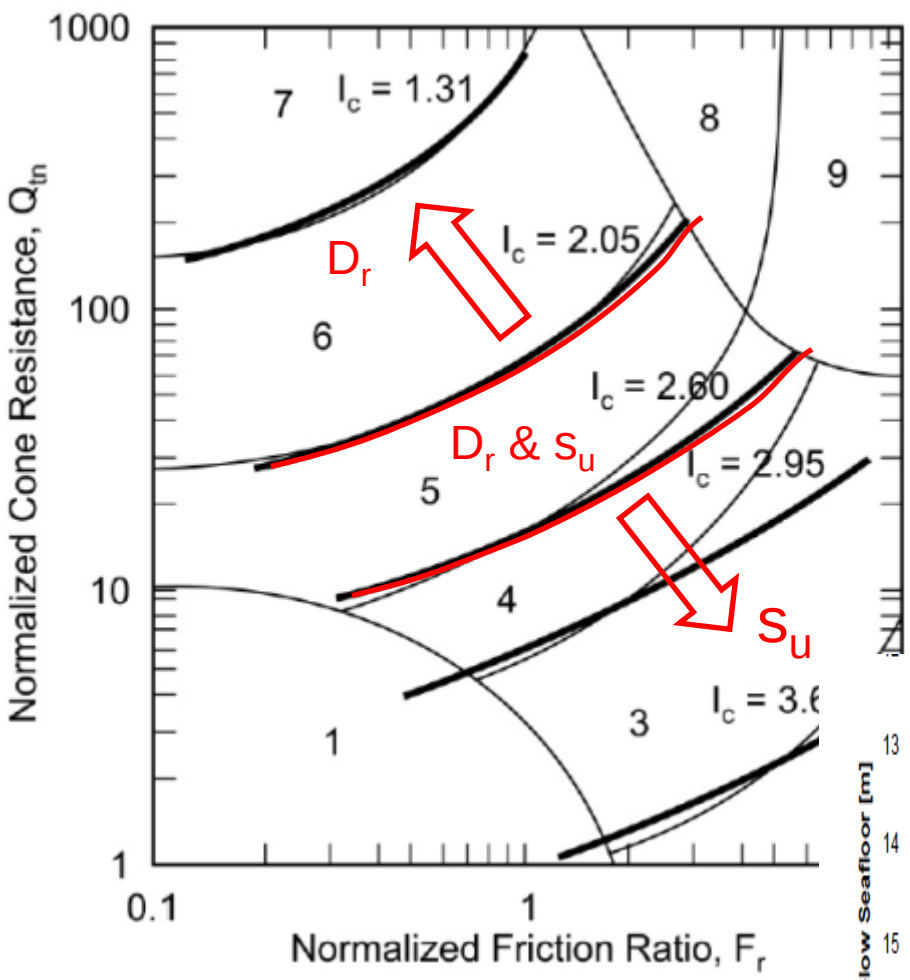


$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$$

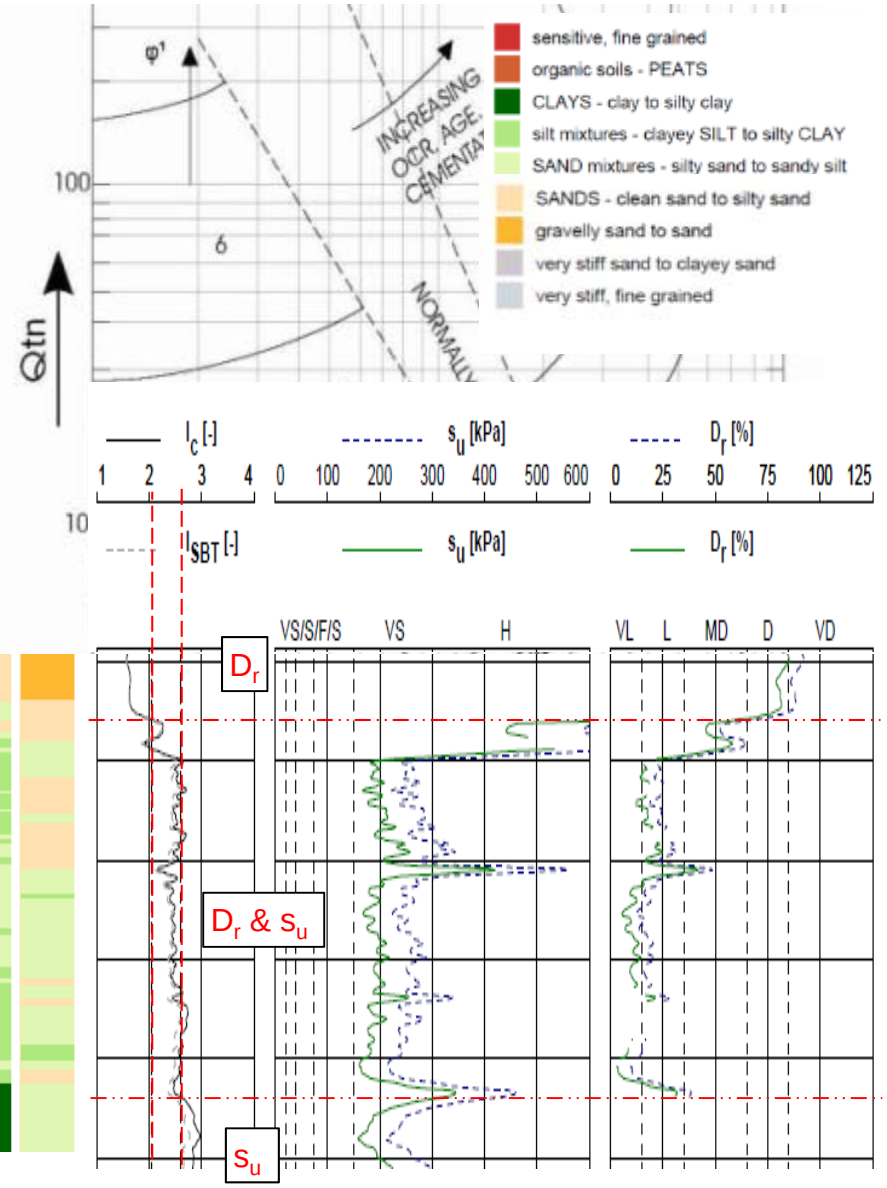


Source: Robertson 1990, 2009 and 2010

Geological Site Investigation – Data Interpretation

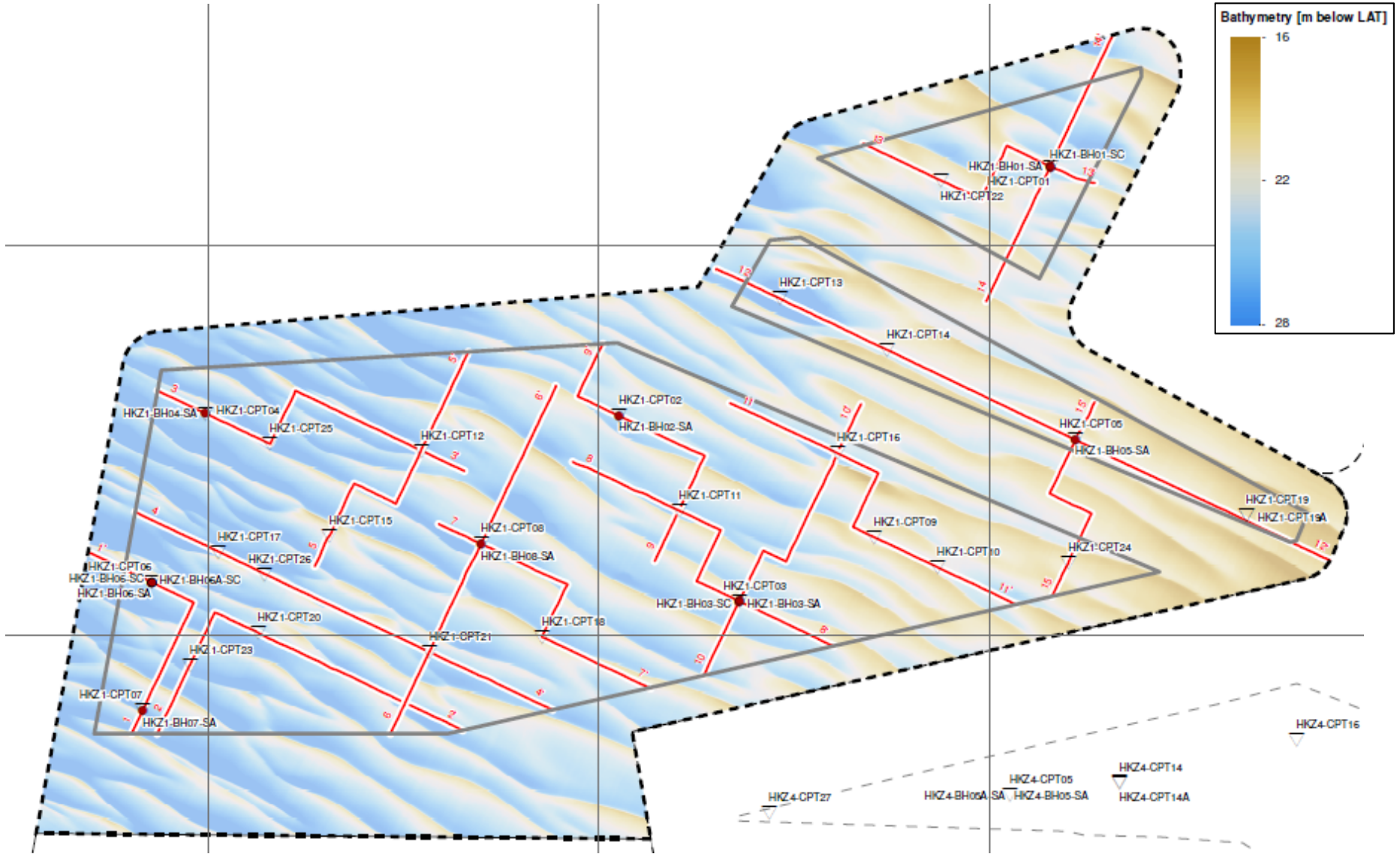


$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$$

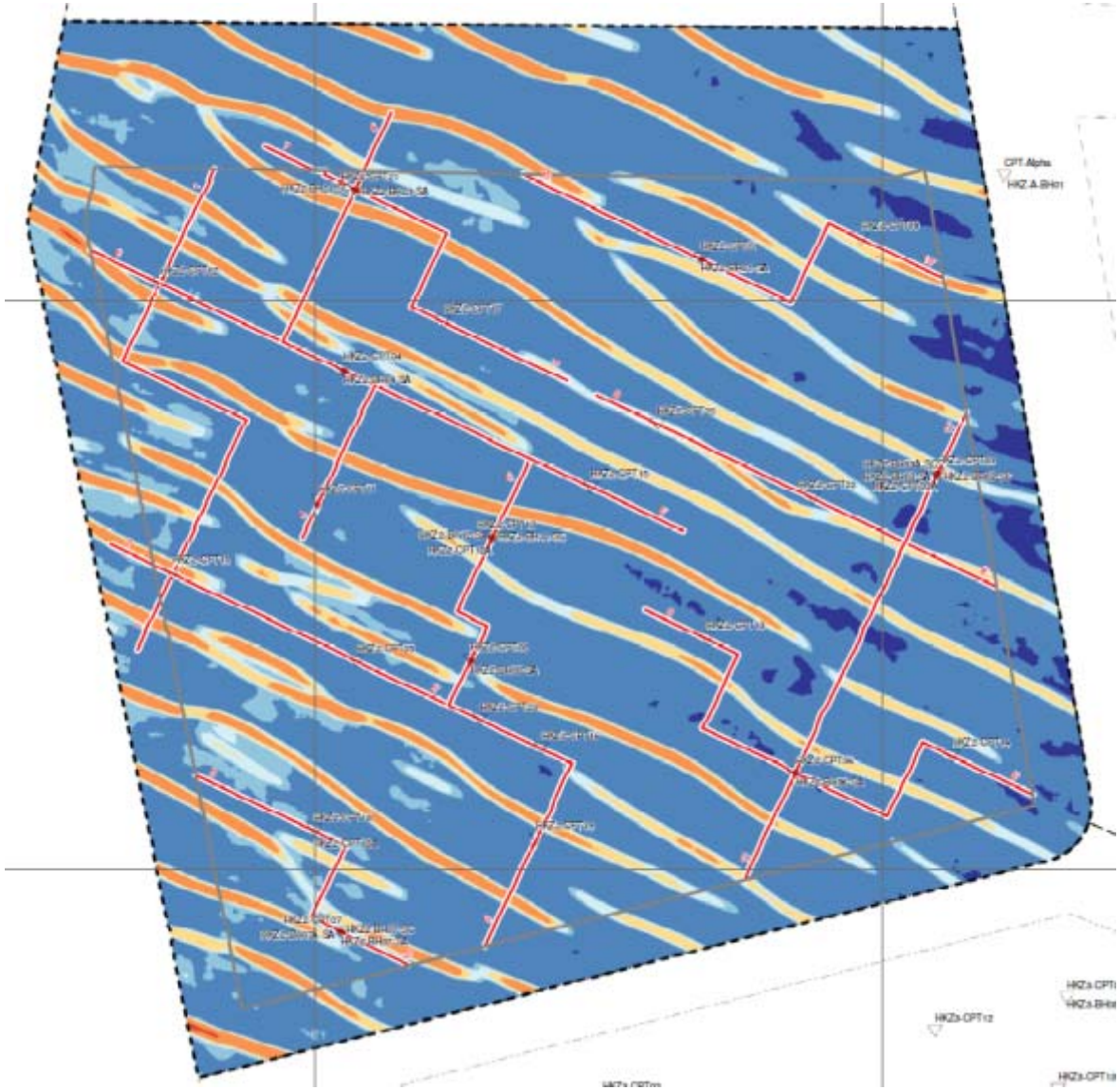


Source: Robertson 1990, 2009 and 2010

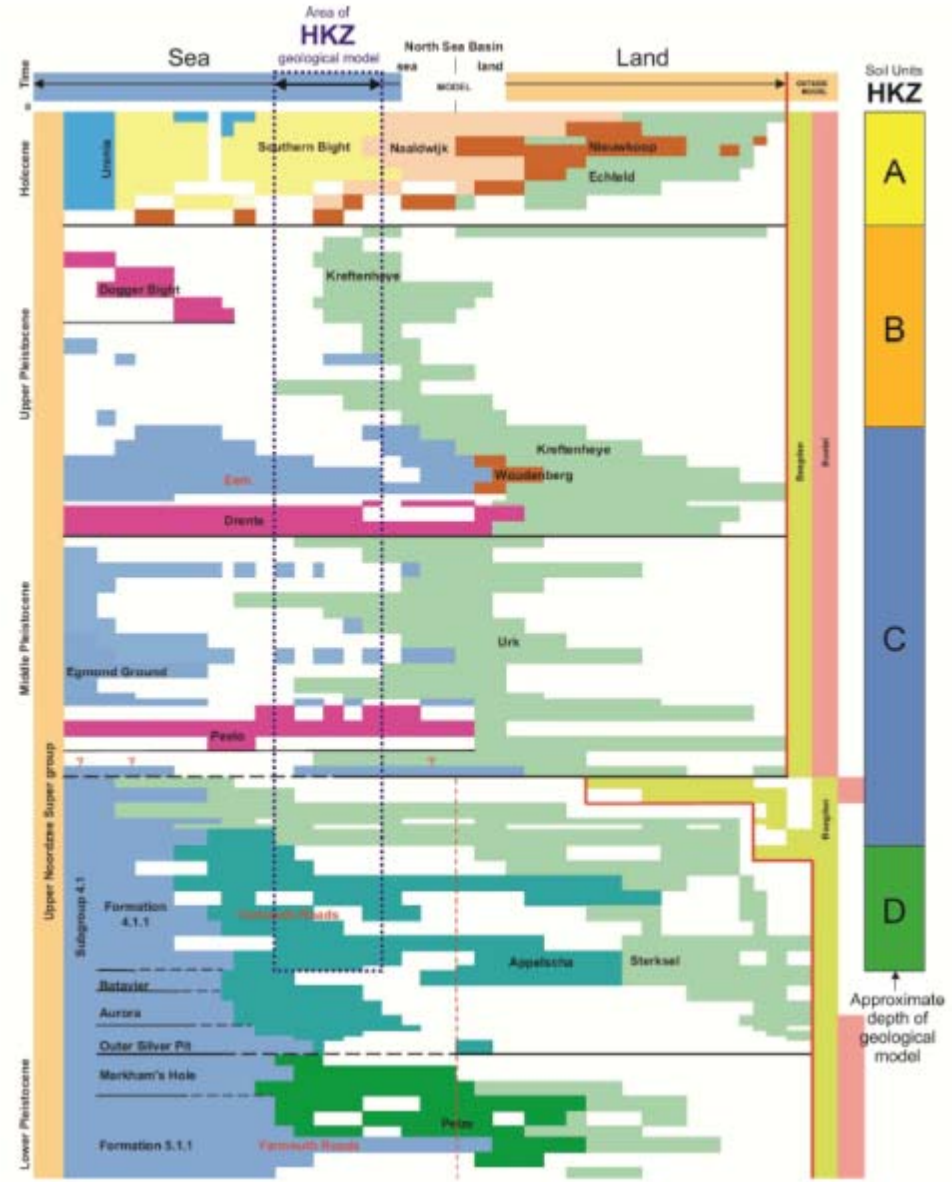
Geological Ground Model – Seafloor Conditions WFSI



Geological Ground Model – Seafloor Conditions WFSII



Geological Ground Model – Lithostratigraphic Framework



Marine deposits

- Undivided
- open marine, low energy
- open marine, high energy
- coastal and lagoonal deposits

Fluvial deposits

- Fluvial, Rhine / Meuse
- Fluvial, Eridanos (Baltic)
- Fluvial, Middle Germany / Bohemian
- Fluvial, Proto Rhine / Meuse

Glacial deposits

- Undivided

Peat

- Peat

Meuse system

- Fluvial deposits of the Meuse (terraces)

Local terrestrial deposits

- Undivided

Source: Rijsdijk et al., 2005

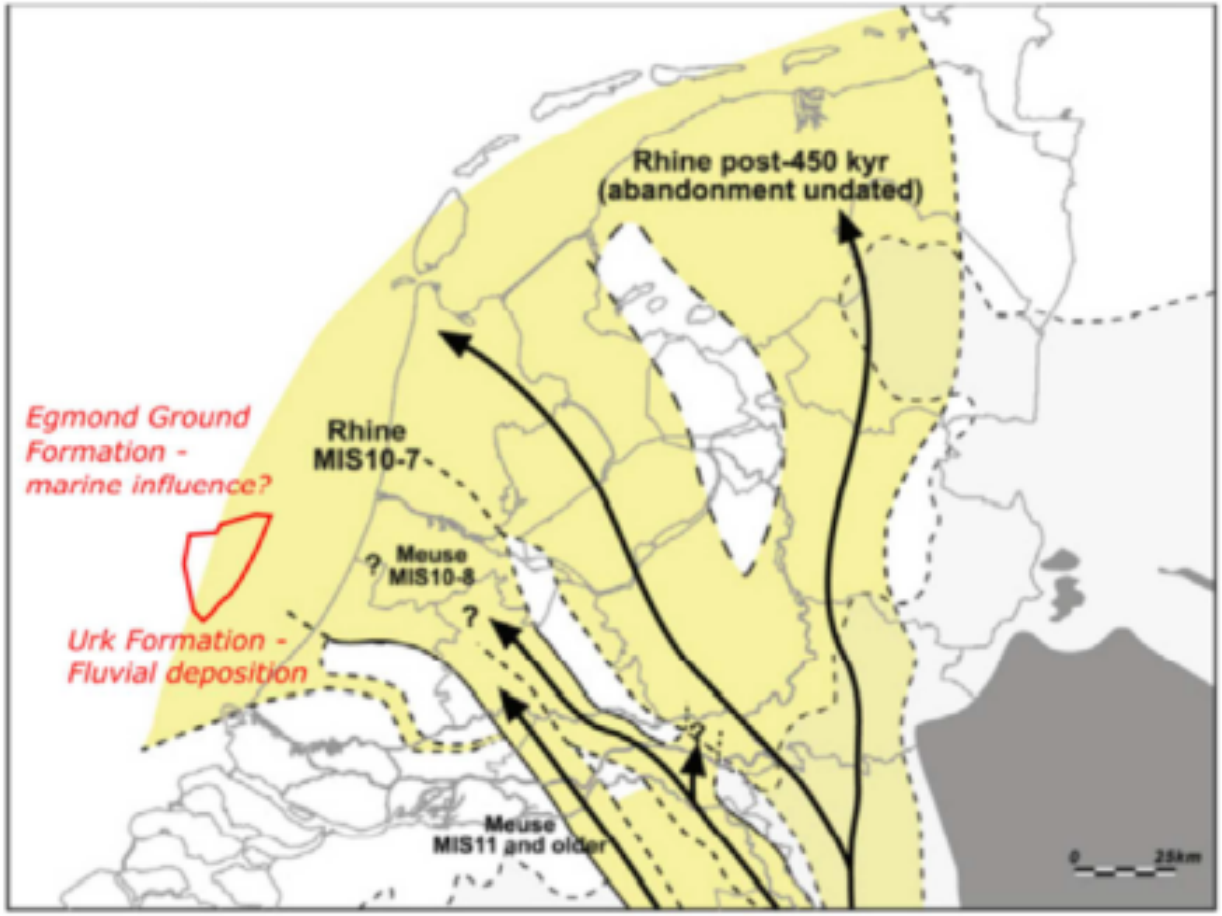
Geological Ground Model – Lithostratigraphic Framework

Soil Unit		Rijsdijk et al. 2005				Geological Dating Analysis	
Unit	Sub-unit	Formation	Member	Age	Epoch	Depositional Environment	Age
A		Southern Bight	Bligh Bank	Holocene	Holocene	marine	Holocene
B	B1	Kreftenheye		Weichselian Eemian (Saalian)	Upper Pleistocene Holocene	fluvial to coastal plain	Weichselian
	B2					lacustrine	Weichselian (prior to LGM)
C	C1	Eem Drente Egmond Ground Urk	Brown Bank	Eemian Saalian Holsteinian	Middle to Upper Pleistocene	marine	Eemian (Early Late Pleistocene)
	C2					fluvio-deltaic to estuarine to coastal plain with marine influences	Cromerian to Saalian (Middle Pleistocene)
D		Yarmouth Roads (possibly Winterton Shoal, Ijmuiden Ground)		Elsterian Waalian	Lower Pleistocene	fluvio-lacustrine	Tiglian(?) to Waalian (Early to Middle Pleistocene)

Source:
Rijsdijk, K.F., Passchier, S., Weerts, H.J.T., Laban, C., Van Leeuwen, R.J.W., and Ebbing, J.H.J., 2005. Revised Upper Cenozoic Stratigraphy of the Dutch Sector of the North Sea Basin: towards an Integrated Lithostratigraphic, Seismostratigraphic and Allostratigraphic Approach. Netherlands Journal of Geosciences – Geologie en Mijnbouw, Vol. 84, No. 2, p. 129-146.

