RP 401

Recommended Practices for Onshore Wind Turbine Foundation Maintenance

AMERICAN CLEAN POWER

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Preface

The following Recommended Practice is subject to the Safety Disclaimer and usage restrictions set forth at the front of AWEA Operations & Maintenance Recommended Practices, Second Edition. It is important that users read the Safety Disclaimer and usage restrictions before considering adoption of any portion of this Recommended Practice. Furthermore, it is the responsibility of the user or the inspector to adhere to industry best practices for safety procedures, which involve conducting a hazard assessment, identifying and recognizing critical situations, such as an imminent structural failure, before starting any wind turbine foundation inspection or maintenance activities.

ACP Operations Wind Performance Committee

This recommended practice was prepared by a committee of the ACP Operations Wind Performance Committee.

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1 Introduction

The purpose of this Recommended Practice is to provide detailed recommendations for the maintenance of wind turbine foundations. Commonly referenced foundation design standards including ASCE/AWEA RP2011, IEC 61400-6:2020 and DNV-ST-0126 all recommend some level of foundation maintenance or monitoring but do not provide detailed guidance. This Recommended Practice addresses the need for a wind turbine foundation maintenance reference providing guidance for the most common maintenance needs including inspections, preventative maintenance and typical repairs.

The recommendations apply to several foundation types with a peripheral arrangement of pretensioned anchor bolts holding the tower to the foundation. This configuration was chosen because most turbine foundations in North America are this type. For different foundation types, similar inspection and maintenance procedures may still be implemented with adaptation. The engineer of record (EoR), or a licensed structural engineer familiar with wind turbine foundation design, may be consulted to assess circumstances not considered in this Recommended Practice. For this document, the term Engineer will be used throughout to refer to the engineer of record or a licensed professional engineer familiar with the practice of wind turbine foundation design and maintenance. As a best practice, any recommendations for changes to maintenance or repairs may be transmitted in writing to the owner from the Engineer for record keeping purposes.

This document contains various topics. Sections 4 through 5 contain background information on the operating conditions, wind turbine foundation definitions and general description of typical foundation designs. Section 6 covers a detailed description of common failure modes and recommended actions followed by Section 7 which summarizes the recommended maintenance for wind turbine foundations. Section 8 provides detailed guidance on certain means and methods of maintenance and repair. The final two sections discuss the impact of design changes and operating loads on foundation maintenance.

2 Background

Renewable energy operators typically employ maintenance crews, remote operations and corporate support staff to maintain and manage wind energy sites. As of 2023, the operating wind energy fleet in the United States consisted of over 71,000 wind turbines with 1,900 turbines brought online in 2023 alone[1]. While each operating company has different performance targets, energy-based availability is a common metric with targets ranging from 96% to 99% turbine energy availability depending on turbine technology. Virtually all industrial scale wind plants are operated remotely from a remote operations center. On-site maintenance crews can operate the equipment but are primarily tasked with equipment maintenance and repair.

2.1 Ownership and Management

There are variations in management of wind plants based on the owner as well as regional and plant size differences. However, there are also many common traits. Operating wind plants are typically overseen by a plant manager permanently located at the project. A wind plant's expected net capacity factor ranges from 30% to 45% depending on the wind resource and type of turbine installed. Wind plant managers commonly develop budgets targeting the average annual production, though variations in wind resource from year to year are expected. Plant production can vary for various reasons other than wind resource including large turbine component failures, recurring faults in turbines and failures of balance of plant systems. While many new wind plants are being constructed, many plants are approaching the end of their design life. Many plants in this older range are being repowered, reusing the existing foundations and in some cases existing towers. The maintenance scope of most wind projects is separated between turbines and the balance of plant which includes electrical collection systems, turbine foundations and other general facilities maintenance.

2.2 Design and Operation

The standard wind turbine mechanical load analysis dictated by IEC design standards indicate that all major structural components of the turbine will have at least a 20-year design life, but many projects anticipate a 30-year or greater project life. Turbine maintenance is generally defined by the OEM and continued with minor variations through the life of the project by an OEM maintenance crew, an independent service provider, or the owner's own maintenance crew. While figures do vary, there is approximately one wind technician for every ten turbines who are employed to perform scheduled maintenance, troubleshooting and replacement of parts excluding large components. Large component replacements are performed by specially trained technicians as needed. The majority of the regular maintenance crews work 8-to-10-hour shifts, Monday through Friday, with a smaller proportion of labor being utilized for nights and weekends.

Wind turbine foundations in the United States are designed by engineering firms licensed in the state which the project is being constructed. A general contractor will build the foundations to the engineering specifications and the engineer of record's sealed design drawings and specifications. After quality checks are passed, the contractor will deliver the as-built records, installation specification and quality control

[1] American Clean Power Association (ACP) (2024) Clean Power Annual Market Report 2023

records. After foundation construction and the initial re-tensioning of anchor bolts, there was traditionally very little planned maintenance for wind turbine foundations. Wind turbine foundations generally have no condition monitoring equipment to alert the operator of foundation performance or failure. Wind turbines are visited periodically throughout the year to address unscheduled outages due to turbine faults and scheduled maintenance, typically two times per year. The technicians mobilized for maintenance crews generally have no training in foundation maintenance requirements or failure modes. Foundation inspections and maintenance are generally carried out by the owner, specialized contractors or Engineer.

2.3 Environmental Conditions

Environmental conditions can affect the maintenance requirements for wind turbine foundations. The following describes the known impacts on typical foundations.

2.3.1 Rainfall and Humidity

Heavy rainfall can impact the grading and backfill around a wind turbine foundation by causing washouts which may result in loss of backfill and potential subsequent pooling of water. Additionally, the general level of rainfall and humidity present will impact anchor bolt and hardware corrosion rates. Dry areas are also susceptible to these same risks as often the soil in arid locations may be less stable and can be more prone to washout due to lack of vegetation.

2.3.2 Freezing Precipitation (Ice/Snow)

Freezing conditions can impact the health of foundations by stressing any gaps or cracks in the concrete and grout through freeze-thaw cycles. Additionally, ice accumulation on the wind turbine structure can sluff off and fall to the base potentially damaging anchor bolt covers, the concrete pedestal or grout.

2.3.3 Marine and Industrial Environment

Marine environments add additional challenges to the maintenance of equipment primarily due to accelerated corrosion. Wind turbines located in marine environments will require additional maintenance on foundation anchor bolts and hardware to manage corrosion. An Engineer or a corrosion specialist should be consulted to determine the appropriate corrosion management plan.

Industrial environments have risks similar to marine environments in that corrosion can be accelerated by contaminants in the air. Wind plants operated in or near an industrial environment should similarly consult the Engineer or corrosion specialist to develop a corrosion management plan.

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.
Foundation Mounting Part/Piece (FMP)	FMP, the portion of the tower that is embedded in the concrete foundation. An alternative tower design to the typical base flange and anchor bolt arrangement (See Figure 8).
Foundation	Structural element which transfers loads to underlying soil or rock.
Grout	Cementitious or epoxy material that enables the uniform transfer of loads between the tower base flange (or spreader plate) and the foundation.
Pedestal	Component of the foundation, its purpose is to support the base of the wind turbine tower and where the exposed anchor bolts are embedded in the foundation.
PVC Sleeve	Embedded into the foundation around the anchor bolts to prevent bonding of the concrete to the anchor bolts.
Spreader Plate	Steel ring plate that evenly distributes the compressive forces from the tower base flange (or grout) to the foundation.
Washer	A thin ring plate that distributes the tension of the anchor bolt and nut and prevents damage to the surface of the tower base flange and embedment ring.
Rock Anchor	Steel threaded fastener grouted into bedrock to anchor the foundation (See Figure 4).

