Importance of CPT in development of offshore windfarms

Tom Lunne, NGI

Outline

- Background
- Overview of potential foundation types, forces and special challenges
- Range of soils typically encountered
- Soil investigation methods used
- Typical soil investigation strategy
- Need for integrated approach: geology, geotechnics and geophysics
- Synthetic CPT scheme
- Some special aspects
- Summary and Conclusions

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Background

- In Europe and other areas offshore field developments in offshore oil and gas industry has declined due to low oil price
- Offshore wind farm developments have increased significantly due to political decision to increase proportion of re-newable energy

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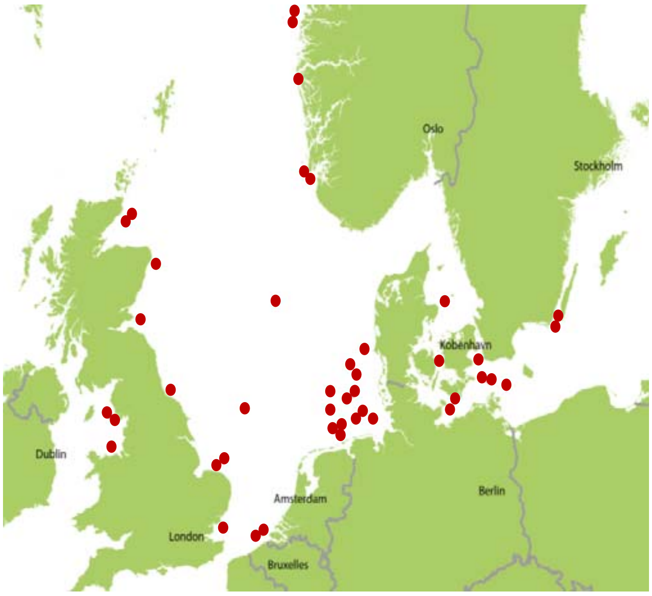
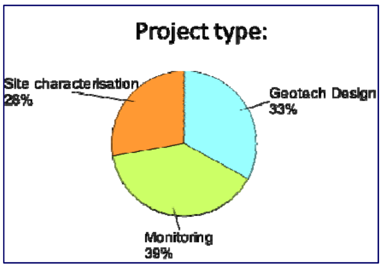
Example: NGI projects in offshore wind





NGI activities

- Site characterization
- Foundation design
- Monitoring

About 15 – 20 % of NGI's turnover

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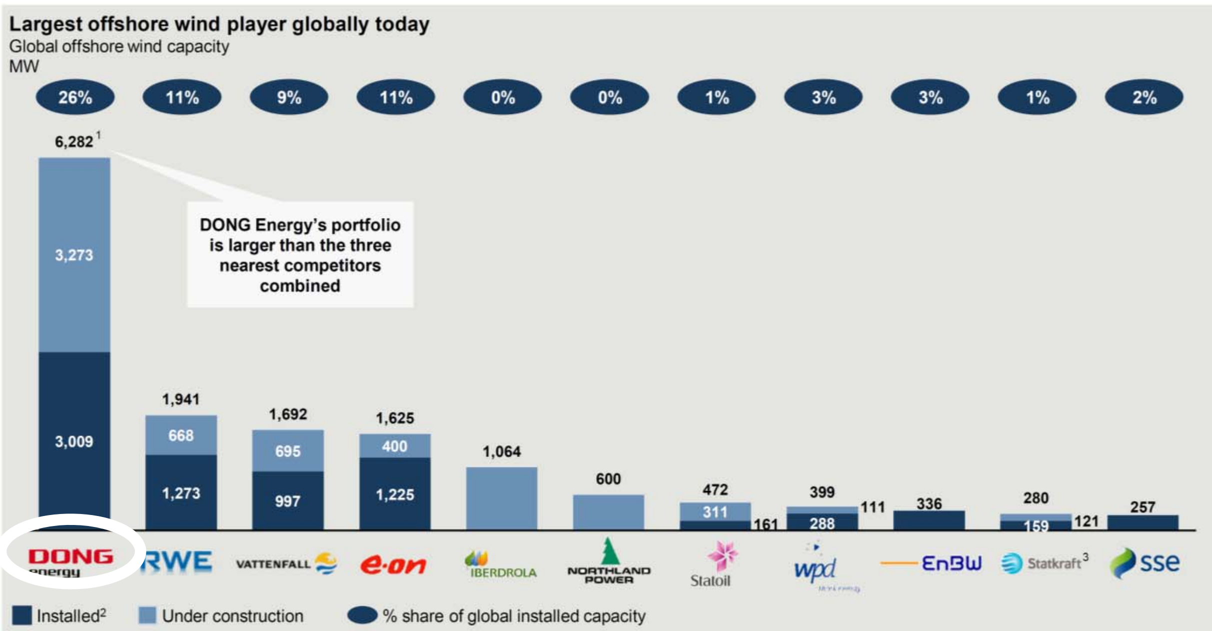
Areas where NGI has been and is involved



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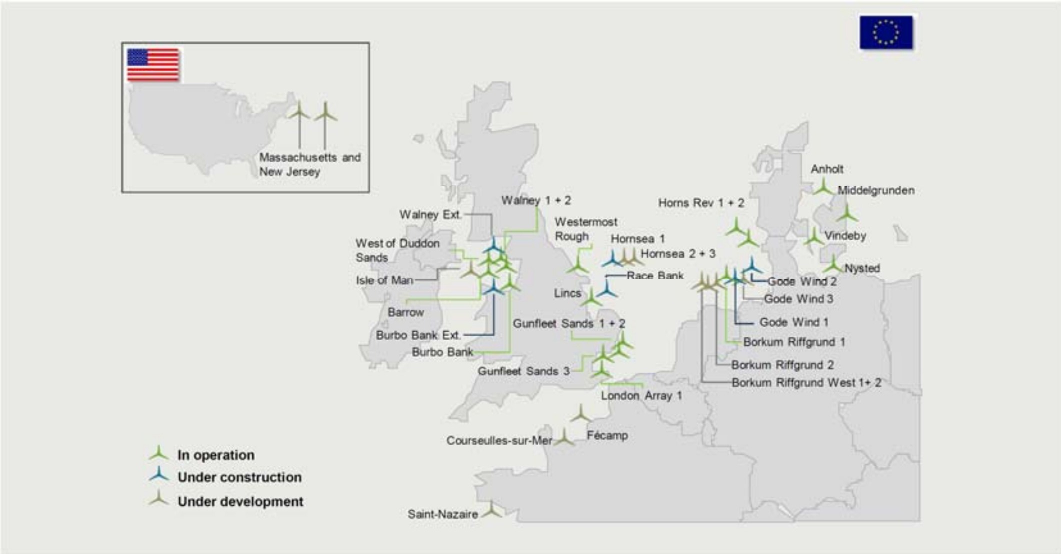
Largest offshore wind player globally today

DONG Energy is the global leader in offshore wind with a unique pipeline of future projects



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DONG energy

Top 10 installed wind parks by 2015

Wind farm	Total (MW)	Location	Site coordinates	Turbines & model	Commissioning Date
London Array	630	United Kingdom	51°38′38″N 01°33′13″E	175 × Siemens SWT-3.6-120	2012
Gwynt y Môr	576	United Kingdom	53°27′00″N 03°35′00″W	160 × Siemens SWT-3.6-107	2015
Greater Gabbard	504[6]	United Kingdom	51°52′48″N 1°56′24″E	140 × Siemens SWT-3.6-107	2012
Anholt	400	Denmark	56°36′00″N 11°12′36″E	111 × Siemens SWT-3.6-120	2013
BARD Offshore 1	400	Germany	54°22′0″N 5°59′0″E	80 × BARD 5.0MW	2013
Global Tech I	400	Germany	54°30′00″N 6°21′30″E	80 × Areva Multibrid M5000 5.0MW	2015
West of Duddon Sands	389	United Kingdom	53°59′02″N 3°27′50″W	108 × Siemens SWT-3.6-120	2014
Walney (phases 1&2)	367.2	United Kingdom	54°02′38″N 3°31′19″W	102 × Siemens SWT-3.6-107	2011 (phase 1) 2012 (phase 2)
Thorntonbank (phases 1–3)	325	Belgium	51°33′00″N 2°56′00″E	6 × Senvion 5MW, 48 × Senvion 6.15MW	2009 (phase 1) 2012 (phase 2) 2013 (phase 3)
Sheringham Shoal	315	United Kingdom	53°7′0″N 1°8′0″E	88 × Siemens SWT-3.6-107	2012

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Background

Very many disciplines involved

- Archeology
- Fisheries
- Unexploded ordnance (UXO)
- Environmental issues
- Oceanography
- Geology
- Geophysics
- Geotechnology

} Integration into a ***ground model***

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Geotechnical challenges

- Large areas and many turbine locations
- Large structures and forces
- Often very complex geology – leading to:
- Large range of soil conditions encountered

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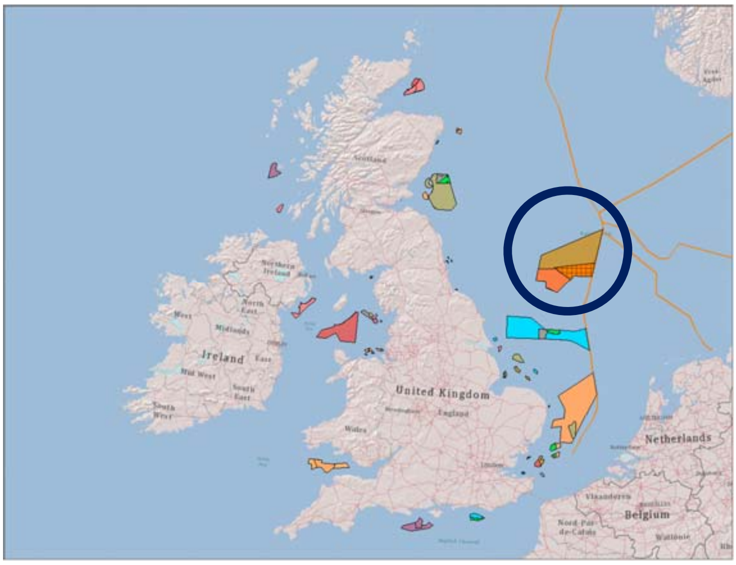
Example Field Plans Offshore UK



Dogger Bank
North Sea

Largest Wind Farm
Area = 8500 km^2

2000 wind turbines water depth 18 – 63m
Estimated output
~ 10 GW

Developers:

- Statoil
- Statkraft
- RWE
- SSE

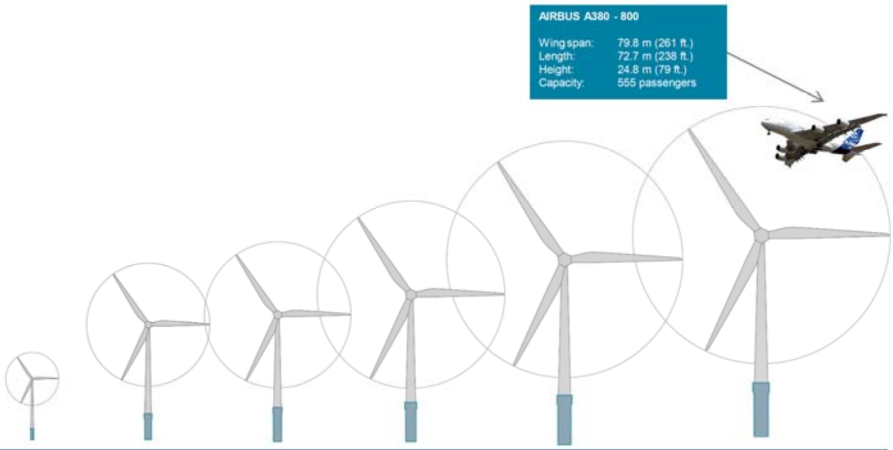
Size of Dogger Bank wind farm zone

Area = 8500 km^2

Corresponding to square of 93 * 93 km

Later project ambitions have been reduced by UK government

Dong's experience with increasing size of turbines



DONG Energy wind farms	1991	2001	2010	2013	2015	2017
Turbine capacity	0,45 MW	2 MW	2,3 MW	3,6 MW	6 MW	8 MW
Rotor diameter	35 m	76 m	93 m	120 m	154 m	164 m
Hub height from water level	35 m	64 m	68 m	81,6 m	102 m	105 m