Geological Ground Model – Site Settings

Prior to Saalian glaciation:
Soil Unit C - Urk Fm/Egmond Ground Fm

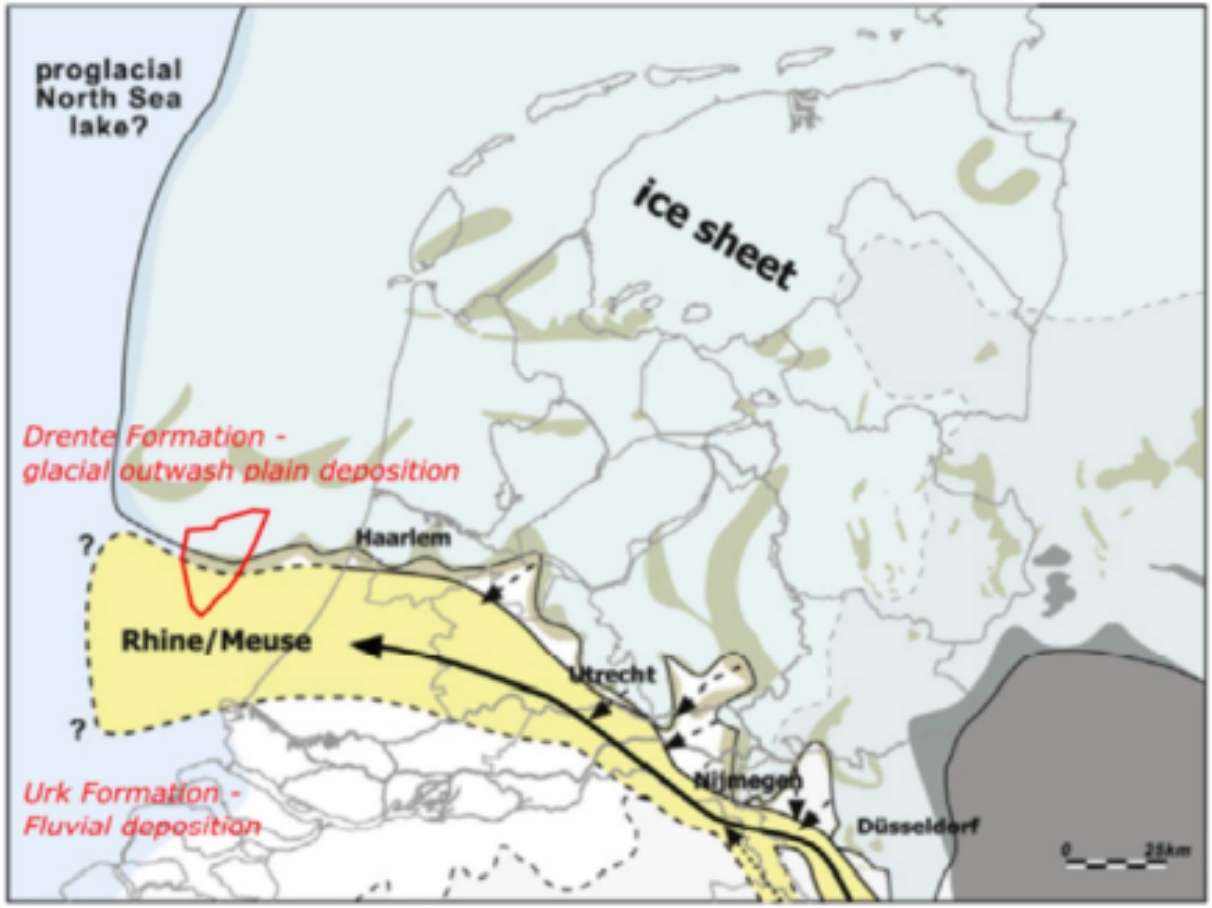


Legend

- 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 (zuid) WFZ

Geological Ground Model – Site Settings

Saalian maximum ice extent: Soil Unit C - Urk Fm/Drente Fm



Legend

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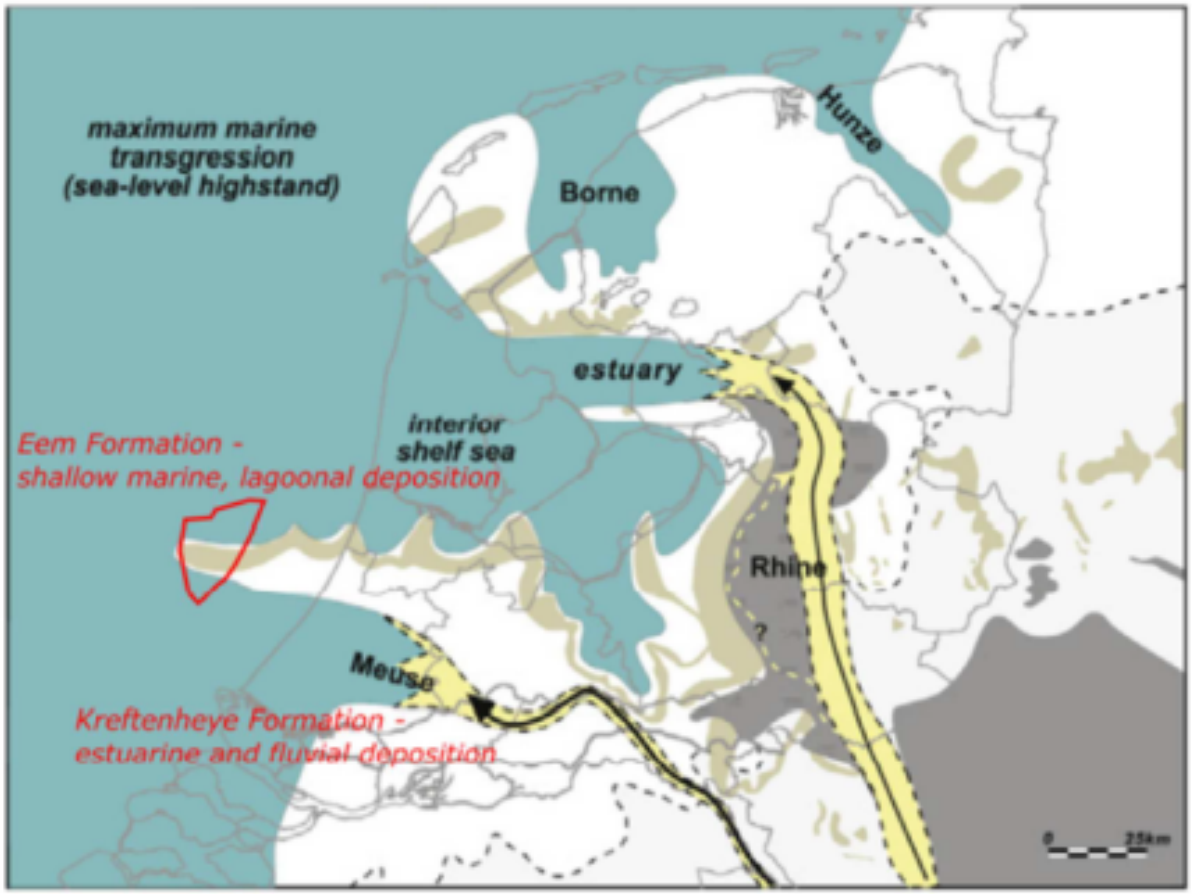
- Present topography >10m a.s.l.
- Paleozoic/Mesozoic
- Ice-pushed ridges
- High-stand sea
- Proglacial lake
- Subglacial basins
- Ice sheet
- Hollandse Kust (zuid) WFZ

Geological Ground Model – Site Settings

Eemian:
Soil Unit C: Eem Fm/Kreftenheye Fm

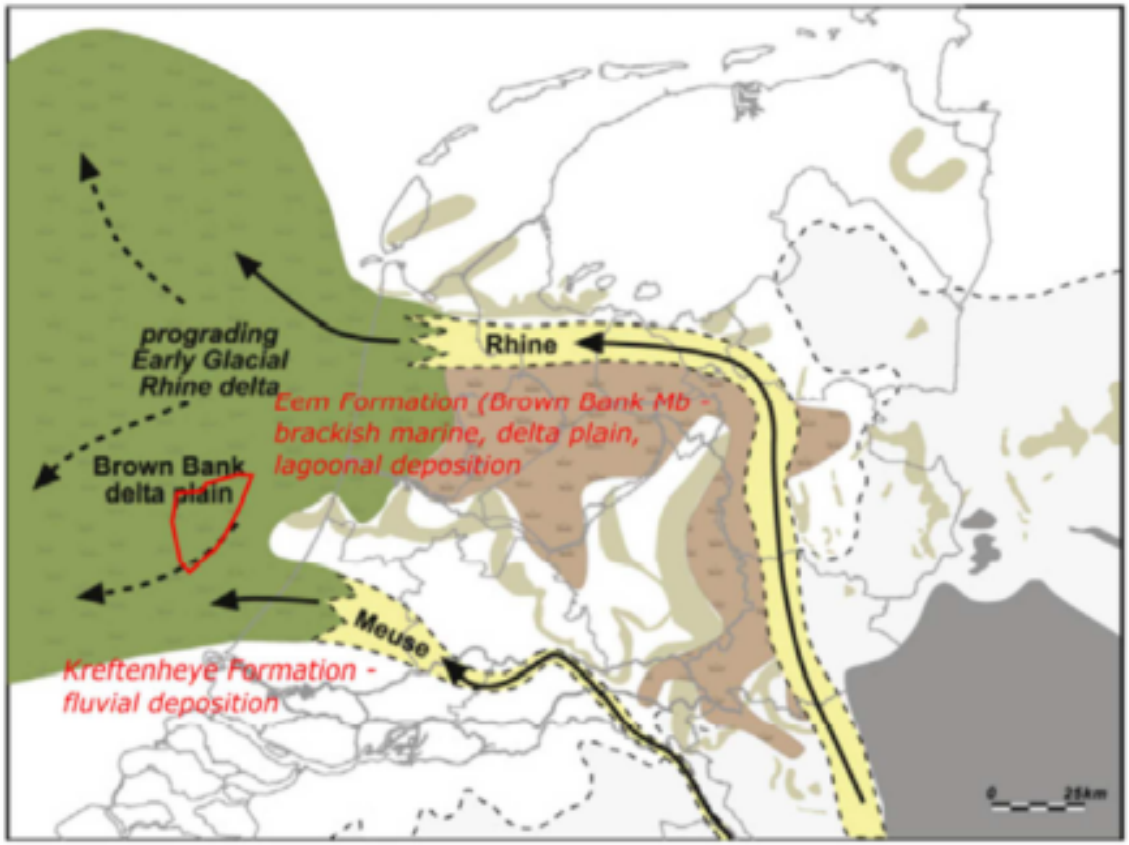


Legend

- 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 (zuid) WFZ

Geological Ground Model – Site Settings

Late Eemian Marine Regression/Early Weichselian: Soil Unit B: Kreftenheye Fm/Brown Bank Mb