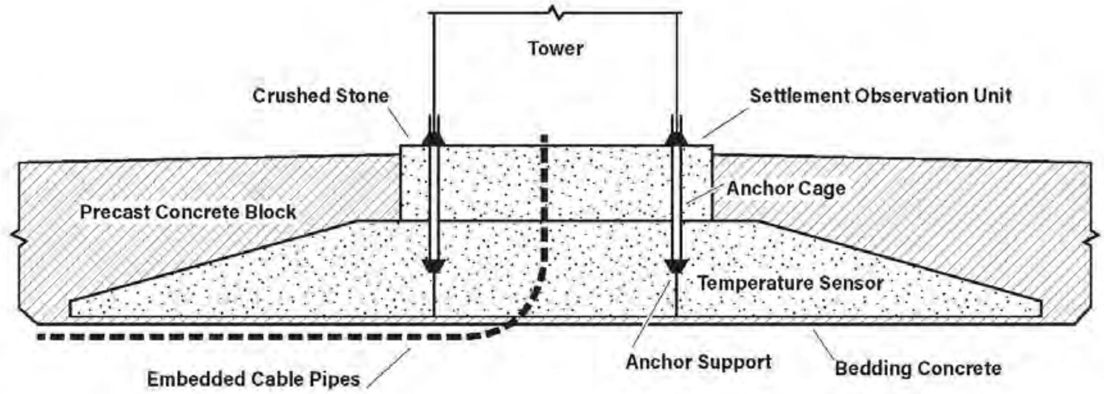

Figure 1. Sectional view of typical gravity-based spread footing foundation.

4 Acronyms

ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials (formerly known as)
ksi	Thousand pounds pressure
ISO	International Organization for Standardization
AWEA	American Wind Energy Association (now ACP, or American Clean Power)
OEM	Original Equipment Manufacturer
IEC	International Electrotechnical Commission
DNV	Det Norske Veritas
O&M	Operations and Maintenance

Figure 2. Typical gravity-based spread footing foundation in construction state prior to being covered with backfill.

5 Functions & Design

The most widely used foundation type is the gravity-based spread footing foundation which relies on the soil bearing resistance, the weight of the foundation, soil backfill and wind turbine weight for stability. Figure 2 shows a typical gravity-based spread footing foundation prior to placement of backfill. The spread footing may be constructed in combination with soil corrections such as engineered fill, stone columns or dynamically compacted soils.

The second most widely used foundation type is the Patrick and Henderson (P&H) style monopole, or tensionless tube foundation. The tensionless tube foundation is a deep foundation which relies on its embedment depth as well as lateral and friction resistance of the soil for stability. A post-tensioned concrete cylinder integral with connection to the tower provides the necessary structural strength to accomplish this. There are several variants of this style of foundation which incorporate a concrete collar with or without post-tensioned rock or soil anchors around the foundation. A typical design of this foundation type is shown in Figure 3.

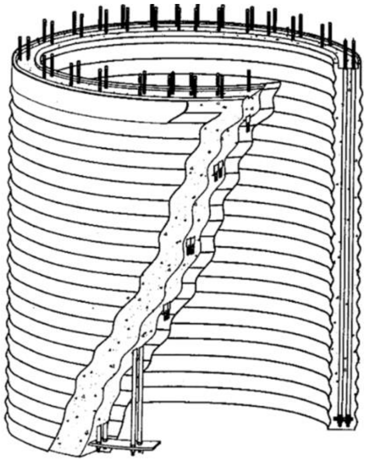

Figure 3. Tensionless tube foundation anchor cage ready for pour in left photo, and three-dimensional image illustrating the design elements of the tensionless tube foundation in the right photo.

The rock anchor foundation is a style of foundation commonly used in strong, massive rock conditions. This style of foundation relies on the embedment of rock anchors in the rock mass and the rock bearing resistance for the anchor cap to provide stability. A typical design of this foundation type is shown in Figure 4.


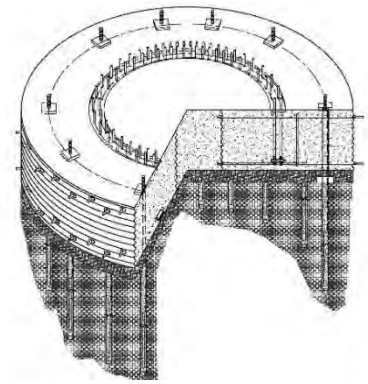

Figure 4. Rock anchor foundation in service in left photo, and three-dimensional image illustrating the design elements of the rock anchor foundation in the right photo.

The pile supported cap foundation can be a rock or soil anchor foundation. This style of foundation is constructed where poor soil conditions are present to depths greater than 40 feet. The foundation relies on the weight of the foundation and the tension and compressive strength of the piles to carry loads to deeper, stronger soil or rock layers for stability. The pile supported cap foundation can be utilized in rock with percussion drilled piles using post-tensioned all thread anchor bolts or utilized in soil with drilled soil anchors post-tensioned. Figure 5 shows the piles installed prior to concrete placement and the completed pile cap after.


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

Figure 6. Rock socket foundation in construction prior to backfill.

The rock socket foundation is the least common foundation type and is used in moderate strength, and massive rock conditions. The rock socket is like the tensionless tube foundation in that it also relies on embedment depth and the lateral and friction resistance of the surrounding material for stability which in this case is rock. Figure 6 shows a rock socket foundation in construction progress after placement of concrete.

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.

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

The foundation mounting part/piece (FMP) is a method for connecting the tower to the foundation and was primarily used around the year 2010, however some FMP type towers were constructed later. This method of connection originated from Europe and was tried in North America at several facilities. Ultimately, the anchor bolt/embedment plate assembly became the preferred option. Figure 8 shows an FMP during and after construction.

Figure 8. FMP connection prior to construction of foundation in left photo and fully constructed FMP style foundation prior to backfill shown in right photo.

6 Scheduled Maintenance & Repair

The role of scheduled maintenance on a structural system is to find and correct any deterioration that would impair its load carrying capability[2]. The following maintenance and repair activities are provided for reference only. It is essential to determine the root cause of any structural issue before proceeding with repair. Damage or anomalies should be shared with the Engineer for assessment.

In the following subsections, foundation subsystem functions are described along with typical failure modes. For each failure mode, an analysis of the effect and the recommended preventative maintenance and repair approach are provided. A summary of the content in this section is also provided in a tabular format in Appendix A for quick reference.

6.1 Grout Spalling

Grout spalling is the loss of material from the grout bed in chunks. When grout spalls, it is a sign of weak and failing grout or turbine base flange impact when separated from the grout by flange movement. Spalling is most often seen with cementitious grout, though it is possible for epoxy grout to fail similarly. Examples of grout spalling in cementitious grout are shown in Figure 9.

[2] Nowlan & Heap, Reliability-Centered Maintenance, 1978.

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

When grout spalls, the load transfer from the tower flange to the pedestal may be disrupted. The loss of a continuous and smooth transfer of load from the tower flange to the pedestal may result in increased stress to the remaining grout and eventually to the concrete pedestal. If enough grout has failed, the originally constructed gap that the grout fills may be reduced enough to result in a loss of tension in the anchor bolts.