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DONG energy

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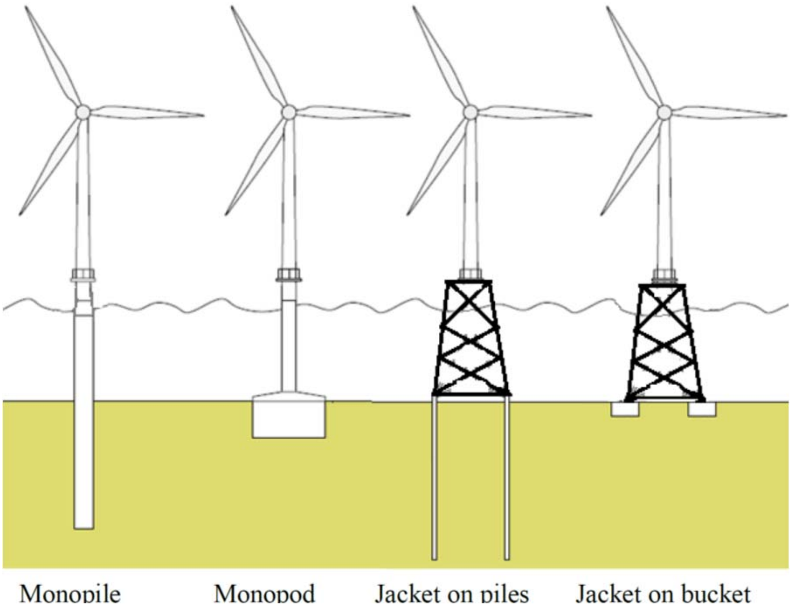
Some foundation solutions



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Monopiles

photo: Ciscon

photo: Anholt Offshore Wind Farm

- Oil and gas
  Length: 30m - 80m
  Diameter: 1m - 2m
  L/*D* approx. 30 - 60

- Offshore wind monopile
  Length: approx. 30m
  Diameter: 4m to 6m
  L/*D* approx. 5 to 7

Most used foundation so far

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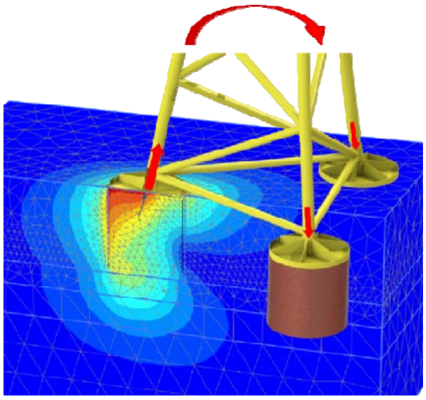

Jacket with buckets also used in some cases

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Beatrice Wind Farm

Loading on wind turbine

Example from Prof. Houlsby's Rankine lecture

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Beatrice Wind Farm

Loading on wind turbine

H = 2MN + 4MN = 6MN
wind   wave

M = 2 x (110 + 40) + 4 x 40
wind   wave

= 300 + 160
= 460 MNm

V = 10MN

Cyclic loading also very important

Example from Prof. Houlsby's Rankine lecture

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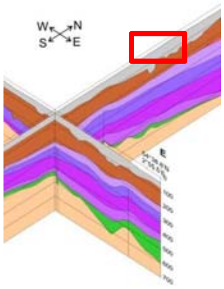
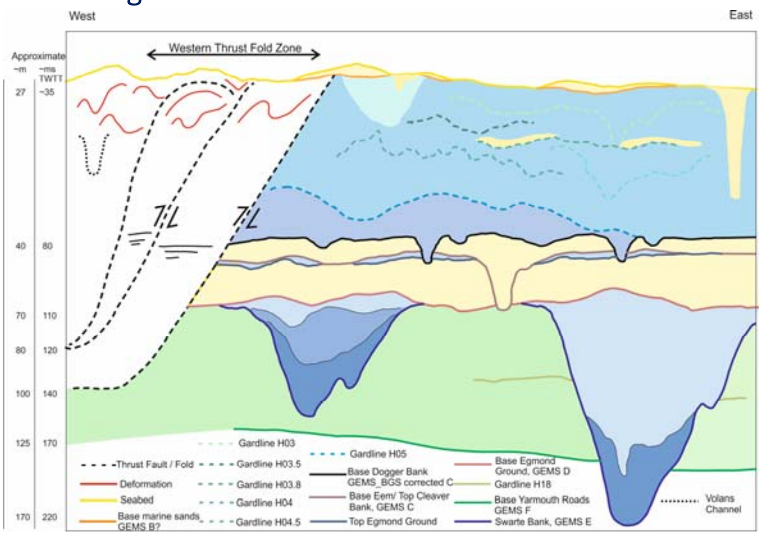
Often complex geology

Multiple sediment sources, terrestrial & marine sediments, glacial deformation, aerial exposure, sediment freezing, tundra, fresh water lakes, rivers, multiple phases of channeling and infill



From BGS



From www.forewind.co.uk

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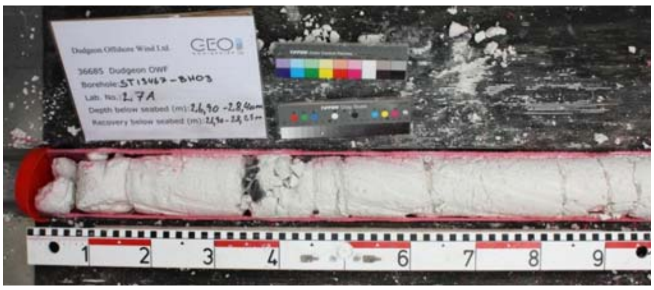
Complex geology and wide range of soils encountered

- Medium dense to very dense sands of varying silt content
- Highly overconsolidated clays, sometimes with fissuring
- Boulder clays with stones and boulders
- Infill soft clays
- Chalk of varying density

Example: chalk, difficult to obtain samples representative for in situ conditions



NGI Water depth typically 15 – 30 m

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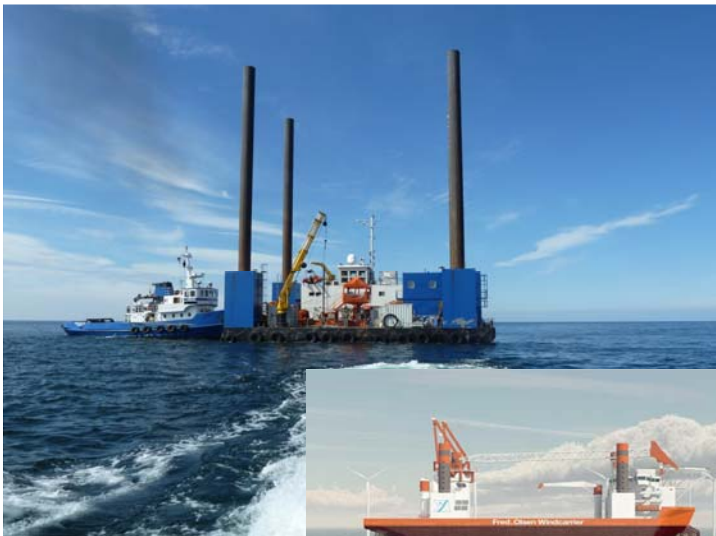
Soil investigation form Jack up rig



<u>Most steady working platform:</u>
Use casing and standard onshore equipment since rig platform is firmly founded on seafloor

Limitation: it is time consuming to move from one borehole location to the net

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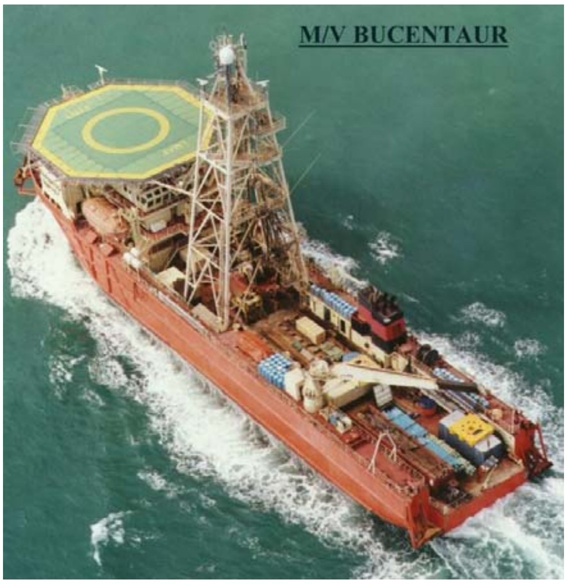
Soil investigation from special soil drilling vessel



Example soil drilling vessel with dynamic positioning

Higher day rates than jack-up rig; but much more efficient moves between locations – Can be most cost effective

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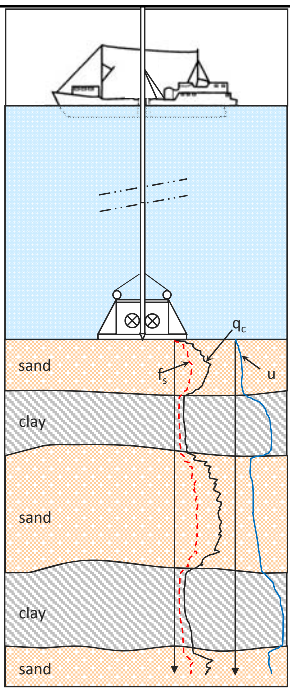

Seafloor mode

Roller wheel principle

Truly **continuous** test
- Increased quality
- Increased efficiency

With heavy duty rig 20 t, profiling to 45-50 m penetration possible

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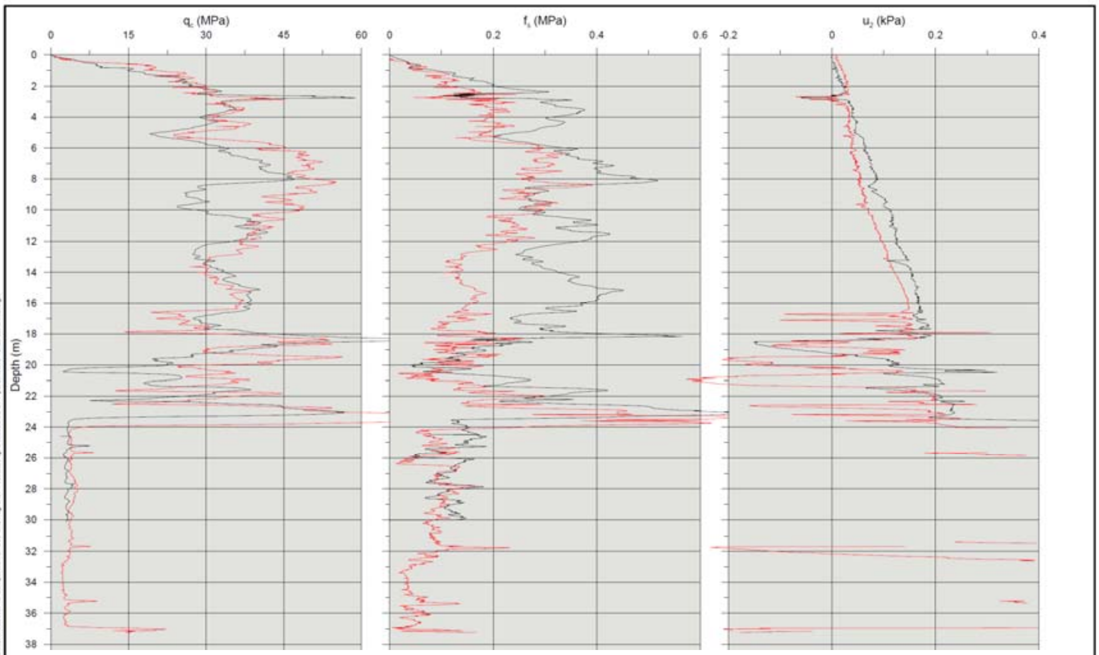

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Example Dogger Bank 40 m penetration can be achieved with seafloor CPTs even in very dense sand overlying OC clay

Down–hole drilling mode
Vessel based drilling

Derrick w/powerswivel and drill string

Downhole deployment tool

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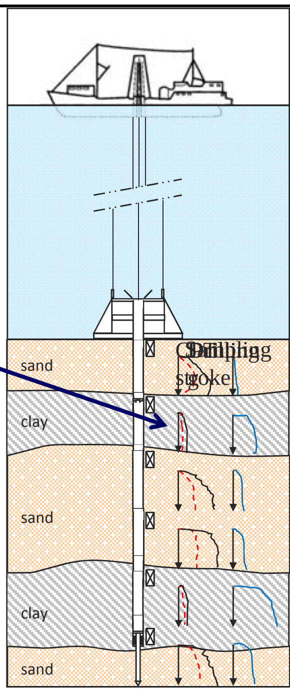
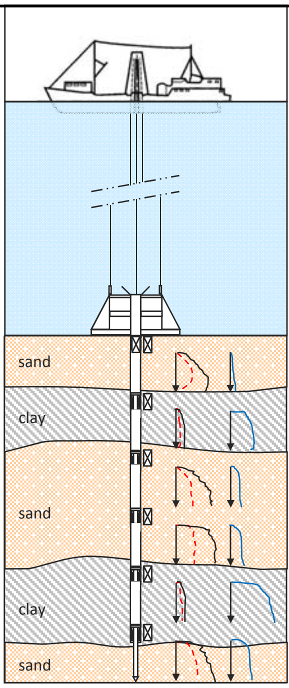
CPT strokes typically 3 m





Down-hole drilling mode

Advantages.
- Can go to large depth
- Can go through hard layers
- Can take samples or other in situ tests inbetween CPTU

Disadvantages:
- Some disturbance due to drilling
- Potential problems with zero readings
- More uncertain depth measurements
- In general quality of CPTU data lower than seafloor tests

