utility scale wind turbine foundation performance evaluation
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University of Minnesota
and
Barr Engineering Company
presenters

Christopher Kopchynski, P.E.
Barr Engineering Company
cak@barr.com
presentation agenda

1. project background
2. foundation engineering
3. foundation construction
4. foundation research
5. performance evaluation interim results
6. computer programming and data analysis
1. project background
Eolos Wind Energy Research Consortium

SITE LOCATION

2/19/2014
eolos clipper 2.5MW wind turbine

- 2.5MW (3350 horsepower) power output
- 80 meter (262 feet) hub height
- 96 meter (315 feet) rotor diameter
- 129m met tower
participants

- funding: U.S. Department of Energy
- engineering and environmental services: Barr Engineering Company
- construction: Ryan Companies
- owners and operators: University of Minnesota
- researchers: various industry, research, educational organizations
advance production of wind-generated energy for the United States through industry-driven research, field-scale demonstration of new technologies, and workforce training

http://www.eolos.umn.edu/
project timeline

- funding opportunity – May 2009
- proposal submission – August 2009
- grant award – November 2009
- environmental and engineering – 2010
- bidding – Fall 2010 to Spring 2011
- construction – Spring 2011 to Fall 2011
- turbine commissioning – November 2011
- research system implementation – 2012
- monitoring – 2013 to present
wind turbine generator system (WTGS)
How does a wind turbine work?

1. Inflow of wind

2. Inflow of wind activates rotor (A) & blades (B)

3. Rotor & blades spin the main shaft (C) and gearbox (D), which spins the generator (G), resulting in electrical output
structural loads

- large lever arm
- overturning moment is dominant
- vertical load and horizontal load relatively small
eolos wind distribution

Wind Data from Eolos Met Tower: 01–Jan–2012 to 24–Jul–2012 00:10:00  Cup & Vane: 3  Elevation: 77m
Averaged by 10min intervals
2. foundation engineering
interdisciplinary process

• geotechnical and structural engineers interact
• geotechnical engineering
  – field investigation
  – laboratory testing
  – geotechnical recommendations
• structural engineering
  – reinforced concrete design
  – construction drawings and specifications
geotechnical field investigation

- one soil boring to 80 feet
- three cone penetration tests to refusal – 30 feet - geophone tests
- one flat plate dilatometer test – 30 feet
- no piezometers since sandy conditions
- soil resistivity tests
geotechnical results

- medium dense to dense sandy glacial outwash
- groundwater well below foundation
- non corrosive, low sulphate attack
- large allowable bearing capacity >>> 10 ksf
- total settlement < 0.4 inches
- differential settlement < 0.2 inches
structural engineering

- WTGS original equipment manufacturer (OEM) requirements
- industry and building code standards
- practices and guidelines
- design procedures
- construction drawings and specifications
OEM requirements

Designed for a C104 Model, C96 installed

• design extreme overturning moment
• service operating moment
• fatigue loads
• minimum rotational stiffness
• maximum differential settlement
wind turbine foundation design steps

INPUT TOWER BOTTOM FLANGE DIMENSIONS, SOIL PROPERTIES, STIFFNESS REQUIREMENTS AND LOADS

1. 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

FAIL

CHECK OVERTURNING STABILITY, SOIL CONTACT PERCENTAGE, SOIL BEARING PRESSURE, AND FOUNDATION STIFFNESS

FAIL

PASS

SELECT TOP AND BOTTOM REBAR SIZE, SPACING AND CUTOFFS

FAIL

PASS

CHECK CONCRETE SHEAR STRENGTH

PASS

CHECK ANCHOR BOLT, GROUT, EMBED PLATE AND FOUNDATION CONNECTION

FAIL

PASS

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
458 cubic yards of concrete
44 tons of reinforcing

#10 @ 7 ½ in o.c.

#10 @ 6 in o.c.
3. foundation construction
excavation
settlement plate installation
lean concrete and settlement plates
bottom reinforcing and anchor bolt cage
top & vertical reinforcing, extension rods & formwork
footing concrete
pedestal reinforcing and electrical conduit
backfill & covers for extension rods

utility scale wind turbine foundation
grout and anchor bolt tensioning
4. foundation research
objective

• improve understanding of large foundation behavior subjected to wind turbine loading
• sensors installed will measure:
  – foundation settlement
  – tower base moments
  – foundation rotation
• correlated to other WTGS readings – Power and Wind Speed
features

• simplicity
• basic behavior
• continuous 20Hz (cycles per second) readings
• synchronized with other WTGS data
• data logger tied into a fiber optic network and the Saint Anthony Falls laboratory
foundation sensors

- twenty four settlement plates
- twenty strain gages
- ten thermocouples
- one biaxial tiltmeter
settlement plates

surveys

• installation – July 2011
• operation – January 2012
• operation – January 2013
• scheduled for this year
strain gages

corrections
• tower pre-stress
• tower thickness
• temperature
• noise filtering processing
• maximum strain reading
bi-axial tiltmeter

20Hz reading corrections

• tower pre-stress
• noise filtering

processing

• vector sum of axes readings
2 Campbell Scientific CR3000’s

- located in the base of the wind turbine
- battery backup
- each one has 2GB backup storage
- ethernet connectivity to internet and servers
eolos storm event