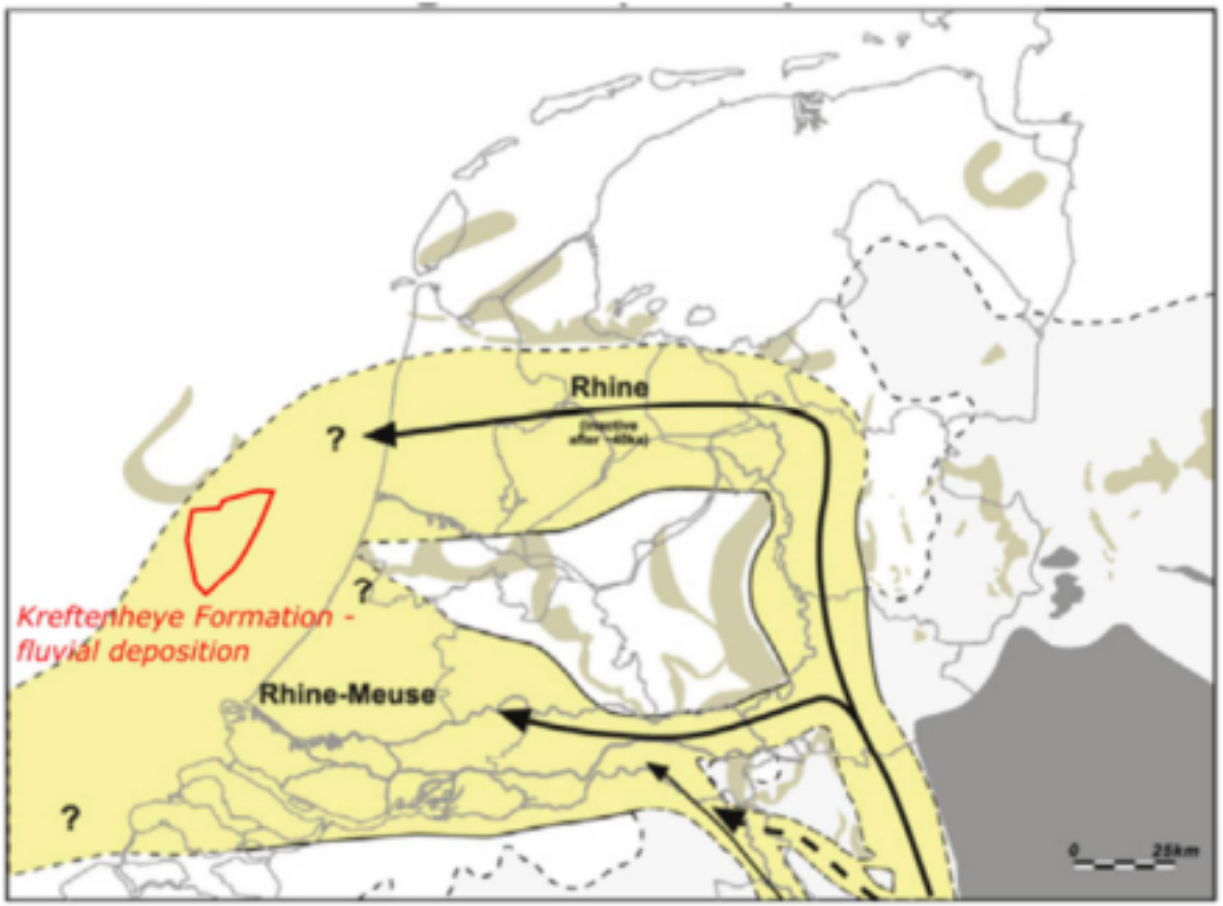


Legend

- 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 (zuid) WFZ

Geological Ground Model – Site Settings

Middle Weichselian:
Soil Unit B: Kreftenheye Formation



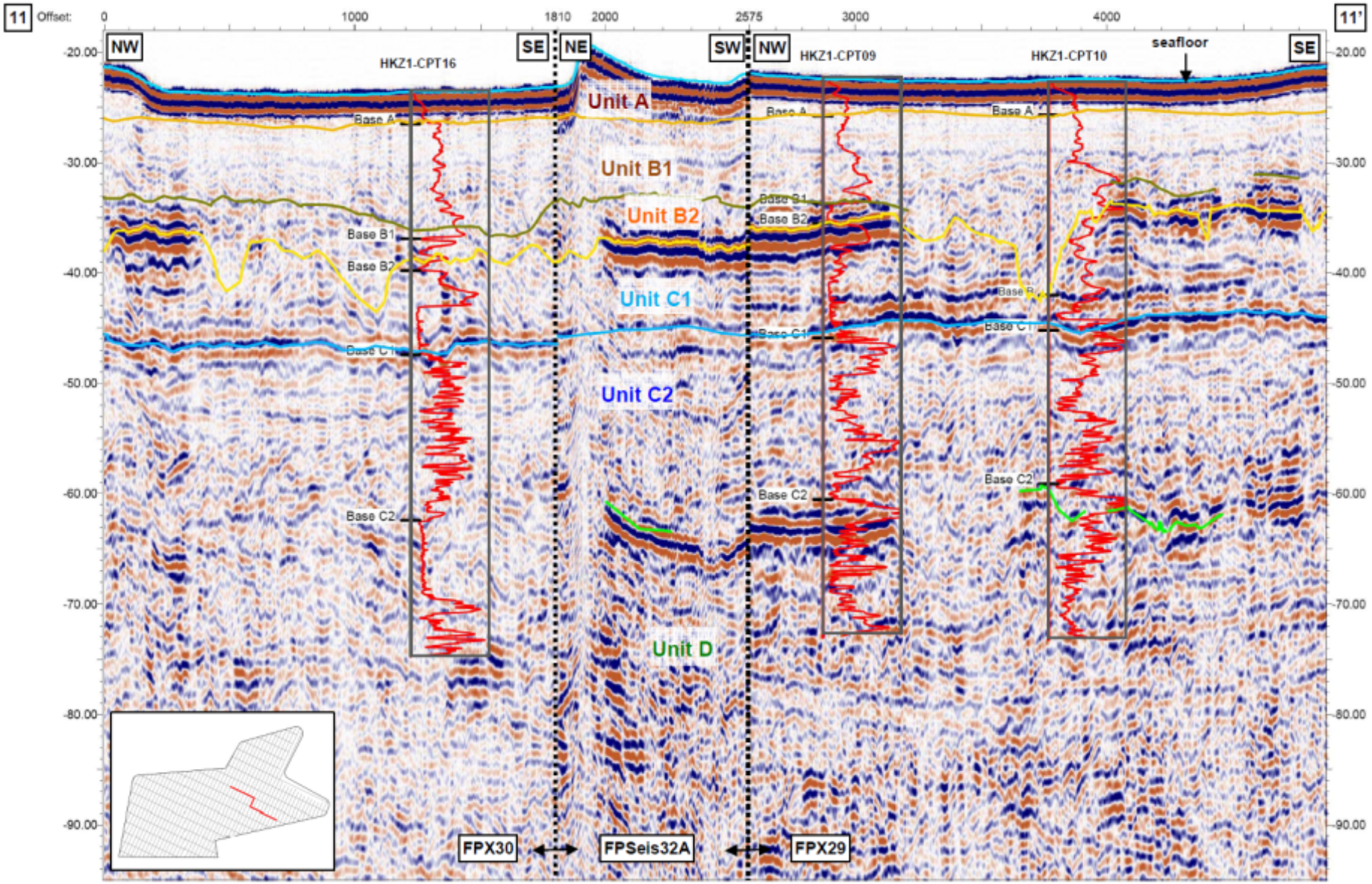
Legend

- 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 (zuid) WFZ

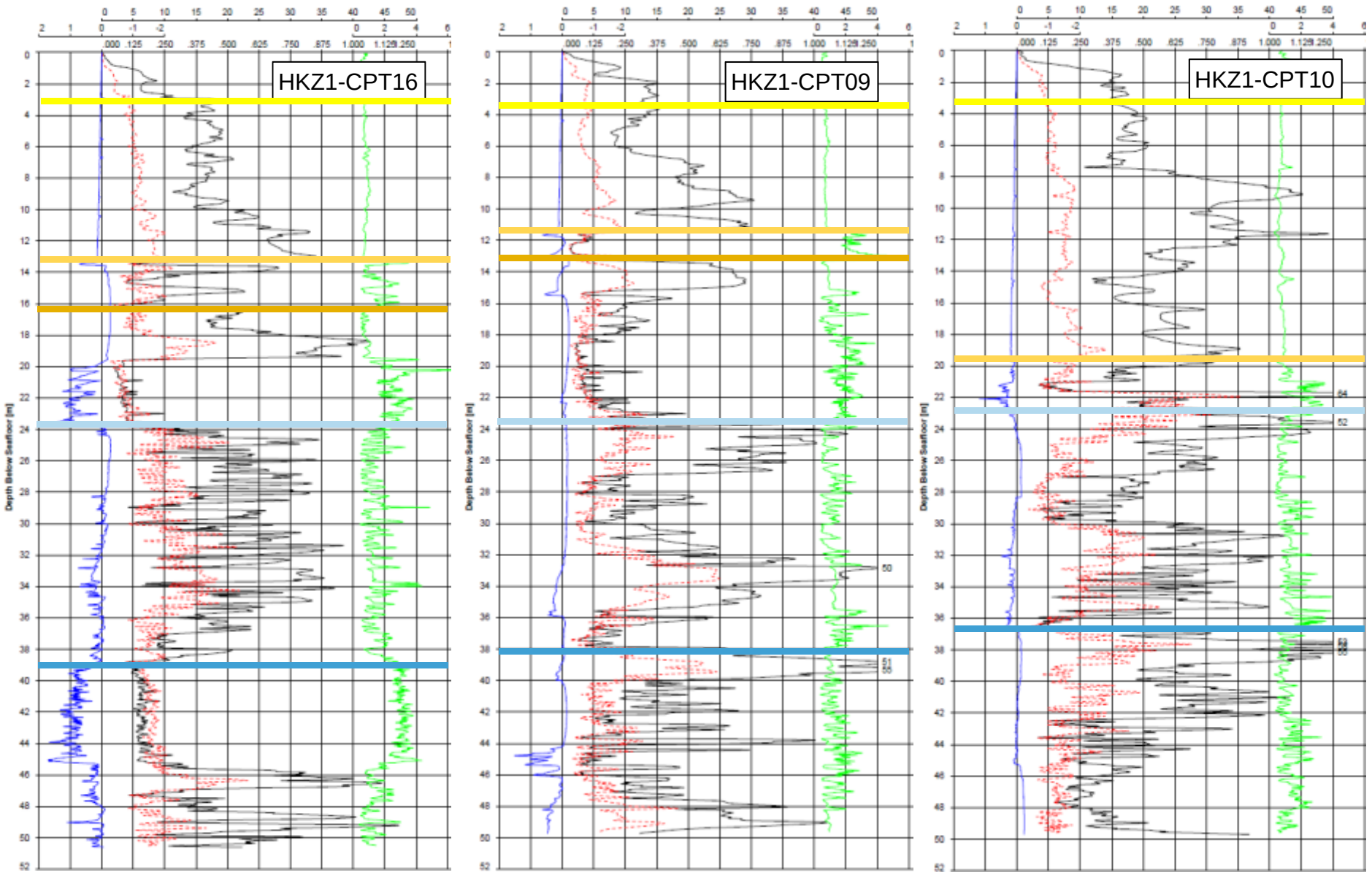
Geological Ground Model – Site Settings

Soil Unit	Soil Sub Unit	WFS I Depth to Base of Unit [m LAT]	WFS II Depth to Base of Unit [m LAT]	WFS I Thickness Range [m]	WFS II Thickness Range [m]	Soil Description
A	-	23 to 31	25 to 30	1 to 8	1 to 8	Dense to very dense silica fine to coarse SAND with shell fragments
B	B1	31 to 53	33 to 51	6 to 24	5 to 24	Dense to very dense silica fine to medium SAND
	B2					Firm to hard clay to calcareous CLAY, with laminae of sand and silt
C	C1	41 to 50	-	0 to 13	-	Interbedded medium dense to very dense silica SAND and firm to hard calcareous CLAY
	C2	54 to 78	53 to 71	10 to 38	10 to 32	Medium dense to dense silica fine to medium SAND, with laminae and beds of clay/silt
D	-	> 90	> 90	> 12	> 15	Medium dense to dense silica fine to coarse (silty/clayey) SAND with laminae of clay; and very stiff to hard (sandy) CLAY with laminae of sand

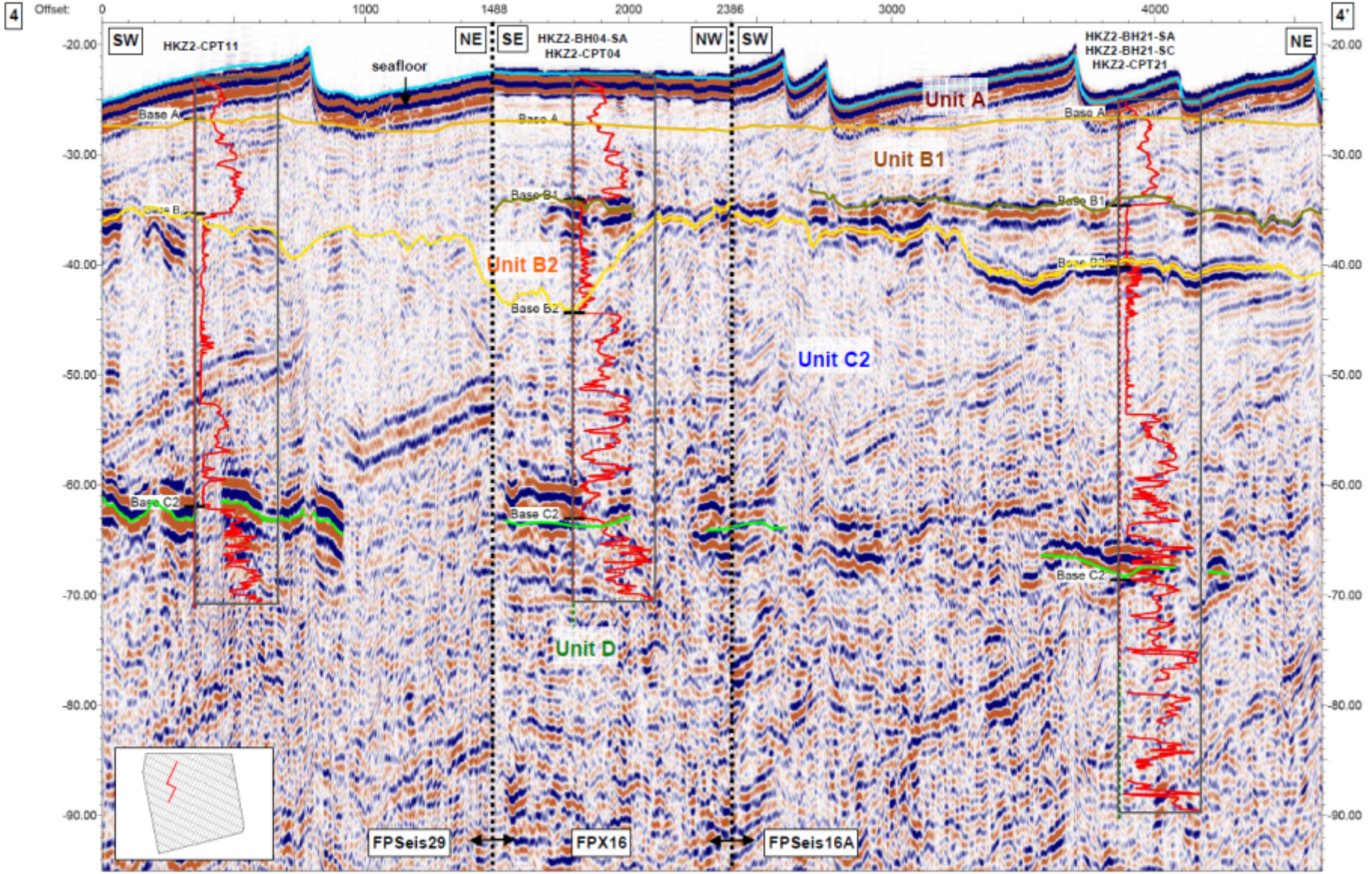
Geological Ground Model – Site Settings



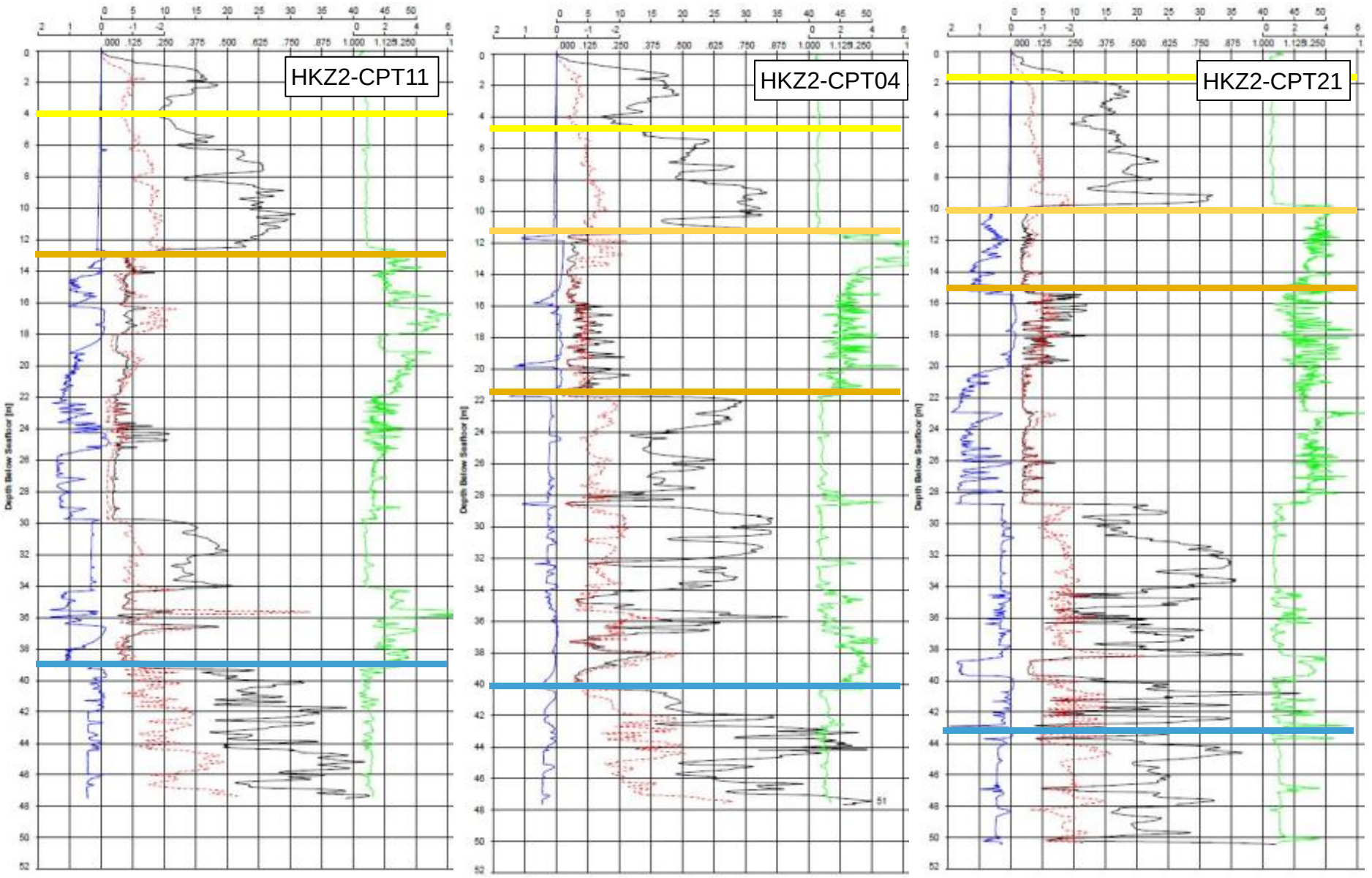
Geological Ground Model – Site Settings



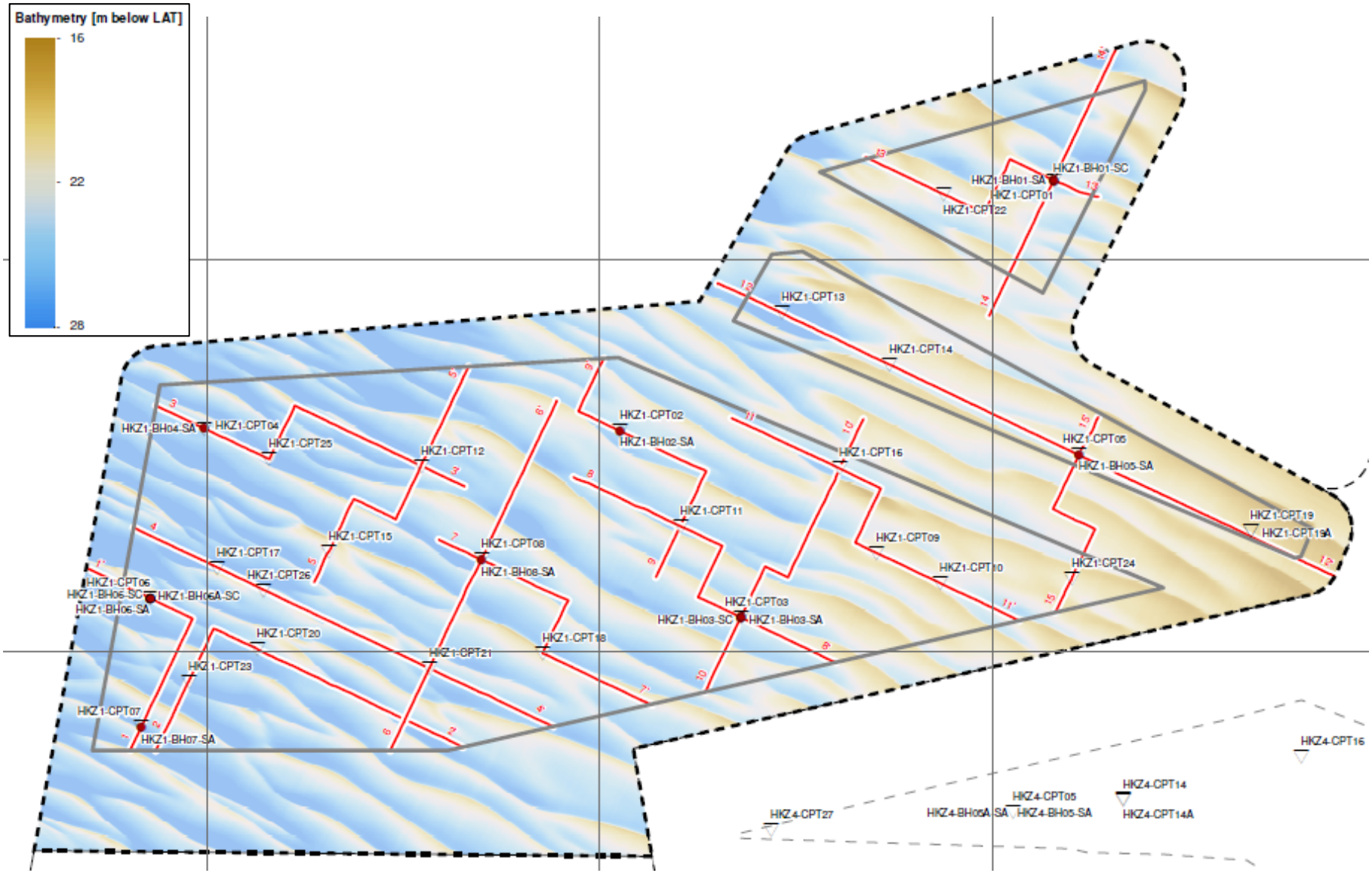
Geological Ground Model – Site Settings



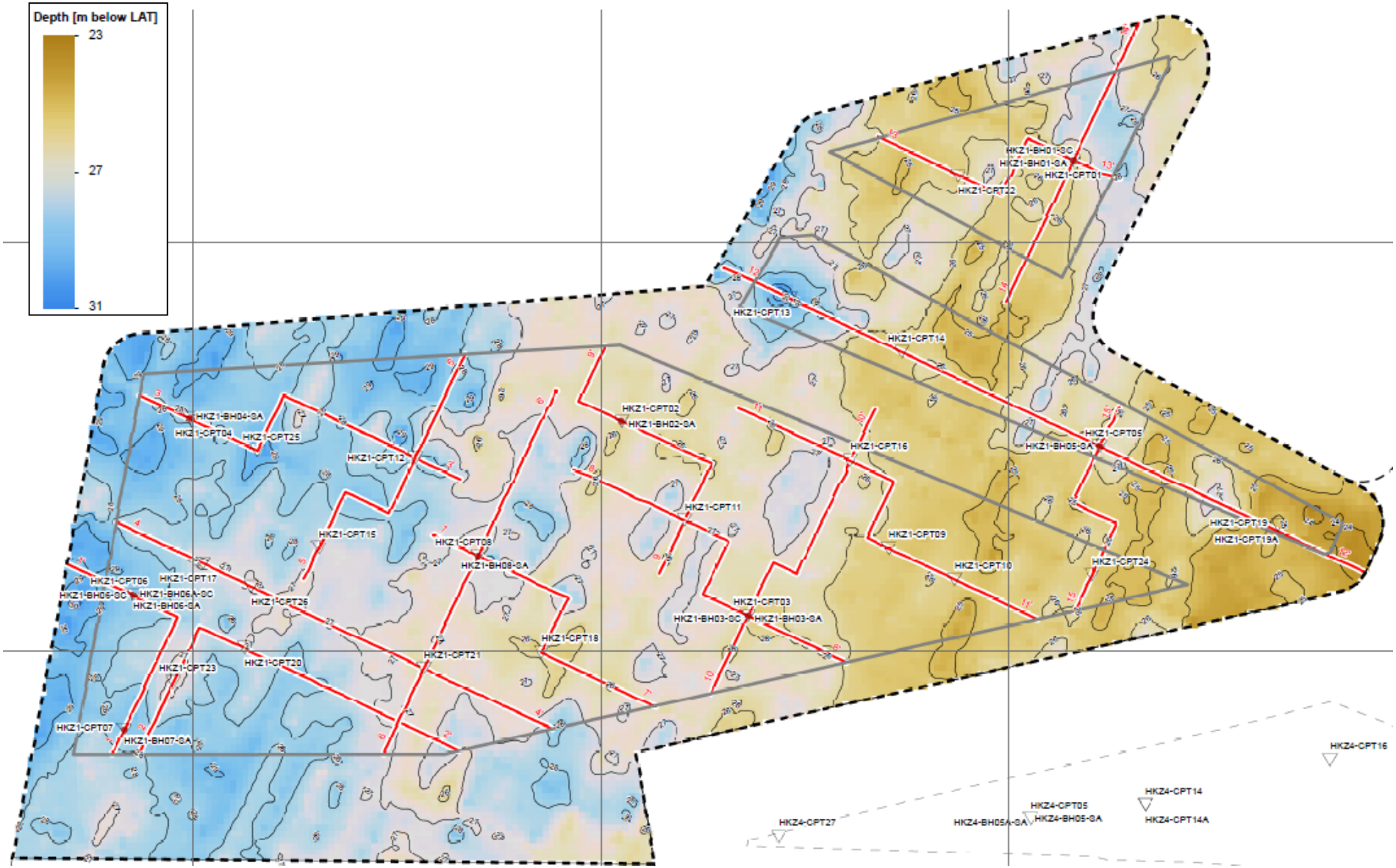
Geological Ground Model – Site Settings



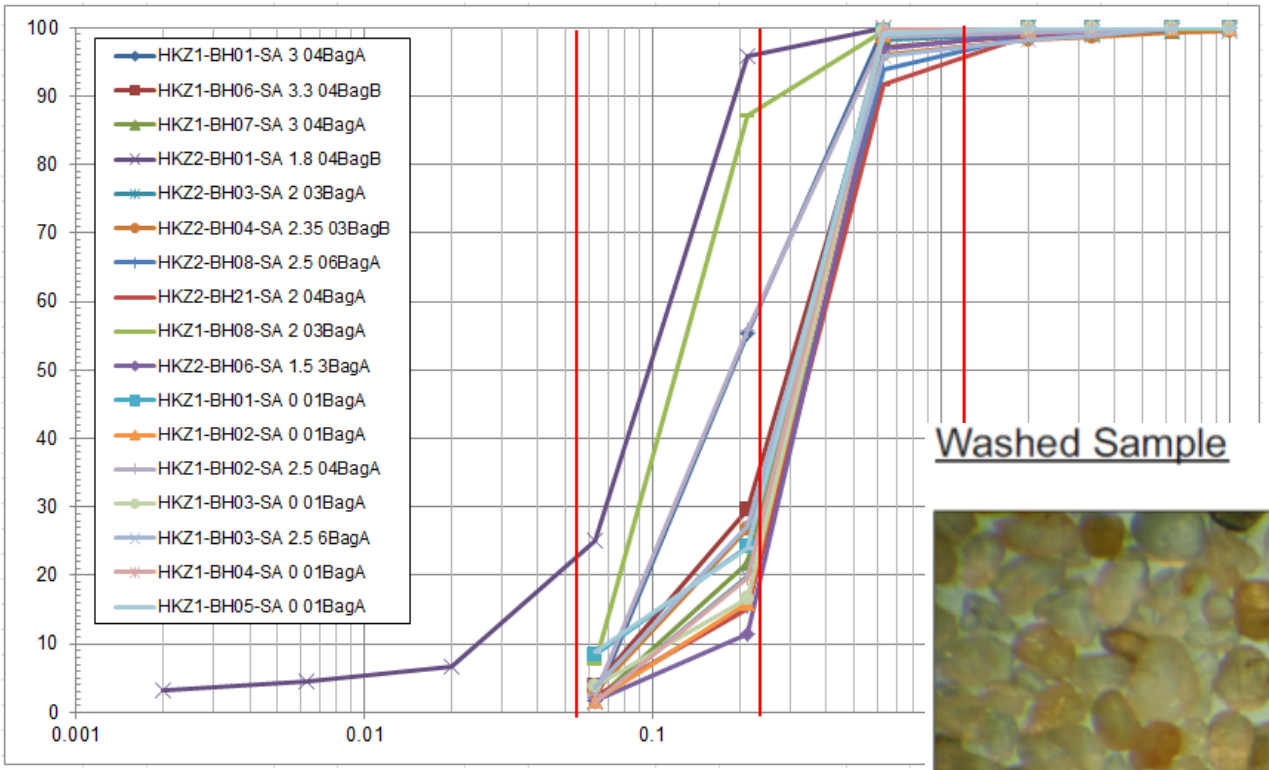
Geological Ground Model – Seafloor Conditions WFSI



