OVERVIEW

1/ Introduction to GDG
2/ Offshore Wind Market
3/ Ireland's Offshore Journey
4/ Site Investigations
5/ Foundations & Monopiles
6/ Research Topics
Introduction to GDG
Background

Established in 2011

• GDG is a specialist geotechnical and offshore foundation design consultancy, providing innovative engineering solutions to the offshore wind sector.

• Established in 2011, GDG has since grown to more than 80 people.

• Our aim is to provide an innovative, cost effective and reliable service designed to meet and exceed our clients’ requirements.

• We strive to attain the highest possible standards and are consistently looking to pioneer and develop new technologies and techniques while ensuring that all relevant design codes and practices are met and exceeded.

• Our staff members are highly qualified, driven individuals who are committed to their Continuous Professional Development (CPD).
Established in 2011

- From Offices in Ireland (Dublin, Cork) and the UK (Belfast, Edinburgh, Bath and London), we service the international market;
- We have worked on projects across the world;
- Our objective is to always provide value engineering design

“GDG - Providing Value Engineering Design to the Offshore Wind Sector, while simultaneously mitigating ground risk”

Geologists
Geotechnical Engineers
Structural Engineers
Environmental Scientists

75+
BUSINESS AREAS

SEVEN SECTORS

- OFFSHORE
- MARINE CIVILS
- URBAN
- INFRASTRUCTURE
- ONSHORE RENEWABLES
- ENVIRONMENTAL
- RESEARCH
GDG WORK ACROSS DIFFERENT SECTORS, ADDRESSING THE COMMON CHALLENGE OF MITIGATING GROUND RISK
MARINE CIVILS

Services & Expertise

- Site Investigation Scoping & Interpretation
- Analysis and Design of Ports & Harbours
- Quay Wall & Jetty Design
- Coastal design, rock revetments, etc.
- Pile Installation analysis
- Site suitability assessments
- Jack-up vessel studies
- Hydrodynamic assessments, etc
- Port Masterplanning
- Marine Assets Inspections & Remediation
- Marina Layout Design
- Revetment & Bund Design incl Slope Stability
- Dredging Design
- Land Reclamation & Material Analysis
ONSHORE RENEWABLES

Services & Expertise

- Site suitability and feasibility studies for onshore wind and onshore solar farms
- Geotechnical risk studies & Peat stability assessments
- Earthworks engineering for roads, crane bases, hardstands, etc.
- Foundation design for gravity and piled bases
- Interaction analysis for soil-structure-turbine behaviour.
- Full Civil BoP Design
INFRASTRUCTURE

Services & Expertise

- Geotechnical Interpretation & Ground Modelling for Road, Railway, Pipeline and Flood Defence Schemes
- Concept Design, Alignments, etc.
- Geological Assessments & Mapping
- Detailed Design
- Material Suitability
- Civil Engineering Design
- Numerical Modelling
- Site inspections & QA/QC
URBAN

Services & Expertise

- Basement & Foundation Engineering
- Soil-Structure Interaction
- Ground Movement Assessments
- Retaining Wall Analysis
- Excavation Support and Propping Design
- Construction Sequencing & Temporary Works
- Pile Design & Piled Raft Analysis
- Tunnel and basement impact assessments
- Ground Improvement Engineering
ENVIRONMENTAL

Services & Expertise

- Contaminated land and environmental risk management
- Contaminated land remediation design and management
- Site feasibility and evaluation of environmental liabilities
- Planning, environmental impact assessment and conceptual design
- (Environmental) Due Diligence and liabilities assessments
- Early design input and front-end specialist support during groundworks
- Value engineering remediation design services and options appraisals
- Environmental project detailed design and supervision
- Operational Environmental Management Systems (development and internal auditing)
RESEARCH & DEVELOPMENT

Services & Expertise

- EU-funded international & multi-disciplinary research projects
- Industry-based PhD researchers
- Nationally-funded research initiatives
- Engagement with SFI-funded research centres
- Support for international & national research priorities through cutting edge research
OFFSHORE

Services & Expertise

- Offshore Survey Management for the Wind Energy Sector
- Offshore Client Repping
- Offshore Ground Modelling Development
- Substructure Concept and Detailed Design for Offshore Turbines
- Offshore Cable Engineering
- Marine Transport and Installation Analysis
- Oil & Gas Substructure Design
- Oil & Gas Installation Analysis
- Owners Engineering & Due Diligence
- Offshore wind foundation engineering
Reference Project Locations

- GDG Project Experience
- Personnel Project Experience
Offshore Wind Market
Introduction to Offshore Wind

• First offshore wind farm was installed in Denmark in 1991 (11 x 450 kW turbines)

• Only Irish offshore wind farm developed at Arklow bank in 2002 (7 x 3.6 MW turbines = 25 MW). At the end of 2018 there was a total of 18 GW of offshore wind capacity installed in Europe.
Why Offshore?

