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Optimisation of structures for offshore wind farms

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List of Additional Technical Services
Design of Foundations and Superstructures for Offshore Wind Turbines Generators

Date: 16th April 2014

- ## General
  - This list of Additional Technical Services includes areas of technical expertise in both structural and geotechnical engineering, latest design challenges directly applicable to the offshore wind industry, or new or state-of-the-art methods of analysis and design, etc.
  - The following specialities are listed in the following Sections
    - Monopile foundations
    - Gravity foundations
    - Jacket foundations
    - Other offshore structures
    - Grouted joints
    - Design methods - p-y springs
    - Design methods - natural frequency
    - Onshore foundations
  - Design improvements and conceptual work
    - Experienced in many types of structure being able to offer expertise in both structural engineering and geotechnical engineering
    - Able to provide independent assessments, technical opinions, and provision of alternate recommendations
    - Experienced in various optimisation exercises with the aim of maximising cost reductions
    - Creation of new ideas or innovative solutions, either for existing designs or development of new products
    - Experience with developing new patents, including preparation of patent applications

- **Monopile foundations**

  - Optimisation for minimum cost
    - Determination of optimum monopile diameter for each site and/or water depth, including carrying-out of optimisation exercises whereby the minimum overall cost and/or weight of the structure is determined
    - Determination of optimum monopile configurations, i.e. optimum D/t ratio to suit strength/fatigue/natural frequency/pile driveability requirements, optimum location of grouted joint (i.e. short or long transition pieces), optimum location and length of conical sections within transition piece (if present), and optimum location and length of conical sections within monopile (if present), etc.
    - Design of alternative monopile construction, e.g. multifaceted monopiles or prestressed/reinforced concrete monopiles

  - Deeper water locations
    - Initial sizing of large-diameter monopiles to suit bigger turbines (up to 8MW or more), exposed sites (e.g. central North Sea), and deep water locations (up to 50 metres or more), e.g. monopiles up to 9 metres diameter or more
    - Understanding of design challenges for of large-diameter monopiles in deeper water depths, including method of installation (drive, drill/drive, or rock-socketed), limitations due to pile driveability, control of noise during driving, and design of laterally loaded piles with low L/D ratio

  - Grouted joints
    - Design of grouted joints, in particular design of grouted joints with shear keys and design of grouted joints which do not slip
    - Development of methodology for design of grouted joints from first principles and which predates the DNV guidelines (grouted joints designed to above methodology have been in service since 2003 and have not experienced slippage, e.g. Arklow Bank)
    - Remediation of grouted joints (repair of grouted joints designed by others which have slipped)

  - J-tube systems
    - Selection of internal or external J-tubes, including sliding J-tube systems that do not rely on the use of divers, permit overdriving or underdriving of monopile, and require no J-tube hole in monopile
    - Development of J-tube systems for minimum overall cost of structure

  - Geotechnical
    - Development of proprietary p-y springs to suit all ground conditions, including chalk (various grades), weathered rock (rocks ranging in strength from completely weathered to slightly

weathered), and IGM's (intermediate materials between hard clay/dense sand and weak rock)
        - Natural frequency analyses of complete structure, i.e. from seabed to pile toe, with non-linear ground supports (p-y springs) provided down complete length of monopile
        - Development of proprietary pile displacement criteria (e.g. displacement criteria for all load cases) and design of monopiles with low L/D ratios

- **Gravity foundations**

    - Conceptual designs
        - Design and analyses of various gravity foundation designs, either creation of new and alternative concepts or copies of existing designs (e.g. large conical sections and/or radial or cross-beam designs, etc.)
        - Particular emphasis on concepts which have benefits of being semi-buoyant at low draughts, minimal cross-sectional area for wave loading, low bearing pressure, and ideal for prestressing, etc.
        - Concept and design of gravity foundations for low bearing pressure and very low bearing pressure sites (e.g. either layers of soft to less firm material extending to depth, or thin layer of very soft to soft sediments overlying more competent material, etc.)
        - Design and analyses of fully-floating or semi-buoyant foundations (for transportation)
        - Investigation into the installation of gravity foundations that do not require (costly) seabed preparation, including creation of various innovative self-levelling mechanisms
        - Investigation into truly self-installing foundations that neither rely on use of (costly) very heavy lift equipment or bespoke installation vessels (e.g. combination of semi-buoyant designs, low-lift installation vessels, controlled lowering to seabed, self-levelling mechanisms, and/or no seabed preparation)

    - Geotechnical
        - Use of state-of-the-art two-layer soil theory for enhanced bearing capacity on thin but relatively weak top soil layers (e.g. thickness of sediment layers less than one-tenth width of foundation)
        - Use of elastic half-space theory to predict settlement and rotations of spread foundations, particularly on layered soils
        - Development of p-z spring concept for settlement of spread footings on soils