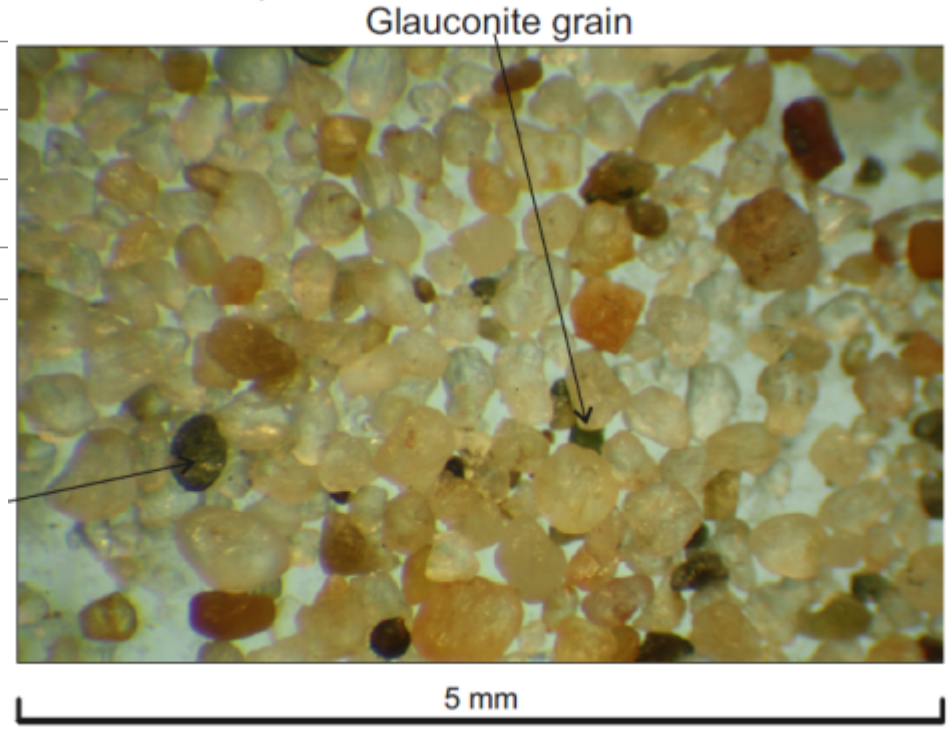
Geological Ground Model – Depth to Base Unit A



Geological Ground Model – Geotechnical Properties Unit A

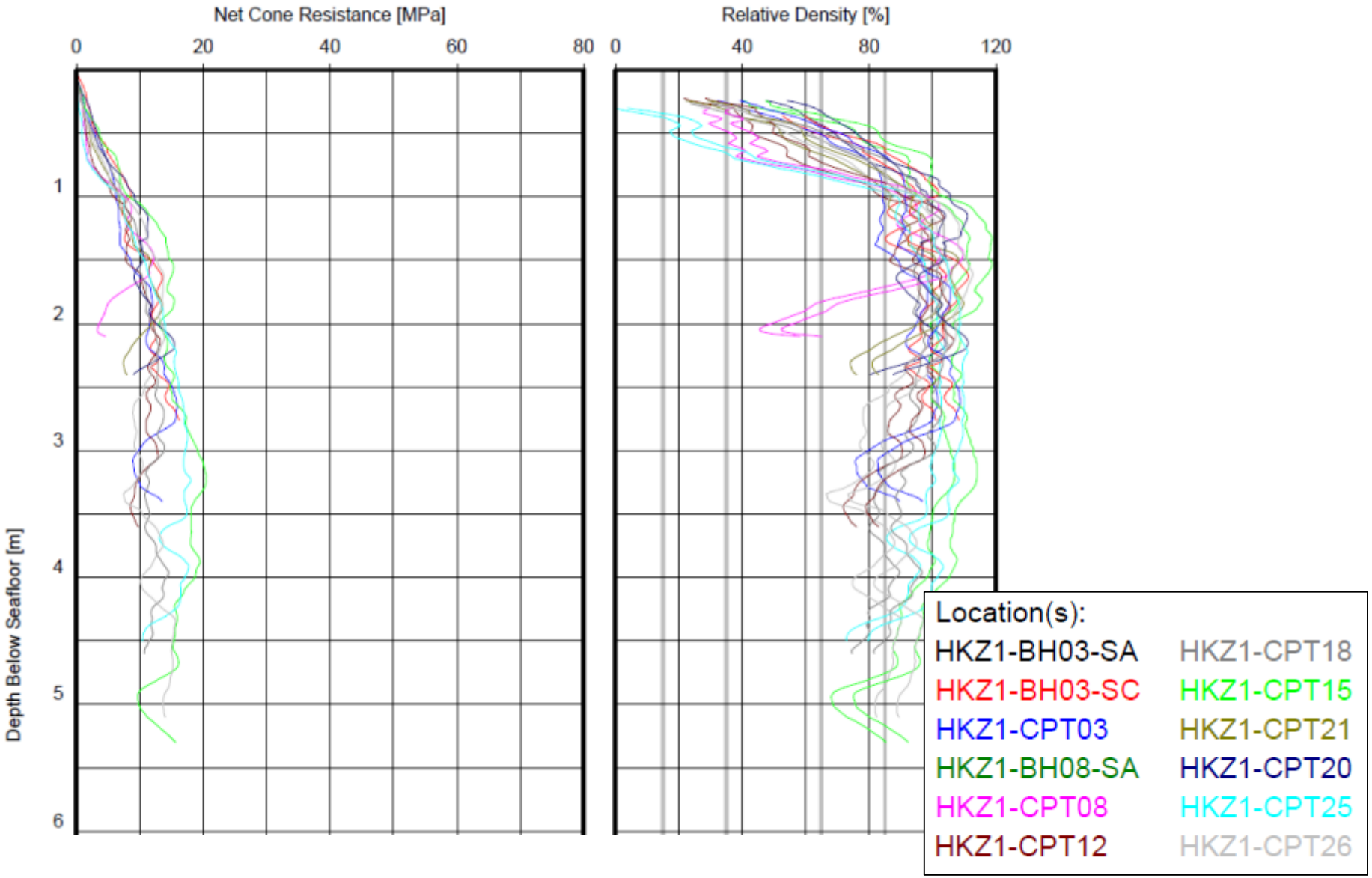


Washed Sample

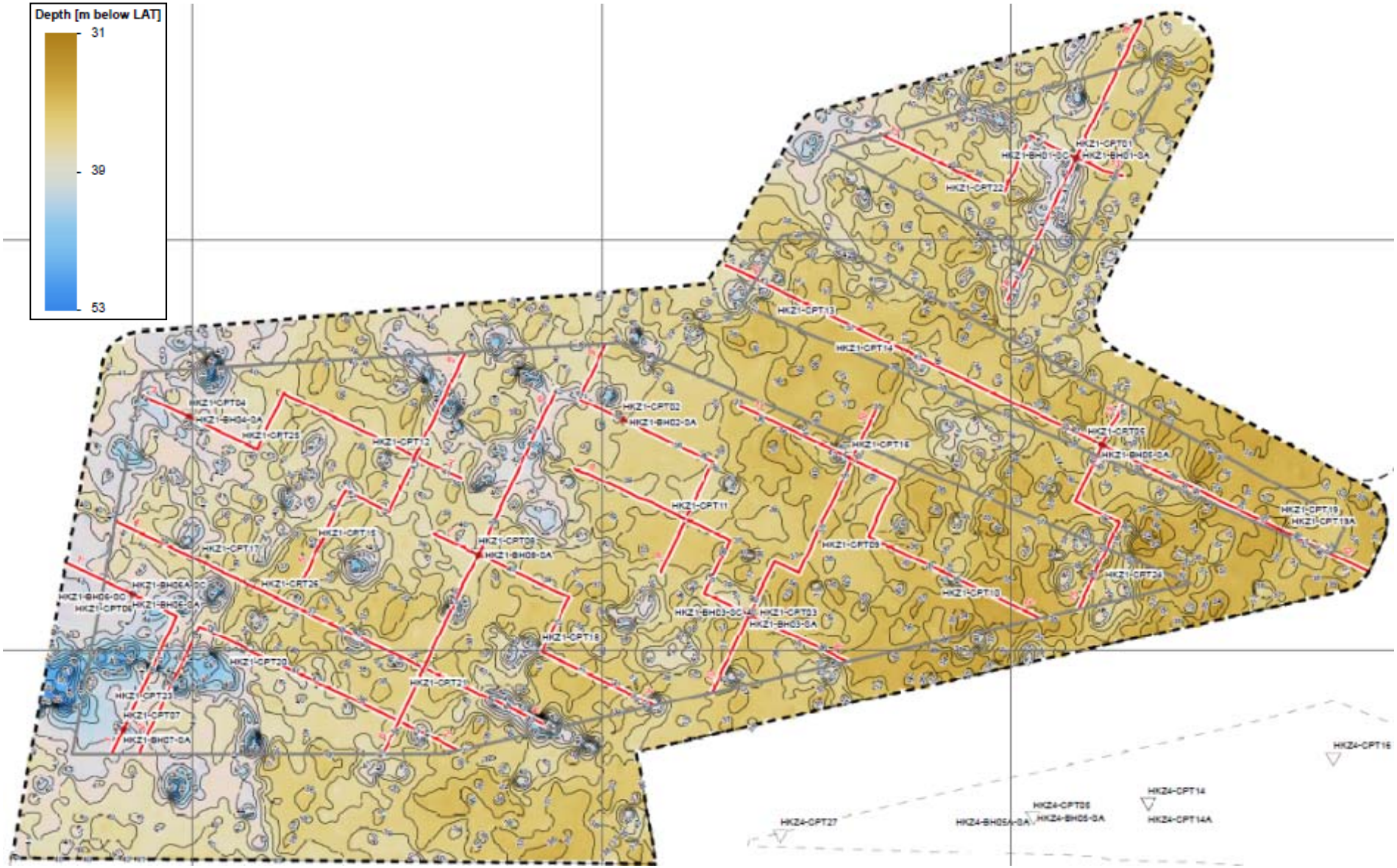


- Present across both WFS I & II
- Thickness from approximately 1 m up to 8 m
- Typically dense to very dense silica fine to coarse SAND
- Some variation across the sites
- Locally clayey and loose to medium dense sand

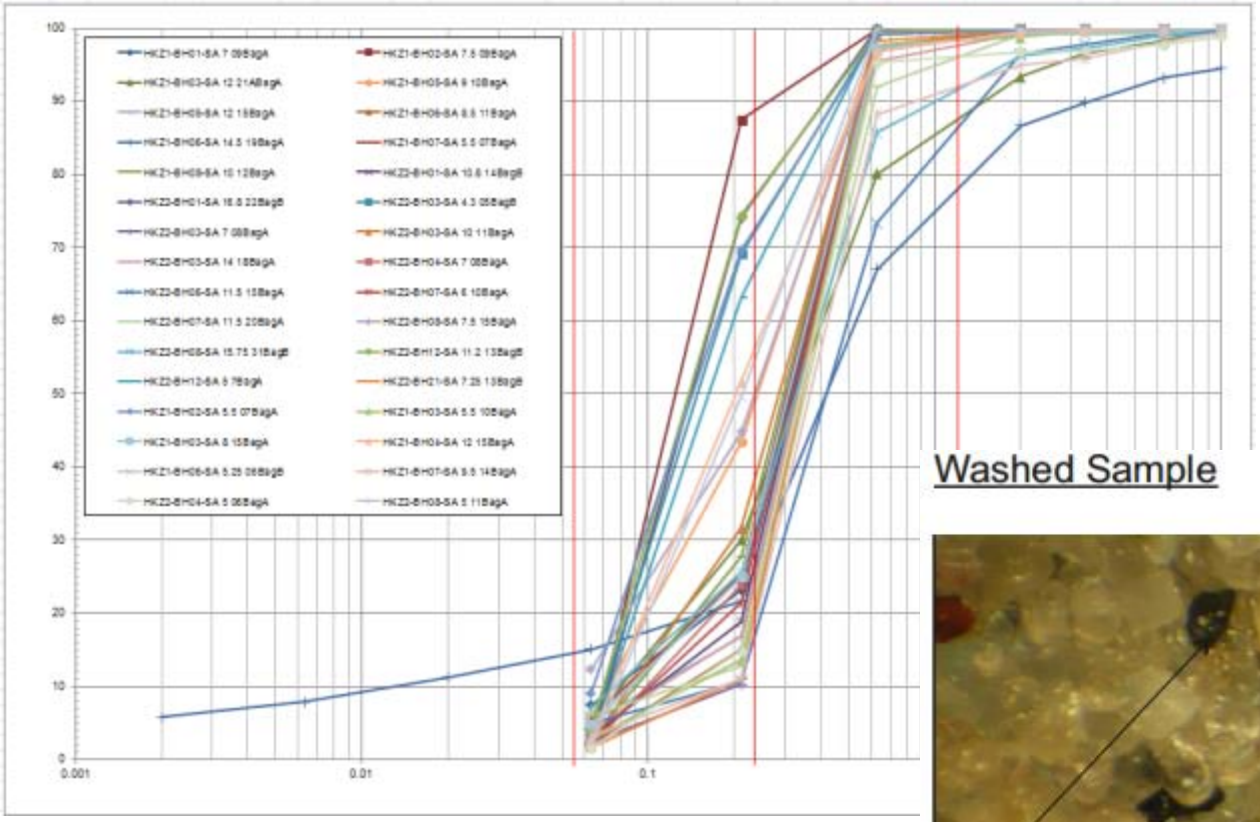
Geological Ground Model – Geotechnical Properties Unit A



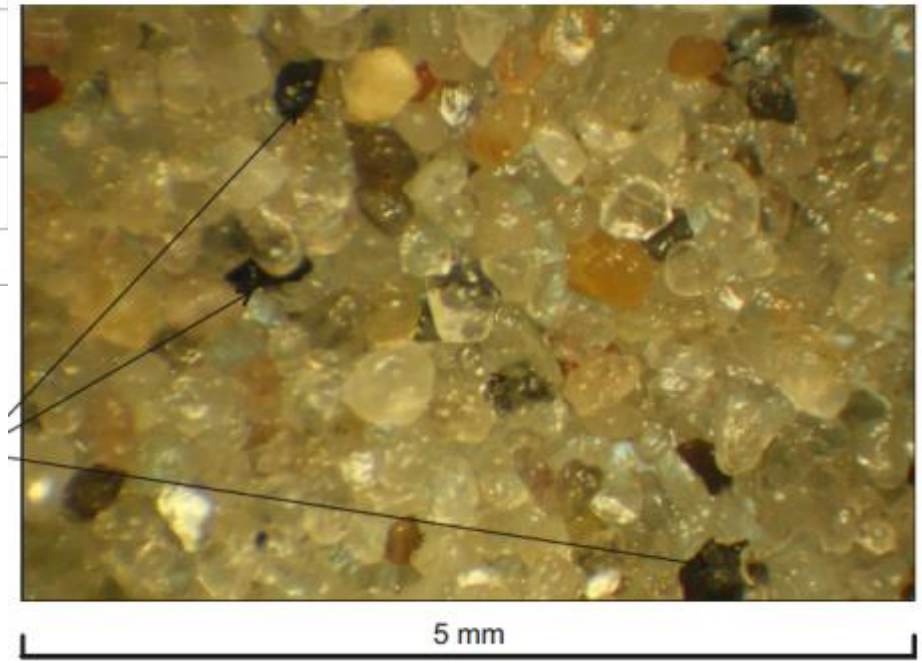
Geological Ground Model – Depth to Base Unit B (B1 and B2)



Geological Ground Model – Geotechnical Properties Unit B1

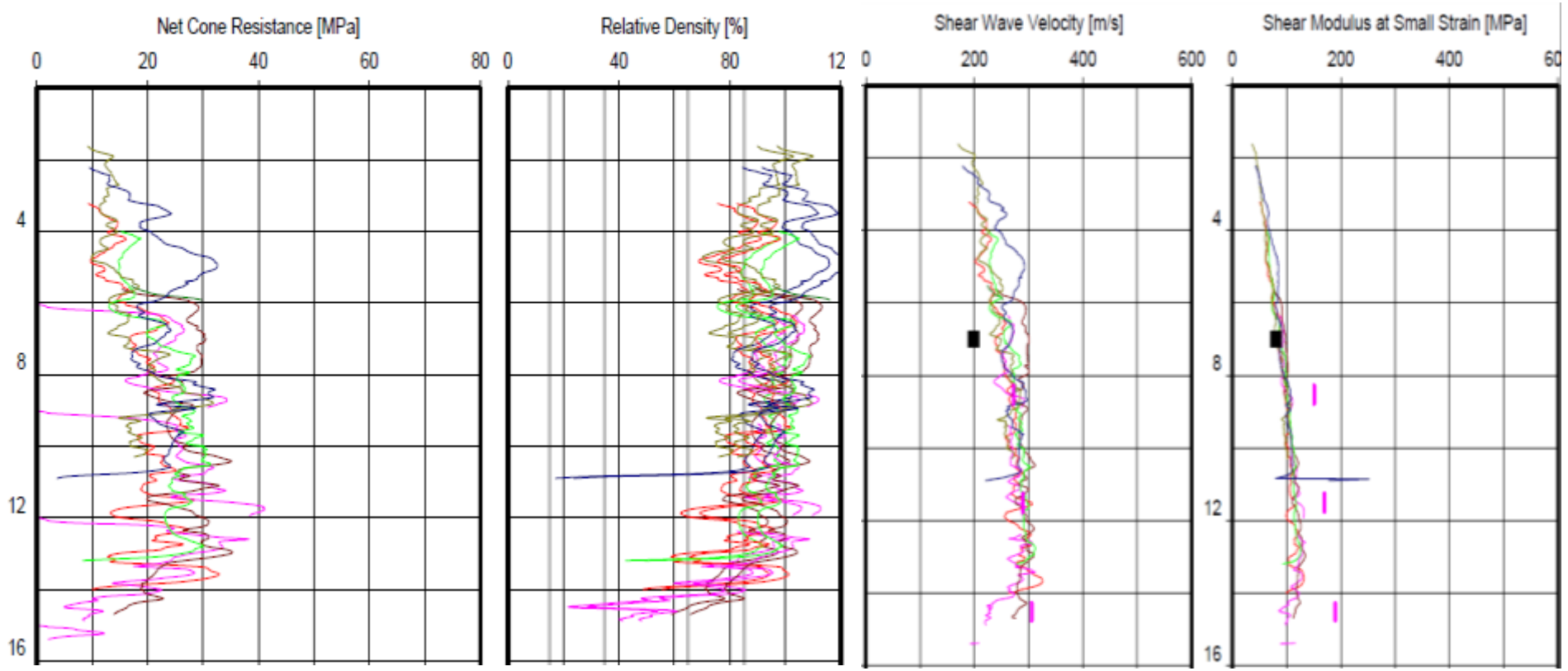


Washed Sample



- Present across both WFS I & II
- Thickness from approximately 6 m up to 24 m
- Typically dense to very dense silica fine to medium SAND
- Some variation across the sites
- Locally clayey and loose to medium dense sand