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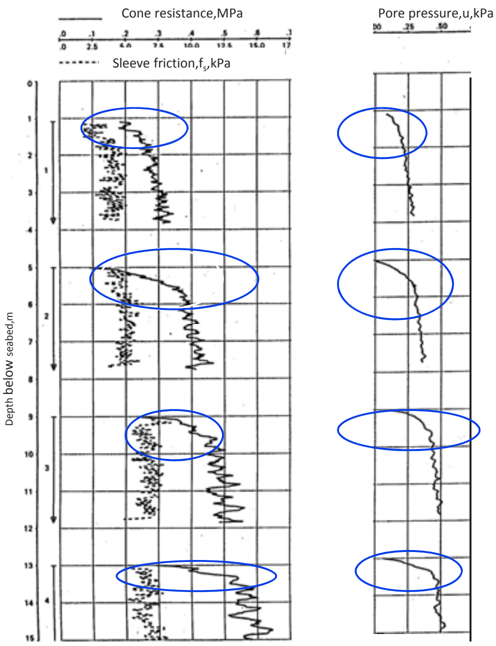

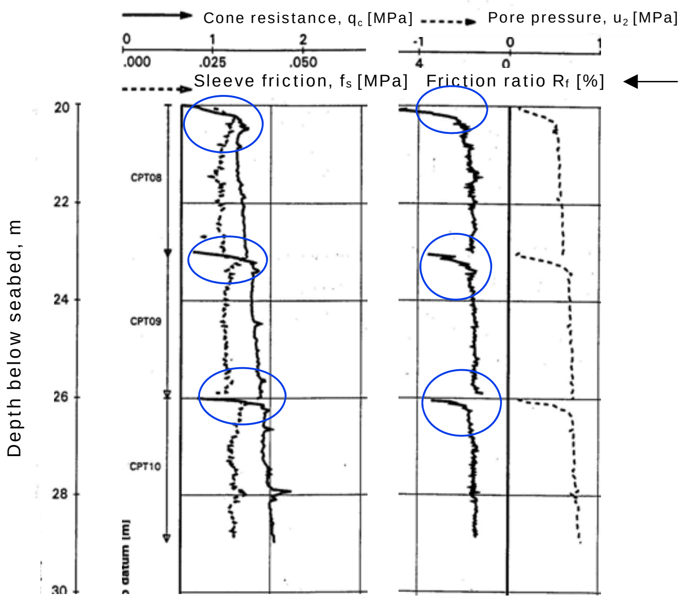

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Example of downhole CPT showing soil disturbance due to drilling

Less disturbance due to drilling

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Soil investigation strategy

<u>Development of an offshore wind park goes over several years</u>

- Location of turbines can change several times due to optimization schemes
- Do basic geophysical and bathymetric surveys covering full area
- Network of CPT's based on preliminary interpretation of geophysics
- Do some soil borings with sampling at selected locations based on CPTs and geophysical
- Establish geological model
- Use geological model to predict soil profile at new turbine locations

- When final turbine locations have been determined do CPT at selected additional locations and also a few boreholes

- Integration of geo – disciplines is essential!

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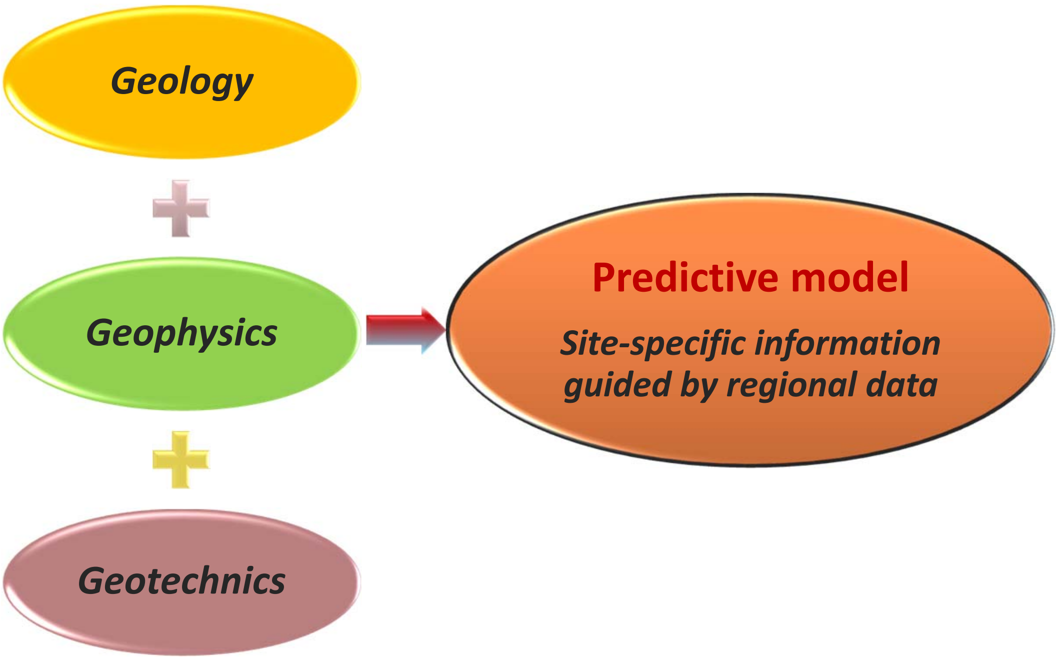
Predictive geo-model for windfarms – *Philosophy*



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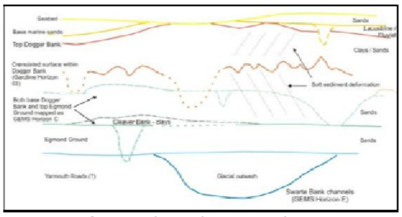
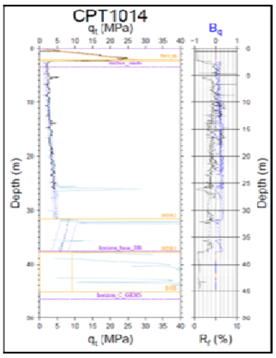
Predictive geo-model for windfarms



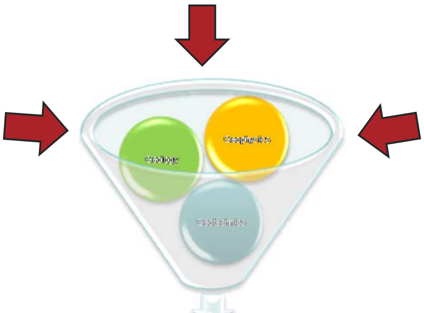
Geological understanding

Developed by
Dr. Carl Fredrik
Forsberg, NGI

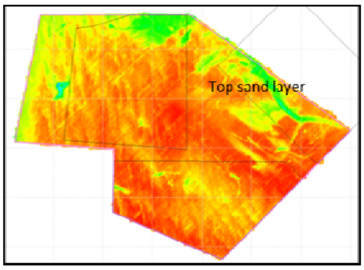
Inter-disciplinary skills required



Geotechnical and geological data



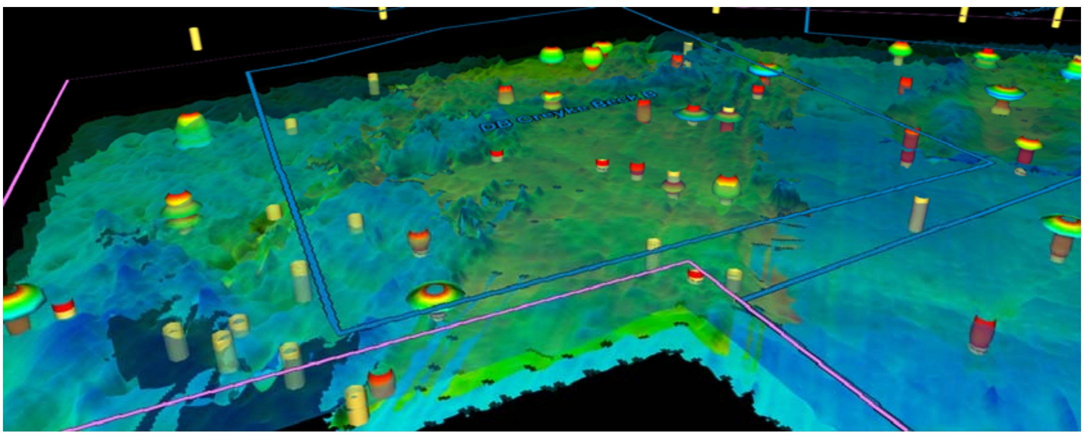
Predictive model: Site specific information must be guided by regional data.



Geophysical interpretation

Basic idea

Use geophysical and geological interpretations to guide the interpolation of geotechnical data from boreholes and CPTs.



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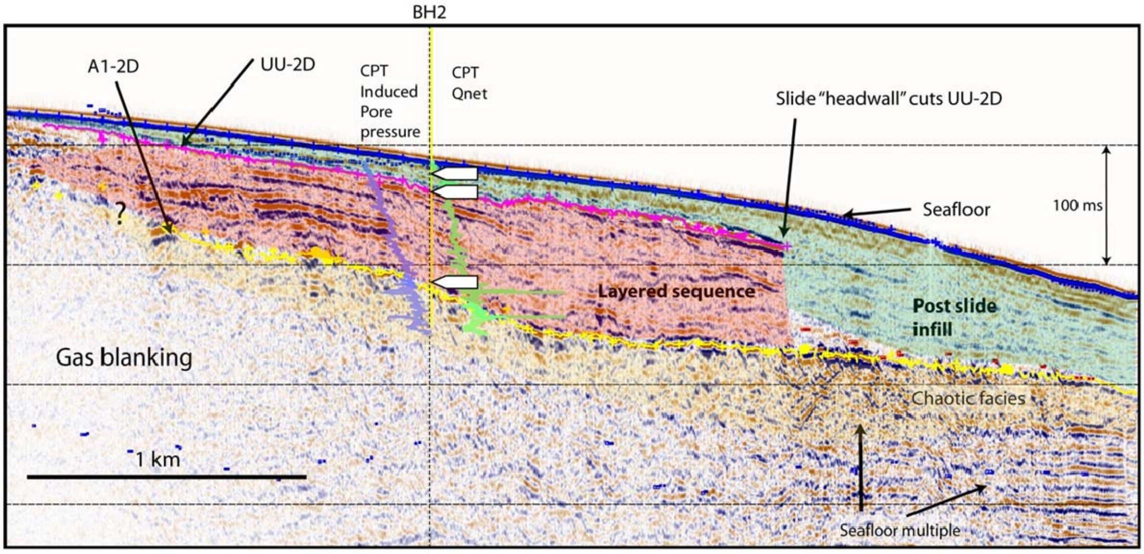
SynCPT – *In practise (1)*

- Matching geotechnical units with geology/geophysics



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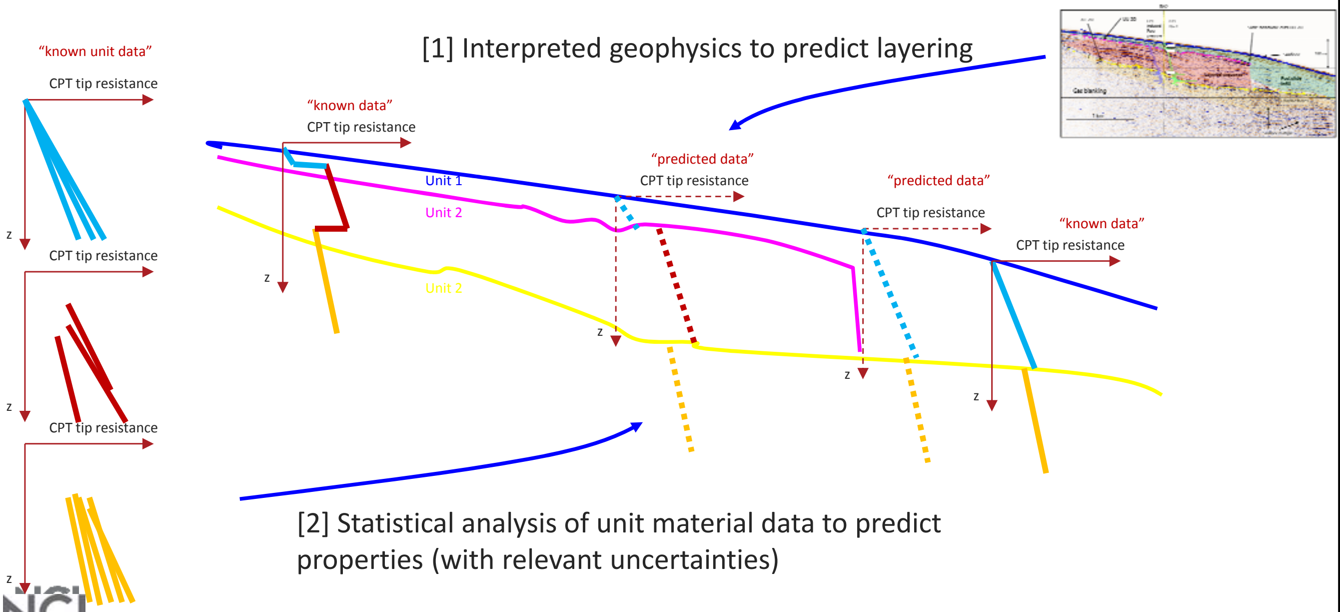
SynCPT– *In practise (2)*



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SynCPT steps

- Parameterise CPT measurements using the unit boundaries to subdivide each record. ✓
- Interpolate the CPT parameters. ✓
- Establish data boundaries. ✓
- Use seismic horizons (where available) to guide horizon depths. ✓
- Use the interpolated CPT parameters and horizon depths to construct synthetic CPT records. ✓
- Evaluate validity of profiles.
- Use profiles to help define areas for characteristic profiles.

