Onshore Wind Turbine Foundation Maintenance: RP 401

August 6, 2024 | 1pm – 2pm ET

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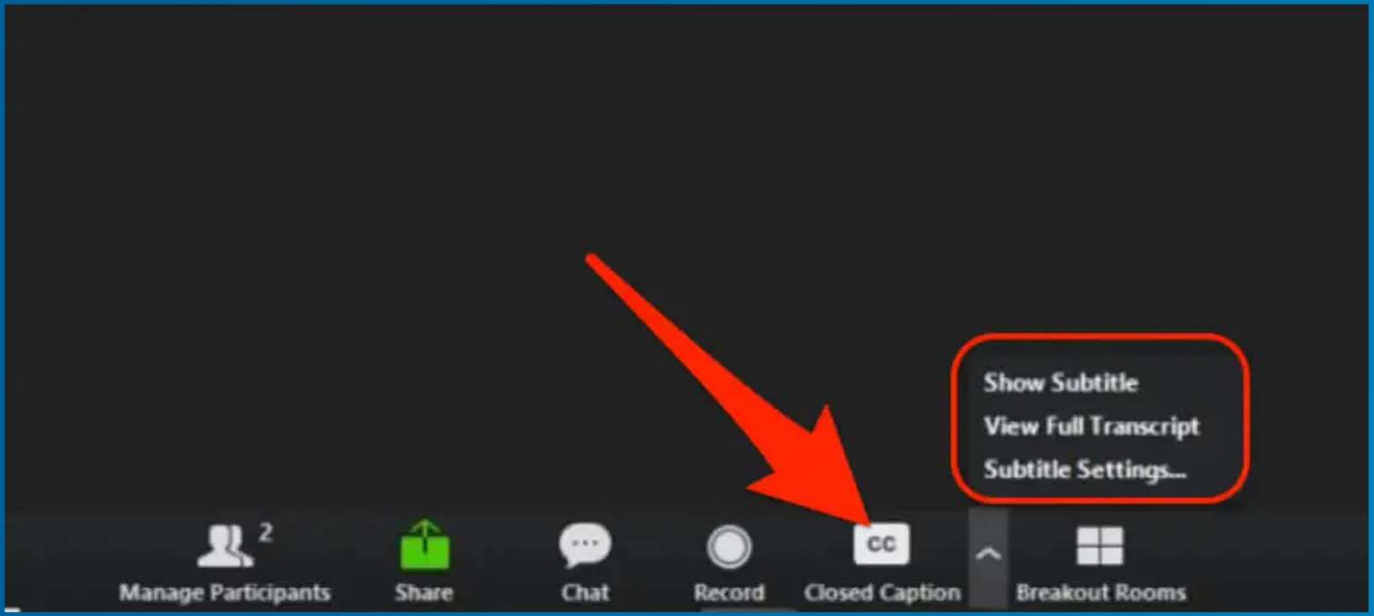
Closed Captions



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Please drop questions Q&A

Here, your questions won't get lost and are most likely to get answered.

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Today's Program is Being Recorded

- The recording will be available to you in ACP's streaming library by the end of this week.
- The slides will be shared with you in the chat as a downloadable pdf.

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Speakers

MODERATOR

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Sr. Director, Safety, Workforce Training, & Operations

ACP

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Director of Engineering

Leeward Renewable Energy, LLC

Wesley Karras
Senior Structural Engineer

Barr

Jesse Tarr
President

Wind Secure

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Poll: Understanding Today's Audience

What best describes your vantage point for interest in today's program?

- ❑Owner/Operator
- ❑Contractor
- ❑Engineer
- ❑Other

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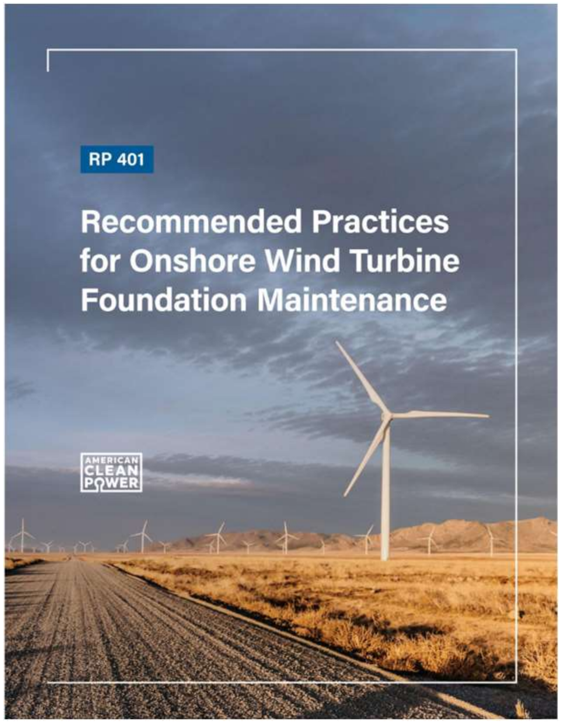
Recommended Practices for Onshore Wind Turbine Foundation Maintenance (RP 401)