The recommended preventative maintenance to address grout spalling is a visual inspection. The purpose of the visual inspection is to identify issues and correct them while still in an early stage of failure. If not corrected early, grout failure may progress to a point where damage could occur to the pedestal concrete, anchor bolts or other parts of the foundation.

Grout can fail in several ways, recommending when to repair in a general sense is not straight forward. However, when grout failures span more than three anchor bolts, a repair should be considered. Grout repair consists of removing the failed material and then filling the area with new grout material. The repair grout strength must meet or exceed the original design criteria and be compatible with existing materials. Removal of grout may require impact tools to chip out soft and failed material under the flange. All defective material should be removed before filling with new grout. Tension on a limited number of anchor bolts should be removed in the affected repair area before starting the repair, and then re-tensioned along with all other anchor bolts after the replacement grout has cured. The Engineer may be consulted on how many consecutive anchor bolts may be released from tension and if loss of tension detected in area of failed grout.

6.2 Grout Cracking

Grout cracks are continuous separation of the material observed in the surface of the grout. When grout cracks, it may be a sign of weak and failing grout. Cracking is most often seen with cementitious grout, though it is possible for epoxy grout to crack as well. Figure 10 shows examples of cracking in both common grout materials. The small vertical cracks in the cementitious grout on the left are very common. Cracks in epoxy grout are much less common.

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

The most common grout cracks are of radial orientation and found in cementitious grout. These cracks are typically shrinkage cracks that occur during the curing of the material and likely do not affect the load transfer from the tower flange to the pedestal if the material is largely intact underneath the flange. Circumferential cracking is less common and may be an indication of a structural problem and should be further investigated. Cracking allows ingress of water and the potential for freeze-thaw cracking and eventual possible spalling. If enough grout has failed, the originally constructed gap that the grout fills may be reduced resulting in a loss of tension in the anchor bolts.

The recommended preventative maintenance to address grout cracking is a visual inspection and repair if cracks are wider than 0.3mm (0.012”). The purpose of the visual inspection is to identify issues and correct them while still in an early stage of failure. If not corrected early, grout failure may progress to a point where damage could occur to the pedestal concrete, anchor bolts or other parts of the foundation.

Repair of grout cracks wider than 0.3mm (0.012”) may be filled by gravity feed using a very low viscosity epoxy type repair product. A compatible coating may be applied over crack repair top of the surface to protect the epoxy containing UV inhibitor. Coatings are recommended to be clear to allow follow-up inspections. Cracks larger than 2.0mm (0.08”) should be assessed by the Engineer to help determine the root cause and recommend an appropriate repair.

6.3 Pedestal Spalling

Spalling of the pedestal concrete is the loss of material from the pedestal in chunks. There are two categories of pedestal spalling, structurally significant and superficial. When concrete spalls and cracks, it may be a sign of weak and failing material. Examples of both categories of pedestal spalling are shown in Figure 11.

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

When pedestal concrete spalls, there may be no immediate impact on the distribution of loads and stresses if the material loss is small and away from the tower base flange. However, large spalls could expose reinforcement, reduce concrete cover and increase the risk deterioration of the rebar through corrosion. Pedestal spalling could be the result of weak concrete, corrosion of reinforcement, impact from debris, or exposure to fire or other environmental factors. Significant pedestal spalling could also be due to alkali-silica reactivity (ASR) of the concrete aggregate, which is less common.

The recommended preventative maintenance to address pedestal spalling is a visual inspection. The purpose of the visual inspection is to identify issues early and correct them while still in an early stage of failure. Pedestal spalling of structural concern is not a common failure mode. If it is being observed, it may be evaluated by the Engineer to help determine the root cause.

The recommended repair for pedestal spalling is dependent on the failure mode. For superficial spalling, filling the spalled cavity (only if reinforcement is not exposed) and sealing the affected area is the most likely recommended action. For other root causes, more invasive measures may be required including removing damaged concrete to around the reinforcement and replacing. For spalling worse than minor or superficial, contact the Engineer for a formal assessment.

6.4 Pedestal Cracks

Pedestal cracks above the soil backfill are observable continuous separations in the pedestal concrete. Radial cracking in the pedestal as shown in Figure 12 on the left is quite common. It is understood this cracking happens during the curing stage and is known as shrinkage cracking. A larger and more concerning crack is shown in the photo on the right in Figure 12.

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

When cracks develop in the pedestal, the distribution of load through the pedestal may be significantly disrupted from the original design intentions. Some minor shrinkage cracking is quite common and not considered a concern, often present and showing no signs of progression over many years. At what time after construction shrinkage cracking typically occurs is dependent on several factors including the concrete mix design, weather conditions at the time of placement, and structure location/exposure making it difficult to predict when shrinkage cracking may occur. Most typically, shrinkage cracking occurs shortly after construction to within the first few years of operation. However, any crack is a potential pathway for water to ingress and freeze thaw cycles may accelerate damage. Circumferential cracking is less common and may indicate a structural issue, the Engineer should be consulted if these cracks are observed.

The recommended preventative maintenance to address pedestal cracking is a visual inspection and repair for crack widths exceeding 0.3mm (0.012”). The purpose of the visual inspection is to identify issues and correct them while still in an early stage of failure. Crack width and depth measurements and mapping may be required to determine the root cause of the cracks prior to repair. Severe cracking at or below the reinforcing steel can incur stress reversals (cycling) and fatigue the reinforcement causing additional damage.

Cracks wider than 0.3mm (0.012”) may be filled by gravity feed using a very low viscosity epoxy. A compatible coating may be applied over crack repair top of the surface to protect the epoxy containing UV inhibitor. Coatings are recommended to be clear to allow follow-up inspections. Cracks larger than 2.0mm (0.08”) should be assessed by the Engineer to help determine the root cause and recommend an appropriate repair.

6.5 Tower Base Flange-to-Grout Gapping

Tower base flange grout gapping may be caused by grout material deficiencies, inadequate confinement, base flange impact loads, or significant anchor bolt tension loss. Observable gaps between the bottom of the flange and the top of the grout are a concern. Examples of gapping are shown in Figure 13.

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.

Any gap present between the grout and tower flange will result in a change to the intended load path from the tower base flange to the grout resulting in higher than intended stresses on both surfaces. The change in the load path may result in progressive failure of grout or pedestal concrete. Gapping may also be dynamic which is evidenced by detectable displacement of the flange with respect to the grout. **Dynamic gapping is a serious and immediate concern that should be addressed by removing the turbine from service, notifying appropriate stakeholders, and consulting the Engineer.**

The recommended preventive maintenance to mitigate the impacts of gapping are to perform a visual inspection and address any findings of gapping. Gaps may be plainly visible and often accompany grout cracking or spalling. Testing with a feeler gage may also be done to confirm if a gap is present.

Gapping associated with grout defects that have not caused other damage, may be addressed by repairing any failed grout and tensioning all anchor bolts to the design specifications. Since gapping is a serious potential structural concern even if dynamic gapping is not observed, the Engineer should be consulted regarding the observation and repair.

6.6 Improper Grading

Improper grading is any grade condition that does not meet the design specification in the foundation drawings. Grading may fail due to drainage conditions or failure of backfill material for various reasons. The photos below show examples of improper grading.