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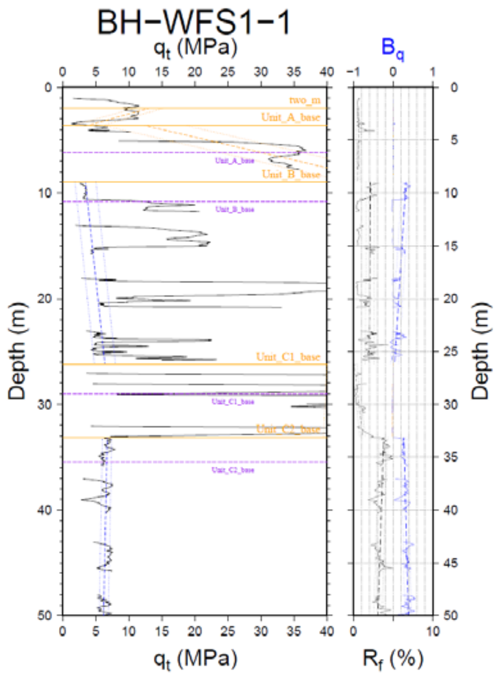
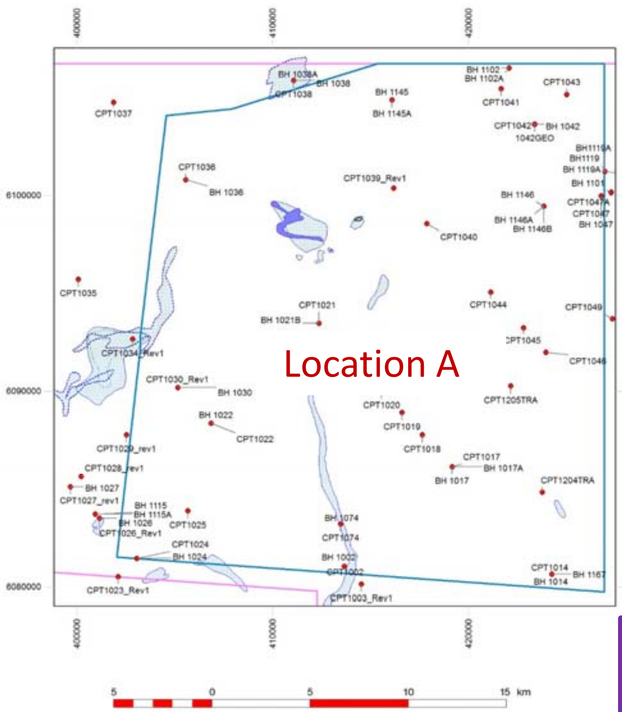
SynCPT - Input data



- CPT measurements: black line
- Unit boundaries: Orange
- Seismic horizons: Pink
- Parametrised curves: dashed lines

- All CPTs in area of interest are parameterised and inserted in data base

SynCPTs

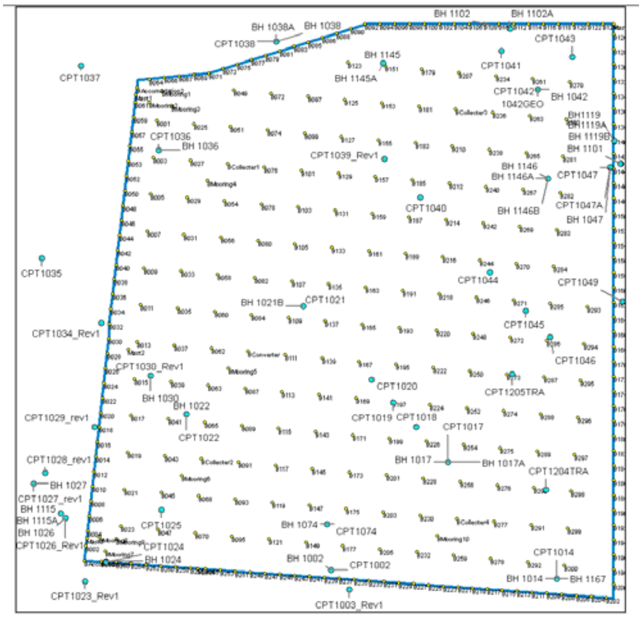


Illustrate with real Example - *Loc. A (UK sector)*

- 33 Boreholes with CPTs and sampling
- 40 seafloor CPTs

Parameter	Range, m	Average, m
Water depth	23.1 – 35.4	28.6
BH penetration	5.0 – 52.0	35.6
CPTUs penetration	3.8 – 37.9	19.5

SynCPTs – Example Loc. A



- Developer proposes grid of 320 turbine locations
- Based on model one SynCPT is produced at each location of the

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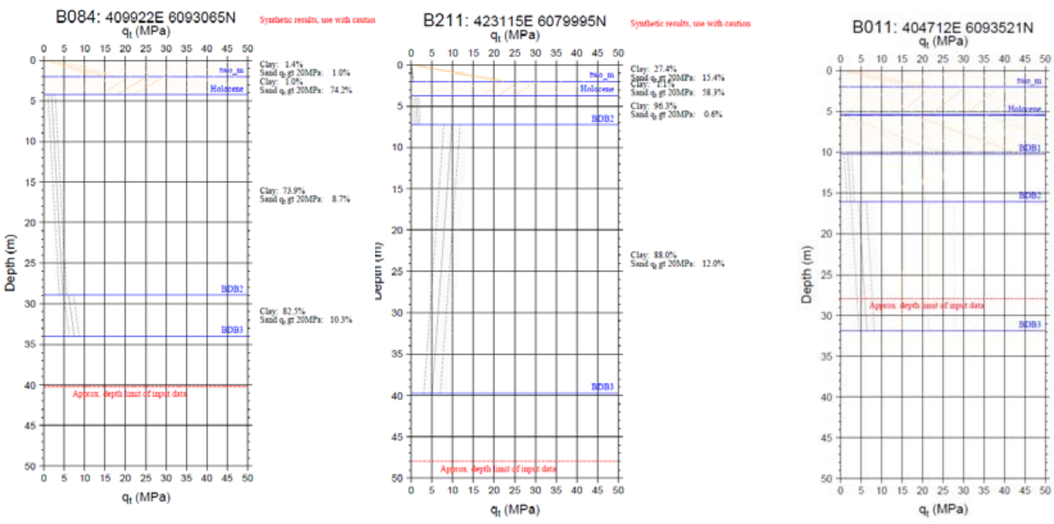
Produce Synthetic CPTs at each turbine location



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Location A example: 320 SynCPTs

Spatial mapping of characteristic soil profiles

The procedure by which the classifications is made is:

- ❑Synthetic CPT profiles are generated at each turbine location
- ❑The synthetic profiles are subjectively sorted into groups with similar appearance
- ❑The relative distribution of each characteristic profile group is found by counting the number of synthetic profiles with which they were associated.

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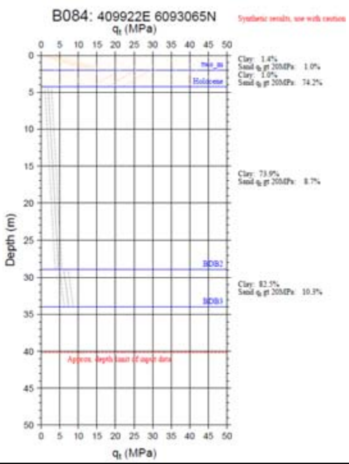
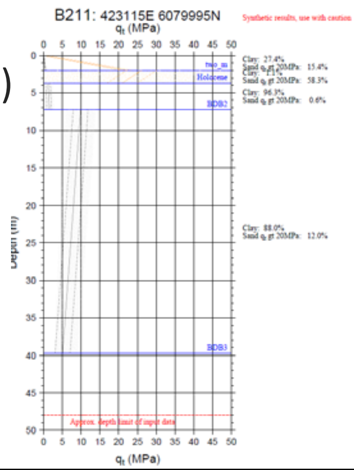
Sorting into 5 typical groups

- Group 1: < 5 m top Holocene sand
  - Holocene sand thickness varies from 2 to 5m.
  - Thickness of clay varies from 30 m (1) to only a few meters (2)

(1)



(2)



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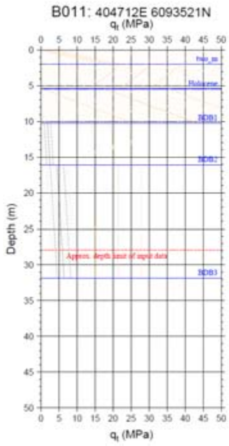
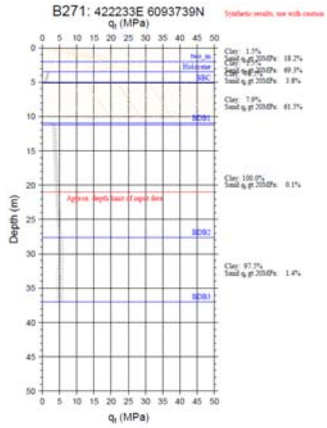
Geotechnical parameters report - spatial mapping of characterisitc soil profiles

- Group 2: 5-13 m top sand
  - Holocene sand overlying Younger Dogger Bank sand (2)
  - Same as (1) but with a layer (2-4m thick) of clay between sand units (2)

(1)



(2)



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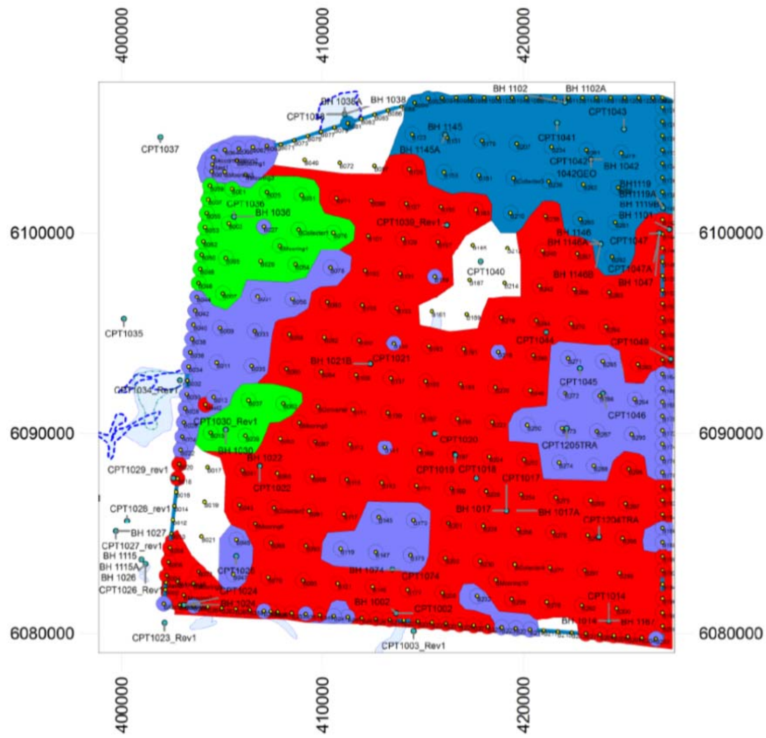
Representative Groups of SynCPTs



- Blank areas are unclassified

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Example Location A

Representative Groups – Example Lcation A

Group	Reference Site	Number of synthetic CPTs	Percentage of total (%)	General soil description
1	1014	137	43	< 5m top sand overlying upper and lower DBK
2	1074	75	23	> 5m top sand interlayered with BCT, overlying upper and lower DBK
3	1041	26	8	>10m top sand overlying upper and lower DBK
4	1036	34	11	2-5 m top sand overlying ~10m thick BDK and upper and lower DBK
Unclassified [b)]		50	15	

This distribution is then used to carry out feasibility studies for optimalization of foundation in terms of cost efficiency.