• Generally higher unrestricted wind speeds
• Reduced impacts on the public compared to onshore
• Able to use higher capacity turbines
• General increase in scale compared with onshore
2018 saw 2.6 GW of offshore wind installed in Europe: capable of powering up to 2 million homes

Overview of grid-connected offshore wind power projects at the end of 2018

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>NO. OF WIND FARMS CONNECTED</th>
<th>CUMULATIVE CAPACITY (MW)</th>
<th>NO. OF TURBINES CONNECTED</th>
<th>NET CAPACITY CONNECTED IN 2018</th>
<th>NO. OF TURBINES CONNECTED IN 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>105</td>
<td>18,499</td>
<td>4,543</td>
<td>2,649</td>
<td>409</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>39</td>
<td>8,183</td>
<td>1,975</td>
<td>1,312</td>
<td>222</td>
</tr>
<tr>
<td>Germany</td>
<td>25</td>
<td>6,380</td>
<td>1,305</td>
<td>969</td>
<td>136</td>
</tr>
<tr>
<td>Denmark</td>
<td>14</td>
<td>1,329</td>
<td>514</td>
<td>61</td>
<td>42</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>1,186</td>
<td>274</td>
<td>309</td>
<td>8</td>
</tr>
<tr>
<td>Netherlands</td>
<td>6</td>
<td>1,118</td>
<td>365</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Sweden</td>
<td>4</td>
<td>192</td>
<td>79</td>
<td>-10</td>
<td>-7</td>
</tr>
<tr>
<td>Finland</td>
<td>3</td>
<td>71</td>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ireland</td>
<td>1</td>
<td>25</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spain</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>France</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Norway</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The global offshore wind market is set to expand significantly over the next two decades, growing by 13% per year in the Stated Policies Scenario. Bolstered by policy targets and falling technology costs, global offshore wind capacity is projected to increase fifteen-fold to 2040, becoming a $1 trillion industry over the next two decades.
Global Growth Projected

- **Historical**
  - 2017: 18.72 GW

- **Projections**
  - 2050: 521 GW
Economics of offshore wind

Economics

- Pre 2015, average price >€120 / MWh
- July 2016 - Borssele 1&2 wind won at €72 per MWh (Dong Energy)
- Oct 2016 - Kriegers Flak won at €60 per MWh (Vattenfall)
- Dec 2016 – Borssele 3&4 won at €54.5 / MWh (Van Oord / Shell)
- March 2017 – First Subsidy-free offshore wind bid – Dong Energy
- Offshore wind in Europe is expected to develop to ≈80 GW by 2030 (at ≈18 GW end of 2018).
Increasing Turbine Sizes Driving Down Cost
Increasing Turbine Sizes Driving Down Cost

- 12 MW capacity
- 220-meter rotor
- 107-meter long blades
- 260 meters high
- 67 GWh gross AEP
- 63% capacity factor
- 38,000 m² swept area

Wind Class IEC: IB

Generates double the energy as previous GE Haliade model

Generates almost 45% more energy than the most powerful wind turbine available on the market today

Will generate enough clean power for up to 16,000 European households per turbine, and up to 1 million European households in a 750 MW configuration windfarm

HALIADE-X 12 MW

GE Renewable Energy is developing Haliade-X 12 MW, the biggest offshore wind turbine in the world, with a 220-meter rotor, 107-meter blade, leading capacity factor (63%), and digital capabilities, that will help our customers find success in an increasingly competitive environment.