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

The majority of foundations rely on backfill to stabilize the foundation. Changes in the backfill and grading can result in less material to resist turbine loading. Additionally, poor grading and drainage can result in ponding of water near the turbine which may change the assumed soil properties in the design as well as present risks to staff maintaining the wind turbine equipment. It is common for the backfill placed over and around a wind turbine foundation to erode over time for various reasons. The backfill is a critical component of the foundation system and should be maintained in accordance with the original foundation drawings and specifications.

The recommended maintenance activity to mitigate improper grading is a visual inspection. The visual inspection is performed to identify any areas with soil erosion between the pedestal and approximately 25ft from the pedestal edge. The grading requirements are typically specified in the foundation design drawings and should be used as the ultimate reference.

The recommended repair for grading defects is to return the grade to meet the design specification in the engineering drawings. Care should be taken to ensure that backfill material meets design specifications for in-place density and that any required compaction is performed. The Engineer should assist in specifying the grading repair.

6.7 Water in Basement

Water may be found inside the turbine tower on the top surface of the pedestal. This location is often referred to as the “basement” as it is common practice to install a deck above the top surface of the pedestal. Water pooled in this location and the resulting corrosion that can occur on grounding cables is shown in Figure 15.

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

Water intrusion in coastal environments and areas with numerous freeze-thaw cycles should be prevented. Over time, the freeze-thaw and/or possible saltwater intrusion into the foundation may cause degradation. The foundation is typically designed for these conditions, but other systems like electrical grounding may not be. Water intrusion and pooling in the basement may present a number of issues, the first of which is safety. Water pooled with residue of grease or oil from the turbine presents a slipping hazard. Additionally, water presents many risks with electrical equipment with the majority of wind turbine cable routing through the basement. It is possible that water could provide a path for an electrical fault or expose a worker to an electrical hazard. Water, even in small quantities, also accelerates corrosion. Bonding and grounding of the tower to the foundation is typically done with a metallic conductor which is susceptible to corrosion. Additionally, the tower base flange when exposed to corrosive conditions is susceptible to corrosion and potential failure.

The recommended preventative maintenance activity to mitigate water in the basement is a visual inspection. Inspectors should look for standing water and signs of water ingress like corrosion on metal surfaces and pooling rings or water stains.

The recommended repair for water ingress depends on the root cause. Common sources of water ingress are poor door seals or door designs without positive drainage, condensation of moist air on cold tower walls that then collects on surfaces, or high ground water conditions. The conditions causing the water ingress should be mitigated along with any repairs of damaged or corroded components and equipment.

6.8 Hardware Corrosion

Most hardware utilized in wind turbine foundations is steel. When galvanized steel is used, hardware corrosion is greatly reduced, but it is not commonly used at wind plants in North America. The potential for corrosion of steel is greater in areas with environmental conditions that promote oxidization such as higher moisture levels or presence of other chemicals which may be man-made or naturally occurring. Figure 16 shows two examples of hardware corrosion. The left photo shows surface level corrosion of anchor hardware in a relatively dry environment. The right photo is an example of hardware from a wind plant located near a marine environment which has advanced corrosion. Note, the anchor bolts in the left photo did not have anchor bolt covers whereas the bolts on the right did. Corrosion of hardware may result in material loss and reduction of hardware strength, seizing of nuts to the anchor bolt and potential loss of anchor bolt tension.

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

The purpose of anchor bolt hardware is to maintain the pretension in the anchor bolt as well as retain the tower flange under expected loading, so long as degradation of hardware does not reduce the anchor bolt tension or strength of the anchor bolts below the design requirements, corrosion does not present a performance issue. However, when corrosion prevents the smooth operation of the hardware, verifying anchor bolt tension becomes more difficult. If corrosion is prevented to ensure the serviceability of the anchor bolt hardware, more advanced issues like loss of strength and tension are significantly minimized.

The recommended preventative maintenance to address hardware corrosion is visual inspection of external and internal hardware. Corrosion of hardware in typical environmental conditions is a process that progresses over many years and can be corrected if identified early. Preventing hardware corrosion may be done by applying a lubricant in the threaded surfaces of the nut and anchor bolt. The most common approach is applying grease to these surfaces and covering the anchor assembly with a cover.

Additional preventative methods could include applying anti-seize compound to the mating surfaces or applying oil to the bolt-nut interface. Anti-corrosive coatings are a potential mitigation, but extreme care should be taken to ensure that the coatings are tested and known to perform in the application. Coatings improperly applied may exacerbate corrosion and removal of the coating could end up being more costly than a lubricant and cover approach. When anchor bolts are excessively corroded there is a high likelihood the nuts are seized to the anchor bolt, and the anchor bolts are not holding proper tension.

Additionally, if hardware is allowed to excessively corrode to the point of material loss, tension may be reduced. If hardware advances to the stage that the nut no longer operates freely on the anchor bolt, corrective action is recommended. Repairs for this condition are dependent on how far the damage has progressed. Application of penetrating oil over a period of several months or longer may break up the corrosion enough to regain smooth operation.

6.9 Anchor Bolt Cover Failure

Anchor bolt covers are utilized in combination with grease to prevent corrosion of bolted hardware in many industrial applications. Bolt covers are intended to prevent grease from washing away due to environmental factors like wind and rain. Bolt covers are however susceptible to damage from debris/impact and cracking typically due to UV exposure. They may also fail to perform their intended function due to misapplication or poor design. When anchor bolt covers fit too tightly around the nut, they can retain moisture and can result in increased corrosion, potentially more than if none were used at all. Figure 17 shows examples of both common issues discussed.

Figure 17. Cracked bolt cover shown in the left photo and a bolt and nut with the cover removed wherein water was being trapped resulting in corrosion of the lower portion of the nut is shown in the right photo.

The impact of failed anchor bolt covers is an increase in the risk of hardware corrosion and the associated problems mentioned in section 8.8 above. The recommended preventative maintenance to mitigate bolt cover failure is a visual inspection and to replace failed anchor bolt covers when found.

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.

6.11 Low Anchor Bolt Tension

Anchor bolt tension that is below the design pretension can result in damage to the foundation, anchor bolts and grout. Low anchor bolt tension is not visible to the naked eye unless the tension is so low that gapping occurs under normal loading conditions. Anchor bolt tension is typically identified using mechanical means to apply the prescribed tension and evaluating the response of the hardware by evaluating the bolt extension or checking for nut liftoff. Nut liftoff is achieved by overcoming the existing tension present in the anchor bolt and at that higher applied tension the anchor bolt nut will separate from the washer, or the washer will separate from the tower base flange.

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 anchor bolt tension can impact the distribution of load to the anchors bolts themselves, the grout, and concrete. Failure to meet the design tension can result in premature failure of these critical components. Anchor bolts may accumulate fatigue damage if the proper pretension is not maintained. Loss of anchor bolt pretension may be the result of normal construction related break-in factors such as concrete creep and shrinkage, anchor bolt relaxation and seating losses from the hardware. These factors are expected and normal. Assuming post construction tensioning has been performed as recommended below, further reduction in tension could be a sign of more critical issues.