If developer comes with new lay out of turbine locations process can quickly be repeated

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Factors influencing reliability of SynCPTs

- Distance between boreholes and CPTs
- Variability of properties within layers
- Accuracy of seismic horizons
  - Time to depth conversion
  - Density of seismic profiles
  - Variability of unit thicknesses/depth

- SynCPT can also be used to identify locations where new CPTs are most needed

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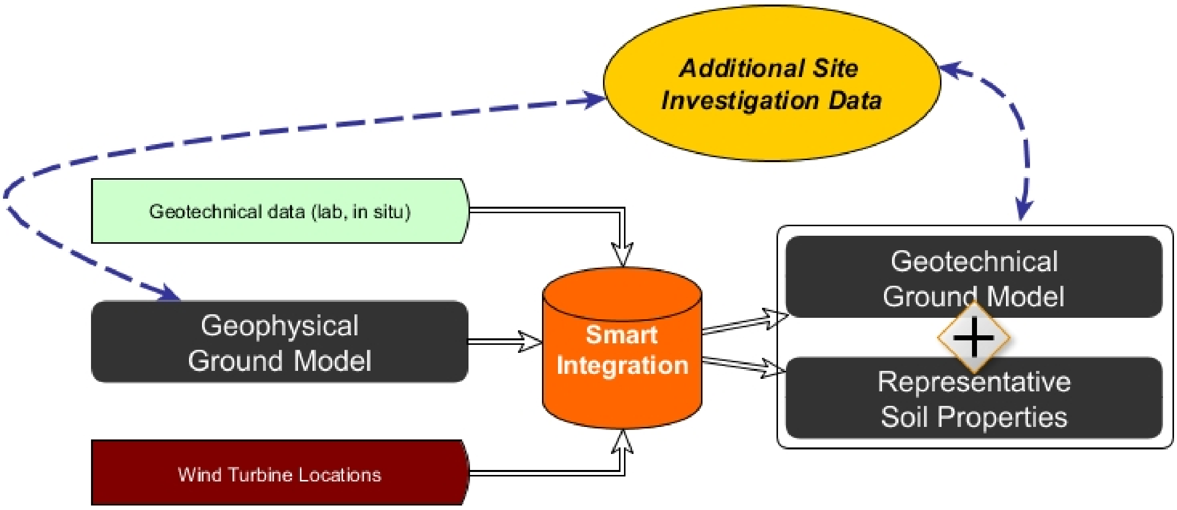
SynCPT scheme



Updating and improving as more data becomes available

Soil investigation final

- When final turbine grid has been decided – do a CPTU at most (each?) location and a few boreholes with sampling
- Purpose to verify SynCPT and check final foundation design

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Aspects of interpretation of CPTU data

- Layering and soil classification
- Design parameters sand
- Design parameters OC clays

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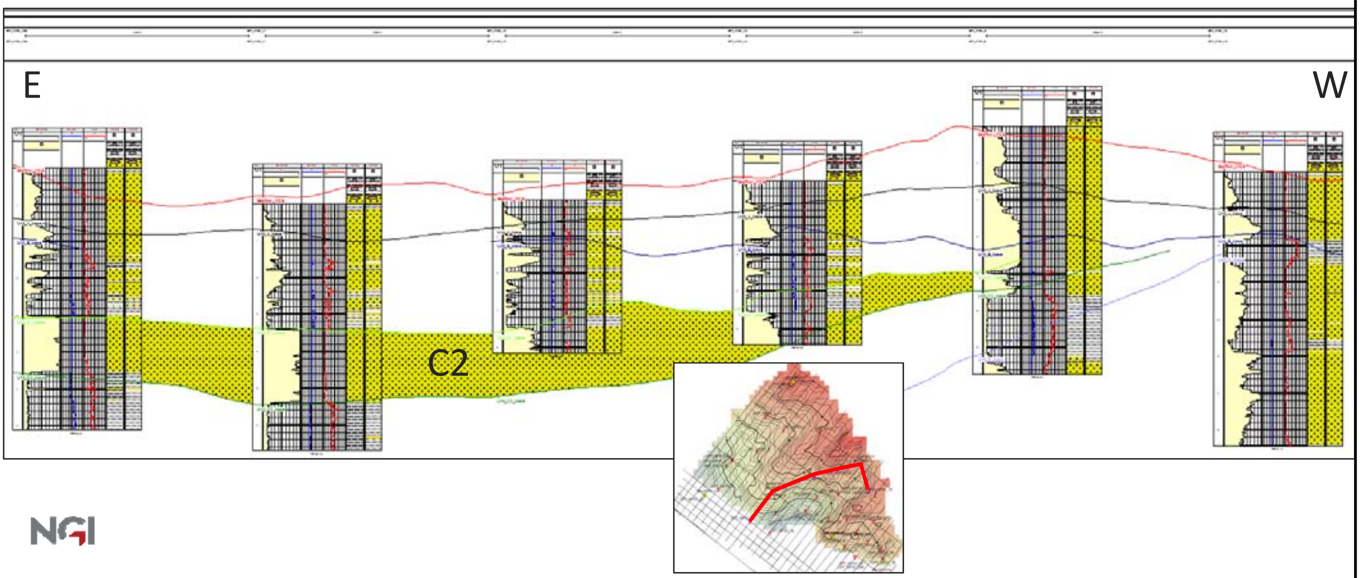
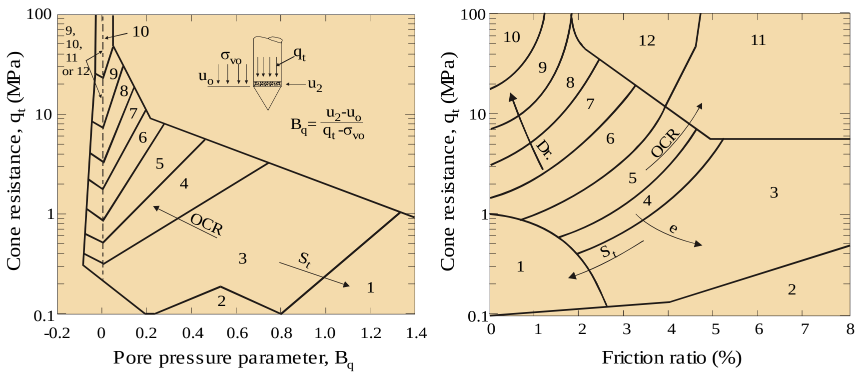
Example of soil stratification from CPT data



Soil behaviour classification chart



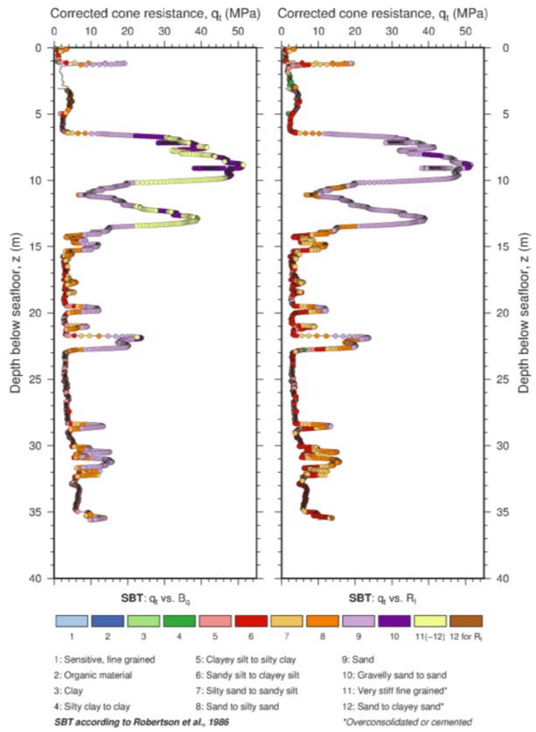
Zone:	Soil Behaviour Type:				
1.	Sensitive fine grained	5.	Clayey silt to silty clay	9.	Sand
2.	Organic material	6.	Sandy silt to clayey silt	10.	Gravelly sand to sand
3.	Clay	7.	Silty sand to sandy silt	11.	Very stiff fine grained*
4.	Silty clay to clay	8.	Sand to silty sand	12.	Sand to clayey sand*

** Overconsolidated or cemented.*

Soil Behaviour Chart

Still most used

Robertson et al.,1986



Alternative way of presenting soil type

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Soil classification may be enhanced by additional sensors

- Ref. John's presentation
- Two quick examples
  - Seismic cone
  - Gamma cone

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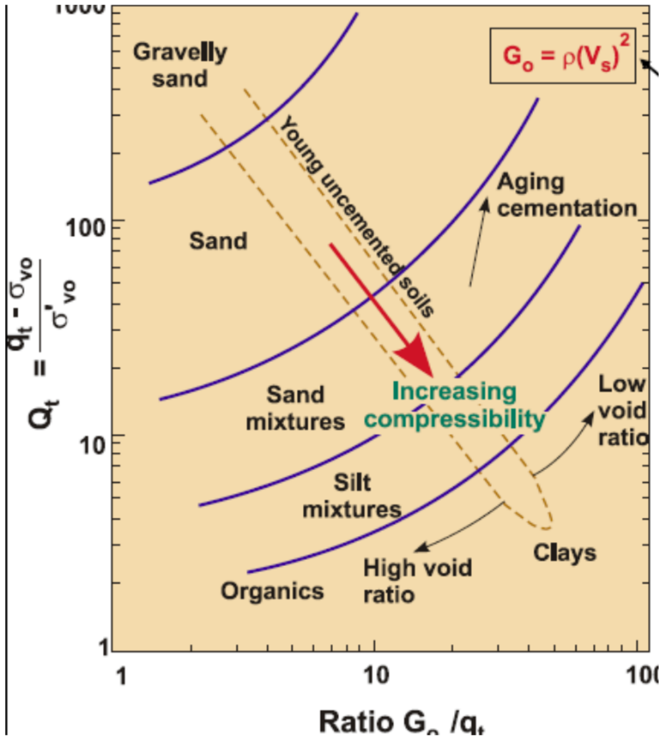

Enhanced soil classification using G_0 (from V_s) from seismic cone

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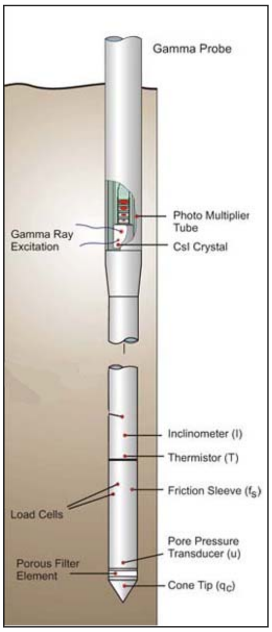
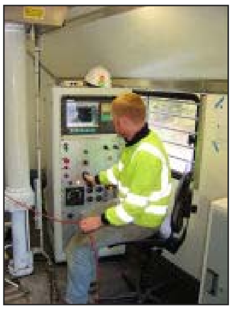
Gamma Cone Penetrometer





-Measure the natural radioactivity variations

-Natural concentrations of radio isotopes varies between geological formations

Enhanced identification of chalk in soil profile

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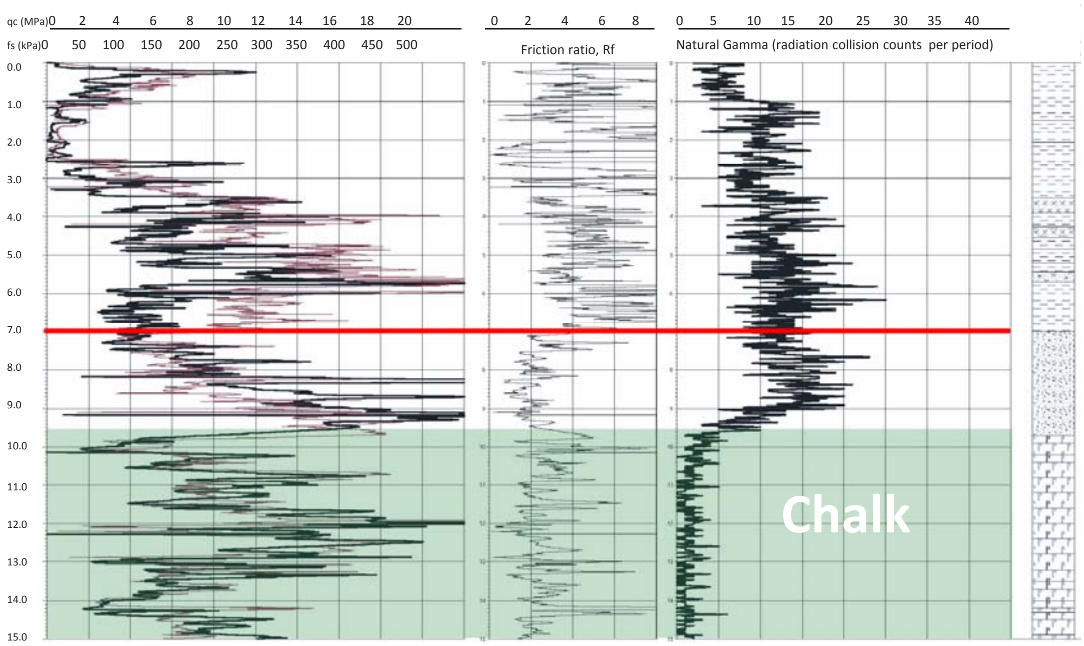
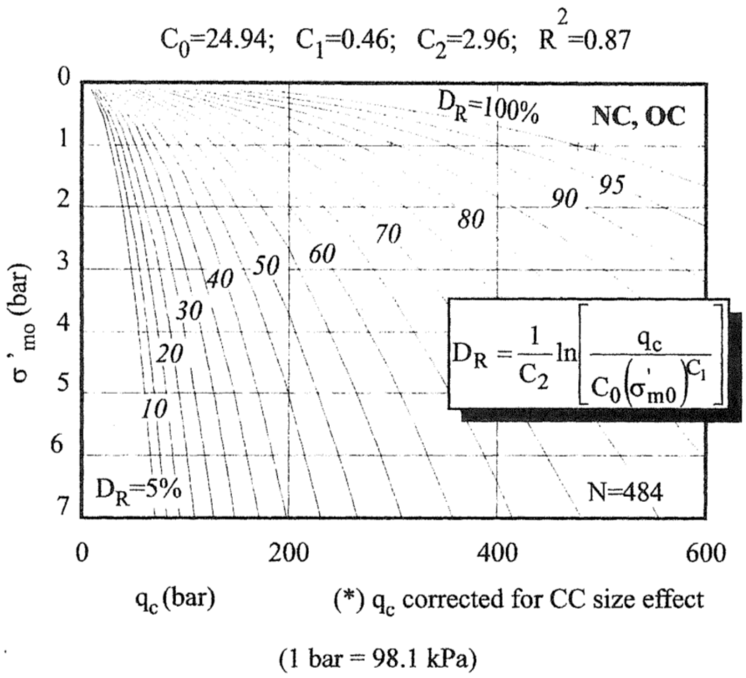
Gamma Cone Penetrometer