Geological Ground Model – Geotechnical Properties Unit B1



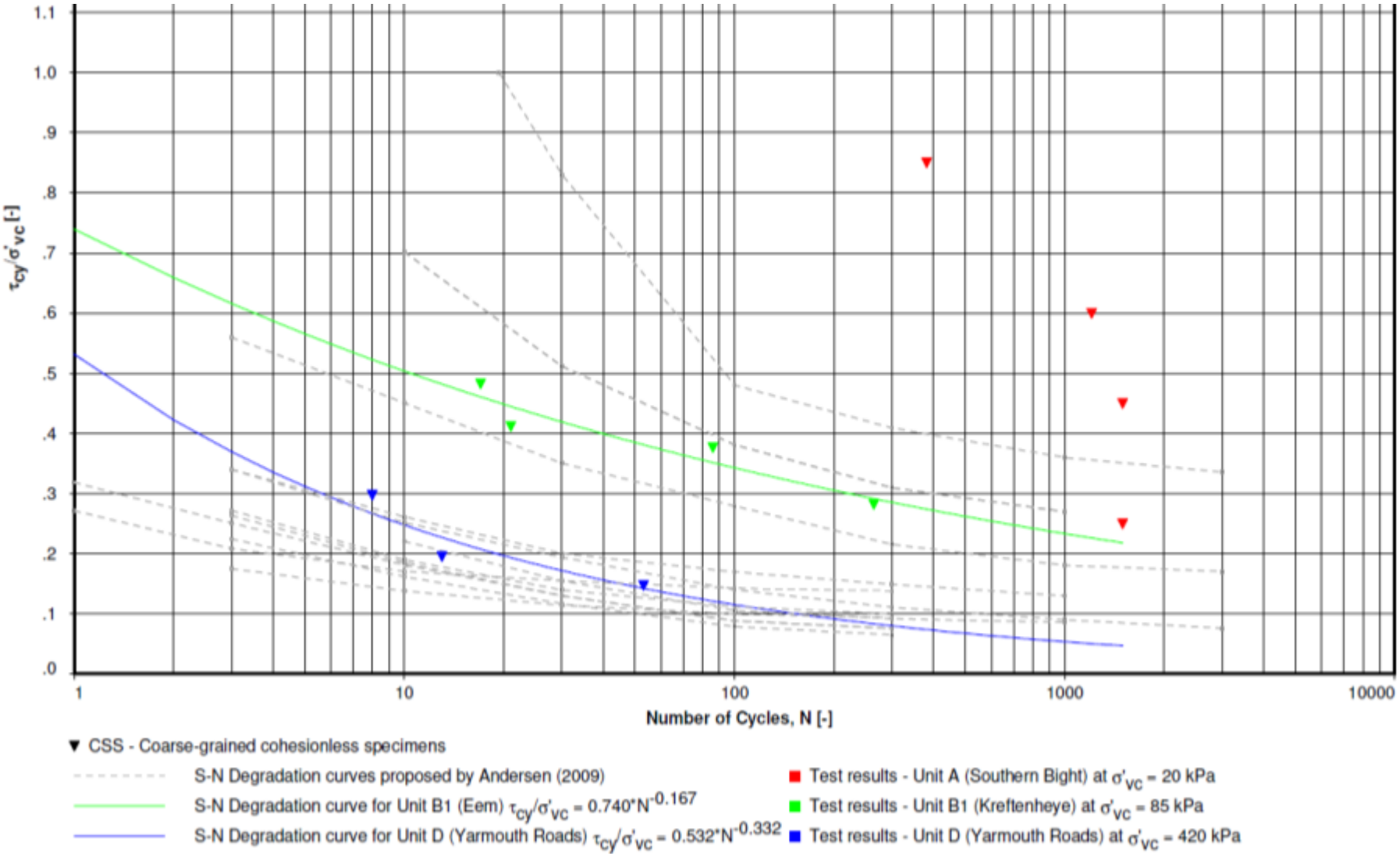
- Shear wave velocity (v_s) measured in-between geophone array
- Shear modulus at small strain (G_{max}) derived from v_s measured
- v_s and G_{max} derived from CPT
- v_s and G_{max} derived from bender element test as part of CU triaxial test
- v_s and G_{max} derived from bender element test as part of CD triaxial test

Location(s):

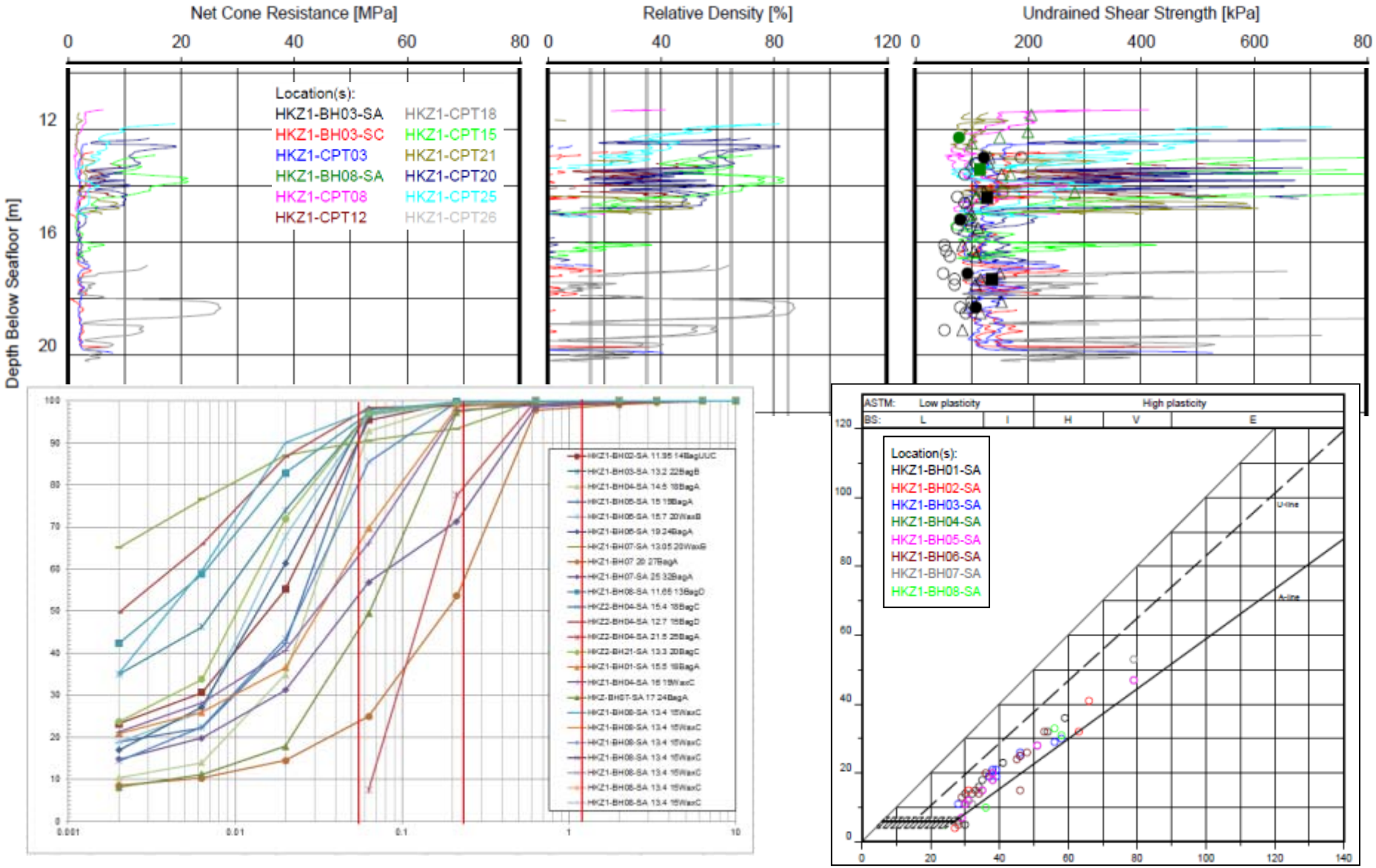
HKZ1-BH04-SA	HKZ1-BH07-SA
HKZ1-CPT04	HKZ1-CPT07
HKZ1-BH06-SA	HKZ1-CPT17
HKZ1-BH06-SC	HKZ1-CPT23
HKZ1-BH06A-SC	
HKZ1-CPT06	

Note(s):
- v_s derived from CPT based on Robertson and Cabal (2010)
- G_{max} when soil behaviour type index I_c>2.6 derived from CPT based on Mayne and Rix (1993)
- G_{max} when soil behaviour type index I_c<2.6 derived from CPT based on Rix and Stokoe (1991)

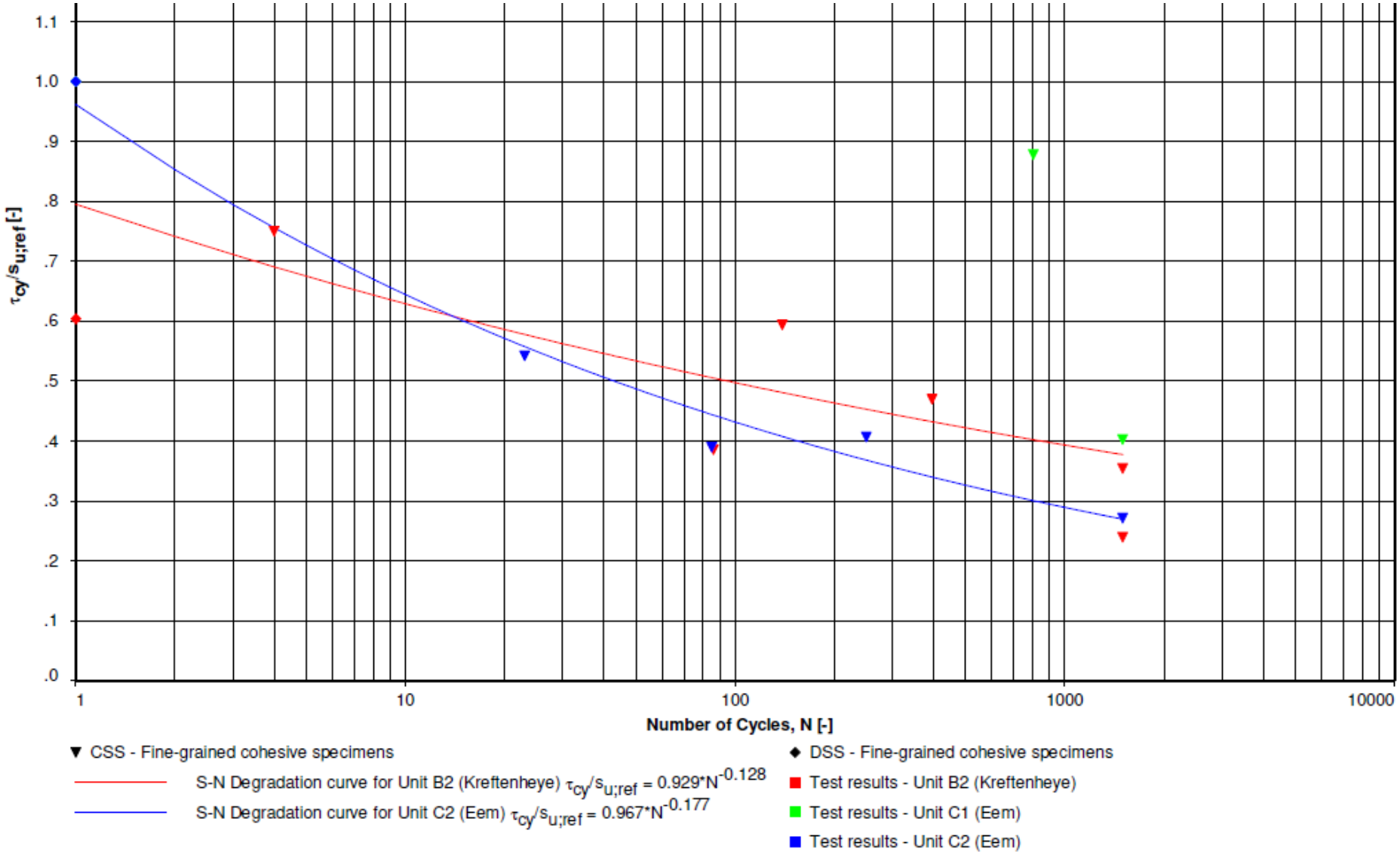
Geological Ground Model – Geotechnical Properties Unit B1



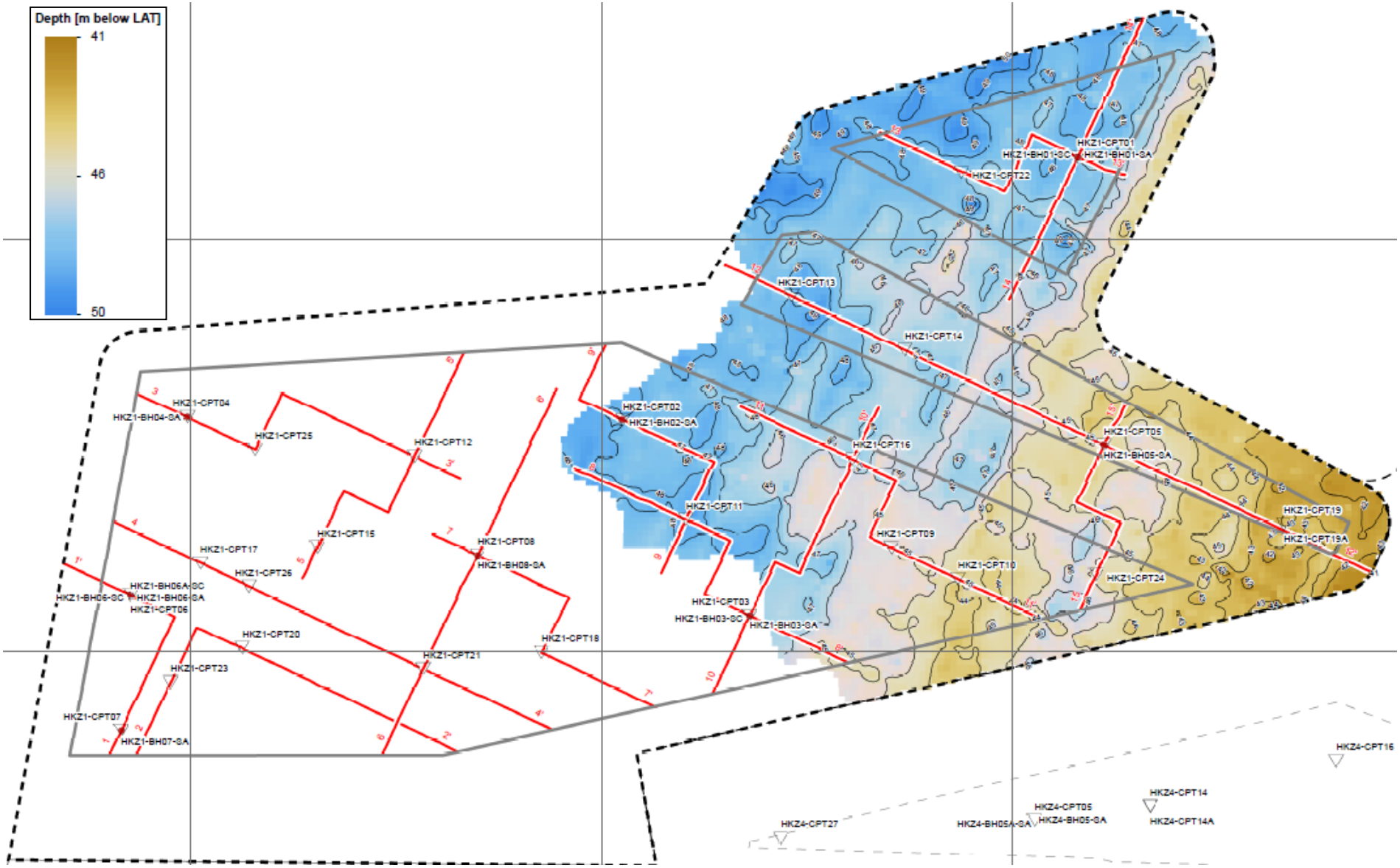
Geological Ground Model – Geotechnical Properties Unit B2



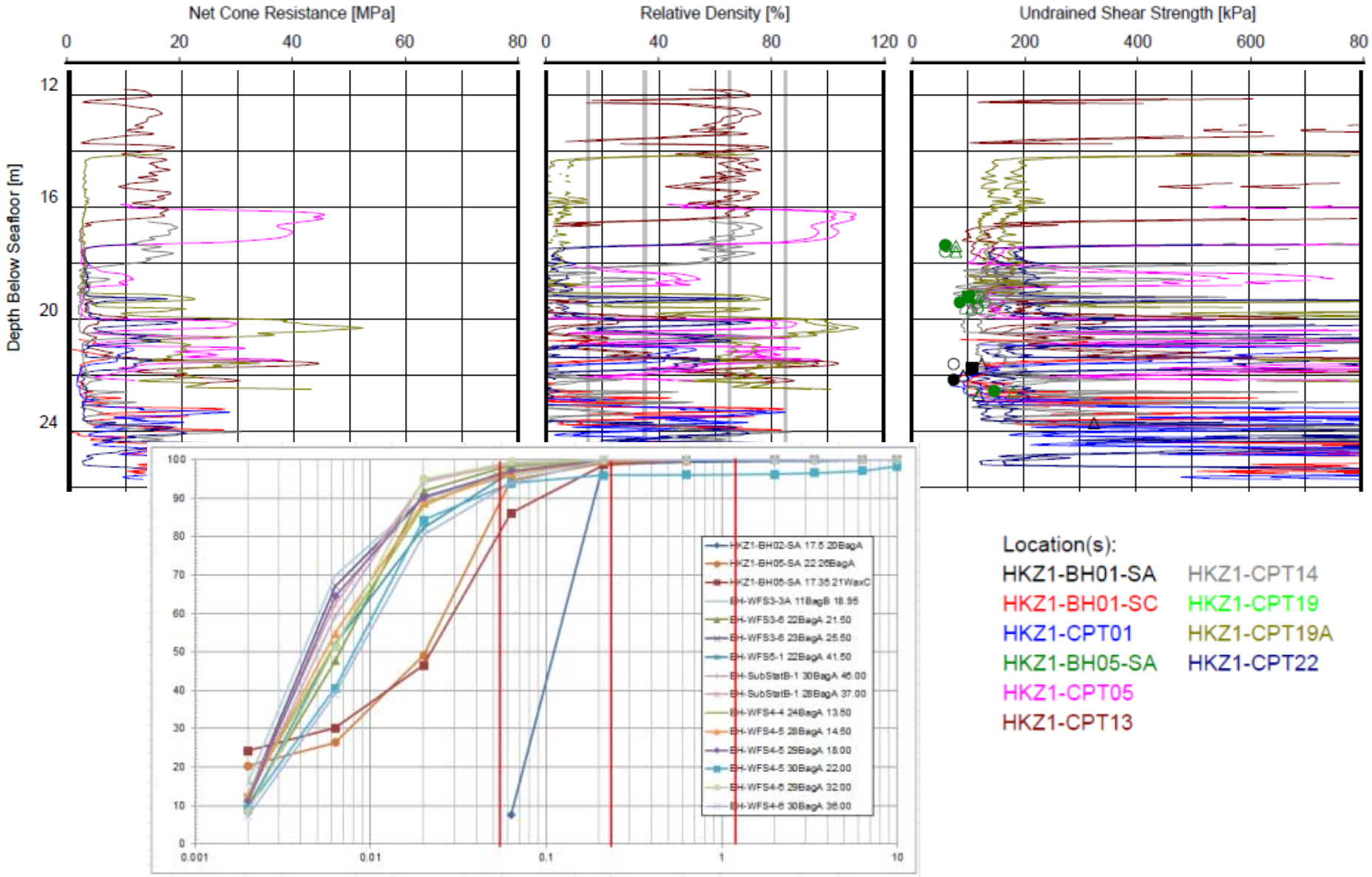
Geological Ground Model – Geotechnical Properties Unit B2



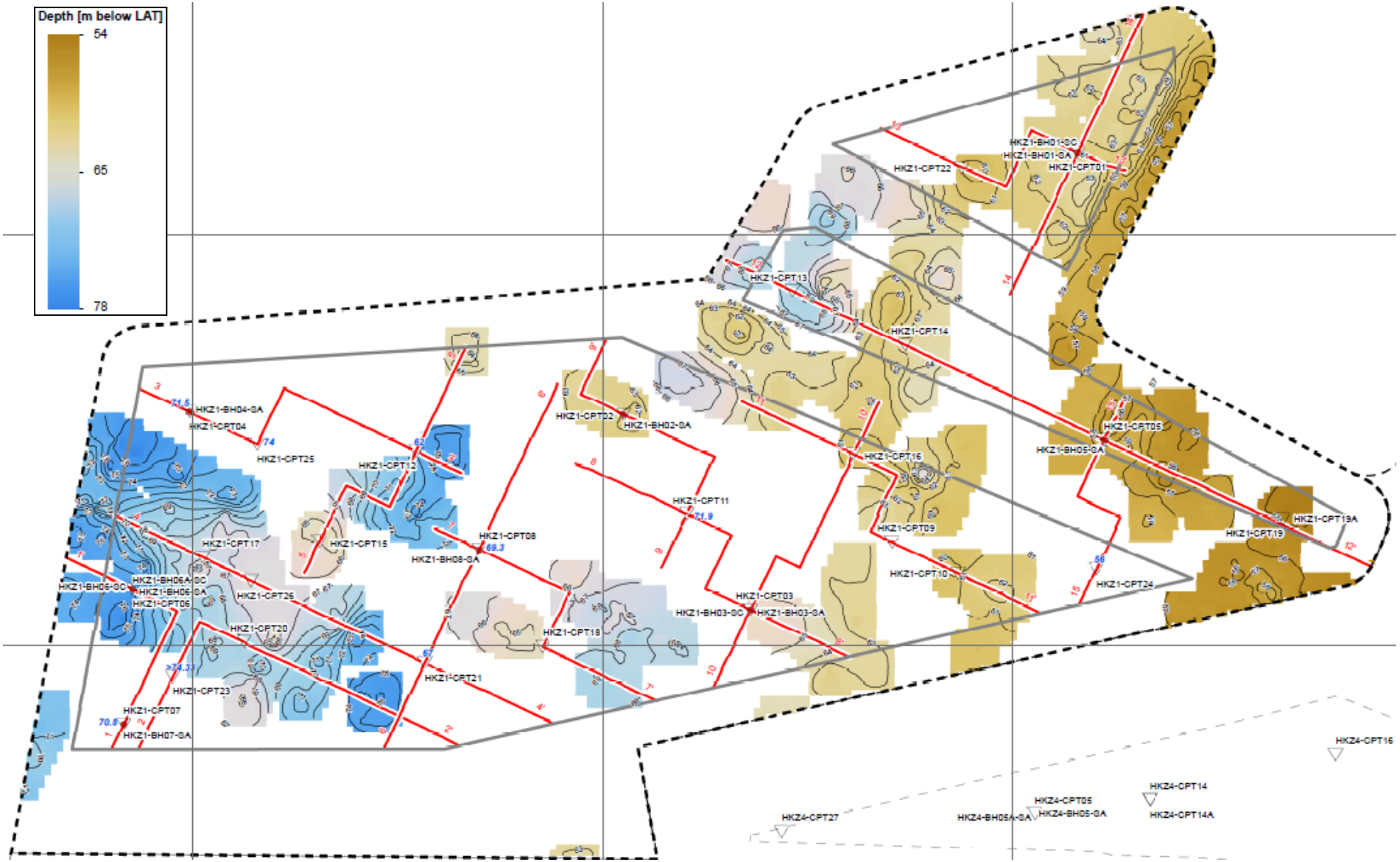
Geological Ground Model – Depth to Base Unit C1