- 1063 ft 324 m
- 853 ft 260 m
- 1046 ft 319 m

Eiffel Tower
Haliade-X 12 MW
Chrysler Building
Ireland's Offshore Wind Journey
Pinch Points for Offshore Wind

Challenges
- Subsidy Regime
- Consent Regime
- Grid
Recent Progress
Climate Action Plan = Government Mandate

“At least 3.5GW of offshore wind by 2030”

- Considering other aspects of the plan more likely to require 5GW+ by 2030
- This will be delivered through a mix of transitional projects and new projects
Economics of offshore wind

Economics

- Pre 2015, average price >€120 / MWh
- July 2016 - Borssele 1&2 wind won at €72 per MWh (Dong Energy)
- Oct 2016 - Kriegers Flak won at €60 per MWh (Vattenfall)
- Dec 2016 – Borssele 3&4 won
- March 2017
- Offshore wind in Europe is expected to develop to ≈80 GW by 2030 (at ≈18 GW end of 2018).
Offshore Site Investigation
Why do Offshore Site Investigation?

Inform the Design Process

Derisk the Project
Offshore Site Investigation: Hazard Identification

Typical hazards that may be present on a site for an offshore renewable project include, but are not limited to:

- Areas of soft soils (e.g. channel infill), which may affect foundation placement and installation depths and restrict installation vessels.

- Areas of mobile seabed, the presence of which may affect foundation behaviour, loads and installation depths and may also affect cable routing, installation and long term burial/protection.

- Very hard soils or bedrock, the presence of which may affect foundation installation methods, installation depths as well as cable routing and burial/protection options and methods.

- Rapid change in foundation conditions that may determine the selection of more than one foundation type for a development area.

- Surface or buried obstructions, boulders, unexploded ordnance (UXO), etc.

- Shallow gas, the presence of which may impact foundation stability and the safe drilling of geotechnical soil borings.
## Offshore Site Investigation: Example Programme

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
</tr>
<tr>
<td>Desk study and geotechnical risk assessment</td>
<td>Advanced analysis of regional geology</td>
<td>Reconnaissance geophysical surveys</td>
<td>Geophysical interpretation</td>
<td>Update risk assessment, plan reconnaissance geotechnical survey</td>
<td>Cable route and infill geophysical survey</td>
</tr>
</tbody>
</table>
# Offshore Site Investigations

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geophysical Investigations</strong></td>
<td></td>
</tr>
<tr>
<td>Wide range of data acquired simultaneously from one vessel</td>
<td>Remote sensing tool that requires ground truthing</td>
</tr>
<tr>
<td>Large areal coverage in short time – efficiency</td>
<td>Qualitative results subject to interpretation</td>
</tr>
<tr>
<td>Continuity between specific point locations</td>
<td>Some systems very weather/noise sensitive</td>
</tr>
<tr>
<td>Wide range of depth of sub-bottom investigation</td>
<td></td>
</tr>
<tr>
<td><strong>Geotechnical Investigations</strong></td>
<td></td>
</tr>
<tr>
<td>Range of systems for different soils and applications</td>
<td>Single data point may need many locations to investigate an area</td>
</tr>
<tr>
<td>Quantitative results used for engineering design</td>
<td>Slower acquisition rates than geophysics</td>
</tr>
<tr>
<td>Physical measurement of soil and rock properties</td>
<td></td>
</tr>
<tr>
<td>Generally, less weather sensitive than geophysics</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Characteristics of Geophysical and Geotechnical Investigations
Offshore Site Investigations
Offshore Site Investigations

- **Seabed systems**
  - Deployed from geophysical vessel
  - Grab samples / piston corer / box corer
  - Vibrocorer
  - Seabed CPT system

- **Downhole systems**
  - Structures/deep foundations investigations
  - Geotechnical drilling vessel
  - High quality sampling
  - Downhole CPT

- Remote systems
In-Situ CPT Testing

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
Offshore Site Investigations

Site Investigations – Geotechnical Challenges

Example – Dogger Bank Wind Farm (UK)

Size of Dogger Bank wind farm zone

Area = 8500 km²
Corresponding to square of 93 * 93 km

Later project ambitions have been reduced by UK government

(after Prof. Lunne, NGI)
Offshore Site Investigation: JACK-UPS

- ADVANTAGE: Most stable working platform: use standard onshore equipment since rig is firmly founded in the seabed
- DISADVANTAGE: TIME CONSUMING TO MOVE BETWEEN LOCATIONS
Offshore Site Investigation: Drill Ship

- ADVANTAGE: Much quicker and more efficient
- DISADVANTAGE: Need to consider DP positioning ability and heave compensated drill string
- Sample Disturbance?
Offshore Site Investigations Require Good Planning
Offshore Site Investigations Require Good Planning