Good identification of chalk

Aspects of interpretation of CPTU data

- Layering and soil classification
- Design parameters sand
  - ❑ ***Relative density***
  - ❑ ***Strength***
  - ❑ Stiffness
- Design parameters OC clays



$$D_R = \frac{1}{C_2} \ln \left[\frac{q_c}{C_0 \left(\sigma'_{m0}\right)^{C_1}} \right]$$

Figure 3. Relative density of NC and OC siliceous sands

For relative densities of sands, most used now: Correlations presented by: Jamiolkowski, Lo Presti and Manassero (2003)

Based on hundreds of high quality Calibration Chamber tests carried out in Italy on Ticino, Hokksund and Toyra sands

Limitations of q_c,σ_{vo}',D_r correlations

- Only valid for the type of sands used in CC
  - Fine to medium uniform, mainly quartz sand
  - Unaged/uncemented
  - σ_{vo}' > 50 kPa
- Not valid for *silty soils*
- Not valid for compressible sand, eg calcareous sand
- Uncertain at shallow depth(< 3 – 5 m)

Some tentative corrections

Additional uncertainties due to problems with determination of max and min void ratio (or density in laboratory)

Relative density in silty sands

- Cone resistance in silty sand is lower than in clean sands.
  Relative density will be too low if using standard correlations
- There are no well established method to correct for silt content
- But for predicting liquefaction potential correlations have been developed based on extensive R&D in US
- Since liquefaction potential is to a large extent dependant on in situ density and stress which also control cone resistance we may use the correction in lack of other methods

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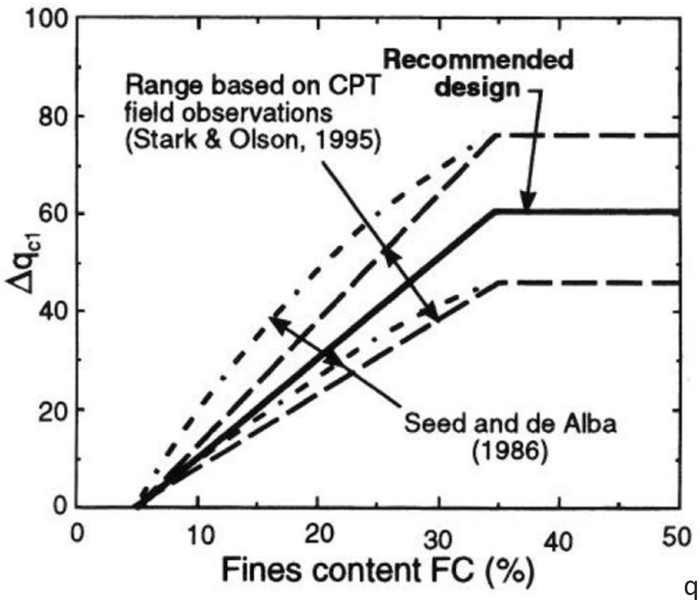

Diagram for correcting q_c for liquefaction analyses

Work out q_{c1} from basic CPT data, then $q_{c1,corr} = q_{c1} + \Delta q_{c1}$

Then use $q_{c,corr}$ in Jamiolkowski et al diagram to estimate D_r

$q_{c1} = (q_c/p_a)(p_a/\sigma_{vo}')^{0.5}$

p_a = reference stress = 100 kPa

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D_r – correction of silt content

Example: q_c = 5 MPa, 10 m depth: σ_{vo}' = 100 kPa; Fines Content = 20 %

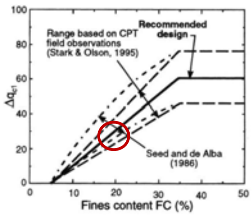
$q_{c1} = (q_c/p_a)*(p_a/\sigma_{vo}')^{0.5}$ p_a = reference stress = 100 kPa

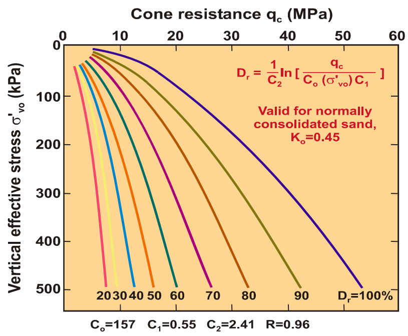
$q_{c1} = (5000/100)*(100/100)^{0.5} = 50$

$\Delta q_{c1} = 30$

$q_{c1,corr} = 80$

$q_{c,corr}$ = 8 MPa





D_r before correction ~ 40 %

D_r after correction ~ 60 %

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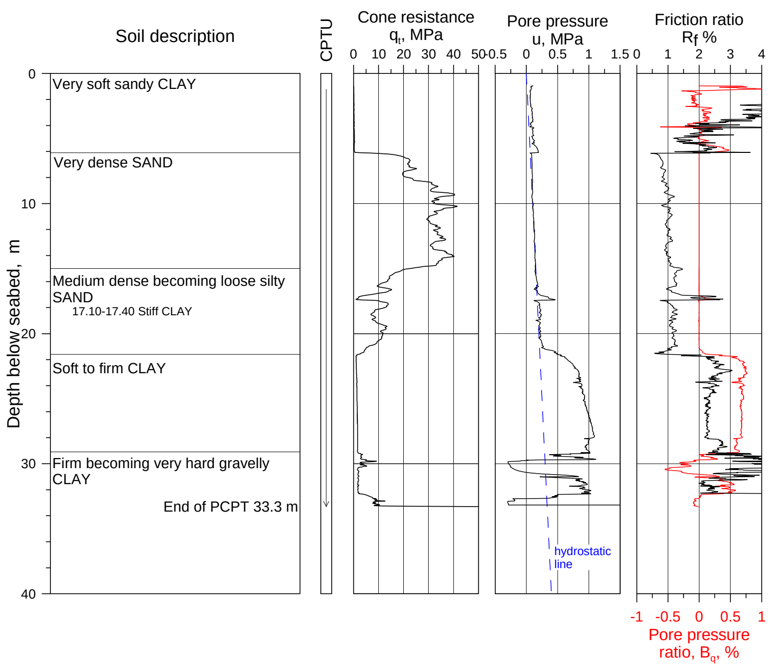
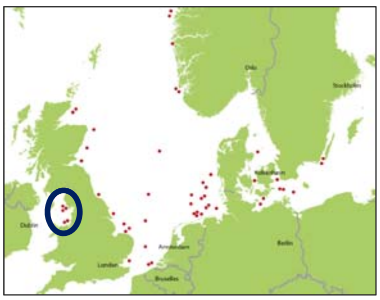
Illustrate later with case history



Typical seafloor CPTU profile



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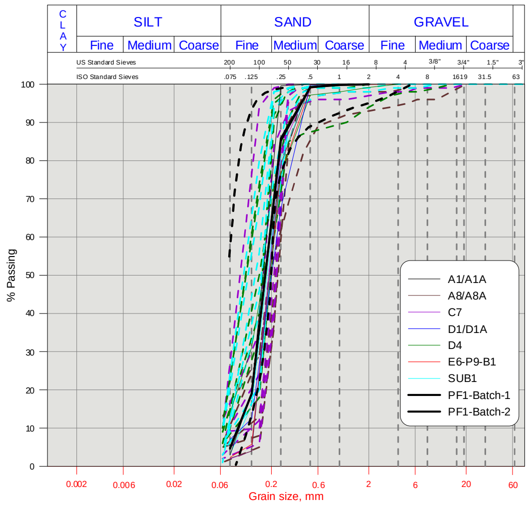
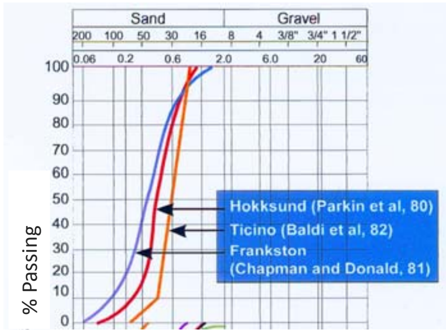
Case in Irish Sea – wind farm development

Upper sand layer



Compare with CC sands



Quite similar to CC sands: Ticino and Hokksund. Use Baldi et al (1985)correlation

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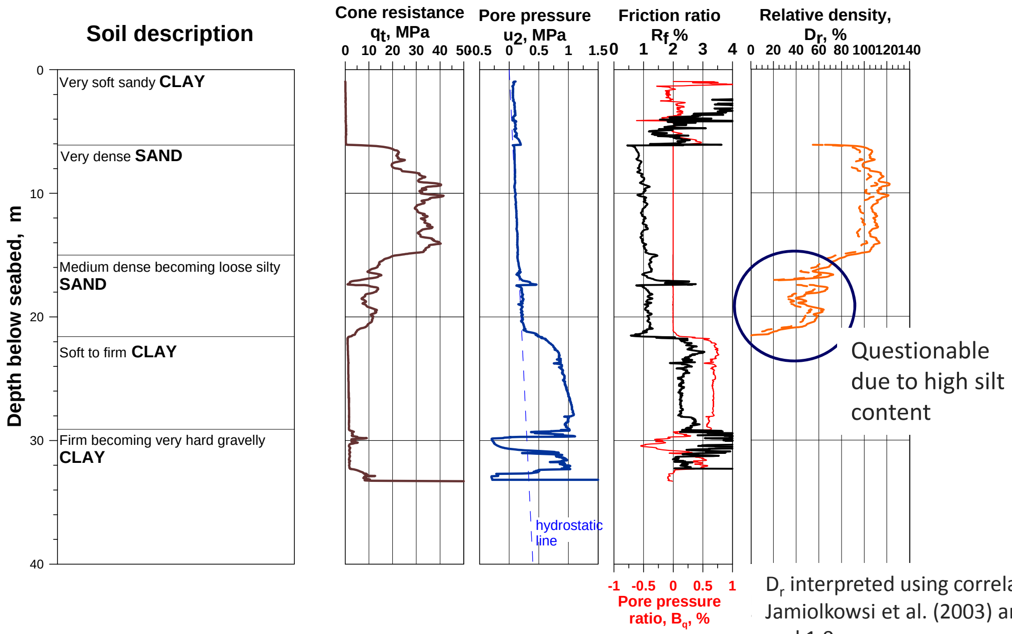
Example from Windfarm in Irish Sea



D_r interpreted using correlation of Jamiolkowsi et al. (2003) and using K_0 = 0.5 and 1.0

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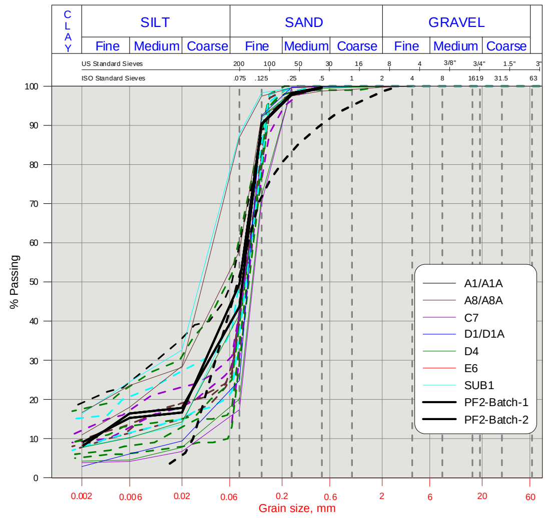
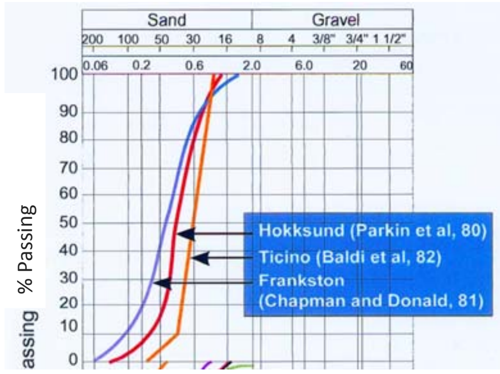