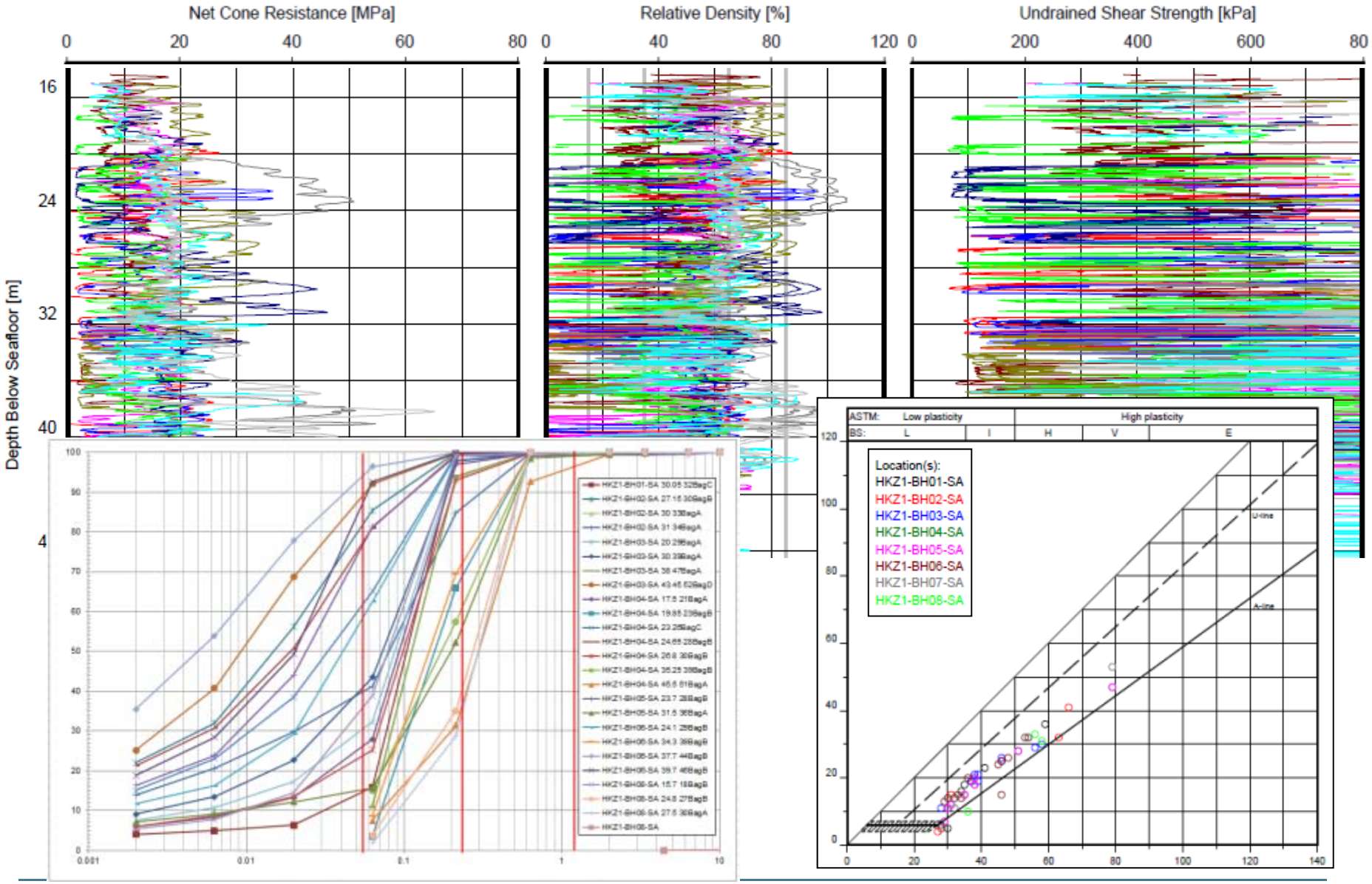
Geological Ground Model – Geotechnical Properties Unit C1



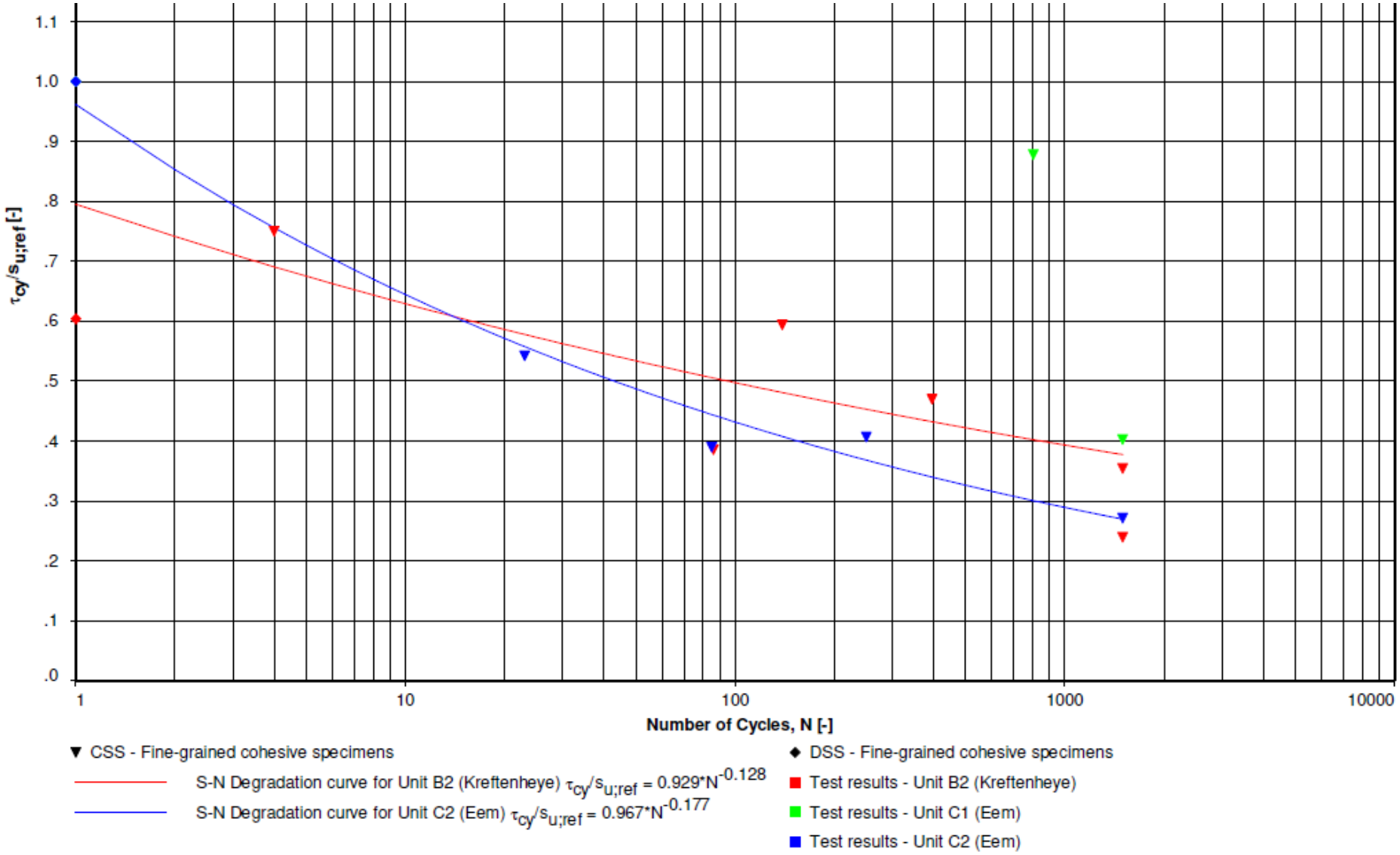
Geological Ground Model – Depth to Base Unit C2



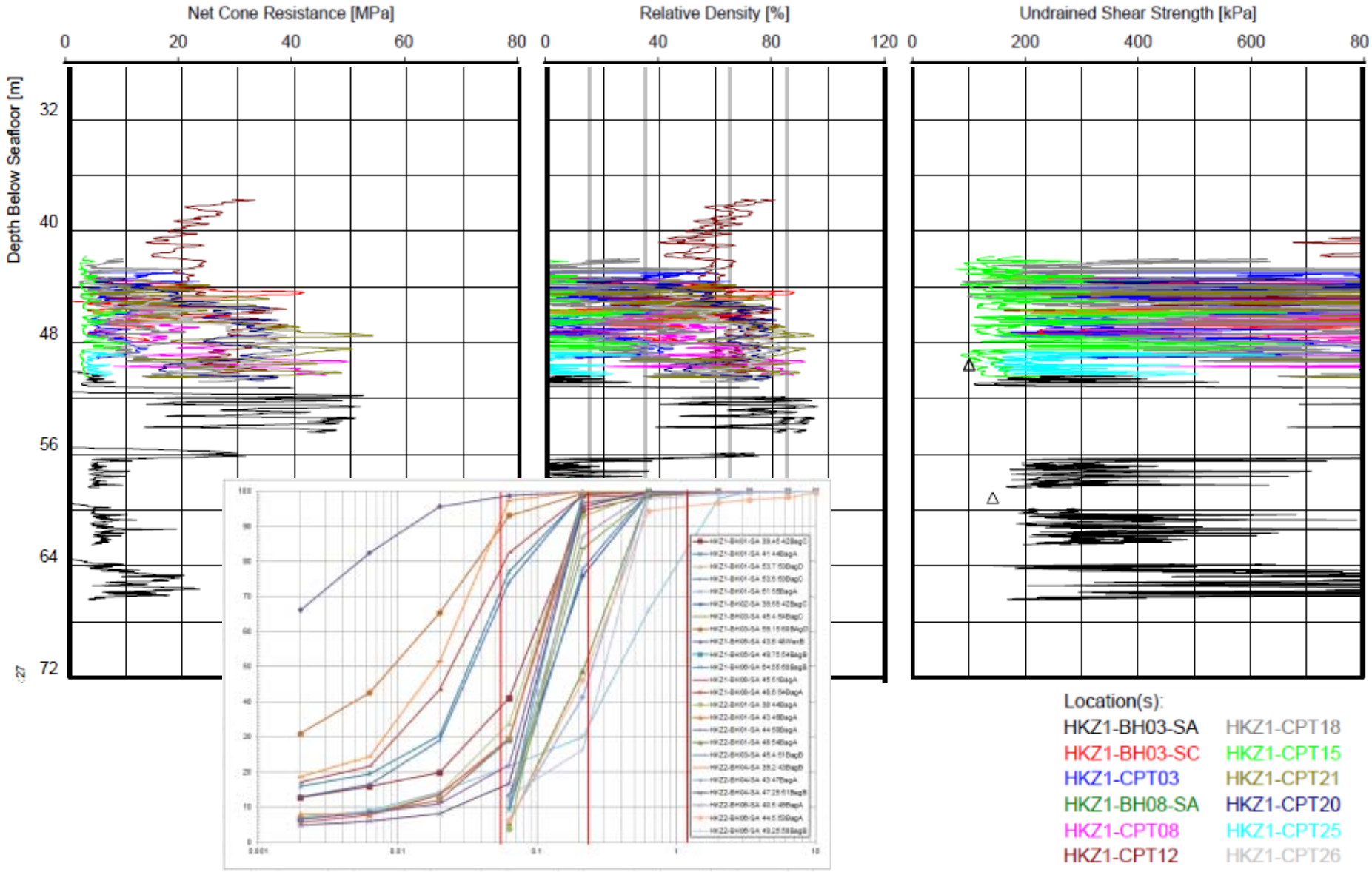
Geological Ground Model – Geotechnical Properties Unit C2



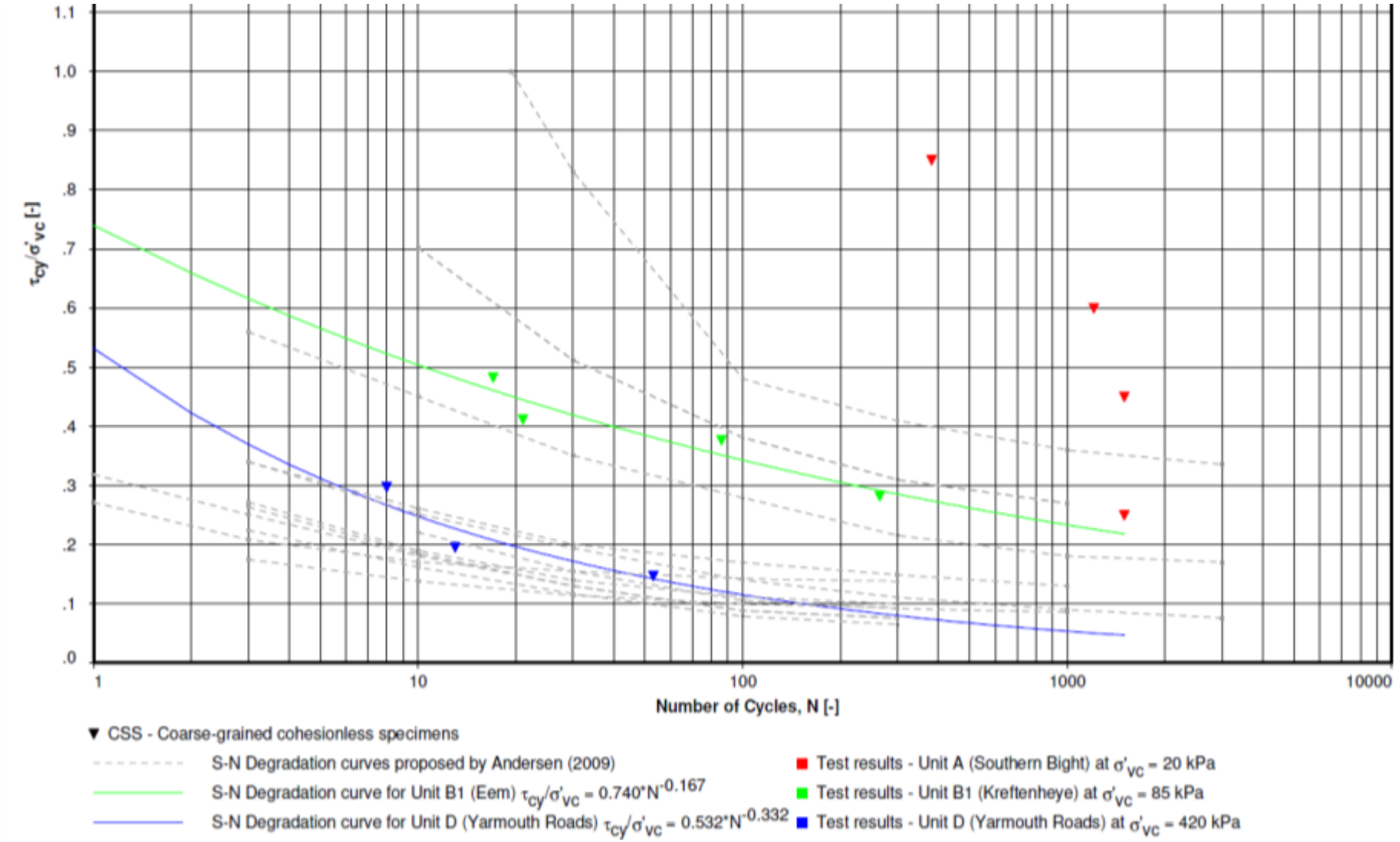
Geological Ground Model – Geotechnical Properties Unit C2



