STAC Study:
Mitigating Anchor Shaft Corrosion and Related Tower Failures

Structure, Tower & Antenna Council
Conseil des structures, pylônes et antennes

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1.0 Introduction

This document provides information about how corrosion affects below-grade steel anchor shafts on guyed communications towers, as well as factors that can affect corrosion rates.

The intent of this document is to provide communication tower owners and operators with a resource to help inform decisions relating to guy tower siting, anchor shaft corrosion protection and anchor shaft inspections. Notably, however, this document is not prescriptive and is not intended to provide explicit direction on how to apply protective measures or conduct inspections. Rather, this document outlines factors that companies and crews should consider when studying protection or inspection options and priorities.

Please contact STAC or a qualified engineer if you have additional questions about anchor shaft corrosion, corrosion protection, or anchor shaft inspection priorities that are not addressed in this document.

2.0 What is Corrosion

Corrosion is a process through which a ferrous material deteriorates as a result of its chemical or electrochemical reaction to its environment. For example, a steel component will have an electrochemical reaction to oxygen over a period of time, causing it to rust. This rusting reduces the structural integrity of the metal components, and potentially puts structural components in a position to fail under the stress of loads that they were originally designed to withstand.

Corrosion and rust-related hazards in the communications tower industry are a result of the composition of communications towers, which utilize below-grade steel and other metal components that can create conditions for corrosion to occur. A variety of factors can also influence the rate at which those below-ground components will corrode, as is outlined elsewhere in this document.

Image 1: Anchor Corrosion

Typical below-grade anchor shaft corrosion.

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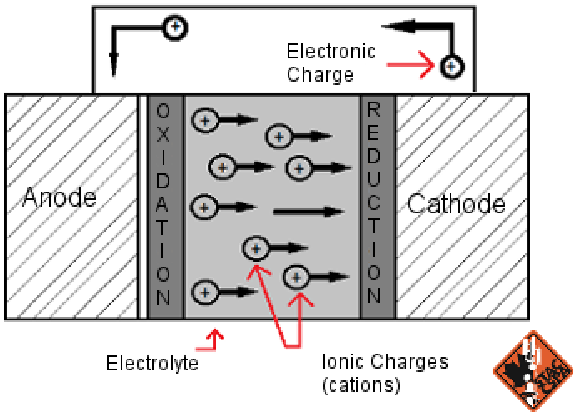
3.0 Why Corrosion Occurs

Corrosion is the natural result of chemical or electrochemical reactions between different types of materials (typically metals) and substances found in their environments. The corrosion process involves the transfer of energy between two metal substances through an “oxidizing” substance, such as water or moisture. As this energy transfer occurs, electrons from the atoms in one type of metal – the “anode” – transfer to the other metal – the “cathode” – in a process called “reduction.” At the same time, the anode also undergoes a simultaneous “oxidation” process due to its exposure to oxygen. When these processes occur together it is called a “redox” reaction and rust is formed. In essence, corrosion results from the atoms in the anode using the electrochemical energy of its environment to revert to the base minerals it was made from.

There are four essential components required for corrosion to occur. Together, those components create what is called a “corrosion cell.” The essential components of all corrosion cells are as follows:

- An anode: The anode is the area or component of a structure that is more “electronegative” and the site where corrosion occurs via an oxidation reaction. This reaction involves loss of an electron at the anode and formation of a positive ion in the electrolyte, resulting in dissolution of the metal.
- A cathode: The cathode is the area or component of a structure that is more “electropositive.” The reduction reaction occurs on the cathode, which involves the gain of electrons.
- An electronic path: In order for the reduction process to occur, there must be a metallic path that allows electrons to flow from the anode to the cathode.
- An electrolytic path: In order for ions to flow between the anode and the cathode, there must also be an electrolytic path, such as provided by water or moisture.

Image 2: Corrosion Cell



A typical corrosion cell includes four main components: an anode, a cathode, an electronic path and an electrolytic path.

A number of other factors can also affect the rate at which a metal object will corrode, including the type(s) of metal involved in the corrosion cell, its surrounding materials or solutions (including soil and concrete), and the presence of any stray electrical currents. These factors are explained briefly in the following sections.