- **Purpose:** Provide detailed recommendations for inspection, maintenance and repair of wind turbine foundations.
- **Working Group Members:**
  - Jesse Tarr – Wind Secure
  - Wesley Karras – Barr Engineering
  - Coral Rodriguez – RWE
  - Ron Grife – Leeward Renewable Energy (Chair)
- **Link:** https://cleanpower.org/resources/recommended-practices-for-onshore-wind-turbine-foundation-maintenance/

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RP 401 Update

- ***Background:*** Initial release AWEA Operation and Maintenance Recommended Practices May 6, 2013
- ***Incorporate Needed Updates:*** Many small changes to maintenance recommendations since the original release as practitioners get more experience.
- ***Increase Background Material:*** Current RP401 has all the basic information. The objective of adding more background material is to educate maintainers (operations and engineering) on the reasons why specific maintenance activities are needed.

Avoid this!

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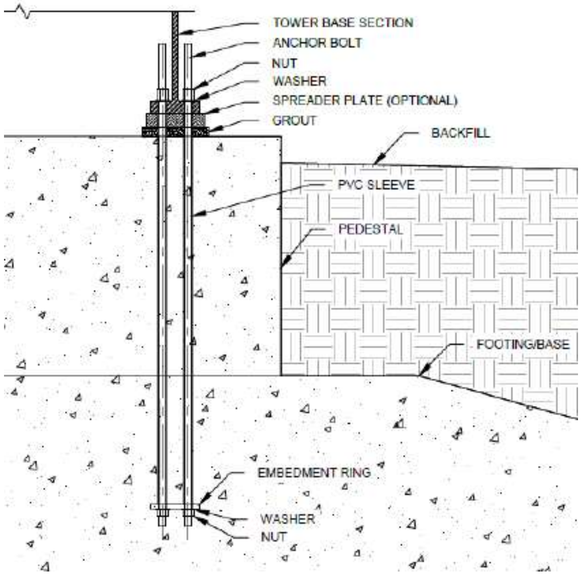
Definitions (Section 3)

Diagram for gravity-based foundation



RP 401 definitions

3 Definitions

Refer to Figure 1 and Figure 2 for a visual reference of the following foundation terms unless otherwise noted.

Anchor Bolt	Steel threaded fastener which attaches the tower base to the foundation. Anchor bolts can vary in length and material could be a range of steel grades between 75 and 150 ksi according to ASTM or Grade 8.8 or 10.9 according to ISO.
Anchor Nut/Hex Nut	Component that retains the anchor bolt to the tower base flange and embedment ring, holding the anchor tension.
Backfill	Soil placed and compacted on top of the foundation to provide stability and resist overturning under loads and provides positive drainage away from the foundation.
Base/Footing	Component of a gravity-based spread footing foundation, its purpose is to spread the loads to underlying soil or rock.
Embedment Ring	Component of the foundation, its purpose is to transfer the tensioned anchor load into the foundation.

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Functions & Design

Descriptions of foundation designs in the wind industry

An anchor bolt/embedment plate assembly is the most common type of connection made between the tower and the foundation. The anchor bolts are tensioned after concrete curing primarily to minimize fatigue of the anchor bolts. However, in the case of a tensionless tube foundation, the anchor bolts also provide pre-tensioned reinforced concrete strength. Figure 7 shows an anchor bolt embedment plate assembly during and after construction.

Example photos

Figure 7. Anchor bolt/embedment plate assembly prior to concrete placement shown in left photo and fully constructed foundation in the right photo.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Background of failure mode

Example photos

Recommended action to mitigate

6.10 Soil Cracking and/or Gapping

When the backfill material, often soil or gravel, is found to have cracks or gaps between the foundation pedestal and the backfill, it is a sign stresses are greater than the elastic range of the backfill. Soil cracking may be a sign of soil contraction in dry periods, freezing and thawing, or distress/overload of the foundation. Soil cracks encircling the foundation toe perimeter may suggest a potential loss of support attributed to excessive uplift (or overturning) or differential settlement of the foundation. Monitoring and developing an understanding of the local conditions and turbine performance is important in diagnosing the cause of the soil cracking. Cracking and gapping found in the soil around the foundation may be signs of unexpected foundation movement.

