Site investigation and soil parameters for OWT foundation design
海上风电现场勘查及设计参数确定

Geotechnical Engineering for Offshore Wind Infrastructure
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Contents

• Site investigation
• Geomodel
• Laboratory program and tests
• Soil design parameters
• Cyclic contours 等值线图
Site investigation
Standards & Guidelines

Marine Site Investigations
Geotechnical: ISO 19901-8-1 (2014)
Geophysical: ISO 19901-8-2
SUT-OSIG, 2014
Petroleum and natural gas industries — Specific requirements for offshore structures —

Part 8: Marine soil investigations

Industries du pétrole et du gaz naturel — Exigences spécifiques relatives aux structures en mer —

Partie 8: Investigations des sols en mer
Flow charts – Offshore Renewables

1. Start
   - Desk study
   - Evaluation of investigation/study and update geotechnical model
   - Undertake investigation/study
   - Consultation: Designers, Developers, Financiers, Contractors etc.
   - Plan study/investigation to mitigate risk

2. Update geotechnical design report and risk register
   - Are residual risks acceptable to the project?
     - Yes
     - NO
   - End
     - Sufficient site investigation

Start: 1
Update rock design report
Risk evaluation
End: 2
Site investigation end

Source: SUT-OSIG
Geotechnical site investigation

Seabed CPT
Downhole CPT
Geophysical techniques – Offshore Renewables

Source: SUT-OSIG
Benefits and observations

- Stratigraphy and spatial variability
- Larger spatial coverage
- Geophysics is combined with geotechnical data
- Ground model without geophysical data (and knowledge of geological processes) is impossible
The challenge

- Often vast areas: 50 to 300 turbines
- Shallow water depths and ~50 m penetration
- Often complex geological history (river deposits, glacial processes, sea level fluctuations, ...)
- Often, sparse data coverage
  - Bathymetry OK
  - Single-channel seismsics (with multiples)
  - Sparse geotechnical boreholes
  - Costly...

Image from: energinet.dk
The challenge

- Turbine relocation common
- Need to obtain quantitative soil parameters

Solution:
- Integration of geology, geophysics and geotechnics
- Use 2D/3D geophysical data to guide interpolation of 1D geotechnical data
Geomodel – Flow Chart

1D Geotechnical Data (in situ, lab) → 2D/3D Geophysical Ground Model

- Geotechnical layering and unit definition

Unit/Horizon matching/correlation

- Intelligent Ground Model (NGI’s intellectual property)

- Synthetic 2D/3D Geotechnical Ground Model & Confidence

Geotechnical Grouping and zonations: match synthetic and field data

Select representative boreholes per soil province (CPTU and lab)

Obtain Relevant Representative Soil Properties (unit, provinces)

Technical Reports

GIS (updated)
Geomodel – In practise (1)

Matching geotechnical units with geology/geophysics
Matching geotechnical units with geology/geophysics

Analysis for all identified units and for relevant measured/derived geotechnical parameters if sufficient data is available

Gridding of parametrised data using an appropriate pixel size/dimension

Gridding takes into account whether a unit was present or not, or whether the borehole/CPT was too shallow to reach it
Prediction: SAND vs. CLAY
Geomodel – In practise (4)

[1] Interpreted geophysics to predict layering

[2] Statistical analysis of unit material data to predict properties (with relevant uncertainties)
Geomodel – In practise (5)
Pseudo-3D visualization:

- Horizons picked from the geophysical survey data, with CPTU locations

- For the CPTU, the width of the cones shows the measured $q_t$, as one prime parameters for the ground model for interpolation between the CPTU locations, guided by the geophysics
Geomodel – In practise (6)
Added value – Flexibility for “Life of Field”
Added value – Optimization of design

- Data-driven assessment of site conditions including uncertainty or variability
- Optimization of design and foundation concepts, based on data availability and integration
Laboratory program for OWT foundation design
Laboratory program for OWT foundation design

- Laboratory tests on all relevant soil layers
- A representative set of lab tests per soil layer may comprise:
  - 1 - 2 oedometer tests
  - 1-2 static DSS, 1-2 static CAUC/E, undrained for clay
  - 1-2 static DSS, 1-2 static CAUC/E, drained for sand
  - 4-6 cyclic undrained DSS tests
  - 5-7 cyclic undrained CAU, $\Delta\tau a$ (drained/undrained)
Laboratory program for OWT foundation design

- Resonant column / bender element (Gmax, damping)
- Remoulded soil data - Soil-skirt interface strength, set-up effect
  Consolidated to lateral in-situ stress after installation

Three zones need to be distinguished
- Inside the caisson
- Outside the caisson
- Below the caisson
Laboratory program for OWT foundation design