- **Jacket foundations**

    - Conceptual work

        - Design and analyses of various tower to top of jacket connections, including conical transition, scalloped conical transition, cross-beam and radial-beam configurations, hyperboloid configurations, and reinforced concrete interfaces, etc.
        - Selection and optimisation of tower to top of jacket connection for minimal fatigue loads, more efficient fatigue design, and hence minimum overall weight and cost of structure
        - Creation of innovative jacket configurations for minimal fatigue loads, minimal forces in braces, and minimum overall weight and cost of structure
        - Creation of innovative and alternative tubular connections (e.g. K-joints and X-joints) for minimal stress-concentration factor (SCF) and hence more efficient fatigue design

    - Geotechnical
        - Development of proprietary p-y, t-z, & q-w springs to suit all ground conditions, including chalk (various grades), weathered rock (rocks ranging in strength from completely weathered to slightly weathered), and IGM's (intermediate materials between hard clay/dense sand and weak rock)
        - Development of proprietary p-y, t-z, & q-w springs based on smooth transitioning curves rather than straight-lines (more accurate representation of soils plus faster modelling time)
        - Natural frequency analyses of complete structure, i.e. jacket plus whole length of the piles, with non-linear ground supports (p-y, t-z, & q-w springs) provided down complete length of piles
        - Push–over analyses of complete structure with non-linear ground supports provided down complete length of piles

- **Other offshore structures**

    - Variations on existing concepts
        - Multi-faceted monopiles (i.e. other methods of fabricating large diameter monopiles)
        - Concrete monopiles (either post-tensioned precast sections or prestressed/reinforced one-piece units)
        - Concrete gravity structures with additional overturning resistance from ground anchors or tension piles
        - Composite structures composed of concrete gravity base and steel jacket or monopile superstructure
        - Steel gravity structures, including fully buoyant concepts (for ease of transportation) and self-installing systems
        - Jacket or tripod structures constructed from reinforced/prestressed concrete (and with steel piles)

    - Alternative or innovative concepts
        - Self-elevating and self-installing systems (foundations towed to site, complete with WTG pre-installed, and self-installs without need for heavy lift vessels)

        - A-Frame concept (propped monopile with cast steel node)
        - Guyed monopile (tension cables supporting monopile)
        - Mass damped monopile (active mass damped or tuned mass damped systems)
        - Compliant monopile with catenary anchors (wind and wave energy is absorbed by the inherent flexibility of the system, thereby significantly reducing dynamic response)

    - Marine current turbines
        - Design of monopile support structures with single or twin rotors and design of cross-arm structures to support twin rotors
        - Development of sliding mechanism to slide cross-arm/rotors up-and-down monopile (for maintenance purposes), including natural frequency analyses of non-linear support structure (cross-arm connection is not perfectly rigid)
        - Development of state-of-the-art methods of dynamic analyses for combined rotor forces and wave loading (method also applicable to wind turbine structures)
        - Rotor forces applied as time histories (3№ forces and 3№ moments) and combined with time histories of wave loading (or regular wave trains) to give overall dynamic response of structure
        - Rainflow counting of output time histories at any point through-out structure to give combined fatigue load spectrum due to rotor and wave loading

- **Grouted joints**

    - MB has been designing grouted joints with shear keys forming an integral part of the grouted connection since 2002 (e.g. Arklow Bank). The methodology was developed from first principles and predates the DNV guidelines. The methodology crucially includes a moment term and avoids reliance on high surface-roughness

    - Design of grouted joints
        - Determination of axial stresses, hoop stresses, and shear stresses across interfaces throughout grouted joint, including development of parametric equations for preliminary assessments and use of 3D finite element analysis for detailed assessments
        - Fatigue design of grouted joints, including determination of stress concentrations throughout connection, avoidance of poor details in regions of peak stress, and fatigue analysis of weld beads
        - Optimisation of grouted connections for minimal cost

    - Design of weld beads
        - Determination of proportion of bending moment from transition piece to be resisted by weld beads, including provision of minimum grout joint length and variation with grout joint length
        - Determination of ultimate limit state loads on weld beads and various methods of accurately modelling the latter

        - Determination of fatigue loads on weld beads together with fatigue assessment of weld beads
        - Prediction of when grout debonds, when tension cracks develop, and subsequent need for provision of weld beads
        - Prevention of slip, provision of mechanical safety, and avoidance of uncertainties associated with allowing local slip to develop

    - However, the large majority of grouted joints designed by others do not have shear keys and consequently have exhibited downwards slipping. This has been attributed by others due to inadequate axial capacity to carry the self-weight, but in fact can also occur during the application of large fluctuating moments

    - Review of current industry proposals
        - Review and assessment of JIP reports, e.g. grouted connections with shear keys, summary report, FE analysis, background report, testing, and guidelines, etc.
        - Proposal of alternative failure mechanisms, e.g. walk-down mechanism (due to fluctuating moment), asymmetric slip (due to presence of cracking, etc.), and need for provision of mechanical safety
        - Differentiation between local slip at grout/steel interface, overall slip of grouted connection, and how reversible slip/cyclic slip at grout/steel interface can lead to overall slip of grouted joint
        - Development of design methods whereby any local slip is prevented in the first-place, i.e. design resistance from weld beads plus any adhesion should be greater than applied longitudinal shear forces
        - Modification of DNV guidelines to include moment term in equations for shear stress
        - Uncertainties with use of conical grouted joints