The recommended preventative maintenance to ensure the anchor bolts meet the design tension is to follow a tension monitoring plan. The plan may include tensioning of 100% of anchor bolts within 90 days of commencement of turbine operation following original construction. 10% anchor bolt tension testing may take place for the following 3 years or until consistent satisfactory results are obtained. Following this, revert to 10% tension checks on 100% of the turbines every three to five years from this point forward. For turbine repowering projects it is recommended to perform 10% tension checks at the time of repowering and continue with 10% tension checks on 100% of the turbines every three to five years from that point forward. If low tension values are found, all anchor bolts may be re-tensioned at that foundation. Foundation design drawings should be referenced for tension values and pass/fail criteria as it pertains to the specified anchor bolt tension. See Section 10.2 for specific 10% and 100% anchor bolt tensioning procedures. Reference foundation design drawings or Engineer for specified tension tolerances.

When performing 10% tension testing it would be preferential to equally test 10% of the interior and exterior anchor bolt. However, interior access can be limited due to high voltage, confined spaces, etc. and if work cannot be completed safely on the interior anchor bolts while energized and/or de-energization is not feasible, testing only the exterior anchor bolts can provide a general idea of overall anchor bolt tension. It should however not be assumed that the untested interior anchor bolts have the same tension as the exterior bolts.

The recommended corrective action for low anchor bolt tension is to re-tension the hardware back to design levels and attempt to determine the cause. Anchor bolt tension loss following the early-stage factors mentioned above could be indicative of a more significant issue. Records of the tensioning results may be maintained and shared with the Engineer to assist in determining the root cause and recommended corrective actions for the low anchor bolt tension results. The anchor bolt tension referred to is the as left or lock-off tension by applying the desired tension and tightening the anchor bolt nut to hold the applied tension.

6.12 High Anchor Bolt Tension

While low anchor bolt tension is the most common, high anchor bolt tension is also possible. This is typically caused by over-tensioning of the anchor bolts due to improperly calibrated tensioning equipment. Over tensioning of the anchor bolts may exceed the compressive strength of the concrete and/or grout or the yield/tensile strength of the anchor bolts. One method for identifying over tensioning is to measure bolt extension with the design tension applied to the anchor bolt. If no stretch is observed in the anchor bolt after discounting for the stretch of the upper portion of the bolt when applying the design tension, the anchor bolt has a higher applied tension. A less reliable alternative method is to apply incrementally higher tension values to the anchor bolt while checking for a slight turn of the nut or lift-off of the nut from the washer/flange. Care should be taken to ensure that anchor bolt yield strength is not exceeded during this method of testing.

Recommendations for anchor bolt tensioning provided in Section 10.2 may be followed to prevent high anchor bolt tension from being applied.

6.13 Anchorage Pullout Failure

One potential failure mode of a typical gravity-based spread footing foundation is cracking/damage of the area around the anchor bolt cage within the foundation due to the transfer of load from the embedment plate into the foundation. High load events or excessive fatigue loads may cause this type of failure that is more relevant to older foundation designs as discussed in further detail in Section 8.9 below. The left photo below shows a less progressed failure of the anchorage pullout due to an overloading event in a concrete core extracted from the anchorage zone. The right photo shows a turbine collapse resulting from an overloading event and subsequent failure of the anchorage pullout area.

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.

Foundation performance due to this type of damage varies based on the level of concrete cracking/damage within the foundation. Early stages of this failure may not be detectable due to backfill covering the area. Slightly progressed damage may result in excessive turbine movement causing faults, while the most advanced stages of damage may result in foundation failure. Structural health monitoring (SHM - Section 10.8) can be installed to detect signs of stiffness loss, serving as a predictive tool for concrete crack formation in the anchorage pullout failure area.

The recommended preventive maintenance to mitigate this type of failure after potential overloading events such as tornadoes, emergency shutoffs, or similar high load events, is to complete below grade inspections (Section 10.9), concrete coring (Section 10.10) or SHM (Section 10.8) based on recommendations provided by the Engineer. Monitoring of the wind turbine as a whole considering the topics addressed in Section 10 may also be considered as triggers for additional inspection for this failure mode. **Note: Failure to act could result in foundation collapse.**

The recommended repair methods are engineered repair or foundation replacement.

6.14 Foundation Out of Level

While the soil properties are carefully studied before siting and designing a foundation, it is possible for foundations to become out of level. Common reasons for foundations to lose their initial level condition are settling and overload events. Regardless of the cause, an out of level foundation is a serious structural concern. If a foundation is suspected to be out of level, the turbine should be taken out of service and the Engineer should be contacted to schedule an inspection. A common approach often recommended is to conduct a professional survey.

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.

Tower tilt changes the fundamental assumptions for the foundation design and may be the result of a serious structural failure. Observable tower tilt could be from a number of factors including failed grout, pedestal-to-footing failure, uneven soil compaction, or failure of the underlying soil or backfill.

The recommended maintenance activity to mitigate this failure is visual inspections. While a visual inspection may not prevent an event from causing this outcome, it can prevent further damage and mitigate impact to public safety in the event the foundation is structurally compromised. If this condition is observed, it is recommended to halt turbine operation remotely, cordon off the area around the turbine within the potential fall zone and contact the Engineer for further direction. **Note: Failure to act could result in foundation collapse.**

7 Preventive Maintenance Schedule

The recommended scheduled maintenance for foundations was described in detail in the previous Section. In this section, the recommendations are summarized for quick reference in Table 1 and Table 2 below to aid in developing a foundation maintenance plan.

These recommendations serve as general guidelines. It is imperative to recognize that certain foundation types may require a heightened frequency of inspections or certain inspections. O&M personnel are advised to tailor these guidelines in consultation with the Engineer to the specific characteristics of the installed foundations for comprehensive assessment and maintenance. Additionally, O&M personnel may review the sealed foundation drawings or contact the Engineer of Record to determine if specific maintenance requirements were developed. Instructions from the Engineer take precedence over those presented herein.

Anchor bolt tensioning and photographic inspections are recommended to be done post construction to ensure that anchor tension is within specification on all foundations after the settling in period and to establish a visual reference baseline for all foundations. Following that, visual inspections are recommended every 1 to 3years based on an evaluation of the risks at the site. Anchor bolt tension checks are to be performed every year for 3 years following the post construction tensioning, after which tension checks may be done every 3 years. Lastly, SHM may be prescribed depending on the level of risk for that failure which the Engineer can provide. As mentioned earlier, all recommendations in this document are general and the guidance from the Engineer takes precedence.

Table 1. Recommendation preventative maintenance schedule for wind turbine foundations.

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.

The items in Table 2 are a sample checklist for visual inspections for a typical foundation with anchor bolt covers. This checklist may be modified as needed to include additional possible failure modes based on the design and components of the foundation.

Table 2. Sample checklist for wind turbine visual inspections.

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		

8 Maintenance and Repair Methods

The previous sections described recommended preventative maintenance and repairs for the identified failure modes. This section provides guidance on how to carry out specific aspects of foundation maintenance and repair that have been developed by practitioners in the field.

8.1 Concrete and Grout Inspections

Concrete and grout inspections are mainly targeted at identifying spalling and cracks. The following tools are recommended to conduct these inspections:

Crack Gauge – A crack gauge is a piece of clear thin plastic with graduated lines of increasing thicknesses printed onto the plastic for a visual reference to aid in estimating the width of a crack. Example shown in Figure 22.

Tapping Hammer – A lightweight hammer is useful for evaluating suspect areas of cracked grout and concrete. Tap testing the grout and concrete with a small, ball peen hammer is useful to audibly confirm the grout and concrete is sound. Hollow spots may be identified, recorded, and monitored to ensure they do not worsen. If possible, the same or similar hammer may be used from inspection to inspection.