- Index parameters
  - Relative density
  - Plasticity index
  - Water content
  - Grain size distribution
- Information on scour development and scour protection
## Laboratory program for OWT foundation design

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Clay</th>
<th>Sand</th>
<th>Clay</th>
<th>Sand</th>
<th>Clay</th>
<th>Sand</th>
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</thead>
<tbody>
<tr>
<td>Frictional characteristics</td>
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<td>x</td>
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<tr>
<td>Peak drained friction angle, $\phi^d$</td>
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<tr>
<td>Undrained friction angle, $\phi_u$</td>
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<tr>
<td>Dilatancy angle, $\nu$</td>
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<td>x</td>
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</tr>
<tr>
<td>Slope of DSS drained failure line, $\alpha^d$</td>
<td>x</td>
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<tr>
<td>Slope of DSS undrained failure line, $\alpha_u$</td>
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<tr>
<td>Interface friction angle, $\beta_{int}$ and $\beta_{ext}$</td>
<td>(x)</td>
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</tr>
</tbody>
</table>

### Monotonic data

- Monotonic undrained shear strength, $\tau_{uu}$
- Initial shear modulus, $G_{int}$

### Cyclic data

- Cyclic drained shear strength, $\tau_{ct}$
- Cyclically induced pore pressure, $u_{ct}$
- Cyclic stress strain data, $\tau_{ct}$ and $u_{ct}$

### Damping

- Consolidation characteristics, intact soil
  - Preconsolidation stress (and OCR)
  - Virgin, unloading and reloading constrained modulus
  - Permeability
  - Remolded soil data
    - Sensitivity, $S_i$
    - Undrained shear strength of reconsolidated remoulded soil, DSS
    - Cyclic undrained shear strength, $\tau_{ct}$
    - Virgin constrained modulus
    - Permeability
    - Thixotropy

### Additional parameters for reference monotonic pile capacity

- Relative density, $D_r$
- CPT resistance
- Plasticity index, $I_p$
- Monotonic UU shear strength, $\tau_{UU}$

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Andersen, et al., 2013
Sturm (2017)
X-ray investigation

Soil samples

Change at 2.9 m

Depth from 2.24 to 3.24 m
X-ray investigation

CROSS SECTIONS

Soil samples

Change at 6.7 m

Depth from 6.24 m to 7.24 m
X-ray investigation for soil units

Soil samples

Unit I
CLAY, very soft, dark greyish brown

2.74 m

Unit II
CLAY, very soft, very dark grey, shell fragments, mica crystals

3.14 m
6.44 m

Unit III
CLAY, calcareous to carbonate, slightly sandy, soft, dark grey to black

7.04 m

Depth below seabed, m

Water content, %

Unit weight, kN/m³

Undrained shear strength, su, kPa

Interpreted from T-bar test

CAUE
CAUC
DSS
Fall cone

Soil description

X-ray image

0 50 100 150 200
0 12 14 16 18 20
0 20 40 60 80
NGI LAB
One of the largest Geotechnical Laboratory in the world
One of the largest Geotechnical Laboratory in the world – NGI LAB
Soil design parameters for OWT foundations
Soil design parameters for OWT foundations

Static strength profiles
Soil parameters for preliminary design

Figure 10.6. Static shear strength in DSS tests on normally consolidated clay (>10% clay content) as a function of plasticity index.

(Andersen 2015)
Soil design parameters for OWT foundations

Cyclic strength profiles

- Definitions of cyclic shear stress, strains and pore pressure
- Results of cyclic DSS and CAU tests
- Interpretation of cyclic testing results
- Application of cyclic contour diagrams in foundation design
Cyclic loading on soils – Definitions

Cyclic loading generates pore pressure

Cyclic contour diagrams (Andersen, 2004, 2015)
Pore pressure & shear strain increase with no. of cycles

Cyclic and average shear stresses

Pore pressure generation

Cyclic, average and permanent shear strains

Cyclic contour diagrams (Andersen, 2004, 2015)
Shear strains depend on test type and $\tau_a$

剪应变取决于试验类型和平均剪应力

DSS, $\tau_a=0$

Triaxial, $\tau_a = 0$

Triaxial, $\tau_a = \tau_{cy}$

Cyclic contour diagrams (Andersen, 2004, 2015)
Soil elements follow different stress paths

Behavior can be determined from laboratory tests and organized in contour diagrams.