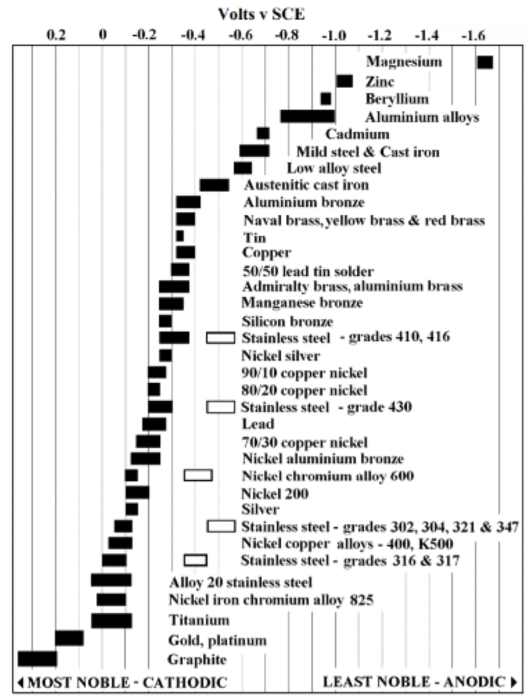
3.1 Dissimilar Metal

"Galvanic corrosion" occurs when different or "dissimilar" metals are connected together. Under such circumstances, the more active (less noble) – or more electronegative – metal will serve as the anode and will begin to corrode over time if exposed to an oxidizing substance. In turn, the less active (more noble) of the two metals will be protected against corrosion so long as the less noble metal continues to serve as an anode in this way.

Image 3, a galvanic series, details the activity (and nobility) of different types of common metals. From a quick look at this chart, it is easy to see the most commonly used galvanic anodes in soil are made of either magnesium or zinc, as these two metals are the most active of those listed in the figure and are significantly more active than any of the listed steel grades.

It is also very important to note that many metals are even more noble than steel, meaning that if combined with steel inside a corrosion cell the steel component would become the anode. Under such circumstances, it is highly likely that the steel component would be subject to corrosion. As such, tower owner's must be aware of deleterious effects that the use of dissimilar metals can have on below grade steel components (such as guy anchor shafts), and this should be considered in the corrosion prevention design for towers. Notably, copper – which is frequently used for grounding and ground radials – is one such metal.

Image 3: Galvanic Series



The galvanic series describes the inherent corrosion potential of each type of metal, from least noble (top) to most noble (bottom). The more noble the metal, the more resistent it is to corrosion. *(Courtesy of Corrosionpedia)*

It should also be noted that steel in concrete (such as an encased anchor block) is typically less active than steel that is in direct contact with soil and will act as a cathode in a corrosion cell. This can result in accelerated corrosion of the un-encased portion of the steel anchor shaft, which will serve as the anode in the corrosion cell.

3.2 Soil-Based Factors

Another factor that can affect corrosion rates is the type(s) of soil in which the steel component is contained. Soil can have a significant effect on corrosion rates in a number of ways, and some soil characteristics that are known to directly affect corrosion rates and severity include moisture concentration, resistivity (or conductivity), chloride concentration, pH, oxygen concentration/soil aeration, and presence of sulfate reducing bacteria. Other soil characteristics that can indirectly affect corrosion rates include its organic content, porosity and texture, which can each influence the previously listed direct factors. While other soil characteristics are also known to potentially affect corrosion severity, these are the factors that are known to most commonly affect below-grade tower components.

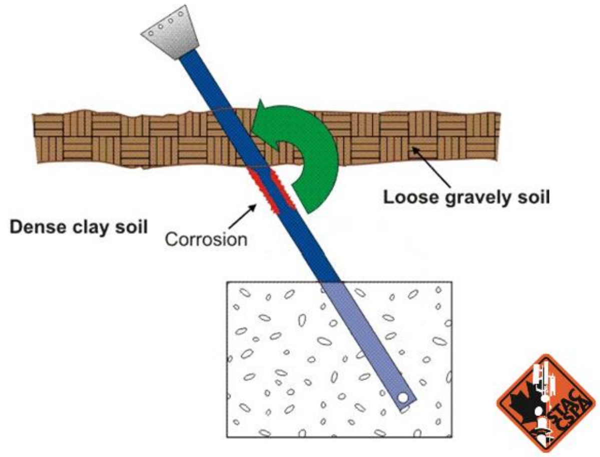
Some common soil characteristics that may cause accelerated corrosion in below-grade tower components are as follows:

- Moist soils and those that typically hold more moisture have a lower resistivity (higher conductivity) and higher current flow;
- The presence of chlorides in the soil reduces the soil resistivity and even potentially reduces the passivity of metal components;
- Sulfate reducing bacteria eats away at metal components by creating iron sulfide corrosion products and hydrogen sulfide;
- Soil acidity drops below pH 4.5.

See section 4.3 of this document for more information about the effects of resistivity and acidity on corrosion rates.

Oxygen concentration (soil aeration) can also affect corrosion rates by increasing the amount of oxygen that below-grade metal components are exposed to, with soils that have higher concentrations of oxygen being more likely to cause accelerated corrosion rates.