Probe – Probing tools such as a steel chisel, awl or flat head screwdriver are useful to determine if grout or concrete have failed.

Liquid Dye – Applying a liquid dye can help to identify the size of cracks and is particularly useful to identify active or moving cracks. If cracks are active, they will wick the dye in and out generally consistent with the timing of the turbine loading.

Tape Measure – common tape measure is useful to document the length of cracks and spalled areas.

Camera – Visual records are extremely useful to document the state of foundation health. Common cell phone cameras are generally adequate for this purpose.

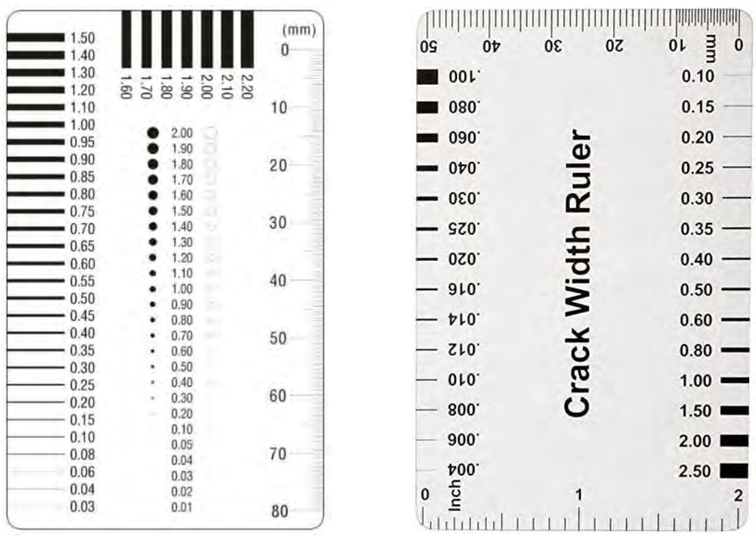

Figure 22. Examples of typical crack width gauges, material is thin clear plastic with black print and are commonly in both inches and millimeters.

8.2 Anchor Bolt Tensioning

There are many variables in the application of tension to anchor bolts that can result in unexpected and possibly undetected errors. Care must be taken to ensure that the correct anchor bolt tension is applied as expected. The two most common methods for tensioning foundation anchor bolts are with the use of an anchor bolt tensioner or the jack and plate method, both shown in Figure 19. Both methods have benefits and challenges. In general, it is recommended to use bolt tensioners on new hardware or hardware that is known to be operating smoothly. Hardware that is not covered and greased, or is old and corroded, may need to have a jack and plate tensioning method used. Every anchor bolt tensioned must have visual confirmation from technicians that the anchor nut is tight to the flange prior to releasing tension from jack(s). If nuts are sticking from corrosion, necessary means must be employed to ensure the anchor bolt nuts are tight to base flange prior to releasing pressure from the tensioning system.

For the jack and plate method, the tension applied can be calculated based on the applied pressure and the area of the hydraulic rams. Experience has shown that the additional step of calibration is a useful and necessary step to ensure the rams are delivering the expected tension force. The jack and plate method has the benefit of being relatively simple to apply and has increased visibility to the hardware when applying tension. The additional access provides the technician with room to install larger wrenches and loosen corroded hardware when needed.

When using a bolt tensioner, the tensioner is positioned over the anchor bolt and the tension applied can be calculated in the same manner as the jack and plate method. Tensioner manufacturers will supply the effective ram area for the tensioner to convert applied pressure to tension force. Note, tension heads from the same manufacturers may not have the same conversion factor and care must be taken to read the instructions supplied with these tensioners to avoid mistakes in applying incorrect tension. The advantage of bolt tensioners is they apply tension in a uniform manner and can be faster than the jack and plate method. However, access and visibility to the anchor bolt nut can be restricted. Additionally, many of these models have a built-in ratcheting mechanism to snug the anchor bolt nut. This built in mechanism typically does not allow enough torque to be transmitted to break corroded nuts loose. When using a bolt tensioner on a foundation with corroded hardware and if attention were not paid to the process, the technician could erroneously conclude that the bolts were all tensioned to 100% of design by assuming the nut is tight based on tension present.

All tension values may be calculated based on effective surface area of the hydraulic ram(s) and confirmed with a Skidmore tension calibrating tool or similar.

8.3 Grout Repair

When considering a grout repair, the scope and size must first be considered. Field experience has shown that grout repairs spanning more than approximately 20 anchor bolts is impractical. If the damaged area is larger, it may be done in stages. The other consideration is the replacement material. Epoxy grout is becoming more common in new construction and is the preferred material for ease of use and installation for repairs.

Grout repairs consist of two main tasks: removing failed material and installing new material. Prior to removing grout, the anchor bolt tension in the sections being repaired may be removed with the nut in a snug-tight condition. The failed grout then needs to be removed with mechanical tools such as electric demolition hammers supplemented hand tools are recommended. Care should be taken not to damage the foundation components during this process. Once damaged grout removal is complete, the area should be thoroughly cleaned and prepped for the new grout. Building a small form to contain the grout is commonly done. In cases where the failed grout is not removed from the entire grout bed from outside to inside of the tower base flange, vent tubes at every third anchor bolt reaching to the back of the cavity should be installed to allow air to escape during grout placement. After the new grout has cured, the anchor bolts in the area of the repair and all other anchor bolts should be tensioned to the design drawings.

8.4 Anchor Bolt Tensioning Equipment

Tensioning system calibrations are to be verified 3 times daily when performing 10% tests and before every tower on 100% tensioning. As ambient temperatures change and equipment rapidly cycles, it is likely that the temperature of the hydraulic oil will change as well, possibly resulting in varying pressure needed to achieve the desired tension. All calibrated machinery including oil gauges must have current certifications. If variations of more than 2% are detected during calibrations throughout the day, the previous tower completed may have 4 anchor bolts tested at random to ensure they have been tensioned properly. If tests reveal improperly tensioned anchor bolts, rectify as necessary.

Maintain pumps, jacks, and hoses in a controlled environment, never store in freezing temperatures. Keep pumps working in a controlled environment if ambient temperatures are below freezing. Heated vehicles and trailers are acceptable for maintaining acceptable working temperatures of the pumps.

An oil pressure regulator should be utilized on the pump to assure that the desired pressure is being achieved consistently. Many pumps available will build up to 20,000psi in as little as 3 seconds. At these speeds, discrepancies by the pump operator in fractions of a second will result in thousands of pounds of differing tension. Setting the pressure regulator to a desired pressure verified by the tensioning calibrator is the only way to ensure the proper tension is applied to each anchor bolt.

The tensioning system should allow for visibility of the anchor nut and washer on the bolt being tensioned to be able to observe the nut and washer lifting under tension, and then being able to visually confirm that the nut has been properly tightened under tension is of utmost importance. Often on operational wind plants nuts and washers corrode each other and to the anchor bolt, thus requiring force to break them free. If the anchor nut and washer are not tight to the tower base flange prior to releasing pressure from the tensioning system, the anchor bolt is not properly tensioned. Appropriate testing will reveal these types of issues.

8.5 Anchor Bolt Tension Validation, “10% Testing”

Approximately 1 year after the project has been 100% tensioned, 10% of the anchor bolts may be selected at random on 100% of the turbines. An even number of anchor bolts may be selected on the inside and outside of the turbine if possible. The testing value should be to the lowest specified value on the foundation drawings. For example, if the foundation drawings specify a tension of 75kips +5/-0 then all 10% testing is to be done at 75kips.