Researchers collect real-time data from sensors on the 2.5 megawatt Clipper Liberty Wind Turbine and 426-foot-tall meteorological tower as a storm rolls through the University's Eolos Wind Energy Research Field Station in Rosemount, MN.

https://www.youtube.com/watch?v=xCLEszYpHZU

TowerStrain_shortened_Barr.wmv
5. interim performance evaluation results
settlement plate readings

• total settlement predicted to be less than 4/10’s of an inch. Differential settlement less than 2/10’s.
• Less than 1/10 of a inch measured in a two year period
• settlement plates around the pedestal more responsive
• the extreme load has not been experienced
corrected strain gage readings

Strain verses Time

Microstrain (µε)

Elapsed Time (seconds)

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corrected rotation readings
Hooke’s Law:

\[ \sigma = \varepsilon E \]

where:

\( \sigma = \text{sigma, stress, psi} \)

\( \varepsilon = \text{epsilon, strain, change in length per unit of original length} \)

\( E = \text{modulus of elasticity} = 29,000,000 \text{ psi} \)
tower moment

- moment equation
  \[ M = \sigma S \]
  where:
  \( M \) = bending moment, in-lbs
  \( S \) = tower section modulus, in\(^3\)

- section modulus equation
  \[ S = \left(\frac{\pi}{32}\right)(OD^4-ID^4)/OD \]
  where:
  \( OD \) = outside tower diameter = 163.74 in
  \( ID \) = inside tower diameter = 160.67 in
tower moment readings

Moment verses Time

Elapsed Time (seconds)

Moment (kN-m)

0 5 10 15 20 25 30

20000 21000 22000 23000 24000 25000 26000 27000 28000

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rotational stiffness

- rotational stiffness equation

\[ K_\phi = \frac{M}{\phi} \]

where:

- \( K_\phi \) = rotational stiffness, in-lbs/degree
- \( M \) = moment, in-lbs
- \( \phi \) = phi, rotation, degrees
stiffness verses moment

Rotation verses Time

Rotation (degrees)

Moment (kN-m)

Elapsed Time (seconds)

5
10
15
20
25
30
35
moment verses wind speed
rotation verses wind speed
C96 power curve

30 mph = 13 m/s
moment verses power output

Eolos 1 sec AVERAGE Tower Moment Vs. Instantaneous Real Power
Data From:01-Mar-2013 00:00:01 to 26-May-2013 16:29:39
Number of DataPoints: 4,365,279

Color Grid Resolution: 8.00kW by 70.00kN\(\cdot\)m

Maximum Operational Design Load: 30,000kN\(\cdot\)m
rotation verses power output
moment verses power output
rotation verses moment
stiffness verses power output
design fatigue spectrum

represented by sets of corresponding:
• ranges, $S_{r,i}$
• means, $S_{m,i}$
• cycles, $i=1$ to $n$
actual fatigue loads

- extract and collect the time series maxima and minima
- $\frac{1}{2}$ cycle
- range
- mean
interim research conclusions

- operating loads are within design limit
- rotational stiffness is above the design requirement and covers the design calculation
- relationships with wind speed and power output are established
- good potential for structural health monitoring
6. computer programming and data analysis
data processing and analysis challenges

• aggregating data
  – different types of data from various files
  – different sampling frequencies
  – different file sizes
  – lots of files
• volume of data and memory management
  – producing large numbers of graphs
• time stamps from stated in different time zones
• assessing accuracy
  – finding data gaps and overlaps
  – cleaning and adjusting data: selecting appropriate offsets
python for data analysis

• open source software
• anaconda scientific python distribution
  — includes many data analysis packages
• ipython notebook - interactive programming
• international python community
• clean, intuitive, object-oriented code
aggregating and processing program file

- aggregate thousands of files into one
- apply offsets and transform with calculations
- normalizing frequencies
- place in a csv file or SQL database
- benefits
  - scalable: to one or many wind turbines
  - flexible: select any time period for any set of wind turbines
interactive programming

```python
ax.legend(['lines', 'labels', '100-v', 'inchsize=12'])

time_start = '2014-04-11 00:00:00'
time_end = '2014-04-11 00:15:00'

timeText = 'Start Time: %s \nEnd Time: %s \nHawaii-Aleutian Time Zone' % (time_start, time_end)
ax.text(right, top, timeText,
    horizontalalignment='right',
    verticalalignment='bottom',
    transform=ax.transAxes, fontsize=12)

fig = ax.figure
fig.set_size_inches(fig.get_size_inches()[1]*fig_ratio*4, fig.get_size_inches()[0]*4)

50]: line3 = ax.right_ax.get_lines().pop()
    line3.get_label()
data analysis program files

- time series graphs for power and tilt
  - 900 seconds per graph
  - 4 weeks – 10,000 graphs
  - due diligence record keeping
- power vs tilt
  - 2 second averages
  - 10 minute averages
time series graph

utility scale wind turbine foundation
power vs tilt 2 second average
power vs tilt 10 min average
comparison between wind turbines

Tilt vs. Power - 10 min Avg.

Power (kW) vs. Tilt (degrees)
presenters

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