A Presentation to Blow You Away: Wind Turbine Foundations

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Overview

Foundation Types
Materials
Market Regulation
Design Requirements
Design Brief
Future Developments
Foundation Types
BASE case

Photo credits: Jenny Hager, Kirk Morgan
Spread Footing

- 50-70 ft across x 8-12 ft deep
- Cast-in-Place
- Robust
Rock Anchors and Cap

- Smaller excavation (30ft dia)
- Anchors
  - installation testing
  - fatigue design
  - corrosion protection
  - long-term monitoring
Piles and Cap

- Costly
- Cap dead weight
- Soil / structure interaction
- Stiffness offset issues
- Pile steel fatigue design
Short Pier*

- 16-18+ ft diameter x 25-35 ft depth
- Stiffness offset issues
- Construction challenges
- Economical

* Not the same as a rock socket foundation
Materials (US)

*spread foundations*
materials –

cement

- 300 to 500 yds and more
- 4500 to 6000 psi (typically 5000 psi)
- \(\frac{3}{4}\)" to 1 \(\frac{1}{2}\)" coarse aggregate
- Entrained air per code
- Fly Ash or GGBFS (less common)
- ASR avoided (or sealers used)
- site geotechnical can influence cement type
• standard cylinders
• hot / cold weather concrete
• mass concrete measures
• workability not a concern with good practice
• attention to curing in extreme conditions
- ASTM A615 60 and 75 ksi
- deformed bars
- #4 to #11 size
  - #14 increasingly used; still not that common
materials – anchor bolts

- ASTM A615 ($f_y = 75$ ksi)
- Custom (e.g. $f_y = 90$ ksi)
- ASTM A722 ($f_y = 120$ ksi)
- cold-formed threads

- common sizes 1 1/4” and 1 3/8”
- sleeves (PVC, heat shrink)

- post-tensioned (80 to 100 kips)
• Materials:
  - Alignment ring & embedment plate
  - ASTM (A36, A529, A572, etc.)
  - 1 to 2 inches thick
  - Dimensions matching tower flange typically
tower flange grout

- modified cementitious or epoxy
- 8000 – 15000 psi
- formed above or recessed
- 1 ½ to 3 in thick
- volume extended
Market Regulation
Standards Bodies / Codes

- International Code Council (ICC)
  - American Concrete Institute (ACI)
    - Committee 378 Concrete Towers
  - American Institute of Steel Construction (AISC)

- American National Standards Institute (ANSI)
  - American Wind Energy Association (AWEA)
    - Wind Standards Committee and Subcommittees

- International Electrotechnical Commission (IEC)
  - Technical Committee No. 88

- EN Eurocodes
- CEB-FIP
Independent Engineers

- Finance
- Equity
- Transactions
Certification Bodies

- Projects
- Turbines
- Components
  - Blades
  - Towers
  - Foundations
  - Misc
Foundation Design Requirements
Performance Criteria

- Stability
- Strength
- Rotational Stiffness
- Settlement
- Durability
- Economy

Photo credits:
Foundation Design Requirements

ASCE/AWEA RP2011, Recommended Practice for Compliance of Large Land-Based Wind Turbine Support Structures

- “IEC 61400-1 Ed.3: Wind turbines – Part 1: Design requirements”
- FUTURE – “IEC 61400-6: Wind turbines – Part 6: Tower and foundation design requirements”
- CEB-FIP Model Code 1990
- DNV, “Offshore Standard C502 Offshore Concrete Structures”
- GL, “Guideline for the Certification of Wind Turbines”

US industry document (used outside US too)

US and International codes and standards
IEC Load Cases

- Operational
- Start-up, shut-down, e-stop
- Machine faults
- Grid interaction
- Extreme wind events
- Combinations of the above
Perspective

- Building or bridge code cycles ($\# \times 10^6$)
- Wind turbine cycles ($\# \times 10^9$ and below)

1. Detail category $\Delta \sigma_C$
2. Constant amplitude fatigue limit $\Delta \sigma_D$
3. Cut-off limit $\Delta \sigma_L$

wind turbine foundation design steps
spread footing

1. Input tower bottom flange dimensions, design loads, stiffness requirements, and soil properties
   - Select preliminary concrete, grout and steel strengths, anchor bolt size and grade, embed plate thickness and grade

2. Select preliminary foundation width, thickness, and embedment
   - Select top and bottom rebar size, spacing and cutoffs

3. Check overturning stability, soil contact percentage, soil bearing pressure, and foundation stiffness
   - Check concrete shear strength
   - Check anchor bolt, grout, embed plate and foundation connection

Check top and bottom bending strength and two way shear
- Check concrete and steel fatigue strength

Fail
- Go back to 1, 2 and/or 3

Pass
- Complete or go back to 1, 2 and/or 3 to optimize

Pass
- Input codes, industry standards, technical references
Rigid plate analysis

Figure 8-1. Loading under idealised conditions.
Effective bearing area

capacity of the foundation is the effective area representation to be chosen.

For a circular foundation area with radius R, an elliptical effective foundation area $A_{eff}$ can be defined as:

$$A_{eff} = 2 \left[ R^2 \arccos\left(\frac{e}{R}\right) - e\sqrt{R^2 - e^2} \right]$$

with major axes

$$b_e = 2(R - e)$$

and

$$l_e = 2R \sqrt{1 - \left(1 - \frac{b}{2R}\right)^2}$$

Scenario 1 corresponds to load eccentricity with respect to one of the two symmetry axes of the foundation. By this scenario, the following effective dimensions are used:

$$b_{eff} = b - 2 \cdot e, \quad l_{eff} = b$$

Scenario 2 corresponds to load eccentricity with respect to the other symmetry axis.
Finite Element Analysis
Barr Iowa Wind Foundation Projects

- Barton I and II
- Carroll
- Century I, II and III
- Charles City
- Crane Creek
- Eclipse
- Endeavor II
- Flying Cloud
- Hawkeye
- Highland
- Ida Grove
- Intrepid
- Laurel
- Lundgren
- Macksberg
- Morninglight
- New Harvest
- Pomeroy I, III and IV
- Rippey
- Rolling Hills
- Tjaden
- Top of Iowa I and III
- Valmont
- Victory
- Vienna I and II
- Walnut
- Wellsberg
Anchored precast beams (RUTE Foundation Systems)
Precast box spread (RUTE Foundation Systems)
Formless integrated tower and foundation (RCAM)
Tower of precast column and panels (Hexcrete, ISU)
Questions?
unexpected conditions –
cattle

• cattle on plastic / curing concrete
• evaluate for restoration via composite action with prepared overlay
• hydro-demolition, preparation and overlay
Are wind turbines designed for tornados?

- Extreme winds in range of 50 m/s
- Gust factoring / load factoring equivalent speed in range of 100 m/s (230 mph) which is less than some tornados.
- Intense shears and reversals across rotor not considered (blade fail / tower strike)

Image: www.bluechannel24.com
Thank you!

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