Anchor bolts may be numbered beginning with the bolt centered (or off centered in the clockwise direction) under the tower door being number 1 with subsequent numbers in ascending order clockwise around the circumferences of the interior and exterior base flanges. The referenced bolt numbers should fall in the same position on every tower of the project. Two exterior/interior anchor bolts will be selected at random as a starting point. From the starting point, tension every 10th anchor bolt until a minimum of 10% of the anchor bolts have been tested.

Any 10% test tension value below or above the specified range provided on the foundation drawings, or a tension range provided by an Engineer, constitutes a failed 10% test. If a 10% test is failed, 100% tensioning of the anchors bolts is recommended.

When performing 10% tension testing it would be preferential to equally test 10% of the interior and exterior anchor bolt. However, interior access can be limited due to high voltage, confined spaces, etc. and if work cannot be completed safely on the interior anchor bolts while energized and/or de-energization is not feasible, testing only the exterior anchor bolts can provide a general idea of overall anchor bolt tension. It should however not be assumed that the untested interior anchor bolts have the same tension as the exterior bolts.

8.6 Anchor Bolt Ping Testing

Ping testing is a common method to identify loose hardware in bolted joints. This method can also be used to investigate the current tension of foundation anchor bolts. The basis behind ping testing is that when a mechanical system is perturbed, much like a guitar string when plucked, the system will produce a set of audible tones (frequencies) and the technician can compare the combination of tones from one anchor bolt to the next. While this method is founded on sound principles, there are variables such as length of the bolt above the base flange, technician experience, fatigue and tooling variations which best make this a complementary practice for gross anomaly detection only. Ping testing of anchor bolts should not be considered a primary means of determining tension values.

8.7 Hardware Corrosion Remediation

Remove corrosion off the hardware with pressure washer, wire brush or motorized brush.

Apply corrosion protection system such as grease or anti-corrosion coatings. This could be directly applied on the anchor bolts after they have been tensioned.

8.8 Structural Health Monitoring (SHM)

Foundation SHM is becoming a more commonly used tool to measure the performance of wind turbine foundations during operation using short-term or permanent installations. There are different variations of SHM equipment and sensors, but generally the intent is to measure or calculate the load being applied to the foundation and measure the resulting foundation tilt and/or frequency response due to the applied loads. Data from these sensors may also be used to measure and monitor the first tower bending mode frequency and thereby estimate the overall system stiffness. Strain gages, tiltmeters, and accelerometers are the most commonly used sensors with measurements being taken by a datalogger and either stored locally for manual download or setup for remote data transfer through a cellular modem or the turbine network.

Wind turbine manufacturers typically list minimum required rotational and lateral stiffnesses and/or a foundation frequency response range which are used as acceptance criteria when analyzing the collected and processed SHM data. Results outside of the wind turbine manufacturer’s limits or significant change in the results over time may indicate potential foundation issues that may be further discussed with the Engineer. It should be noted that while SHM is becoming more commonly recommended and can be a valuable tool, it is not a replacement for typical inspection and maintenance activities.

SHM can also be referred to as dynamic testing.

8.9 Below Grade Inspections

Foundation below grade inspection is typically used to inspect the buried portions of gravity-based spread footing type foundations, although below grade inspection can be used on other foundation types as appropriate. These inspections are most commonly used when assessing existing foundations for concrete cracking due to unexpected loading events or potential repower or life extension projects. Figure 23 below is an example of an older foundation design (pre-2010) that relies on concrete strength plus the single vertical bar at the anchorage pullout zone. Figure 24 below is a newer design that has more vertical reinforcement that is relied upon only for the anchorage pullout zone strength as recommended by ASCE/AWEA RP2011 in response to limited cases of foundation failures.

For a spread footing the typical below grade inspection consists of 2 trenches, one on the predominant upwind side of the foundation and a second approximately 90 degrees to the first while avoiding the turbine stairs, pad mounted (PMT) transformer, and buried utilities. Trenches generally extend from the foundation pedestal or vertical portion of foundation 6 to 10ft to allow for inspection of the intersection of the pedestal and footing and a portion of the footing. A trench width of 3ft is typically acceptable and the depth of the trench will vary based on the foundation design.

The exposed concrete surfaces should be free of soil and debris by means of scraping, sweeping, or pressure washing to expose any potential cracks and the surfaces thoroughly inspected. The condition of the concrete may be documented, and any cracks measured in both length and width and photographs taken.

As a safety precaution all spoils from excavations should be placed far enough away from trench to not increase cave in risks but remain on top of the spread footing. If the entire foundation is to have soil removed, consult an Engineer prior to soil removal and do not operate the turbine without any soil on top of spread footing. All excavated soil should be compacted and replaced in the trench. For soil removal larger than two trenches, backfill density testing should be completed per the original design drawings and specifications to confirm backfill has proper compaction.

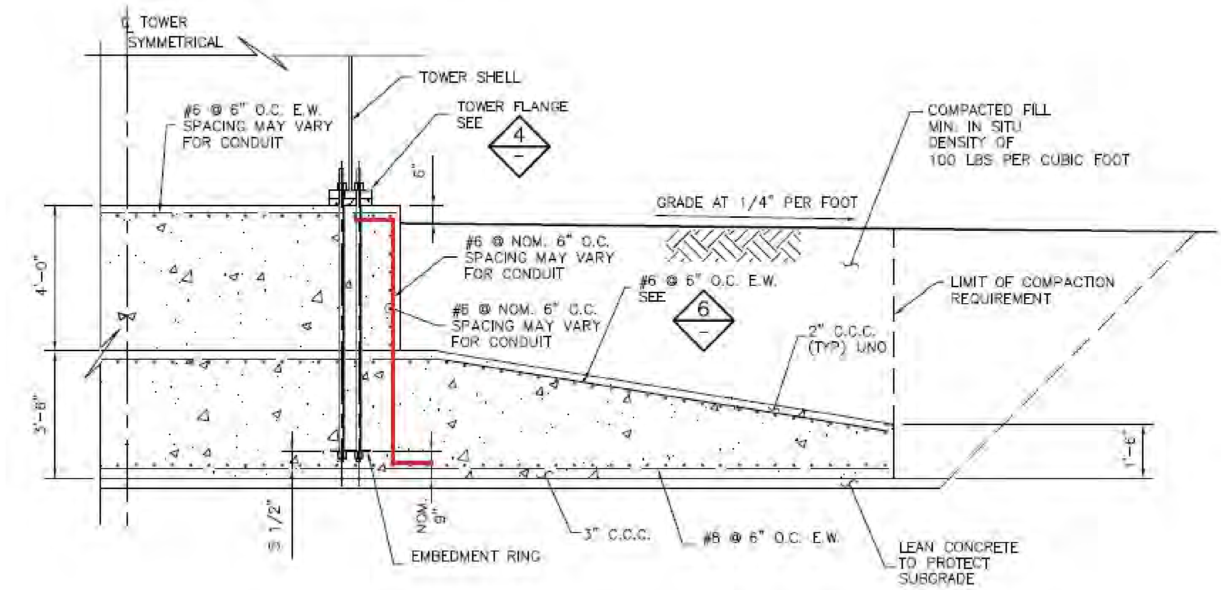

Figure 23. Pre-2010 Foundation design with minimal vertical reinforcement.