Image 4: Corrosion Caused by Differential Oxygen Concentrations



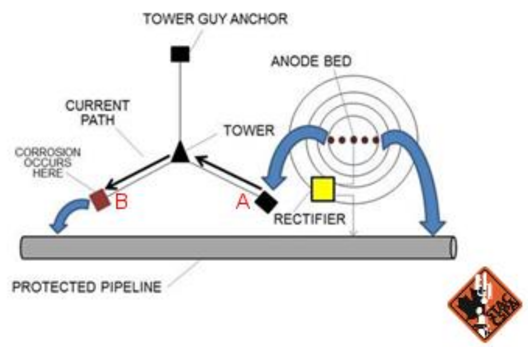
Differential concentrations of oxygen can result in corrosion on anchor shafts, such as in situations in which the anchor is embedded in different types of soil. In this image, the portion of the shaft imbedded in loose gravel will be exposed to a greater concentration of oxygen than the portion buried in dense clay, causing accelerated corrosion.

The combination of different types of soil can also cause the creation of a corrosion cell. This is primarily because a component buried in two different types of soil, such as a single anchor shaft, may be exposed to different levels of oxygen. In this scenario, the part of the component that is exposed to the lesser concentration of oxygen could face accelerated corrosion. This issue can also affect different anchors on the same tower in some cases, causing an anchor buried in a more oxygenated soil to corrode faster than those in less oxygen-rich soils on the same site. Other factors such as differences in temperature, soil chemistry and compaction can also result in the creation of corrosion cells and increased corrosion rates.

3.3 Stray Currents

Stray electrical currents that interact with below-grade metal components can also contribute to accelerated corrosion of those components, as areas discharging current will experience metal loss proportional to the amount of current being discharged. Stray currents occur on below-grade metallic structures largely because metals are significantly more electrically conductive than soil, and because electrical currents flow most aggressively along paths of least resistance. As such, buried, metallic components can be attractive alternative paths for currents emitted by a wide range of either alternating current (AC) or direct current (DC) power sources.

Image 5: Stray Current Corrosion



Typical stray current interference path on a tower.

Image 5 depicts a typical stray current pattern on a tower. As shown, the current from a foreign anode bed transfers from the earth to the tower anchor at Point A and travels along the structure to where it discharges from the other anchor back into the earth at Point B.

The same pattern is applicable to communication tower anchors themselves, where the guy wires can act as a preferential path for stray currents. While this risk to anchors is increased with greater distance between anchors, anchors can be affected regardless of how close or far apart they are. As such, it is important for site owners and tower engineers to be cognizant of nearby sources of below-grade electrical currents and how stray currents from those applications could affect anchor shaft corrosion rates and severity. Some common sources of electrical currents to be mindful of include rail transit systems, pipelines and electrical substations, among others.

NOTE: One (1) amp of current discharging over a period of one year will result in approximately 10 kg of metal loss on an unprotected steel component.

4.0 Identifying Towers at Risk of Anchor Shaft Corrosion

4.1 Why Identify At-Risk Towers

Like other powerful forces of nature, corrosion can wreak havoc on manmade materials and objects and can ultimately prevent them from working as intended, primarily by reducing the density of necessary metal components.

Where corrosion is present, a single amp of current discharging off of a structure can cause a steel component – like an anchor shaft – to shed as much as 10 kg of steel in just a single year. At the same time, the loss of just an ounce or two of steel off an anchor shaft can have costly and potentially devastating consequences.

Images 6-8: Anchor Shaft Corrosion

The first two images below depict corroded anchor shafts. The third image shows a tower that fell in Canada in 2017 due to anchor shaft corrosion *(courtesy of Global TV)*.

Corrosion of anchor shafts and other below-grade structural components can be particularly difficult to identify because the corroded sections of the components may be entirely underground, and not necessarily visible through an inspection of above-grade components. In fact, even clean inspections of some portions of a buried anchor shaft cannot fully ensure that lower below-grade portions of the same anchor are not corroded.

Meanwhile, corrosion at any point on an anchor shaft has the potential to reduce the anchor's structural integrity and could cause the anchor to fail, as well as the tower it is supporting as a likely result. This can occur when any portion of an anchor shaft corrodes to the extent that it reduces the anchor's strength and diminishes its ability to withstand its share of the tower load.

Any tower failure, including those caused by corroded guy anchors, could pose significant problems for tower owners and crews, and can have numerous negative consequences. The most important of these potential consequences is the safety hazard a tower collapse would pose to crews and the public, which could result in serious injuries or even death to anyone who is on or near the tower at the time of its collapse.

Other potential consequences include:

- Damage to reputation: Tower collapses – and particularly any that cause injuries or fatalities – can undermine the reputation of the site owner and/or companies involved in a project, as well as the tower industry as a whole. This can result in increased public resistance to new tower sites, or negative public sentiment about a company or companies.
- Cost of replacing tower: It is far more expensive to replace a collapsed tower than it is to inspect and maintain guy anchors.
- Loss of revenues: Collapsed towers can result in a loss of service to nearby customers, resulting in lost revenues to service providers.

Even if neither the tower or the anchor fails, however, corroded anchors may still need to be replaced if they reduce the tower's overall load capacity. As such, a qualified engineer must assess any anchor shaft that shows signs of corrosion to determine its structural integrity and load capacity.