“Fail to prepare. Prepare to fail”
Ground Model Development

- Assessment of Geophysical Data
- Assessment of Geotechnical Data
  - borehole data and in-situ test data
- Integration of Geophysical and Geotechnical Data
- Interpretation of unit horizons and integration with borehole data
- Development of isopach maps of different unit interfaces (GIS format)
- 3D presentation of sub-surface structure
Foundations and Monopiles
Cumulative Foundations Installed

2018 data

Source: WindEurope
Foundation Selection

Technical feasibility assessment

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Category Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>Likely: &lt;40m, Possible: 40-50, Unlikely: &gt;50</td>
</tr>
<tr>
<td>Seabed slope</td>
<td>N/A</td>
</tr>
<tr>
<td>Depth to bedrock</td>
<td>Likely: 40+, Possible: 30-40, Unlikely: &lt;30</td>
</tr>
<tr>
<td>Shallow Gravel</td>
<td>N/A</td>
</tr>
<tr>
<td>Shallow till layer</td>
<td>N/A</td>
</tr>
<tr>
<td>Boulder field</td>
<td>No boulder field, Boulder field, N/A</td>
</tr>
</tbody>
</table>

Other Considerations

- Manufacturing and Staging
- T&I
- Environmental
- Industry Experience
- Decommissioning

Other Considerations

- Manufacturing and Staging
- Environmental
- Industry Experience
- Decommissioning

Review of Site Data

Environmental Considerations

- Material CO₂ Emission
- Marine noise
- Benthic impact

Industry experience

- Established Design Certification
- Commercial Scale Fabrication
- Installation
- Decommissioning
- Removal of all infrastructure
- Cost of removal
- Potential for recycling materials
Monopiles

- >80% of all offshore wind turbines founded on Monopiles
- Suitable <45m water depth
- Single large diameter, 4 – 10m steel tubes driven into the seabed
- Typically 20 – 35m embedded length, low slenderness (L/D<6)
- Resist environmental (lateral) loading by mobilising horizontal earth pressures in the soil
- Usually requires a transition piece to connect to turbine tower
Monopiles

- Open ended for quick driving.
- Tubular steel for high moment resistance
Concept Design - Monopiles

- Site Conditions Assessment
- Geotechnical Interpretation
- Monopile Concept Selection (Bolted vs Grouted – TP or TP-less)
- Substructure Analysis
  - Geotechnical Design
    - Pile Length Check
    - Pile Head Rotation Check (SLS-GEO)
    - Lateral Earth Pressure Check (ULS-GEO)
    - Axial Pile Capacity Check (ULS-GEO)
  - Structural Design
    - Integrity of monopile Structure (ULS-STR)
    - Fatigue assessment (FLS-STR)
- Preliminary Scour Assessment
- Seismic Assessment
- Secondary Steel Design
- Materiel Take-off
Jacket Concept Design

- Suitable in deeper water
- Suitable for higher loads
- More hydrodynamically transparent
- Flexible mechanism of achieving load transfer
  - Driven piles
  - Drilled piles
  - Suction caissons
Gravity Base Concept Design

- Suitable in areas of shallow rock
- Challenges in fabrication and installation
Loading

Loads acting on an offshore wind turbine (Segeren and De Vries, 2013)
Loading

**MAGNUS PLATFORM**
- Sustained $V = 140$ MN
- Storm $V = 354$ MN
- Storm $H = 31$ MN
- 4 Groups of 9 Piles
  - $D = 2134$ m, $L = 80$ m

**HUTTON TLP**
- Sustained $V = 35$ MN
- Storm $V = 91$ MN
- Storm $H = 12$-15 MN
- 4 Groups of 8 Piles
  - $D = 1830$ m, $L = 58$ m

**e.g. 10+MW Turbine**
- Sustained $V = 20$ MN
- Storm $V = 20$ MN
- Storm $H = 15$ MN
- Moment $M = 600$ MNm
- Monopile
  - $D = 9$ m, $L = 30$ m
Introduction - Monopiles
Monopile Design

- OWTs founded on monopiles are dynamically sensitive structures and are typically designed to have a 1\textsuperscript{st} natural frequency between the 1P and 3P excitation bands.
- Kallehave et al. (2015) has shown that a 10% increase in natural frequency can approximately double the fatigue life of structure and result in ~10% reduction in steel tonnage.