Cyclic contour diagrams (Andersen, 2004, 2015)
Laboratory cyclic testing on soils

Cyclic DSS
Cyclic Triaxial
Triaxial/DSS cyclic

- Typical results - cyclic
  - Shear stress vs N
  - Axial strain vs N
  - Permanent pore pressure vs N
  - Shear stress vs shear strain
  - Stress path

Cyclic test on Kaolin clay
\( \gamma_a \) or \( \gamma_{cy} \), >15%, failure
Interpretation of cyclic testing on soils (DSS)
Interpretation of cyclic testing on soils (DSS)

Number of cycles to failure ($\gamma_a$, $\gamma_p$, $\gamma_{cy}$)

- $1.3$ (-1.7; -15.0; 15.0)
- $56$ (-2.0; -14.9; 15.0)
- $N_s > 10$
- $2$ (15.0; >15.0; 11.5)
- $5000$ (0.2; 0.0; 0.5)
- $N_s > 10^4$
- $N_s > 10^5$

$\tau_{cy}/\tau_{u,DSS}$ vs. $\tau_{a}/\tau_{u,DSS}$
Interpretation of cyclic testing on soils (CAU)
No. of cycles to failure depends on $\tau_a$ and $\tau_{cy}$

Cyclic shear strength is $\tau_{f,cy} = \tau_a + \tau_{cy}$

周期剪切强度

破坏循环数取决于平均剪应力和周期剪应力
Cyclic shear strength: \( \tau_{f,cy} = \tau_a + \tau_{cy} \)

DSS

Drammen Clay, OCR=1

\[ \frac{\tau_{f,cy}}{s_u} = \gamma_a / \gamma_{cy} \]

\[ N_f = 1 \]

\[ N_f = 10 \]

\[ N_f = 100 \]

\[ N_f = 1000 \]
Cyclic shear strength: $\tau_{f, cy} = \tau_a + \tau_{cy}$

Drammen Clay, OCR=1

Triaxial

\[ \tau_{f, cy} = \tau_a + \tau_{cy} \]

Extension

Compression

\[ \tau_{f, cy} = \tau_a - \tau_{cy} \]

\[ \tau_{0} \]

\[ \gamma_a / \gamma_{cy} = N_f \]

\[ N_f = 10, 100, 1000 \]

\[ \tau_{a,f} / S_u^c \]

\[ \tau_{cy,f} / S_u^c \]

\[ N_f = 1 \]

\[ \tau_{0} \]

\[ \gamma_a / \gamma_{cy} = N_f = 1 \]

\[ 15/0.1 \]

\[ 15/0.5 \]

\[ 0/15 \]

\[ 15/15 \]

\[ 15%/0.5\% \]
Application of cyclic contour diagrams in foundation design

周期加载等值线图在风电基础设计中的应用
How to describe the design load

We need to transfer general, often highly irregular load data, to standard input format for soil cyclic degradation calculations - parcels of loads with increasing magnitude of cyclic amplitude.
Equivalent number of cycles

Contours show behavior as function of N with constant $\tau_a$ and $\tau_{cy}$

In a storm $\tau_a$ and $\tau_{cy}$ vary from one wave to the next

Storm can be transformed to an

**Equivalent number of cycles of the maximum wave, $N_{eq}$, that gives the same effect as the irregular load history**

by

- Pore pressure accumulation
- Strain accumulation
Application of cyclic contour diagrams in foundation design

In order to account for cyclic degradation and accumulated deformations of the soil during cyclic loading, a representative cyclic load composition needs to be established first.

The lifetime design storm was established by scaling and multiplying the 35 hour storm load history by the load range factors and number of storm events.

等效周期数

$N_{eq} = 27$
Application of cyclic contour diagrams in foundation design

We should get

- Equivalent number of cycles
- $P_{cy}/P_a = 0.73$
Application in foundation design

DSS

We know

- Equivalent number of cycles
  \[ N = 27 \]
- \( \frac{P_{cy}}{P_a} = 0.73 \)

For limit equilibrium and finite element:
\[ \frac{\tau_{cy}}{\Delta \tau_a} = \frac{P_{cy}}{P_a} \]

Stain compatibility at failure

\[ \tau_{f, cy} = \tau_a + \tau_{cy} \]
Triaxial

We know

- Equivalent number of cycles
- $\text{Pcy} / \text{Pa}$
- For limit equilibrium and finite element:
  \[ \frac{\tau_{cy}}{\Delta \tau_a} = \frac{\text{Pcy}}{\text{Pa}} \]

Stain compatibility at failure

\[ \tau_{f, cy} = \tau_a + \tau_{cy} \]
Application of cyclic contour diagrams

HVM cap model

Capacity analysis of bucket foundation.

Cyclic strengths are input parameters

Sizing determination

NGI ADP model – 3 D
Plaxis stiffness analysis
Cyclic parameters for preliminary design

NGI database

Sand cyclic strength contours

(Andersen 2015)
Cyclic parameters for preliminary design

NGI database

Clay cyclic strength contours (Andersen 2015)
Summary

✓ Site investigation
✓ Geomodel
✓ Laboratory program
✓ Soil parameters
✓ Cyclic contours
Thank you for your attention