The figures below show soil conditions that were due to a foundation overload that resulted in foundation uplift which disturbed the backfill and resulted in radial soil cracking and significant gapping around the pedestal. After inspection, this foundation was found to have a significant anchorage pullout failure.

Figure 18. Gap between pedestal and backfill from close-up in left photo and aerial view of foundation soil cracking in right photo.

The recommended preventive activity to mitigate the impact of these failure modes is visual inspection and training turbine maintenance crews to look for this defect during regular turbine maintenance visits and after significant loading events discussed in Section 10. If these conditions are observed and cannot be attributed to normal soil conditions, the recommended action is to remove the machine from service and contact the Engineer. **Note: Failure to act could result in foundation collapse.**

If the condition is a result of excessive loading or unstable soil conditions, corrective measures must be taken to ensure the stability of the structure. The resolution of these issues is varied and requires assessment by the Engineer to determine a corrective action plan.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Grout spalling

Figure 9. Early-stage spalling in left photo and late-stage spalling with significant cracking in right photo.

Grout cracking

Figure 10. Radial cracking in cementitious grout in left photo and circumferential cracking in epoxy grout shown in right photo.

Failure Mode Descriptions (Sections 6.1 – 6.14)

Pedestal spalling

Figure 11. Structurally significant pedestal spalling in left photo and minor debris/impact pedestal spalling in right photo.

Pedestal cracking

Figure 12. Pedestal radial shrinkage crack in left photo and more significant circumferential cracking in the right photo.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Grout loss under flange

Figure 13. Loss of grout with the potential for gapping shown in the left photo and significant loss of grout with gapping due to low anchor bolt tension shown in right photo.

Poor grading/backfill loss

Figure 14. Poor grading resulting in pooling of water in left photo and example of low backfill height in right photo.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Water pooling

Soil gapping/cracking

Figure 15. Water pooled shown in left photo and corrosion of grounding cables due to water in the basement shown in left photo.

Figure 18. Gap between pedestal and backfill from close-up in left photo and aerial view of foundation soil cracking in right photo.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Foundation out of level

Anchorage zone damage

Figure 2019. Cracked concrete core taken at the anchorage pullout area in the left photo, turbine collapse due to foundation overloading event and anchorage pullout failure in the right photo.

Figure 21. Example of a foundation out of level resulting in visually observable tower tilt compared to neighboring turbines. Solid vertical lines are drawn representing two plumb and vertical towers to the right whereas the tower on the left has a tower centerline, shown with a dashed line, that is not plumb.

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Failure Mode Descriptions (Sections 6.1 – 6.14)

Anchor bolt hardware corrosion

Figure 16. Hardware with surface corrosion is shown in the left photo and hardware with advanced corrosion is shown in the right photo.

Figure 19. Jack and plate tension method setup shown in left photo and bolt tensioner on an anchor bolt in the right photo [ITH Bolting Technology, www.ith.com].

Low/high anchor bolt tension

Anchor bolt cover failure

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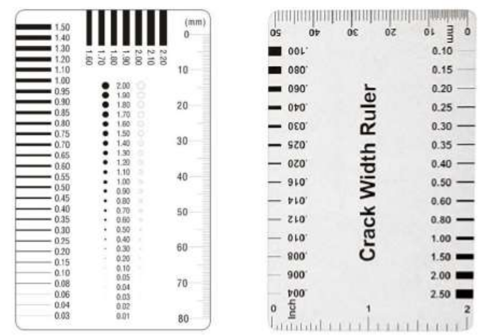
Scheduled Maintenance (Section 7)

Preventive Maintenance Scope	Interval
100% anchor bolt tensioning	Within the first 6 months following construction and following failure of a 10% tension testing check
Photographic inspections	Within the first 6 months following construction and every 3 years thereafter, depending on frequency of 10% testing Include photos in case of any observed anomaly or defect
Anchor bolt tension verification (10% tension test)	Every year for the first 3 years until a consistent baseline is established and then every 3 years thereafter on all turbines
Visual inspection checklist	Every 1 to 3 years depending on conditions and risk
Structural health monitoring (SHM)	Consult Engineer if an overloading event occurs or inspections indicate potential issues.