Finally, to determine which guy towers are at greatest risk of corrosion-related failures, site owners must consider whether each individual tower – and potentially even whether each individual anchor – is subjected to factors that can affect the likelihood of corrosion occurring. These factors include those that can mitigate the potential for corrosion, as well as those that can exacerbate that potential, such as those listed below.

Notably, the order in which these factors are listed below is not indicative of the priority with which site owners should use to determine which towers may be at the greatest risk of anchor shaft corrosion and must be considered altogether to determine whether a tower could be at heightened risk.

4.2 Corrosion Protection

Guy tower sites with anchors that have insufficient or no corrosion protection are likely to be at high risk of anchor shaft corrosion, as all buried steel components will naturally rust and corrode over time. Thankfully, there are several known and effective methods to protect against corrosion, each of which can protect buried components for a period of time.

Commonly used methods to protect below-grade anchor shafts from corrosion include:

- ***Galvanizing:*** Most, if not all, guy anchors in Canada have been galvanized, as required by CSA S37 standard, Annex F, and in accordance with ASTM A123/A123M–17 or ASTM A653/A653M-17. Section F.2.1 of the pertinent annex in the CSA Standard reads:

  > *"Although all anchorage steel located below grade should be hot dip galvanized, Clause 8.5.2 requires that anchorage steel located below grade and not encased in concrete have corrosion protection in addition to galvanizing."*

  While galvanizing steel components is a highly effective form of protection against above-grade or "atmospheric" corrosion, this galvanized protection can deteriorate very quickly itself below grade if not additionally protected. In fact, galvanization can deteriorate completely within as little as a year's time, when in contact with dissimilar, more cathodic metals. (For more information about dissimilar metals, please refer back to section 3.1 of this document.)

Image 9: Galvanic Coating

Coating or "galvanizing" steel in a layer of zinc can help protect it from the effects of corrosion. *(Courtesy of Philgalv Industrial)*

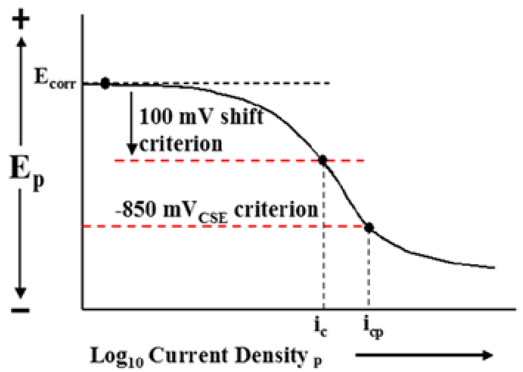
  As with the corrosion of anchor shafts and other steel structures, the rate at which galvanic protection will deteriorate is similarly affected by several external factors, including environmental factors – such as soil type and nearby sources of underground water – and what other forms of protection are used to protect the anchor shaft. Even under ideal conditions, however, galvanic protection alone is insufficient to properly protect steel anchor shafts against corrosion and must be supplemented through additional forms of protection.

- ***Cathodic protection (galvanic/sacrificial anodes)*:** Cathodic protection utilizes electrical current, which in the case of galvanic or sacrificial anode systems, is the created by the voltage difference of dissimilar metals. Cathodic protection protects important buried metallic components against corrosion by rerouting a discharging current to a readily corroded galvanic or "sacrificial" anode, which corrodes instead. Because these installed anodes cause currents to discharge off the anode to the structure – instead of discharging off the structure directly – they essentially sacrifice themselves in order to shield the target metal they're designed to protect on the anchor. As a result, the anode is subjected to the vast majority of the corrosion that would otherwise affect the anchor shaft itself.

NACE International Standard SP0169-2013 specifies two main criteria for determining whether a buried steel structure, such as a piping system, is receiving "adequate cathodic protection." The following criteria should limit corrosion to 0.025mm per year for those types of systems, which is more than sufficient for most communication tower applications:

1. A minimum of 100 mV of cathodic polarization.
2. A polarized structure to electrolyte potential of -850 mV or more negative as measured with respect to a saturated copper/copper sulphate (CSE) reference electrode.

