Challenges of geotechnical analysis and design of offshore foundations

Agenda
2. Challenges in site specific soil assessment
   • Quantitative Ground modelling
   • Design parameters
   • Assessment of cyclic soil properties
3. Challenges in foundation analysis and design
   • Soil modelling
   • Foundation modelling
   • Interaction modelling
4. Closing remarks
Norwegian Geotechnical Institute

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019

Total NGI
270 permanently employed
38 nationalities

Male / Female
69% 31%

Education

86%

PhD 26%
MSc 49%
BSc 11%

Challenges of geotechnical analysis and design of offshore foundations (Harun Küşat ENGİN)

http://abhytheia.com/2016/02/07/why-what-how/

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

©Equinor

Nonlinear foundation response

Engin et al. (2019)

Lack of agreement between predictions and measurements

Skau et al. (2018)

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

• Design Basis
  • Structural data
  • Geometry
  • Loads
  • SI reports*
  • Requirements, constraints
  • ...

  • Soil Parameters Assessment
    • Layering*
    • Index properties*
      • Density
      • Ip, w, Pl, ...
      • Permeability
    • Compressibility parameters*
    • Drainage conditions
    • Monotonic parameters
    • Cyclic parameters
    • ...

  • Foundation Behavior Assessment
    (Monotonic & Cyclic)
    • Penetration
    • Capacity
    • Stiffness
    • Damping
    • Interaction
    • ...

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

- Soil Parameters Assessment
  - Layering
  - Index properties
    - Density
    - Ip, w, PI, ...
  - Permeability
  - Compressibility parameters
  - Drainage conditions
  - Monotonic parameters
  - Cyclic parameters
  - ...

- Seismic inversion
- BHs
- Lab tests
  - Atterberg limits, ...
  - Oedometer, CRS, DSS, C(A)UC, C(A)UE, ...
  - DSScy, C(A)UCcy, C(A)UEcy, ...
  - Bender elements, resonant col., ...

- Field tests
  - Databases
  - Empirical correlations
  - Analytical solutions
  - ...

Andersen (2015)

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

- Foundation Behavior Assessment (Monotonic & Cyclic)
  - Penetration
  - Settlements
  - Capacity
  - Stiffness
  - Damping
  - Interaction
  - Installation effects, set-up effects,
  - ...

- Empirical correlations
- Analytical solutions
- Finite element analyses
- ...

Zhang et al. (2015)
Sturm (2019)
Page (2018)
Engin et al. (2019)
2. Challenges in site specific soil assessment – Quantitative Ground modelling

Challenges: i.e. OWF

- Turbine relocation common
- More fast-track projects
- Need to obtain quantitative soil parameters
- (Changing) metocean conditions
- SI optimization*

Solutions:

- Planning, Acquisition, Processing
- Use geophysical data to guide interpolation of 1D geotechnical data (e.g. CPT, ...)
  - Quantitative Ground modelling

* useful for spudcan penetration assessment for the wind farm installation jackups, which typically has no site specific SI
2. Challenges in site specific soil assessment – Quantitative Ground modelling

Challenges
- Inversion
- Quantification
- Uncertainties

Sauvin et al. (2019)
2. Challenges in site specific soil assessment – Design parameters

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Challenges in estimating $s_u$:

- **Assess in-situ / undisturbed state:**
  - OCR
  - Direction of loading (anisotropy)
  - Sample disturbance
- Rate and duration of loading
- ...

Engin et al. (2019)

Lunne et al. (1997)

D’Ignazio (2018)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

- Cyclic and average shear stresses
- Cyclic, average and permanent pore pressure generation
- Cyclic, average and permanent shear strains

Andersen (2015)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Sturm et al. (2012)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Sturm et al. (2012)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Küşat ENGİN)

Sturm et al. (2012)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Sturm et al. (2012)
2. Challenges in site specific soil assessment – Assessment of cyclic soil properties

The behaviour of the soil under cyclic loading can be described by Contour diagrams, which relate:

- Cyclic shear stress, \( \tau_{cy} \)
- Cyclic shear strain, \( \gamma_{cy} \)
- Average shear stress, \( \tau_a \)
- Average shear strain, \( \gamma_a \)
- Number of cycles, \( N \)
- Accumulated pore pressure, \( u_p \)

Andersen (2015)
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Engin et al. (2019)

Norén-Cosgriff et al. (2015)
2. Challenges in site specific soil assessment – Assessment of cyclic soil properties

Challenges of geotechnical analysis and design of offshore foundations (Harun Küřsat ENGİN)

Engin et al. (2019)
3. Challenges in foundation analysis and design

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGIN)

General design approach (Sturm, 2017)

- Design Basis: Soil layers and properties, Loads, etc.
- (Assume) foundation dimensions
- Assess (cyclic) soil design profiles
- Calculate foundation capacity
- Check installation
- Assess serviceability
- Calculate foundation stiffness and soil reactions

Iteration with other disciplines
3. Challenges in foundation analysis and design – Soil modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Andersen (2015)
3. Challenges in foundation analysis and design – Soil modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Soil modelling

- Semi-empirical approach: Using cyclic contour diagrams
- Implemented in FE:
  - UnDrained Cyclic Accumulation Model (UDCAM)
  - Partially Drained Cyclic Accumulation Model (PDCAM)
- High Cyclic Accumulation Model (HCAM)
- …