Location	Item	Criteria	Y/N	Comments
External	Pedestal	Crack(s) > 0.3mm (0.012”) or spalling		
	Grout	Crack(s) > 0.3mm (0.012”) or spalling		
	Flange	Gap with grout		
	Hardware	Heavy corrosion		
	Anchor Covers	Failed or missing covers		
	Backfill	Pooling, cracking, gapping, low backfill height		
Internal	Pedestal	Crack(s) > 0.3mm (0.012”) or spalling		
	Grout	Crack(s) > 0.3mm (0.012”) or spalling		
	Water	Moisture/corrosion		
	Hardware	Heavy corrosion		

Maintenance & Repair Methods (Section 8)

- Above grade visual inspections
- Anchor bolt tensioning
- Grout repair
- Anchor bolt tension validation (10% testing)
- Anchor bolt ping testing



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Maintenance & Repair Methods (Section 8)

- Structural health monitoring (SHM)
- Below grade inspections
- Concrete coring
- Engineered repairs

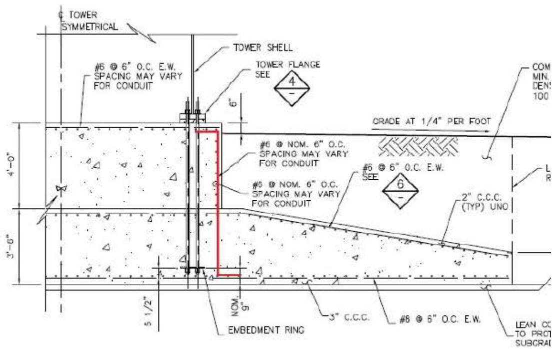

Figure 23. Pre-2010 Foundation design with minimal vertical reinforcement.

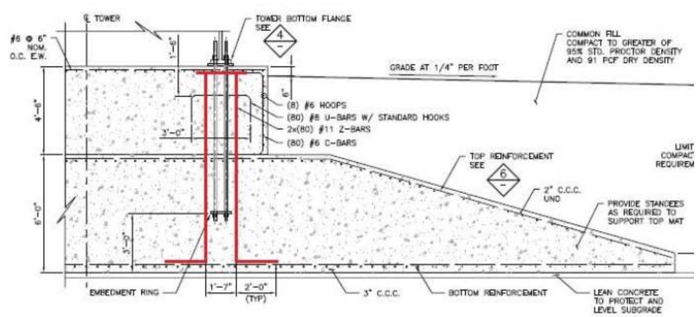

Figure 204. Post-2010 Foundation design example with additional vertical reinforcement.

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Poll

Do you believe you can apply the information in RP401 to further your knowledge and understanding of wind turbine foundation maintenance?

- ❑Yes
- ❑No
- ❑Not sure yet

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Questions?

Thank You!

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Please Complete Our Exit Survey

ACP PowerCasts Exit Survey

Anonymous · 6 questions

1. Overall, how satisfied were you with this PowerCasts program? *

0: Dissatisfied, 5: Very Satisfied

0 1 2 3 4 5

2. I gained knowledge, skills or understanding relevant to my job and/or my understanding of the clean power industry. *

- [ ] Strongly Agree
- [ ] Somewhat Agree
- [ ] Neutral
- [ ] Somewhat Disagree

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Thank you!

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Functions & Designs (Section 5)

Tensionless tub/P&H

Figure 3. Tensionless tube foundation anchor cage ready for pour in left photo, and three-dimensional image illustrating the design elements of the tensionless tube foundation in the right photo.

Rock anchor

Figure 4. Rock anchor foundation in service in left photo, and three-dimensional image illustrating the design elements of the rock anchor foundation in the right photo.

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Functions & Designs (Section 5)

Pile supported

Figure 5. Pile supported cap foundation in construction in left photo and completed foundation in right photo.