D_r in lower, silty sand



Sand very different from CC sands,
Correlations have to be used with caution, if at all

Fines content 10 – 35%

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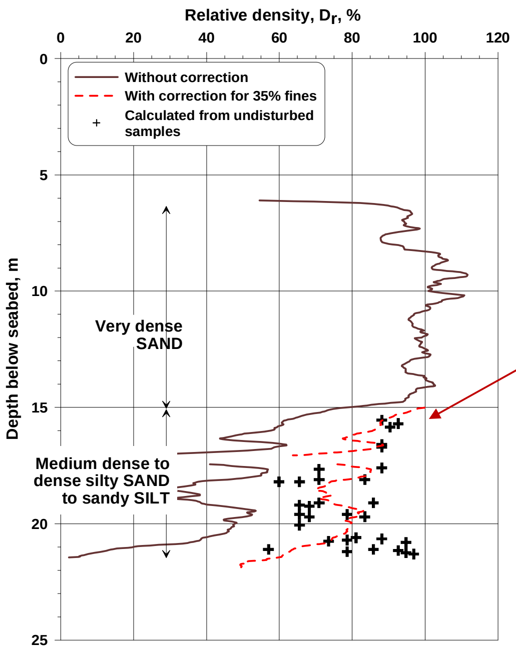

Jamiolkowski et al. (2003) correlation using K_0 = 0.4
q_c correction assuming 35 % fines. Lab D_r from measurements on «undisturbed» samples

Example from Wind farm in Irish Sea

Corrected using liquefaction correction chart

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Correlations by Jamiolkowski et al. and others really valid for σ_{vo}' > 50 kPa – corresponding to about 5 m depth; ie uncertain 0 – 3/4 m below sea floor

Mainly an issue offshore in connection with pipeline/seabed structures

For shallower depth new approach has been suggested by Emerson et al. (2008)

Effects of shallow depths on CPT interpretation

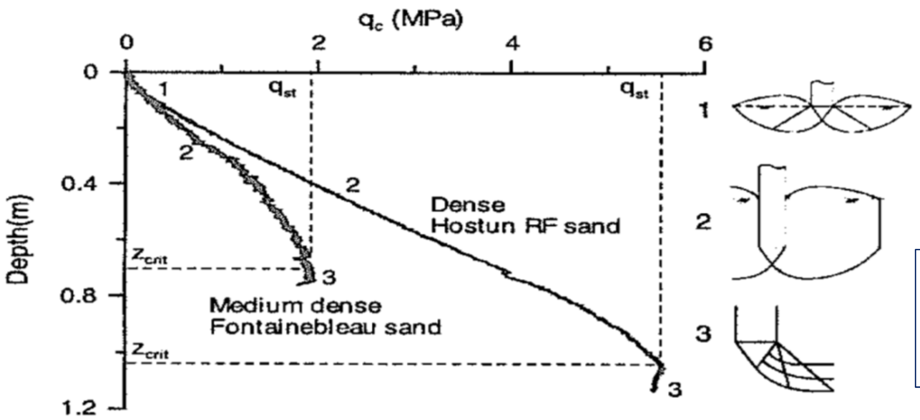


Figure 1. Cone resistance profiles recorded in laboratory CC tests in homogeneous samples alongside associated failure mechanisms.

A good start, but method needs further development; NGI is pursuing this in ongoing R&D project

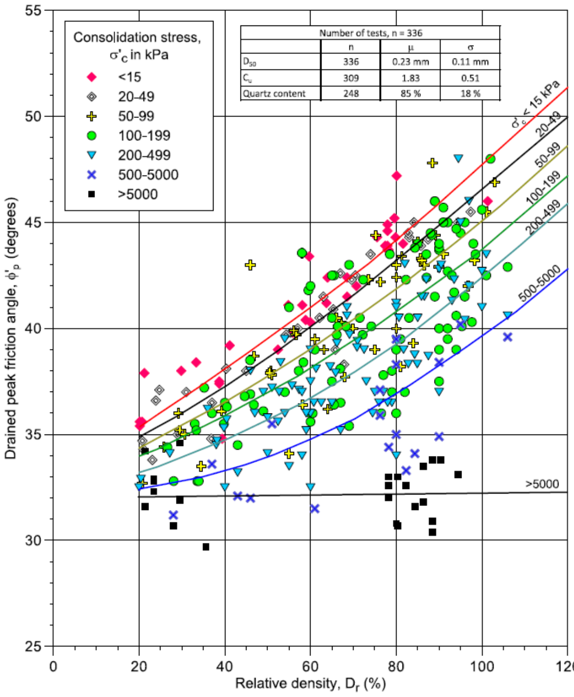
z_{crit} = critical depth

q_{st} = «limit» value of q_c

Emerson et al. (2008)

Drained peak friction angle, ϕ'_p, as function of D_r and σ'_c

Based on database of CAUC tests on North Sea sands, mainly quartz, fine to medium uniform sands



NGI From Andersen and Schjetne (2013)

σ'_c = mean consolidation stress

Drained peak friction angle, ϕ'_p, as function of D_r and σ'_c

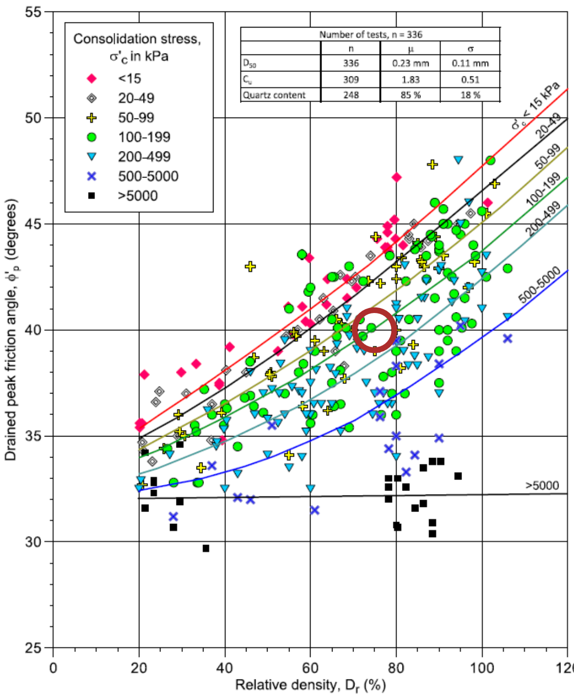
Example:

D_r = 75%

σ'_c = 150 kPa

⬇

$\phi'_p = 40^o$



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σ'_c = mean consolidation stress

Cyclic strength

- Based on a comprehensive laboratory testing programme correlations for evaluating cyclic strength has been developed.
- Input parameters are: D_r, σ_{v0}', OCR

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Aspects of interpretation of CPTU data

- Layering and soil classification
- Design parameters sand
  - Relative density
  - Strength
- Design parameters OC clays
  - Stress history – OCR
  - Lateral stress ratio: K_0
  - Undrained shear strength

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Estimation of OCR and K_0

- $OCR = k * (q_t - \sigma_{vo}) / \sigma_{vo}'$ k = 0.2 – 0.4 (in OC clay 0.3 fits well)
- $K_o = f(OCR, I_p)$ Brooker and Ireland (1965)

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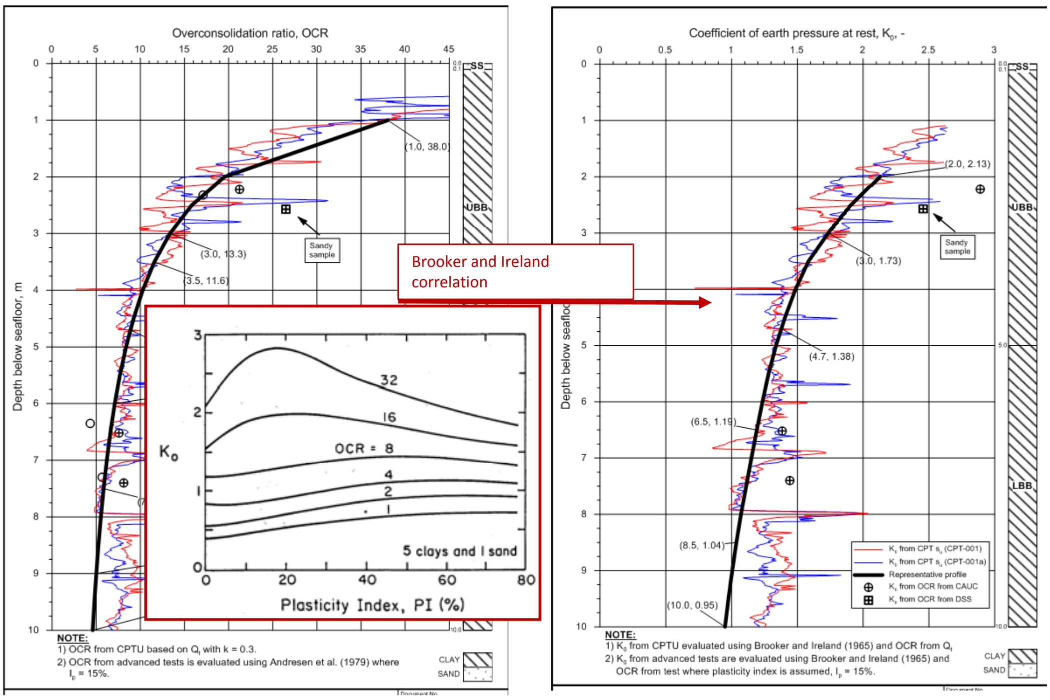

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Undrained shear strength in OC lay

- Usually reasonably good fit using

$s_{uC} = (q_t - \sigma_{v0})/N_{kt}$ and $N_{kt} = 15 – 20$

s_{uC} is undrained shear strength from triaxial CAUC tests consolidated to best estimate in situ stresses and sheared in compression

In large projects N_{kt} is from local calibration of site specific data

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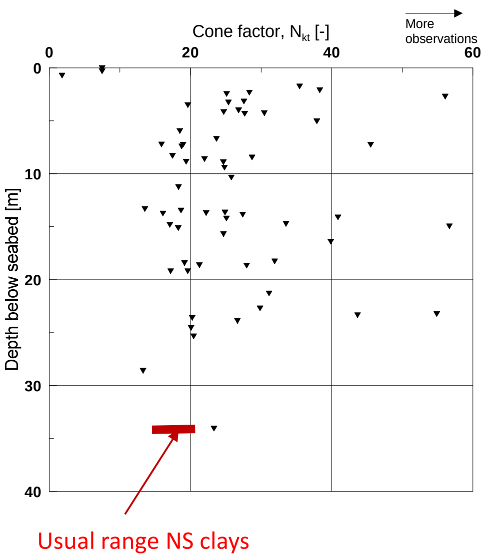
Undrained shear strength,

$s_u = (q_t - \sigma_{v0})/N_{kt}$

Usually $s_u = s_u^{CAUC}$ $N_{kt} = 15 – 20$ for OC clays

Reasons for exceptionally large scatter in N_{kt} values:

- Fissuring/inhomogenieties due to desiccation, ice loading etc
- Sample disturbance



N_{kt} for complete Dogger Bank area

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Dogger Bank clays

Why all the scatter?

- **very complex geologic history** (clay soils have strong memory!): desiccation due to drying and freezing, thawing, faulting, erosion, glacial loading, ….
- **desiccation/freezing** → blocky fabric, slickensides, fissures, micro/macro features, all of which are variable, even over small spatial scales → **highly erratic soil properties**
- **sample disturbance** and **scale effects** for lab tests

Blocky structure = planes of weakness; evidence of desiccation

Slickensides are isolated within diameter of sample

Note distorted layers = sample disturbance

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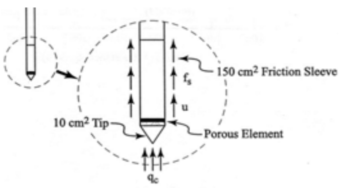
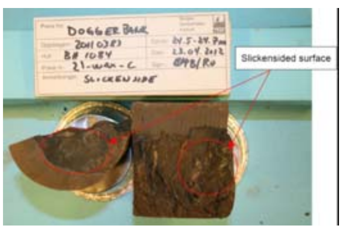
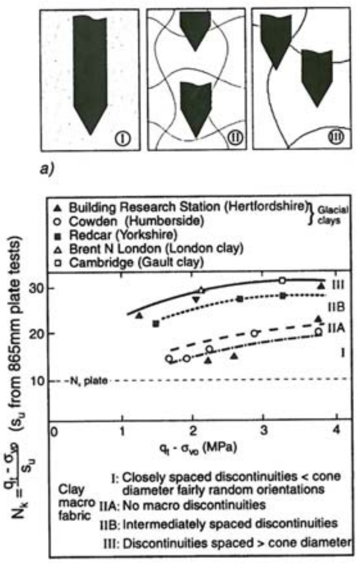
Previous experience in fissured London clay

Effect of clay fabric on cone factor N_{kt}



$s_u = q_{net}/N_{kt}$





Marsland (1974)

Example from fissured UK clays

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The big uncertainty regarding clay is: what is the 'operational' shear strength?