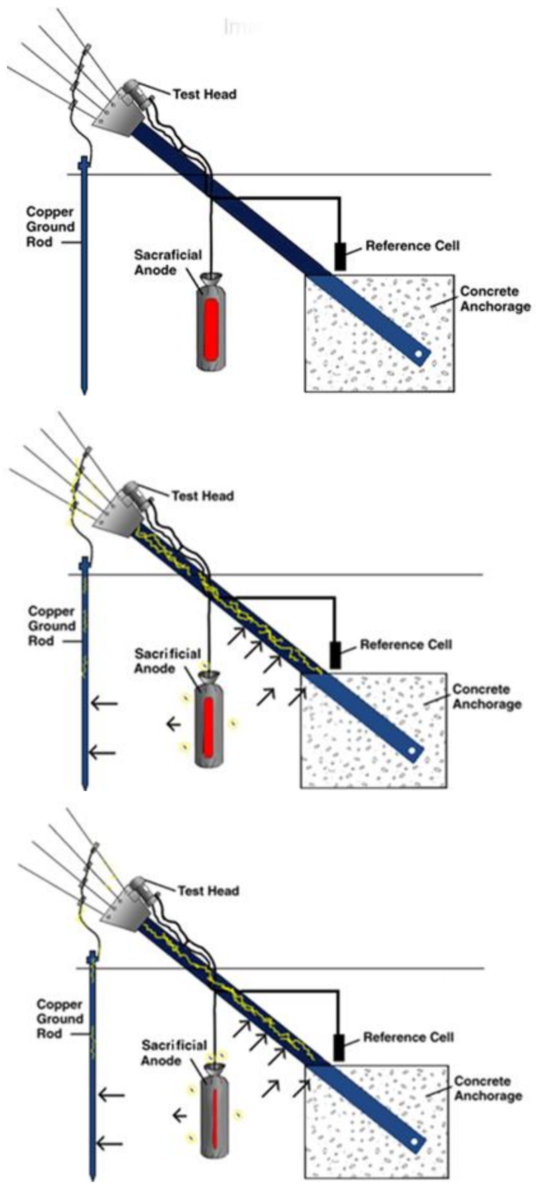
Image 10: Cathodic Protection Requirements



NACE International – a non-profit association for the corrosion control industry – identifies adequate cathodic protection requirements for buried steel components such as underground piping in Standard SP0169-2013. For more information about this criteria, please visit www.nace.org *(Courtesy of NACE International)*

While the use of galvanic anodes is a highly effective form of corrosion protection, it is important to note that anodes themselves will eventually corrode to an extent that renders them incapable of providing further protection. In addition to environmental factors and the rate of the charge passing through an anode, the size and shape of the anode itself also help determine how long it will continue to provide protection. Typically, an anode is considered to be at the end of its useful life when ~80% of its material has been consumed.

Image 11: Cathodic Protection Anodes



Sacrificial anodes can be used to counteract corrosion currents that would otherwise occur on below-grade anchor shafts, helping to protect the shafts against corrosion. The sacrificial anode will corrode over time and must be replaced after approximately 80% material loss. *(Courtesy of AnchorGuard)*

It is generally recommended that any new cathodic protection system be designed to include enough anodes of sufficient size to protect each individual anchor shaft against corrosion for 20 years under the known circumstances of the specific tower site. That said, even when a diligent and qualified engineer designs a cathodic protection system with this goal in mind, there is no guarantee that the anodes will provide protection for the entire 20-year period. Unexpected environmental conditions can cause anodes to corrode much quicker than anticipated, as can a variety of other factors.

Cathodic protection systems that do not use enough anodes or do not use anodes of an appropriate size or material are at high risk of corrosion. Fortunately, this problem can be mitigated through the installation of additional anodes. Nonetheless, it is imperative that a qualified engineer determine the correct number and size of anodes for each tower site.

Similarly, incorrectly installed anodes – or those that are not installed at the correct locations vis-à-vis the anchor shafts – can also cause a tower site to be at risk of corrosion. Some examples of incorrect installations include when the anode is not in close enough proximity to the anchor shaft it is supposed to protect; when an installed anode remains dry and is not “activated” to provide cathodic protection; when an anode is installed without an appropriate backfill material for that anode type; or when the electrical lead from the anodes are not connected properly to the structure.

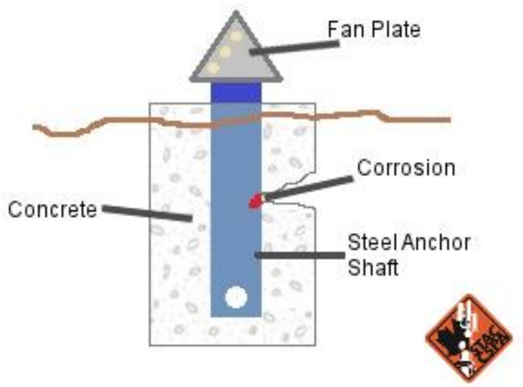
Given that cathodic protection is the second-most common form of protection against corrosion used on Canadian anchor shafts – following only galvanic protection – STAC recommends that Canadian site owners place a greater emphasis on the proper design of cathodic protection systems going forward. This may include the use of reference electrodes, test heads, and/or coupons, which are discussed further in section 6.0 of this document.

- ***Concrete encasement:*** Encasing below-grade anchor shafts in a thick layer of reinforced concrete is another popular method of corrosion protection in Canada, as the concrete can act as a non-conductive interface that disturbs the normal cycle of flowing electrons. To utilize this protection, the entire below-grade portion of each anchor shaft as well as each anchor block must be encased in their own reinforced concrete shield. Typically, about one foot (30 cm) of the above-grade portion of each anchor shaft is also encased in reinforced concrete, which helps to ensure that sitting ground-water does seep into the encasement. The concrete encasement should also extend a bare minimum of three inches on all sides beyond the rebar used for each anchor.