Geological Ground Model – Geotechnical Properties Unit D

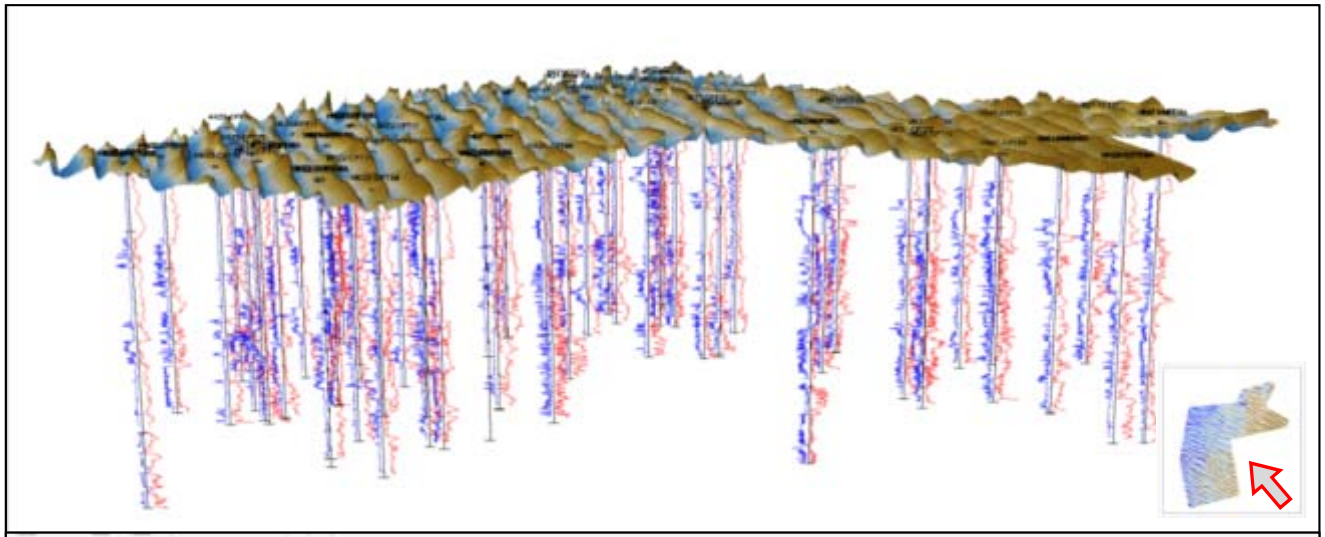


Geological Ground Model – Geotechnical Properties Unit D

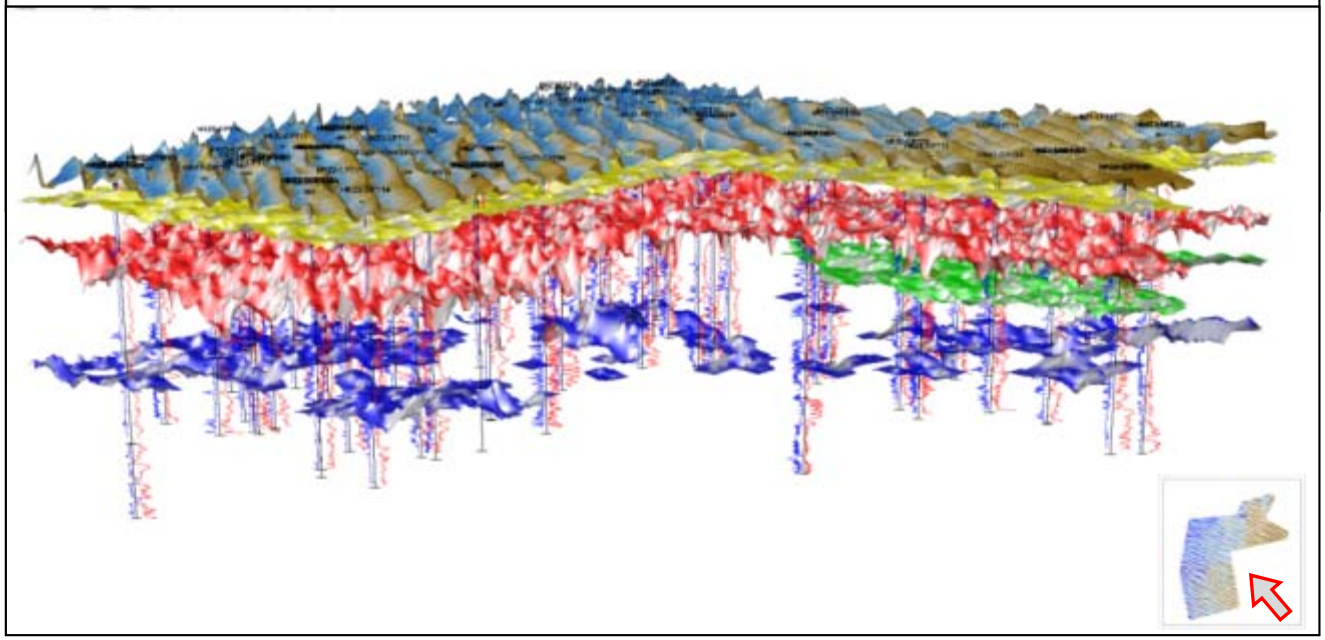


Geological Ground Model – Spatial Visualisation

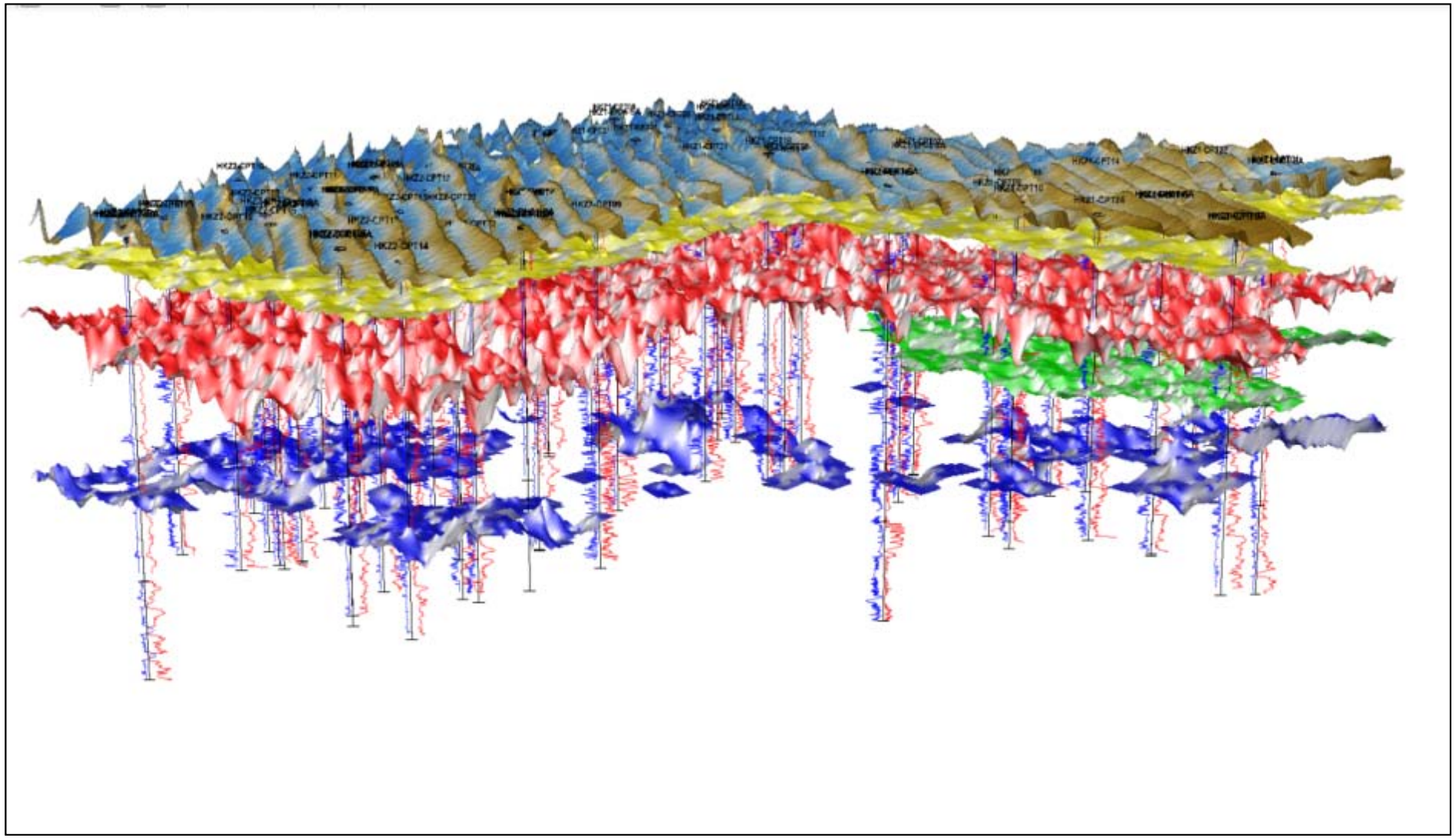
- Bathymetry data
- CPT data (Red: Qc; Blue: friction ratio)



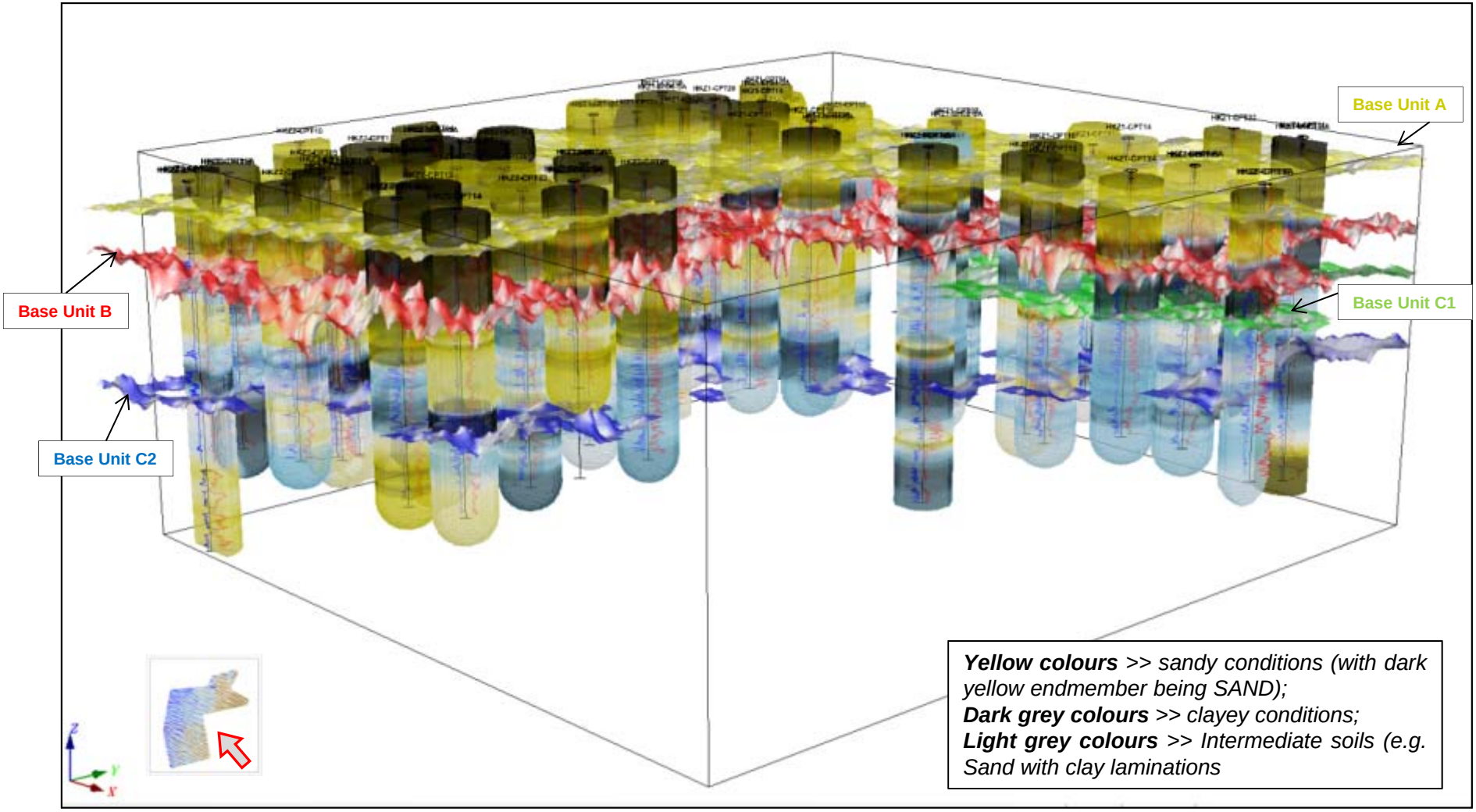
- Geophysical interpretation:
- Yellow: Base Unit A
- Red: Base Unit B
- Green: Base Unit C1
- Blue: Base Unit C2



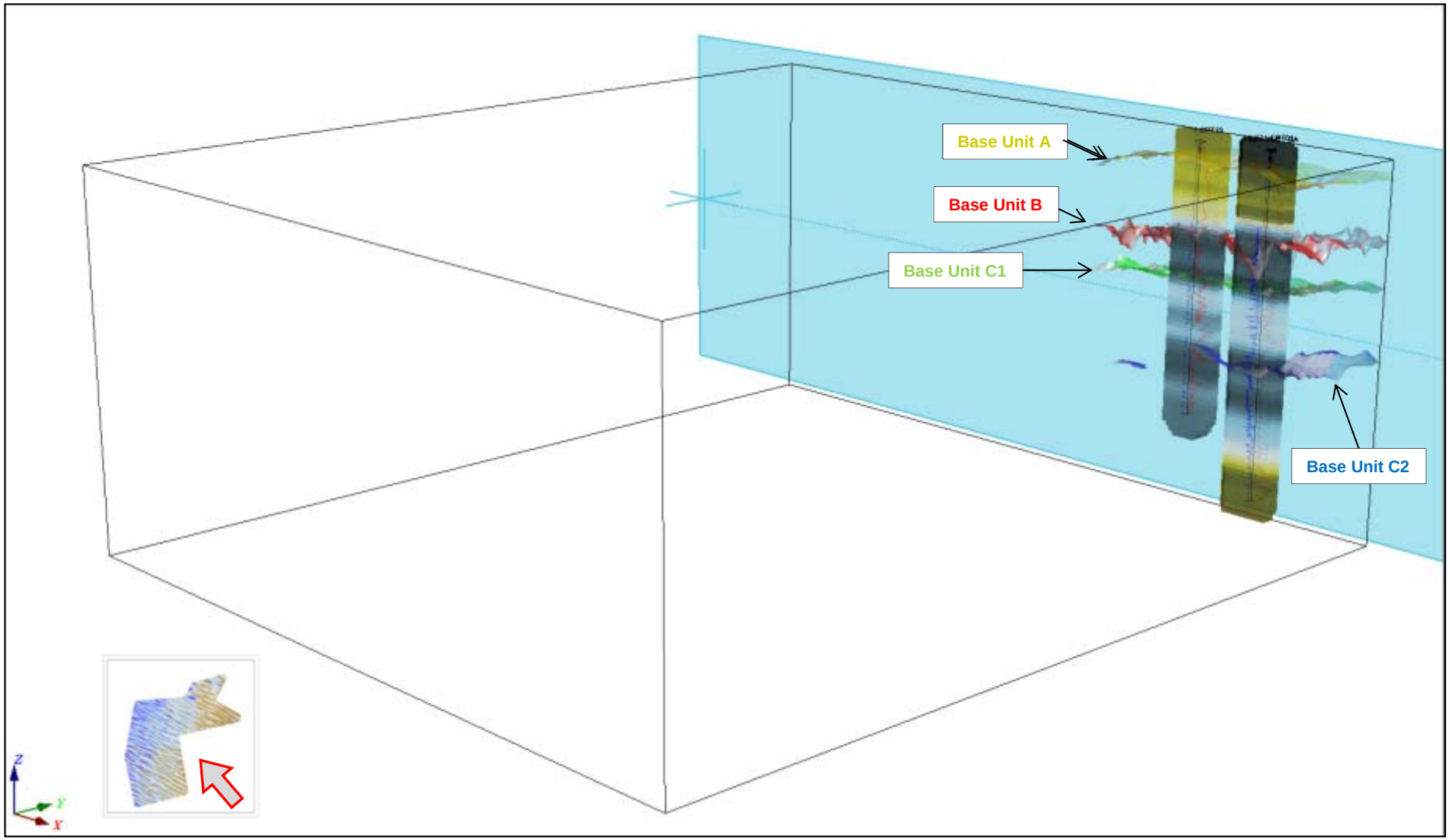
Geological Ground Model – Spatial Visualisation



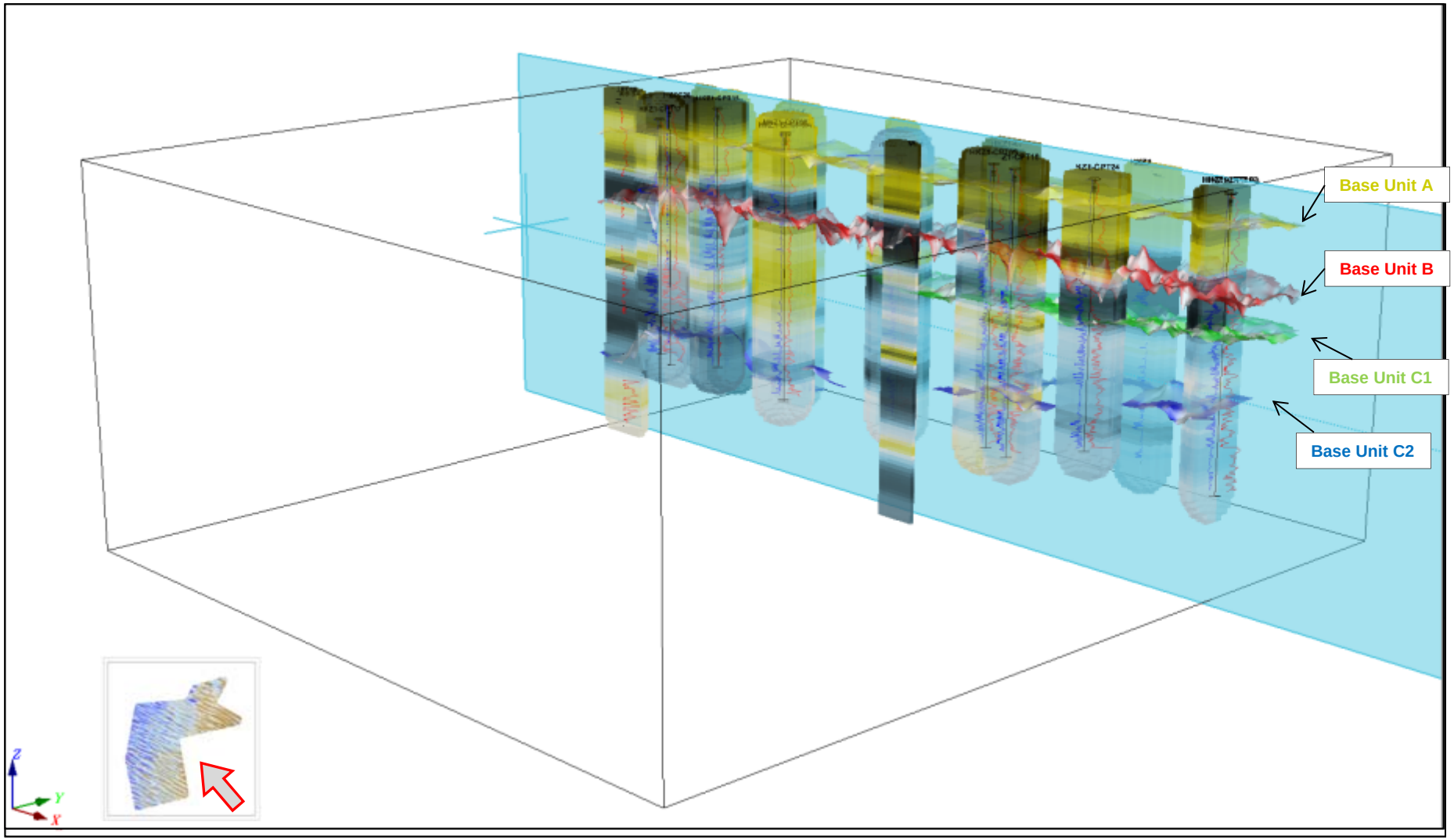
Geological Ground Model – Spatial Visualisation



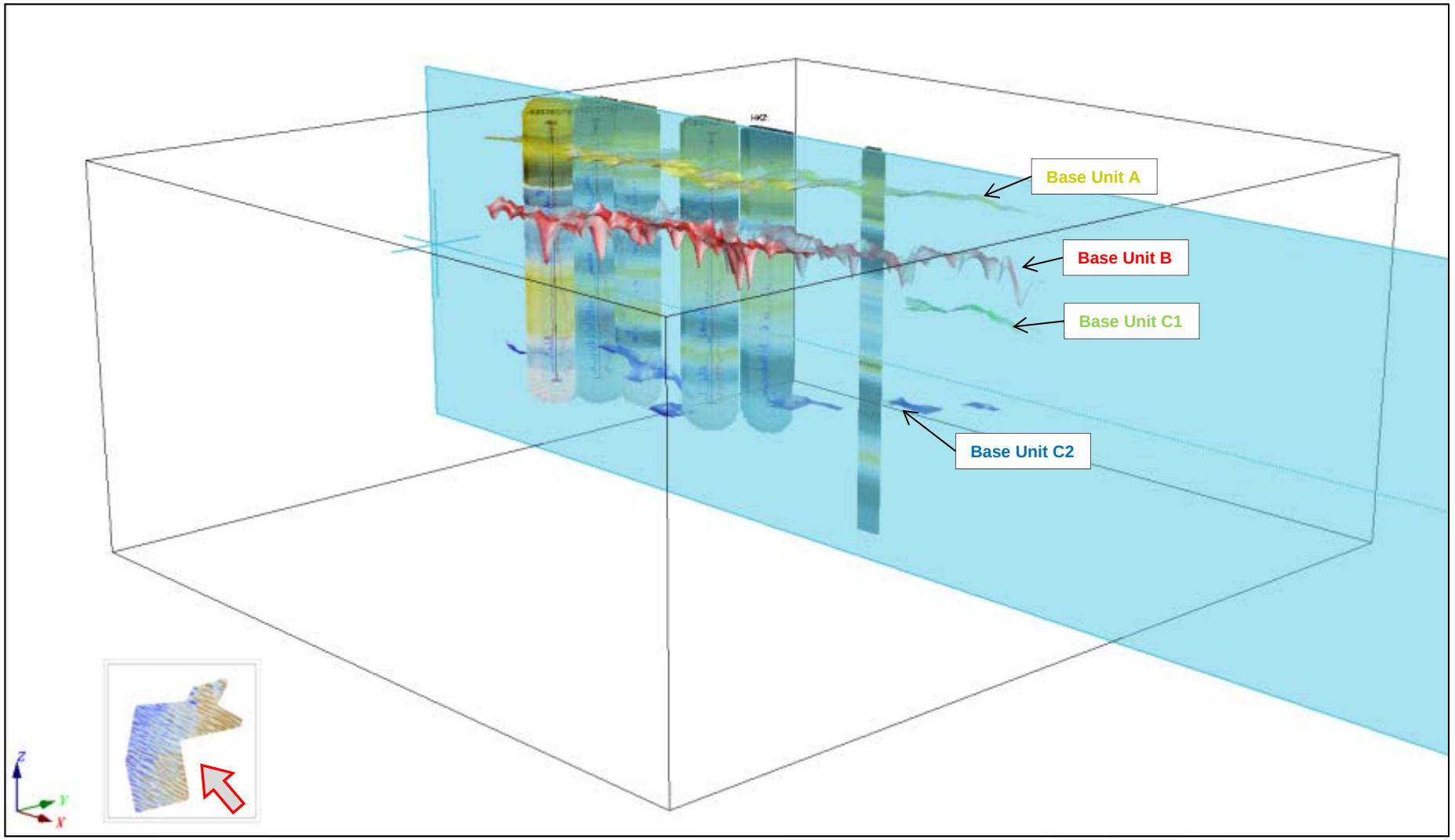
Geological Ground Model – Spatial Visualisation North to South



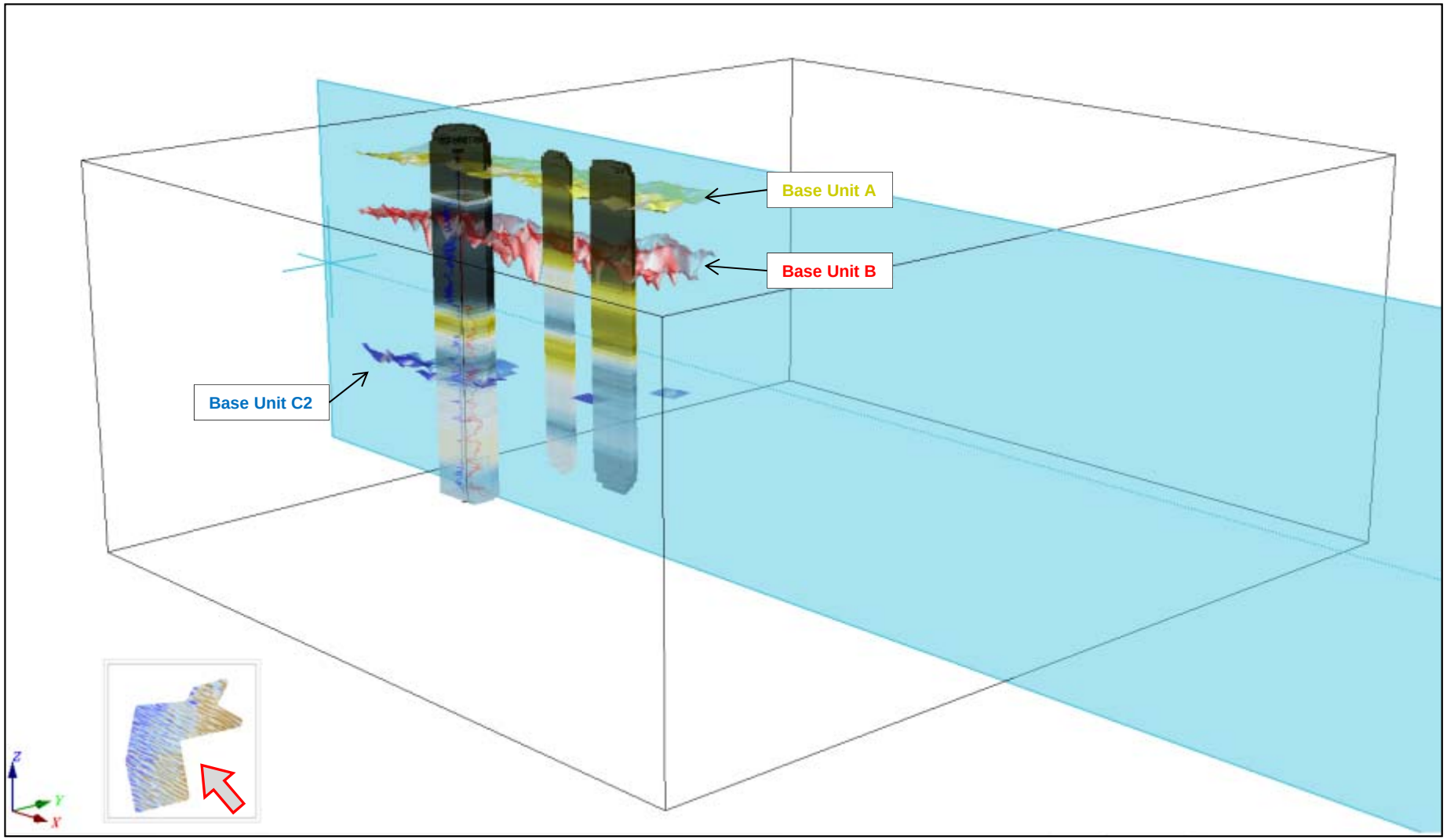
Geological Ground Model – Spatial Visualisation North to South