Rock socket

Foundation mounting part (FMP)

Design Changes (Section 9)

- Anchor bolt covers/corrosion protection
- Anchor bolt tension modification
- Foundation reinforcements
  - Collar retrofit, FRP wrap, post-tension cables

Operating Loads (Section 10)

- Foundation load changes
  - Increase rated power, repowering, component upgrades
- High load shutdowns
- Major turbine component failures
  - Turbine fires, catastrophic drivetrain failures, blade failures, tower blade strike, PMT failure incl. fires
- Irregular turbine operation and events
  - Loss of grid power, extreme weather events, extreme and fatigue load considerations

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Appendix A: Failure modes, their effects, and recommended actions

Table A-1. Summary of failure modes, their effects, recommend preventative maintenance and recommend repair

Ref. Section	Failure Mode	Effect on System	Impact	Recommended Preventative Maintenance
8.1	Grout - Spalling	Load from the tower flange is not evenly distributed to the foundation.	Tension of anchor bolts is potentially reduced. Grout continues to fail over time. Without repair, gapping can occur between grout and flange resulting in further structural damage.	Visual inspection of internal and external grout, repair of spalled grout.
8.2	Grout - Cracking	No immediate effect to foundation function so long as grout is consolidated. However, significant cracks could be a sign of grout failure.	Cracking may continue through freeze-thaw cycles and lead to spalling.	Visual inspection of internal and external grout, filling of cracks over 0.3mm (0.012"). Cracks larger than 2.0mm (0.08") are significant and could be a sign of more critical issues.
8.3	Pedestal - Spalling	Load from grout is not evenly distributed to the foundation.	Tension of bolts is potentially reduced. Concrete continues to fail over time. Without repair, further structural damage can occur. Reduced reinforcement concrete cover.	Visual inspection of internal and external pedestal concrete, repair of spalled concrete.
8.4	Pedestal - Cracking	No immediate effect to foundation function. However, significant cracks could be a sign of pedestal failure.	Cracking may continue through freeze thaw cycles and lead to spalling.	Visual inspection of pedestal both internal and external, filling of cracks over 0.3mm (0.012"). Cracks larger than 2.0mm (0.08") are significant and could be a sign of more critical issues.
8.5	Tower Base Flange to Grout Gapping	If gapping at the flange is present, the loads generated may be outside of the design assumption for the foundation.	Fatigue cycling of the foundation bolts may occur. Cracking of the grout and pedestal are likely to occur.	Visual inspection and repair of conditions leading to gapping. If gapping is suspected, a thin object such as a piece of paper or plastic can be used to gage the size of a gapping area.
8.6	Improper Grading	Amount of material resisting overturning loads may not meet engineering design criteria.	Grading resulting in ponding of water.	Visual inspection to check the grading meets engineering specification and there are no signs of ponding. Correct grading issues if present.

Appendix A: Failure modes, their effects, and recommended actions

Ref. Section	Failure Mode	Effect on System	Impact	Recommended Preventative Maintenance
8.7	Water in Basement	No likely impact on structural loads.	Corrosion of internal hardware including steel tower components, electrical ground cables	Inspect basement for water ingress and correct if found.
8.8	Hardware Corrosion	No immediate effect to foundation loads.	Degradation of hardware: anchor bolt, nut, and washer potential section loss. Nuts seized to the bolt. Bolts not holding design tension. Washers failing over the lifetime could lead to oscillating loads on the base bolts affecting the fatigue lifetime of the foundations.	Apply approved systems for corrosion protection to all interior and exterior anchor bolts, nuts, and washers such as grease or coatings.
8.9	Broken Anchor Bolt Covers	No immediate effect to foundation loads.	Anchor bolt corrosion. Cracked bolt covers can be deleterious as they can trap rainwater inside the cover and submerge the bottom portion of the bolt assembly.	Replace damaged anchor bolt covers.
8.9	Improperly Functioning Anchor Bolt Covers	No immediate effect to foundation loads.	Anchor bolt corrosion.	Install anchor bolt covers.
8.10	Soil Cracking and/or Gapping	Indication of possible foundation movement.	Impact on turbine operation and possible failure of foundation. May allow storm water infiltration and potential tilting on tensionless tube design.	Visual inspection and backfilling with compacted soils.
8.11	Anchor Tension Too Low	Distribution of loads to anchor bolts, grout and concrete will not meet design specifications.	Anchor bolts may accumulate fatigue damage, lack of concrete post-tensioning load may result in premature failure.	Periodic validation of anchor bolt tension.
8.12	Anchor Tension Too High	Distribution of loads to anchor bolts, grout and concrete will not meet design specifications.	Anchor bolts may experience yielding loads, excessive post-tensioning load may result in premature failure.	Validation of anchor bolt tension during and after construction.
8.13	Anchorage Pullout Failure	The foundation is not able to support turbine loads.	Possible failure of foundation.	Structural health monitoring, coring, below grade inspections or other method at frequency determined by Engineer.
8.14	Foundation Out of Level	Reactive loads transferred to vertical rebar.	Vertical rebar may fail if foundation design is not adequate for fatigue.	Survey or SHM.