  If applied correctly, concrete encasement can insulate the protected steel shafts from harmful charges that can cause corrosion as well as other harmful environmental effects, such as freezing and thawing moisture and pH acidity. Concrete encasement is not without its own challenges and drawbacks, however, as any cracks in the concrete can introduce a dedicated path and environmental effects to reach the below-grade anchor shaft, potentially causing accelerated corrosion, focused at the crack location. Furthermore, the use of concrete encasement makes it virtually impossible to inspect below-grade anchor shafts through a dig-to-block inspection, meaning site-owners have little recourse to determine whether those anchors are potentially affected by corrosion.

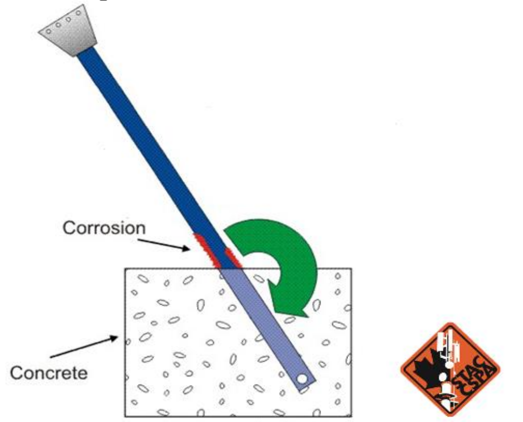
  Finally, it is worth noting that particular attention must be paid to ensuring that the joint between each anchor shaft and block is properly encased in concrete when preparing to use concrete encasement protection, as these joints may be particularly susceptible to corrosion otherwise. As noted above, steel in concrete (such as an encased anchor block) is typically less active than steel that is in direct contact with soil and will be more likely to act as a cathode in a corrosion cell. This can result in accelerated corrosion of any un-encased portions of the steel anchor shaft, which will serve as the anode in the corrosion cell, as seen in Image 13.

Image 12: Concrete Encasement



Encasing below-grade anchor shafts in concrete protects the steel shafts from the effects of corrosion and is one of the acceptable means of corrosion protection in CSA-S37.

Image 13: Corrosion at the Block



Buried anchor shafts that terminate in a concrete block may see accelerated corrosion on the buried portion of the un-encased shaft due to the differential corrosive potentials of concrete and soil.

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- ***Painting/taping:*** Like concrete encasement, "painting"/"taping" is another method of protecting below-grade anchor shafts by creating a non-conductive layer between the steel shafts and the external environment, disrupting the cycle of flowing electrons. Because this method utilizes a comparatively thin layer of a non-conductive bituminous coating – instead of several inches of concrete on all sides – painting/taping is a quicker and potentially cheaper method of corrosion protection to apply to steel anchor shafts. If applied correctly, both concrete encasement and painting/taping should provide equivalent corrosion protection.

  That said, painting/taping also faces some restrictions and limitations. Specifically, this method of corrosion protection is primarily only applicable to anchor shafts that are not already corroding – or which have only minimal corrosion – and which are still structurally sound. All anchor shafts must also be thoroughly cleaned before the bituminous coating can be applied. Painting/taping protection is more prone to potential damage than is concrete during the backfill stage or when additional work is being completed nearby, and one small scratch in the protective layer can be all that is required for corrosion to start.

Any guy tower site that does not utilize at least two of the corrosion protection methods detailed above to protect each below-grade anchor shaft is at extremely high risk of facing corrosion-related problems – up to and including tower failure – and should be investigated immediately. The same is true of sites that have corrosion protection that is beyond its recommended useful life. Sites with corrosion protection that is nearing its recommended useful life are also at high risk.

4.3 Site Characteristics

In addition to reviewing the condition of each site's corrosion protection systems, tower owners should also consider the following site-specific characteristics, which can affect below-grade corrosion rates:

- ***Soil resistivity*:** Because the physical characteristics of the Earth's soil changes from location to location, the rate at which any plot of soil will conduct electrical currents also changes, thus affecting the rate at which below-grade components will be exposed to potential corrosion-inducing currents. Soil resistivity (ρ_E) is the measurement used to determine a soil's ability to resist the flow of electrical current and is typically measured in ohm-meters (Ω-m) or ohm-centimeters (Ω-cm). The higher a soil's resistivity, the less susceptible it is to conducting the electrical charges that contribute to corrosion. The following general guidelines, taken from British standards, can be applied to resistivity measurements:
  - ρ_E > 100 Ω-m = slightly corrosive
  - ρ_E between 50-100 Ω-m = moderately corrosive
  - ρ_E between 10-50 Ω-m = corrosive
  - ρ_E < 10 Ω-m = severely corrosive

There are three main factors that can significantly affect soil resistivity: moisture, temperature and salt content.