Kallehave et al. 2015  Kallehave et al. 2012
Monopile Design

Traditional Monopile Design

- Lateral Pile Response typically using 1D ‘p-y’ approach
- API ‘p-y’ curves derived from small diameter (0.6m diameter), slender pile tests – Not suitable for monopiles typically >4m
- API approach thought to be conservative for monopiles
- Implemented in 1D FE model software (e.g. LPile / Oasys ALP)
Monopile Design

- Offshore wind turbine design is typically undertaken with two separate models
  - Turbine and Tower structure developed by the turbine manufacturer
  - Foundation model developed by the foundation designer
- Often 2 or 3 load iterations are required to achieve convergence.
- 50 or more geometry iterations per position, within each load iteration.
- Overall wind farm optimisation typically requires many thousands of individual analyses.

![Turbine & Tower model](image1)

![Foundation model](image2)
Monopile Design

• **3D FE modelling**
  Model entire soil continuum and capture complete SSI
  + Most accurate if correctly calibrated
  + Model detailed soil stratigraphy and complex SSI interface response
    – Computationally and personnel intensive

• **1D p-y approach**
  Pile is modelled with elastic beam elements and soil is modelled with non-linear springs along pile embedded length
  + Computationally fast compared with 3D FE
  + Most common tool for offshore lateral pile design
    – Soil layers can be represented by discretised springs but no interaction between layers occurs

• **Foundation super-element approach**
  Entire pile-soil interaction is modelled by representative springs at mudline
  + Computationally fastest
  + Often used in Turbine and Tower dynamic models to account for SSI
    – Difficult to calibrate for piles in layered soils and variable strength profiles
Monopile Design

Monopile Design – Natural Frequency Check

- Structural fatigue checks - Materials within structure to last beyond specified design life.
  - Fatigue check performed using linearized ‘p-y’ springs
  - Should include driveability analysis – Stresses and blowcounts from driveability analysis used in structural fatigue checks

- Dynamic check to ensure natural frequency of structure lies outside excitation frequency bands to avoid resonance.
Monopile Design

Monopile Research

- Current Practice is to use API/DNV ‘p-y’ approach
- API curves derived from small diameter, slender pile tests – Not suitable for large diameter monopiles
- API approach has been shown to be largely conservative for monopiles
- Very limited database of field scale monopile tests
Blessington Monopile Research

- 15 Piles - Lateral Static Load Tests
- 3 Piles - Lateral Cyclic Tests
Monopile Design

- 15 Piles - Lateral Static Load Tests
- 3 Piles - Lateral Cyclic Tests
Limit States

The Monopile design optimisation is undertaken in view of the following limit states:

Geotechnical Design
- Pile Length Check
- Pile Head Rotation Check (SLS-GEO)
- Lateral Earth Pressure Check (ULS-GEO)
- Axial Pile Capacity Check (ULS-GEO)

Structural Design
- Integrity of monopile Structure (ULS-STR)
- Fatigue assessment (FLS-STR)

In addition to the above limit state analyses, a frequency assessment is undertaken to ensure that operational frequencies of the WTG are avoided.
3D Model Calibration

- RWE Vibro Project
  - 5 x 4.3m Diameter Pile Tests in Sand (primarily)

- Blessington Monopile Research
  - 15 Piles - Lateral Static Load Tests in Sands
  - 3 Piles - Lateral Cyclic Tests in Sands
Monopile Design

**Graph:**
- Applied Lateral Load, $F$ [kN]
- Groundline Displacement, $y_g$ [mm]

- **Data Points:**
  - L=3m, D=0.51m
  - L=2.25m, D=0.51m
  - L=1.5m, D=0.245m

**Legend:**
- P1 - Test Data
- P1 - FEM
- P2 - Test Data
- P2 - FEM
- P3 - Test Data
- P3 - FEM
- P4 - Test Data
- P4 - FEM
Monopile Design

