Improving pile foundation models for use in bottom-fixed offshore wind turbine applications
Personal Background

- Eric Van Buren; Houston, Texas
- BSc in Civil Engineering from Texas A&M University (2008)
- MSc in Structural Engineering from Texas A&M University (2009)
- Develop cost-effective foundation systems for bottom-fixed offshore wind turbines in intermediate water depth (30m-70m)
- Planned project completion in September 2012
- Part of NOWITECH, WP 3: Novel Substructures for Offshore Wind Turbines since August 2009
NOWITECH
Norwegian Research Centre for Offshore Wind Technology

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Improving pile foundation models
Motivations for Research

• Reducing uncertainty in pile design
  – Wide variety of methods, wide range of solutions
• Existing models are outdated
  – Developed in 1970’s for oil and gas applications
• Existing models are incomplete
  – Quasi-static, ignore damping, not necessarily conservative
• Dynamics of foundations important for wind turbines
  – Natural frequency of wind turbines close to frequency of loading
Pile Foundations Models

- Fully coupled finite element model simulation
  - Most comprehensive modeling technique, includes many additional non linear effects
  - Includes interactions between soil layers (vertical) and between adjacent piles (horizontal)
  - Very time consuming and expensive, requires extensive soil lab testing

- Dynamic p-y curve methods
  - Utilize combinations of NL springs and dampers to model stiffness and damping
  - Can be tightly coupled with existing wind turbine analysis software

- Multiple non-linear spring representation (p-y curves)
  - Foundation modeled with springs distributed along length of pile
  - Dependant on accurate soil profile and characteristic parameters

- Single non-linear spring representation
  - Entire foundation modeled with single springs at mudline for each DOF
  - Does not account for pile flexibility or soil profile non-homogeneity

- Model with an equivalent fixity depth (Apparent Fixity Length)
  - Very simple and fast in computations, more representative than fixed condition
  - Does not capture any soil-structure interaction

- Assume fixed boundary conditions
  - Extremely simple, fast computations
  - Gross misrepresentation of stiffness of the foundation

Red: Models being developed in PhD (Coupled)
Blue: Existing models (Uncoupled)
Pile Foundations Models (cont.)

- Fully-fixed
- Apparent Fixity Length
- Uncoupled Springs
- Distributed Springs

Dynamic p-y

Fully coupled FEM
Dynamic behavior of piles

• Nonlinear material properties
  – Soil is a three phase material with constantly changing characteristics
  – Stiffness and damping behaviors are not constant in time
  – Stiffness and damping can be frequency dependent

• Nonlinear geometry
  – Interaction between adjacent piles
  – Large voids with no soil can be found inside piles

• Nonlinear interaction effects
  – Contact interface between soil and pile
  – Slippage
  – Gapping
Pile-soil stiffness

- Nonlinear with respect to:
  - Depth below mudline
  - Strain magnitude
  - Strain rate
  - Stress history
  - Frequency of loading

- Permanent Deformations
  - Plastic deformations of soil
  - Soil grain realignment

- Cyclic effects
  - Stiffness degradation
  - Stiffness increase

- Soil-pile interface
  - Slippage between soil and pile
  - Gap formation between soil and pile
Pile-soil damping

- Two main categories
  - Material (hysteretic damping)
  - Radiation (geometric) damping

- Material damping
  - Softening and hardening of soil
  - Soil is “damaged” by particle realignment

- Geometric damping
  - Wave propagation through soil
  - Highly dependent on frequency of loading
  - Dependent on thickness of soil layers

- Soil-pile interface
  - Slippage
  - Gapping

- Pile interaction
  - Effect of adjacent piles
  - Radiation damping interaction

- Important for fatigue life of structure
  - Provides critical damping when turbine is parked
The p-y curve model

- Developed in the 1970s for offshore oil and gas applications
- Main analysis tool in most offshore structure design standards
- Utilizes a number of nonlinear soil springs to approximate stiffness
- Dependent only on depth below the mudline and displacement of the pile
- Different models for sand and clay

![Diagram of p-y curve model](image)
Shortcomings of the p-y model

- No interaction between soil layers
- No interaction between adjacent piles
- P-y curves assume slender pile behavior, monopiles are much more rigid
- P-y curves primarily developed for (static) lateral capacity calculations
- Damping levels are mostly a total guess
- Pile size effects likely to effect the results
- Soil resistance assumed to be equally distributed across diameter
- No provision for gapping, slipping or plastic deformations
- Shown to under-predict stiffness during dynamic loading
- Static conservatism not necessarily dynamic conservatism
Dynamic p-y curves

- Developed for applications other than offshore foundations, nonetheless useful for offshore wind turbines
- Utilize a number of springs and dashpots placed in various arrangements
- Allow for hysteretic and radiation damping
- Allow for slippage and gapping
- Allow for permanent deformations of soil
- Allow for pile group effects
Application to wind turbines

- Damping capabilities allow some energy from rotor, wind and wave loading to be dissipated through the soil.
- More accurate stiffness description provides a better look at changes in the natural frequency of the structure.
- Interaction effects allow for an accurate analysis of lattice tower structures.
- Can be added to existing wind turbine analysis programs through external dynamic model library structure such as a DLL.
- Will allow for a tightly coupled analysis of the full structure without significantly slowing simulation times.
Finite Element Modeling

FE model utilizing the criteria of dynamic p-y curves

- Use of a sequential FE analysis combined with a traditional p-y model in an aero-hydro-servo-elastic simulation will be used to develop the dynamic soil model library
- Used in conjunction with the NOWITECH 10MW offshore reference turbine
Coupled Foundation Models

Fully-Coupled FE Model

- Foundation, or ‘Geo’ module implemented through dynamic soil link library
- Geo Module can be fully coupled with any Aero-Servo-Hydro-Elastic code (FAST, FLEX5, ADAMS, etc.)
- Adding an analysis tool for the foundation system is the last piece needed to provide a proper analysis of the entire wind turbine system
Further Work

- Investigate the effects of the added capabilities on the full turbine system
  - Fatigue life
  - Structural optimization
- Extend investigations to suction caissons and other foundation solutions
  - Potential foundation concepts can be used in conjunction with a number of different tower concepts
- Investigate dynamic processes of scour and the impacts on soil stiffness and damping
  - Changes in soil properties can have significant impacts on the fatigue life of the structure
  - Impact will be more significant with shallow foundations such as suction caissons
- Validate numerical models with field data
Questions?

Thank you for your attention

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