Grimstad et al. (2012), D'Ignazio et al. (2017)

Sturm (2019)
3. Challenges in foundation analysis and design – *Foundation modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

**Pile analysis under lateral loading**

- Direct simple shear (DSS) test
- Scaling
  
  \[
  \frac{p}{p_u} = \frac{\sigma'_v}{\gamma'z_{su}} \leq 1
  \]
  \[
  p_u = N_p s_u
  \]
  \[
  N_p = (3 + J z/D) + \gamma' z_{su} \leq 9
  \]

**API/Matlock curves**

- Matlock (1970) monotonic
- Matlock (1970) cyclic for $X \geq X_r$
- Matlock (1970) cyclic for $X < X_r$
- 'modified Matlock' cyclic for $X < X_r$
3. Challenges in foundation analysis and design – *Foundation modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Pile analysis under lateral loading

\[ \frac{y_m}{D} = 0.2\% \]

\[ \frac{y_m}{D} = 31\% \]

Essentially replace the scoop failure surface with a flat base shear plane

External loading

Tension gap

Rotation point

\( p-y \) curves for wedge mechanism

\( p-y \) curves for flow-around mechanism

\( S-u \) curve for pile tip

Zhang & Andersen (2019)
3. Challenges in foundation analysis and design – *Foundation modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

A computation procedure to analyse pile response after a cyclic load history

Zhang et al (2019)

- Lateral load history
- Global beam-column model
- Spring 1
- Spring 2
- Spring 3
- Spring n

Perform cyclic accumulation and evaluate $N_{eq}$ for each of the springs

Extract stress-strain curves from the cyclic contour diagrams based on $N_{eq}$ of each spring

Construct p-y curves for each spring

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019
3. Challenges in foundation analysis and design – *Foundation modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

FEM
- Overshoot (undrained FEAs)
- Mesh dependency
- Simplifications
- Limitations
- ...

Engin et al. (2019)

Shin et al. (2018)

INFIDEL

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Challenges
- nonlinear response
- hysteretic behavior
- effect of multidirectional loading
- iterative procedure (soil-structure interaction)

The REDWIN models

Bucket foundations

Includes the effect of the vertical load

The REDWIN models

Modelling approach

Skau et al (2018)
3. Challenges in foundation analysis and design – Foundation modelling

Verification

The REDWIN models

Good accuracy to Finite Element Results

100 000 times faster
Challenges of Offshore Geotechnical Engineering

3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Validation

The REDWIN models

Experimental data from:

Page (2018)
3. Challenges in foundation analysis and design – Foundation modelling

Penetration analyses

Sloping ground  
Penetration depth = 2.0 m  

Dilation - punch through?!  
3. Challenges in foundation analysis and design – Foundation modelling

Capacity

Engin et al. (2018)

Expansion of capacity envelope – geometrical effects
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürti̇n ENGİN)

Stiffness
- Loads and cy/a ratio depend on stiffnesses
- Load reference point

![Diagram showing stiffness curve]

Load reference point

Spudcan geometry
- D = 22 m
- h_s = 2 m

Loads
- Preload = 160 MN
- V_SWL = 100 MN

7.0 m

OCR
- 40

s_u = 130 kPa

G_max = 400 * s_u DSS = 35 880 kPa

DSS = 35 880 kPa

OCR
- 4

s_u = 130 kPa

G_max = 750 * s_u DSS = 67 275

DSS = 67 275 kPa

Depth below seabed, z (m)

Both layers
- s_u / s_u DSS = 0.69
- s_u / s_u DSS = 0.56
- γ' = 10 kN/m³


Engin et al (2018)
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürrsat ENGİN)

**Stiffness**
- Loads and cy/a ratio depend on stiffnesses
- Load reference point

---

**Challenges of offshore geotechnical engineering**
Bodrum, Turkey – September 2019

Engin et al (2018)
Foundation stiffness – considering large deformation effects

Engin et al (2019)
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Küşat ENGİN)

Rate effects

Engin et al (2019)
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Damping

\[ D_{\text{found}} = \frac{E_h}{4\pi E_s} \]

Johansson et al. (2015)
3. Challenges in foundation analysis and design – Foundation modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Interaction modelling

Engin et al. (2015)

Sturm (2019)
5. Closing remarks

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGIN)

- Turbulent wind
- Unsteady aerodynamic effects
- Irregular waves
- Current
- Soil-pile interaction

Nonlinear foundation response

Engin et al. (2019)

Skau et al (2018)

Challenges of Offshore Geotechnical Engineering
Bodrum, Turkey – September 2019

Equinor
Acknowledgements

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Hans Petter Jostad
Knut H. Andersen
Hendrik Sturm
Ana M. Page
Marco D’Ignazio
Youhu Zhang
Maarten Vanneste
Huynh DV Khoa
Kristoffer Skjolden Skau
Victor Bjørn Smith
Guillaume Sauvin
References

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

- D’Ignazio - Selection of soil parameters for finite element modelling of clays. Seminar organized by the Geotechnical Society of Singapore (GeoSS) & Centre for Soft Ground Engineering and Department of Civil and Environmental Engineering. National University of Singapore, August 3rd 2018.
- Zhang Y, Andersen KH, Jeanjean P - Cyclic p-y Curves in Clays for Offshore Structures, Offshore Technology Conference, OTC 2019, Houston, DOI: 10.4043/29346-MS
Thank you...