Murphy et al. 2018

- Plaxis 3D and HS soil model used to capture field test response
- New approach to derive soil model input parameters based on CPT correlations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Equation</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Friction Angle</td>
<td>φ'</td>
<td>( \varphi = 17.6 + 11 \log \left( \frac{q_t}{\sigma_{atm}} \right) \left( \frac{\sigma_{vo}}{\sigma_{atm}} \right)^{0.5} )</td>
<td>Deg</td>
<td>Kulhawy and Mayne (1990)</td>
</tr>
<tr>
<td>Overconsolidation Ratio</td>
<td>OCR</td>
<td>( OCR = \frac{1.33 \cdot q_t^{0.22}}{K_{ONC} \cdot \sigma_{vo}^{0.33}} \frac{1}{\sigma_{atm}} )</td>
<td>-</td>
<td>Kulhawy and Mayne (1990)</td>
</tr>
<tr>
<td>Tangent stiffness modulus</td>
<td>E_\text{eod}</td>
<td>( E_{\text{eodNC}} = q_t 10^{1.09-0.0075\sigma_v} ) ( E_{\text{eodOC}} = q_t 10^{1.78-0.0122\sigma_v} )</td>
<td>kPa</td>
<td>Kulhawy and Mayne 1990</td>
</tr>
<tr>
<td>Secant stiffness modulus</td>
<td>E_50</td>
<td>( E_{50} = \frac{(1-2v)(1+v)}{1-v}E_{\text{eod}} )</td>
<td>kPa</td>
<td>Brinkgreve 2013</td>
</tr>
<tr>
<td>Unload/Reload Stiffness</td>
<td>E_\text{ur}</td>
<td>( E_{\text{ur}} = 3 \times E_{50} )</td>
<td>kPa</td>
<td>Brinkgreve 2013</td>
</tr>
<tr>
<td>Reference E_\text{eod}</td>
<td>E_\text{eod}^{ref}</td>
<td>( E_{\text{eod}}^{\text{ref}} = \frac{c \cos \varphi - \sigma_{3}' \sin \varphi}{K_{ONC} \cdot \cos \varphi + p_{\text{ref}} \sin \varphi} )</td>
<td>kPa</td>
<td>Brinkgreve 2013</td>
</tr>
<tr>
<td>Reference E_50</td>
<td>E_50^{ref}</td>
<td>( E_{50}^{\text{ref}} = E_{50} \left( \frac{c \cos \varphi - \sigma_{3}' \sin \varphi}{c \cos \varphi + p_{\text{ref}} \sin \varphi} \right)^{m} )</td>
<td>kPa</td>
<td>Brinkgreve 2013</td>
</tr>
<tr>
<td>Reference E_\text{ur}</td>
<td>E_{\text{ur}}^{ref}</td>
<td>( E_{\text{ur}}^{\text{ref}} = E_{\text{ur}} \left( \frac{c \cos \varphi - \sigma_{3}' \sin \varphi}{c \cos \varphi + p_{\text{ref}} \sin \varphi} \right)^{m} )</td>
<td>kPa</td>
<td>Brinkgreve 2013</td>
</tr>
</tbody>
</table>
Monopile Design
Monopile Design
Monopile Design

(a) CM2 (D = 0.762, L/D = 3)

(b) CL2 (D = 2.0, L/D = 5.25)
Research Topics
Monopile Design – Soil Damping

- Soil damping can significantly effect the loads and fatigue life of offshore structures.
- Soil damping for offshore wind turbines is poorly understood and often very conservative values are used in design.
Monopile Design – Soil Damping

Current Research Study

- Use 3DFE and advanced constitutive soil models which can capture soil hysteresis and damping
- Develop models including full turbine and calculate the damping response
Shallow Gas: Identification at Early Stage Site Selection
Shallow (typically within the upper 30m of the seabed) gas in marine sediments have two main potential sources:

- Biogenic gas produced by bacterial degradation of organic matter at low temperatures;
- Thermogenic gas produced by high-temperature degradation and cracking of organic compounds at considerable burial depths.

Subsurface shallow gas evidence (from seismic profiles) in the form of:

- Acoustic turbid zones;
- Enhanced reflectors;
- Gas chimneys;
- Bright spots;
- Acoustic blanking

Morphological evidence (from multibeam, side-scan) of seepage at seabed in the form of:

- Seabed domes;
- Pockmarks;
- Methane-derived authigenic carbonates (MDAC);
- Mud diapirs.
Other Monopile Research

- RWE Vibro Project
  - 5 x 4.5m Diameter Pile Tests
  - Comparison between vibrated and impact driven installation
- Vibrated Installation can:
  - Reduce time of installation
  - Reduce noise and environmental impact to sealife
  - Reduce Cost
Conclusions

Summary

- Offshore Wind Industry undergoing significant expansion over the coming decade
- Costs related to offshore wind have reduced dramatically over the past 3 years
- Massive Opportunity for Ireland Going Forward
- Geotechnics underpins the entire design process
- Need optimisation and efficiency while managing the risk
- Appropriate SI provides a platform for successful development
Thank You

Paul Doherty
+353 (0)1 207 1000
pdoherty@gdgeo.com
www.gdgeo.com
AOB and Questions