Because water contains oxygen, it is also an oxidizing substance and can therefore cause corrosion in steel and other metals. This includes moisture in the soil. The more moisture a plot of soil contains, the less resistive that soil is to electrical currents. As a result, metal objects inside that soil would be more likely to corrode at an accelerated rate.

The amount of moisture present inside any single plot of land can change significantly over time as it is exposed to rain and snow, sun and heat, vegetation, and various other factors. Some of these factors are discussed more thoroughly further in these pages. Importantly, however, site owners should be aware of the fact that moisture levels can affect corrosion rates of underground anchor shafts and anodes – among other metal materials – and that they do not always remain consistent.

Image 15: Soil Corrosivity by Resistivity

Resistivity Range (Ω-cm)	Classification	Life Expectancy (Years)
AFM 88-9[1]	Corrosion Activity	
<2,000	Severe	-
2,000 – 10,000	Moderate	-
10,000 – 30,000	Mild	-
>30,000	Unlikely	-
Senatoroff[2]	Corrosion Activity	
<750	Corrosive	-
750 – 2,599	Extremely Corrosive	-
2,600 – 9,999	Moderately Corrosive	-
>10,000	Non-Corrosive	-
Ewing[3]	Corrosion Activity	
<2,000	Bad	0 – 10
2,000 – 4,500	Fair	10 – 17
4,500 – 6,000	Good	17 – 25
6,000 – 10,000	Excellent	25
Romanoff[4]	Corrosion Classification	
<700	Very Corrosive	-
700 – 2,000	Corrosive	-
2,000 – 5,000	Moderately Corrosive	-
>5000	Mildly to Non-Corrosive	-
Husock[5]	Soil Resistivity	
<1,000	Very Low	Possibly 5 years*
1,000 – 5,000	Low	Possibly 10 years*
5,000 – 10,000	Medium	Difficult to predict
>10,000	High	Depends on soil Homogeneity

**Means one would be 'lucky' if no corrosion failures occurred in the structure within this time period. It does not infer that the structure would be corroded beyond repair.*

The soil resistivity classification chart above demonstrates observed ranges for typical soils. The lower the resistivity, the more corrosive the soil is to metal. This soil corrosivity table is applicable only to buried steel that is not interconnected to other metals. For steel anchors that are connected to copper and concrete encased steel, galvanic corrosion will occur even in soils that may be considered "non-corrosive" in the table above. *(Courtesy of Stantec)*

Temperature is another factor that can affect a plot of soil's resistivity. When soil temperature drops below the freezing point, the moisture molecules will also freeze, reducing the moisture's ability to cause corrosion. Conversely, hot, dry conditions can cause the upper layers of soil to dry out. In both cases, soil resistivity can increase by a factor of 10 or more. While these conditions lower the inherent risk of corrosion, higher resistivity environments also reduce the amount of protective current that a galvanic (sacrificial) cathodic protection system can output.

Finally, salt content within a plot of soil can also significantly impact soil resistivity, having the effect of reducing resistivity and increasing the potential for corrosion. Soluble salts can enter soil through a variety of means, including through run-off water and deliberate efforts to reduce resistivity or to clear snow and ice. Some soils also have a higher salt content naturally.

Site owners exploring potential sites for new guyed towers that will require buried steel anchor shafts should ensure they obtain the geotechnical data required to properly assess a site's soil corrosivity, including a resistivity measurement and information about the amount of moisture and salt in the soil measured, as well as its temperature. The type of soil found on site can also be important information that should be contained in each geotechnical report, as soil type can indirectly influence resistivity since some soils are more prone to retaining moisture, temperature or salts.

At the same time, site owners should also be aware of other related factors that can affect a plot of soil's corrosivity, some of the most common of which are described in the remainder of this section.

Image 16: Geotechnical Reports

GEOTECHNICAL RECOMMENDATIONS

Based on the results of this study, the following net design parameters may be used to evaluate the capacity of the existing foundation system. A factor of safety on the order of 2 to 3 should be applied to the ultimate skin friction, passive pressure, and bearing pressure values provided below. The cohesion, internal angle of friction, unit weight, and sliding friction coefficient values given in the following table are based on the borings, published values and our past experience with similar soil/rock types. These values should, therefore, be considered approximate.