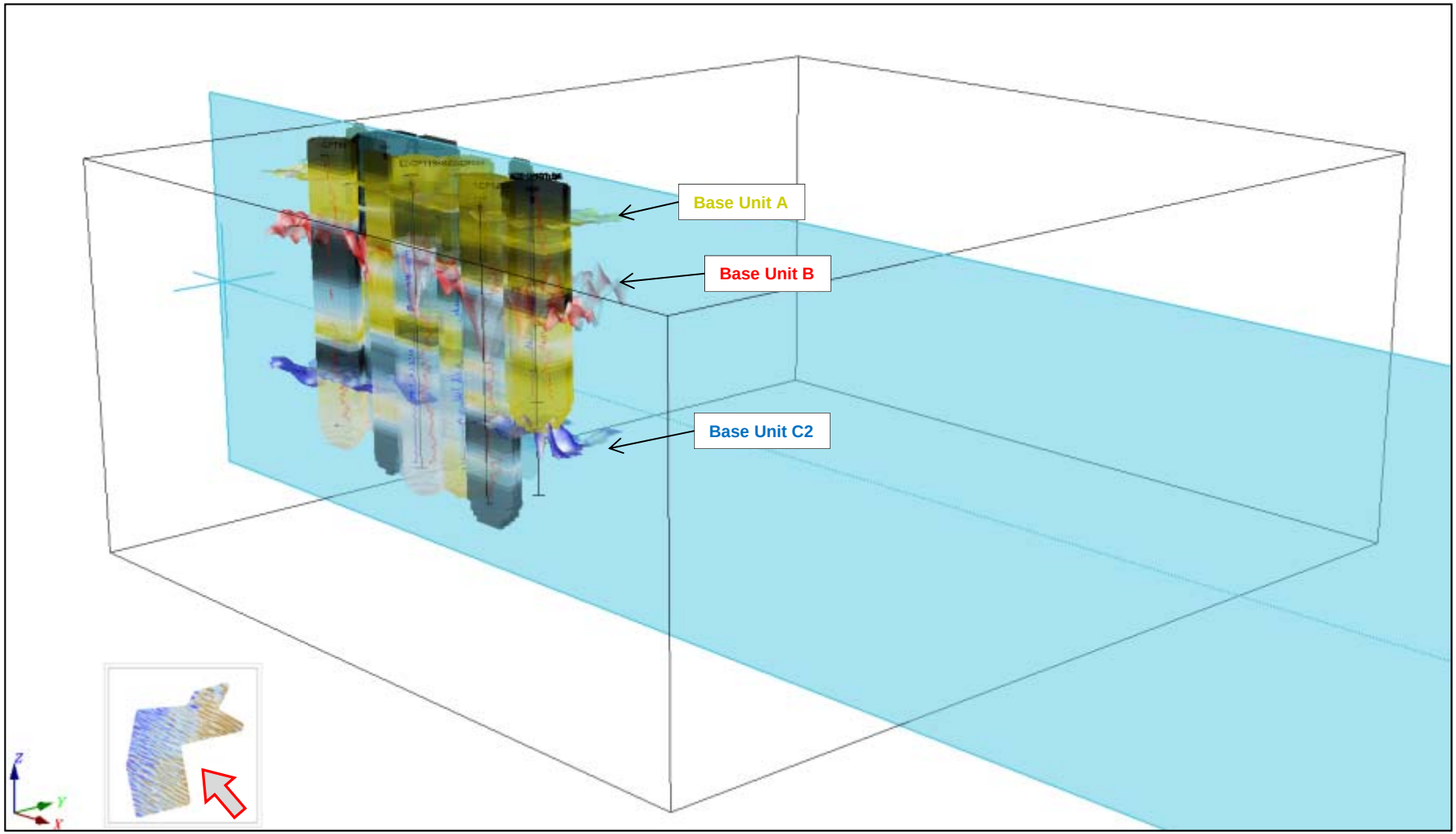
Geological Ground Model – Spatial Visualisation North to South



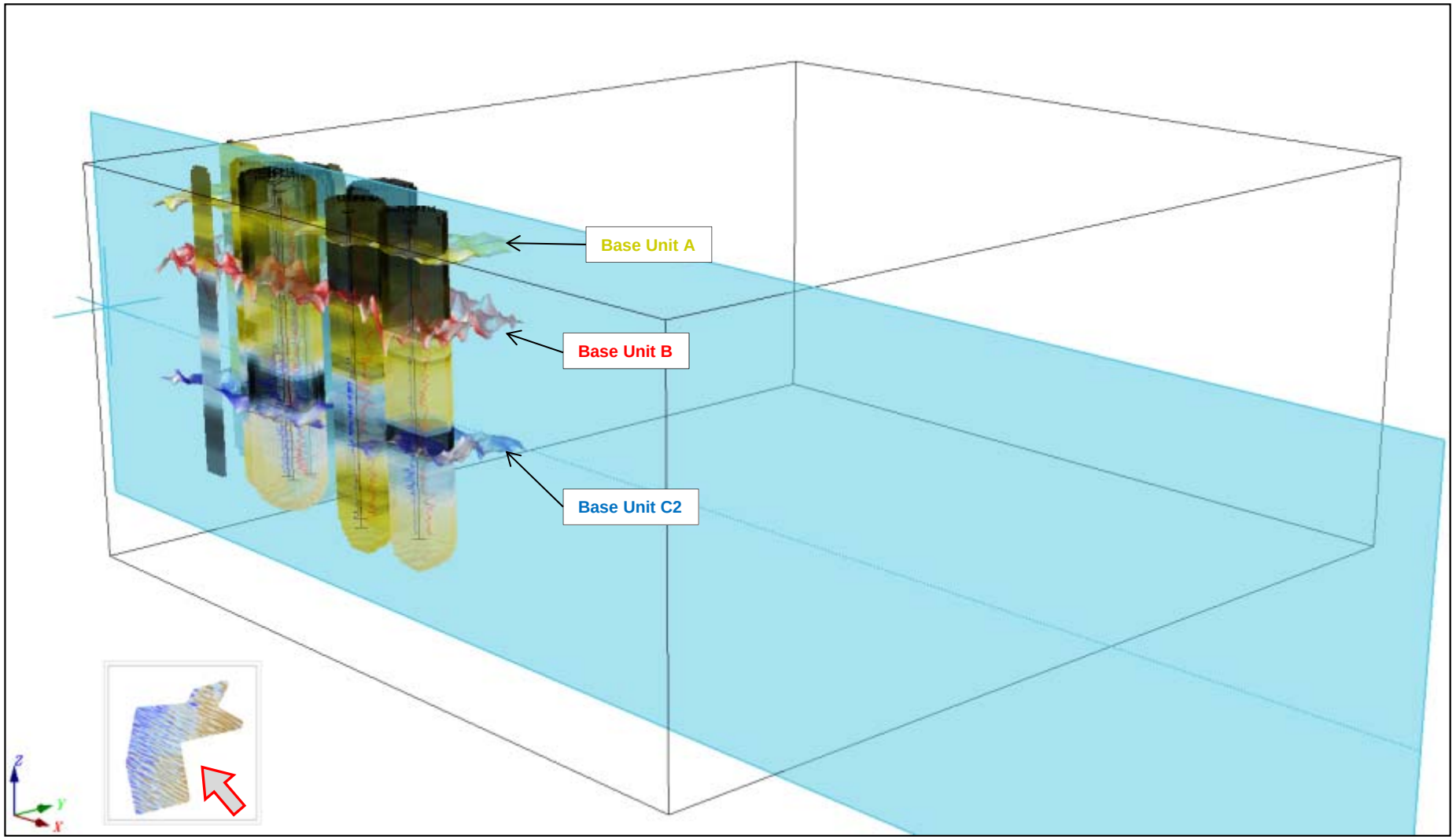
Geological Ground Model – Spatial Visualisation North to South



Geological Ground Model – Spatial Visualisation North to South



Geological Ground Model – Spatial Visualisation North to South



Potential Site-Specific Hazards Assessment

Geological Feature & Hazard Type	Occurrence Area	Constraints on Structure	PL	JU	GB	SC	CB
Migrating bedforms / mobile seabed sediments	Entire WFS I & II	▪ All: exposure or burial of structure due to local, general and regional scour or sedimentation affecting structure stability, structure stiffness ▪ CB: exposure or burial of cable affecting thermal characteristics	H (L)	L (N)	H (N)	H (L)	L (N)
Loose to medium dense sand	Locally in Unit A	▪ All: cyclic loading of seabed and structure can affect structure stability and structure stiffness ▪ CB: liquefaction of sand can affect cable flotation and thermal characteristics	H (N)	L (N)	H (N)	L (N)	L (N)
Very dense sand/ hard clay	Unit C – very dense sands in soil unit A, B1 and C1 Hard clay in Soil Unit B2,C1 and D	▪ PL: early refusal of pile installed by impact driving ▪ SC: limited penetration ▪ CB: trenching difficulties	L (N)	N (N)	N (N)	L (L)	L (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

Potential Site-Specific Hazards Assessment

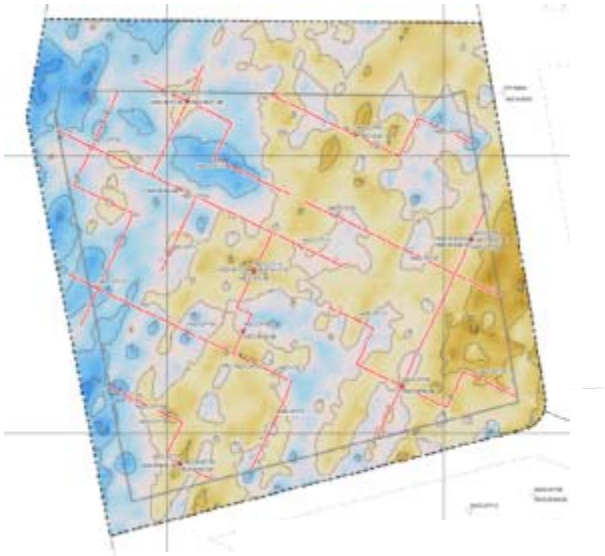
Pile Foundation:

- 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 subsurface

Jack-up Platforms:

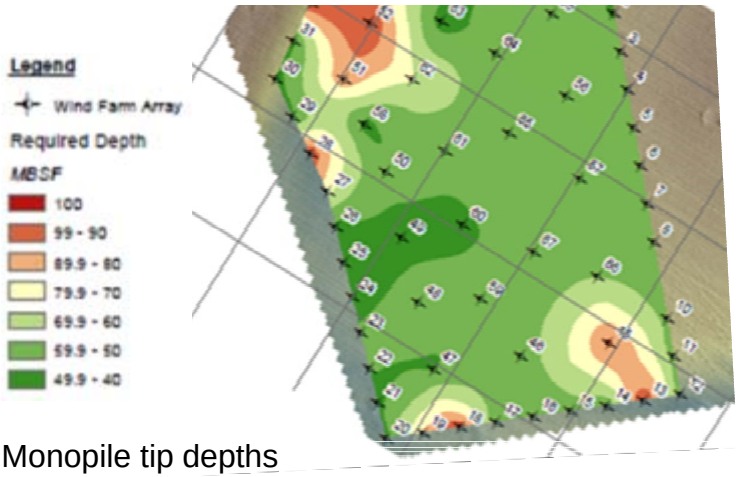
- Use of jack-up platforms for temporary works is assessed feasible
- Particularly, scour and soil deposition around spudcans should be allowed for:
  - *Scour can make periodic re-levelling of the jack-up necessary, can increase required leg length and can reduce spudcan soil resistance after jack-up placement;*
  - *Risk assessments for jack-up siting should consider structural integrity for a scenario of strongly non-uniform soil support of a spudcan, i.e. moment loading;*
  - *Soil deposition around and on a spudcan will affect required extraction forces*
- Considerations for jack-up leg punch-through will primarily apply to jack-ups equipped with spud-pile type foundations with relatively high bearing pressure at the spud-pile tip. Jack-ups equipped with spudcans can probably benefit from high bearing resistance available from Soil Units A and B1.

Geological Ground Model - GIS Ground Model and add-ons



The current GIS ground model can be extended with e.g. :

- Monopile sizing and mapping for any location using scripted design profile selection and design analyses
- Jack-up penetration and punch through probability mapping for entire wind farm
- Mapping of local and regional scour potential
- Strategic visualisation of any supplementary site investigation data still to be acquired



Monopile tip depths

Geological Ground Model - GIS Ground Model and add-ons

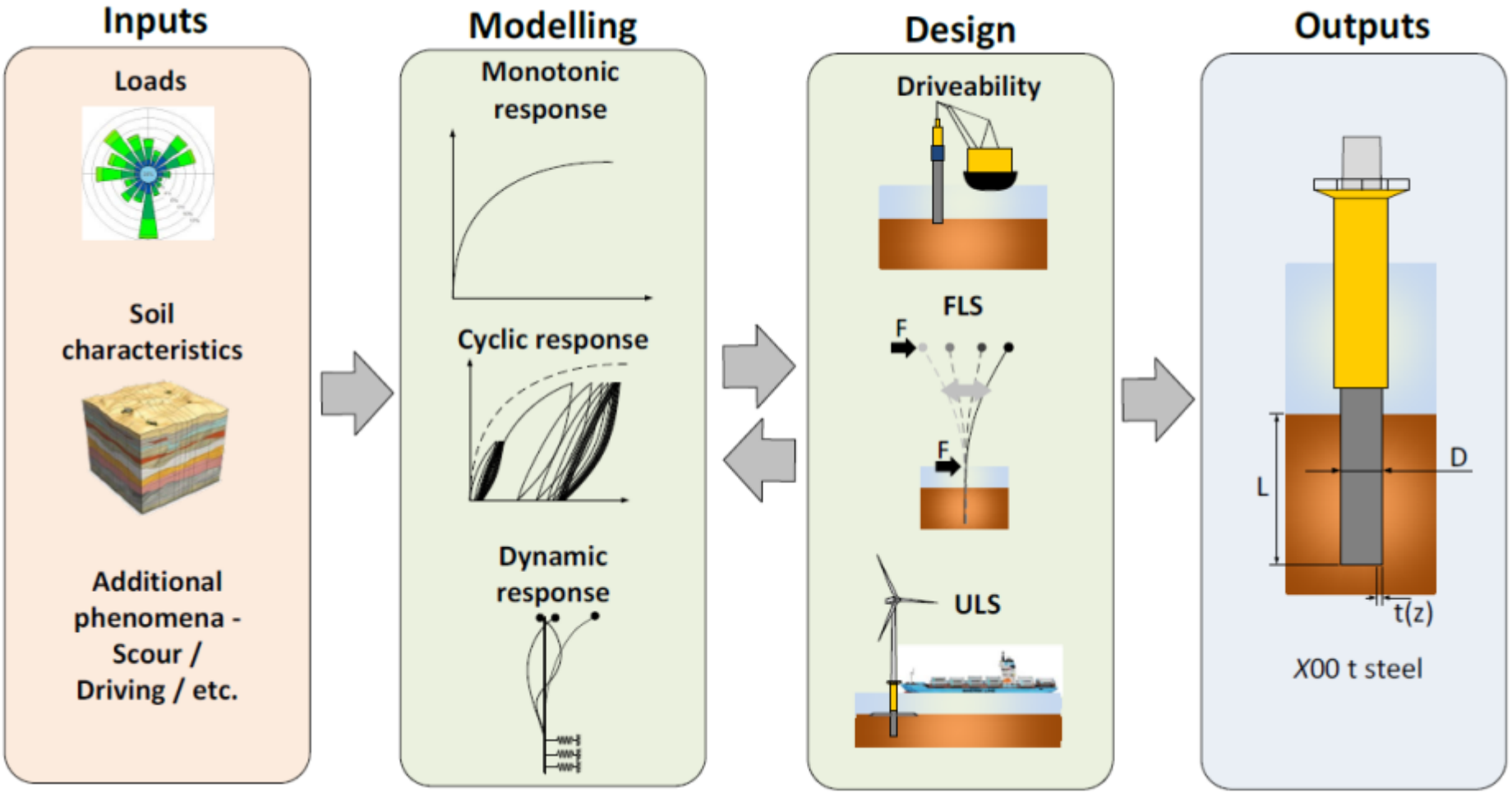
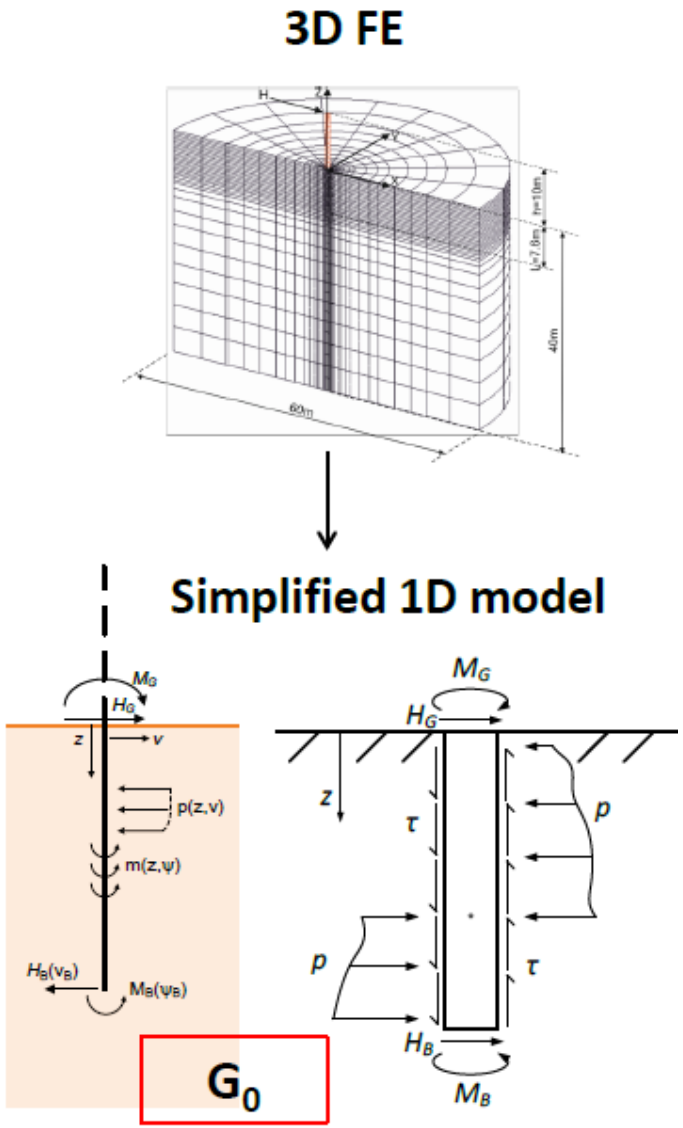


Image used with permission from Oxford University

Geological Ground Model - GIS Ground Model and add-ons



- Development of a pile response (i.e. p-y data) model based on FEA: e.g. PISA Project
- Efficient 1D model of representative aspects of monopile response (not included in conventional API design):
  - distributed shear
  - moment rotation
  - base shear resistance
- Quick GIS mapping of versatile 1D model results, covering a range of design conditions and constraints

Concluding Remarks

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

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

- Soil conditions at individual geotechnical locations as well as within soil units between geotechnical locations show sequences of sand, clays and intermediate soils.

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

Conclusion DNV on the site investigation and deliverables for HKZ (WFSI and II):

“This comprehensive geotechnical campaign was defined as a joint effort between multiple parties and reviewed by DNV GL with the objective to reduce the need for boreholes in later stages of development. With a proper CPT calibration and additional CPTs at each planned turbine location it is likely that additional boreholes may be omitted.”

THANK YOU

For further questions on the site investigation of HKZ WFSI&II or for details of our services, please contact me at m.klein@fugro.com / +31(6)10 84 28 29 / www.fugro.com