    - Remediation of existing grouted joints (to prevent further slippage)
        - Investigation into potential mitigation options, e.g. clamps, stoppers, shear connectors, frames, pinning, and others
        - Recommendations for remedial works, understanding of load-transfer mechanism under various loading conditions, preparation of calculations, limitations on site (installation), cost estimates, and potential design concerns
        - Review of schemes proposed by others, e.g. stoppers and temporary bridge bearings

- **Design methods - p-y springs**

    - P-y springs are non-linear springs or curves used to represent the lateral resistance and displacement of monopiles or piles in the ground. Precise determination of these springs is required in order to accurately model the strength, stiffness, and overall dynamic response of offshore structures

- P-y springs for IGM's (intermediate geo-materials)
  - IGM's are materials that have properties in between that of soil and rock (e.g. SPT blow count N > 50); these are frequently encountered on sites but are generally not covered well by the codes or proprietary software such as LPILE
  - Development of proprietary p-y springs for cohesive IGM's, for material ranging in strength from hard clays to weak rocks
  - Development of proprietary p-y springs for non-cohesive IGM's, for material ranging in strength from dense sands to weak rocks

- P-y springs for weathered rock
  - Significant depths of weathered rock are frequently encountered on sites; however, these are generally not covered well by the codes or proprietary software such as LPILE ('weak' and 'strong' rock in the latter refers to intact rock masses rather than fractured rock masses which can contain many discontinuities and significant zones of weathering, etc.)
  - Development of proprietary method to represent the strength and stiffness of the fractured rock mass based on the size and number of discontinuities, etc., and the extent and degree of weathering, etc
  - Development of proprietary p-y springs for a range of strengths and degrees of weathering of weathered rock, from highly weathered, through moderately weathered, to slightly weathered rock masses

- Cyclic loading
  - Calculation of cyclic degradation based on soil type, magnitude of loading, and number of cycles, etc.
  - Use of concept of threshold strain whereby effect of cyclic degradation is minimised
  - Use of simplistic methods based on pile displacement criteria to avoid significant cyclic degradation

- Pile diameter effects
  - Recommendations of pile diameter effects for large diameter piles (strength and stiffness), including explanation for apparent effects from some measurements
  - Familiar with much of current research already carried out for large diameter piles or piers used to support bridge structures and onshore wind turbine foundations in the USA
  - Explanation of why the measured natural frequency of some structures differs from the design natural frequency; there appears to be some confusion in the industry that this is entirely down to the soil stiffness
  - Correct derivation of stiffness parameter ε_{50} from triaxial test results
  - Soil damping

- Piles with low L/D ratios

        - Understanding of limitations of p-y method and how latter can be modified for piles with low L/D ratios
        - Analysis of low L/D ratio piers according to theory of Steckner and others, including analysis of all horizontal and vertical forces on pier and accurate variation of soil reactions with depth
        - Recommendations for short embedments in rock layers (avoidance of high soil reactions and reduction in capacity due to wedge failures, etc.)

    - Companion t-z and q-w springs
        - Derivation of companion t-z and q-w springs for axial loading of piles for all soil/rock materials described above
        - Use of smooth curves (hyperbolic shape) rather than simple straight lines as often presented in the codes
        - Variation with pile diameter and method of installation

- **Design methods - natural frequency**

    - Non-linear systems
        - Natural frequency calculated for non-linear systems; non-linearity either within structure (e.g. non-linear joints) or as supports (e.g. p-y springs, etc.)
        - No limit on number of springs (e.g. p-y springs located down whole length of pile or monopile)
        - Automatic linearisation of non-linear springs according to load level and spring stiffness

    - Conversion to equivalent linear systems
        - Depth of fixity and equivalent linear springs determined to suit required load-level and support conditions, e.g. mudline, depth to point of zero lateral displacement, or depth to full fixity, etc.
        - Determination of most accurate linear support conditions to be used in dynamic analyses to give exact match of 1st and 2nd modes and/or incorporation of correct accelerations, displacements, and inertial loads at hub-height, etc.

- **Onshore foundations**

    - Foundation design and review
        - Design and analysis of all foundation types, e.g. spread or gravity foundations, piled foundations, rock anchored foundations, and large caisson or monopile type foundations
        - Interpretation of ground conditions, difficult ground conditions, plus ground improvement
        - Optimisation of foundations for minimal cost and design and detailing of most cost effective foundations

    - Additional technical expertise

- Design and analysis of various types of tower connection, including extensive use of strut-&-tie models and correct detailing to ensure safe transfer of forces into rest of foundation
- Familiar with many international building codes, state-of-the-art reports, and rules and regulations from certification bodies that cover all aspects of the foundation design, including fatigue of components not normally covered by common codes, etc.
- Familiar with causes and concerns of frequent problem areas encountered in onshore foundations, including transfer of forces from embedded steel sections and continuity of reinforcement under plinth area, etc.