A problem with industry standard testing used so far is that only relatively small volumes of soil have been tested and which can give unrepresentative strengths due to the clay fabric features. In London clay and other UK clays this has been tackled by doing large plate load tests involving larger soil volumes. The shear strength involving larger soil volumes have been called *"operational shear strength"*.

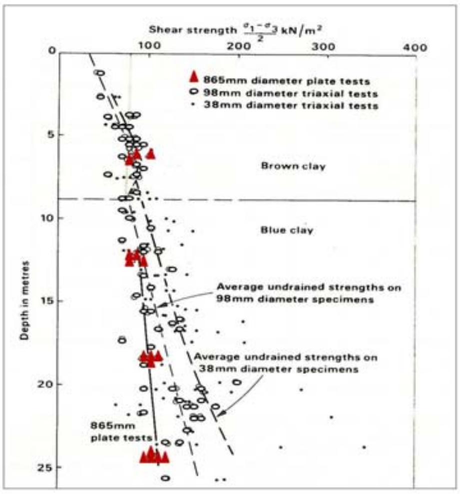

Plate load tests in London clay has shown that operational strength found from plate load tests can be different to small scale laboratory tests and show much less scatter

Results of plate load tests in London clay

Plate dia. = 0.9 m

Experience from London clay (Marsland, 1974)

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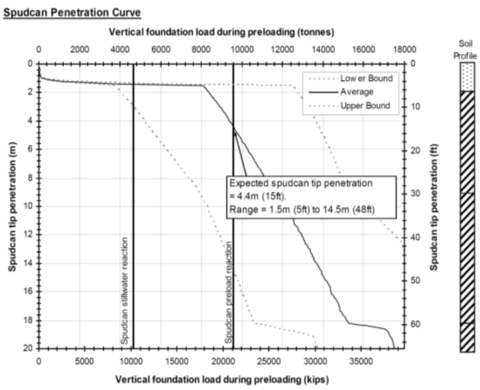
Back calculation of s_{uC} from spud can penetration in Dogger Bank clay



- Spud can diameter: 8 m
- Actual penetration 12 m
- Bearing capacity calculation using industry practice and NGI software

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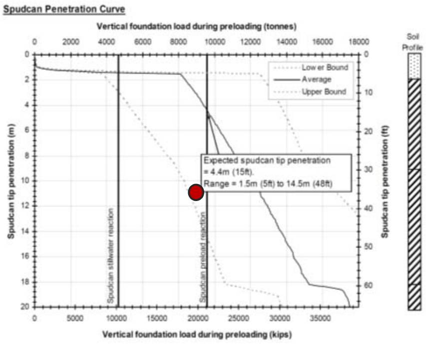
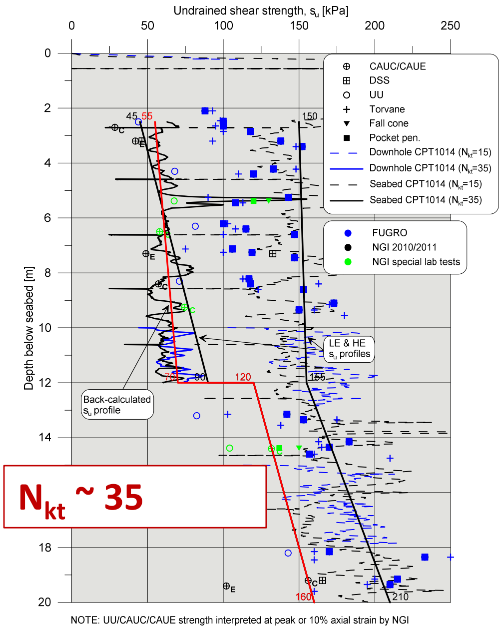
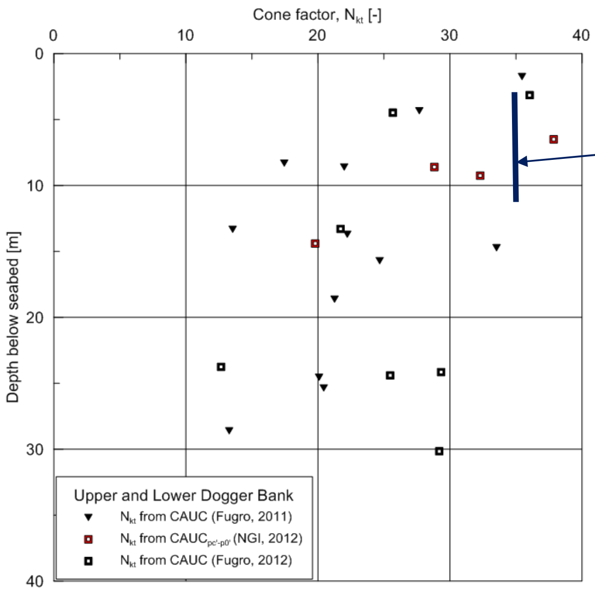
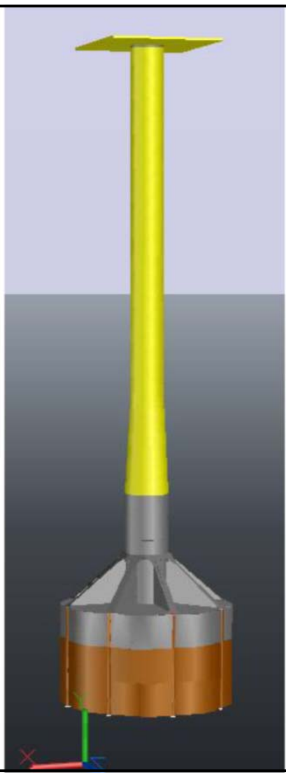
Back calculation of s_{uC} from spud can penetration in DB clay







Back calculation spud can penetration



Installation bucket foundation at same location as spud can

Back calculation complicated by clay chamber and upper sand layer

Bucket geometry and inner structural members including Clay chambers.

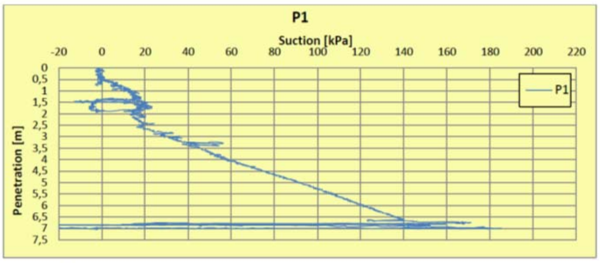
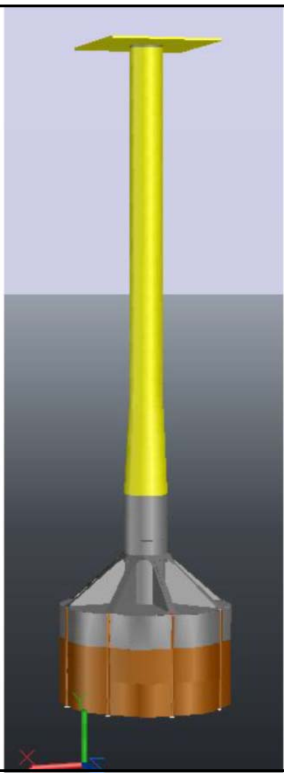


Figure 2.5: Required suction versus penetration depth.



Installation bucket foundation at same location as spud can

Assumptions:

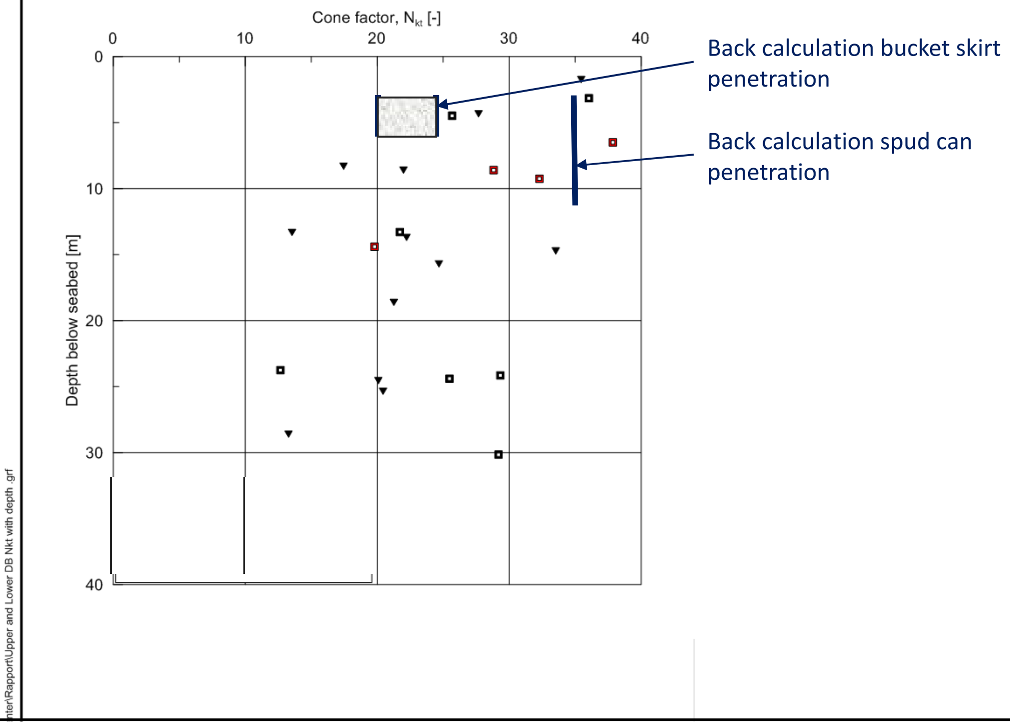
Skirt side friction = s_{uD}/S_t

$s_{uD} = 0.8 – 1.0 \cdot s_{uCAUC}$

$S_t = 1.0 – 2.0$

Result: Average s_{uC} ~ 88-110 kPa (3.5 – 7m)

Corresponding to N_{kt} ~ 20 - 25



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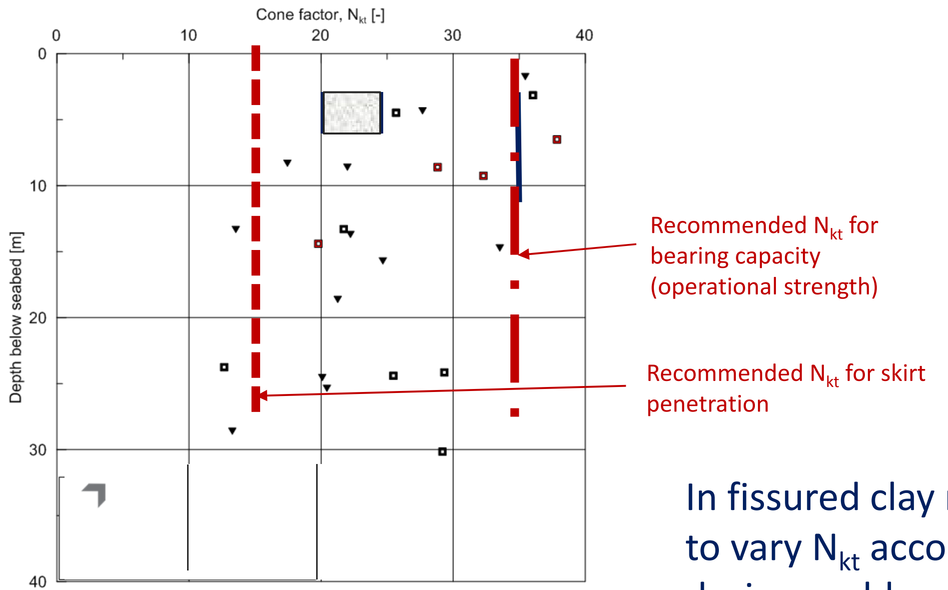

In fissured clay may have to vary N_{kt} according to design problem

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Outline

- Background
- Overview of potential foundation types, forces and speccial challenges
- Range of soils typically encountered
- Soil investigation methods used
- Typical soil investigation strategy
- Need for integrated approach: geology, geotechnics and geophysics
- Synthetic CPT scheme
- Some special aspects
- Summary and Conclusions

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Summary and Conclusions

- Offshore wind farms are large projects – up to several 100s turbines
- Blade diameters up to 150 m+ with enormous horizontal forces
- Main foundation type is presently monopile, but others including jacket with buckets are also being used
- Often very complex geology resulting in a large range of soils
- Final foundation design will largely be based on CPTU data
- Integration of geology, geophysics and geotechnics is essential, with the synthetic CPT being a very useful tool
- Challenges in interpretation of CPTU in several soil types including silty sands and highly structured OC clays

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Thank you for your attention!

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