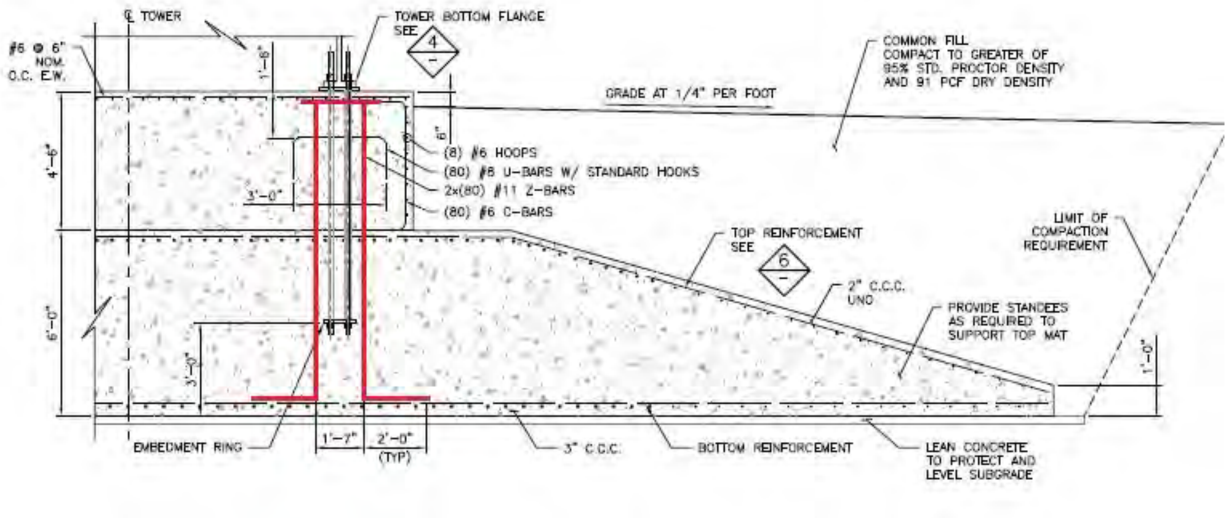

Figure 204. Post-2010 Foundation design example with additional vertical reinforcement.

8.10 Concrete Coring

Typically, after completing a desktop study typically to identify the potential critical failure mechanisms, foundation coring may be performed to identify the presence and evolution of cracks within the foundation. Special coring drills are used to drill and extract the core after carefully identifying the location of existing anchor bolts and rebar depending on the location and orientation of the core. A trench may have to be excavated to gain access for coring. Cores should be inspected for cracks, poor consolidation, voids and can be sent to a laboratory for petrographic analysis. Compressive strength test samples may also be obtained from the core samples. Following the coring process the bore holes are filled with grout. When carefully performed, concrete coring is considered safe for foundations with review by the Engineer because there are inherent risks with the process.

8.11 Engineered Repairs

Repairs beyond the typical corrective maintenance items mentioned may be required based on the severity of the observations made. These repairs will likely require additional details and specifications by an Engineer. Examples of engineered repairs could include different types of foundation retrofits and more extensive grout, concrete, and backfill remediation.

9 Design Changes

This section will address typical design changes that may be needed to address issues identified as part of the scheduled maintenance program.

9.1 Anchor Bolt Covers/Corrosion Protection

Anchor bolt covers are a common design change that may be required to mitigate corrosion of the anchor bolts. As mentioned previously the need for bolt covers varies depending on site conditions/environment. However, if a review of the conditions and risk factors concludes that bolt covers should be employed, a layer of marine grade grease may be applied to the hardware prior to installation of the covers. In addition, inspection of bolt covers must be added to the preventative maintenance checklist and replacement of a number of anchor bolt covers on an annual basis must be assumed for future years. Risk factors for failed bolt covers include presence of cattle, falling ice/debris and UV degradation.

9.2 Anchor Bolt Tension Modification

It is possible that the Engineer may determine that a change to the anchor bolt tension specification is required. These changes should be documented by the Engineer before being implemented.

9.3 Foundation Reinforcements

Foundation design modifications or reinforcements may be required to address issues that have been identified during construction or operation of the wind plant. These changes will require additional details and specifications by the Engineer. Examples of reinforcements include pedestal collar reinforcements and grout flange area increasers.

10 Operating Loads

This section will address changes in wind turbine operation that affect wind turbine foundation maintenance. If any of the events below occur, further inspection or monitoring may be required.

10.1 Foundation Load Changes

Changes in the foundation design loads may occur when wind turbine controls changes are made. Examples of changes impacting loads are increasing rated power, repowering, or upgrading turbines with changes to major equipment. Changes to the foundation loads should be calculated by the turbine OEM and supplied to the Engineer for review to determine the structural impact. These modifications may require additional maintenance or inspection on a one time, or ongoing basis.

10.2 High Load Shutdowns

High load shutdowns are those where the wind turbine shuts down during maximum power output in a rapid manner. The shutdowns may also be called emergency stops or hard stops (e-stops). The abrupt change in load can cause higher stress than normal ramp up and controlled shutdowns. While all wind turbines are expected to experience high load shutdowns as part of normal operating conditions from time to time, repeated shutdowns could exceed the amount assumed in the foundation design and compromise the structure.

Turbines experiencing unusually high occurrence of high load shutdowns should be carefully inspected for signs of stress which include cracking in the base flange grout, pedestal concrete, and backfill. The visual inspection checklist from Section 9 is a starting point for such an inspection. Abnormal findings may be documented with photos and provided to the Engineer for review.

10.3 Major Turbine Component Failures

Failure of turbine major components including turbine fires may introduce unusual loads to the foundation. Foundations should be carefully inspected if a major component failure was suspected to be of unusual nature or potentially high load which may include any of the following:

- Turbine fires
- Significant drivetrain failures where a drivetrain component fails catastrophically

- Blade failures
- Tower blade strike
- PMT failures including fires

10.4 Irregular Turbine Operation

Any load that exceeds the design operating envelope for a wind turbine has the potential to damage a foundation due to fatigue or ultimate strength exceedance. The operating envelope is the range of environmental conditions which include wind speeds and temperatures, as well as the control states such as generator power, rotor speed, pitch angle and yaw angle. Regular maintenance and repair of wind turbine control equipment such as pitch systems, yaw systems and anemometry are critical to ensuring that foundation loads are not exceeded during operation of the machine. Modern wind turbines are equipped with sensors to prevent such events but delay of repair or bypassing these systems puts the entire structure at risk.

The IEC-61400-1 ed3 requires that wind turbines are able to arrest the rotor following a fault including the loss of grid power. Blade control systems typically employ either electric pitch or hydraulic pitch systems where a battery or hydraulic accumulator system is used to store energy for pitching blades in the event of a loss of control power. Additionally, towers and foundations may experience unusual loads during extended periods of nacelle removal. Failure to maintain these systems has the potential to result in damage to the wind turbine structure including the foundation.

Turbines experiencing abnormal operating conditions, including extreme weather events, and those described above should be carefully inspected for signs of stress which include cracking in the pedestal, concrete, and soil. Abnormal findings should be documented with photos and provided to the Engineer for review.

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

The failure modes are listed in Table A-1 along with a short description of the impact on structural loads, the impact on the overall foundation system and short description of the recommended maintenance task. Section 8 goes into more detail on each item in the table.

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.

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.