Tower Mast Foundation (B-1) - Ultimate Design Parameters

Depth (feet)	Soil/Rock Description	Unit Weight (pcf)	Average N-Value (bpf)	Ultimate Bearing Pressure (psf)	Sliding Friction Coefficient @ Base	Internal Angle of Friction (Degrees)	Cohesion (psf)
0 – 4	Medium stiff to stiff fat clay	120	10	Ignore	-	-	-
4 – 7	Soft highly weathered shale with limestone fragments	130	47	18,000	0.40	0	3,000
7 – 13	Soft decomposed shale	130	22	15,000	0.35	0	2,500
13 – 14	Soft highly weathered shale	140	50/2"	24,000	0.40	0	4,000

Guy Anchors (B-2, B-3 and B-4) - Ultimate Design Parameters

Depth (feet)	Soil/Rock Description	Unit Weight (pcf)	Ultimate Skin Friction (psf)	Ultimate Passive Pressure (psf)	Internal Angle of Friction (Degrees)	Cohesion (psf)
0 – 5.5	Medium stiff to very stiff fat clay	120	Ignore	Ignore	-	-
5.5 – 7.5	Stiff sandy fat clay and soft decomposed shale	130	2,500	5,000	0	2,500
7.5 – 10	Soft decomposed to moderately hard shale	135	3,000	6,000	0	3,000

Geotechnical reports provide information about soil conditions that can help identify whether a site may be susceptible to accelerated corrosion based on naturally occurring elements.

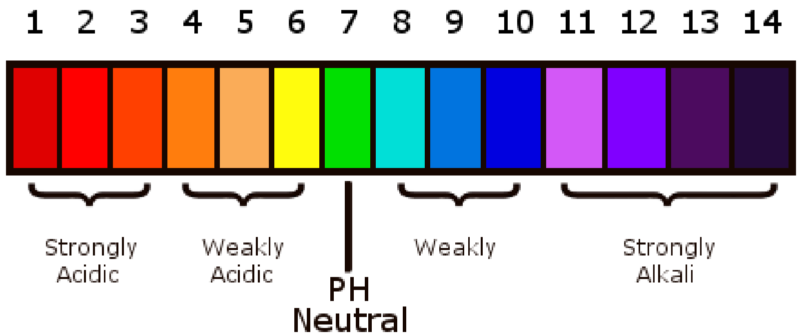
- ***Risk of saturation:*** Since corrosivity varies greatly based on the concentration of moisture in the soil, sites with high water tables, those that are in swamps, or those situated in saturated soils should be considered at higher risk of accelerated corrosion. As such, the risk of saturation is another factor that site owners must take into account when planning new sites that will include below-grade steel components such as anchor shafts. These sites can see significant variation in soil moisture levels due to flooding, ground swelling, or seasonal changes in water levels. As a result, moisture levels recorded in the soil during a geotechnical analysis provided one day may not remain consistent.

  Any such site should be prioritized for cathodic protection or another form of corrosion mitigation.

- ***pH levels:*** The acidity of a plot of soil is another factor that can affect corrosion rates and which can potentially cause below-grade components to corrode more quickly than expected. This is measured in pH levels, with lower numbers indicating higher acidity. Any plot of soil with a pH level below 4.5 can result in higher rates of corrosion than would be otherwise expected.

  While all soils have an inherent pH level, it is important for site-owners to not only identify each plot of soil's natural pH level, but also whether additional variables could cause those levels to change. One such variable is the presence of biological factors, such as high vegetation around the area where below-grade components are buried, which can alter pH levels and potentially increase rates of corrosion in those components.

Image 17: PH Scale



The above chart shows the PH scale indicating acidic and alkali zones.

Notably, this type of vegetation may not be present when a site is built but could still grow over that site later, creating a potential hazard several years after the tower was built or last serviced or inspected. Sites that are near to or submerged in swamp are also prone to biological factors that can affect pH levels and corrosion rates, as are those that are frequented by cattle or other livestock since manure can also affect soil acidity. Much like with vegetation, of course, the presence or lack of livestock on a site may not remain constant, making it potentially difficult for site owners to determine if a site could be exposed to this risk.

- ***Ground radials:*** As discussed in Section 3.1, dissimilar metals electrically continuous with below-grade anchor shafts can also affect corrosion rates. This is a concern on any site that has – or that is near to – one or more ground radial, which are often used to extend communications signals at AM broadcast sites, in particular. Many AM sites, for example, use copper ground radials that are more noble than the steel tower components, and which would effectively use steel anchor shafts as protective anodes, thus accelerating corrosion of the steel.

  One way to potentially mitigate any accelerated corrosion caused by electrically continuous ground radials is to interconnect the anchor shaft anodes with the ground radial system, ensuring that electrical currents do not discharge off the anchor shafts directly. In some situations, however, this approach can cause the protective anodes to deplete much quicker than otherwise expected, as they provide protection to the entire length of bare copper. As such, it is recommended that you consult a qualified engineer before utilizing this strategy at any given site.

  Another potential solution is to isolate the ground radials from the below-grade anchor shafts entirely. This solution may result in the ground radials being subject to stray current interference. Again, it is recommended that you consult a qualified engineer before utilizing this strategy at any site.

- ***Biotic factors:*** In some cases, below-grade anchor shafts can also be subjected to what's called microbial corrosion, which results from the anchor shafts interacting with specific bacteria that is known to accelerate corrosion. While this phenomenon is very rare in the communications tower industry, it could still affect sites on occasion – particularly sites located in swampy areas.

  One way to partially mitigate the threat of microbial corrosion is to ensure crews always use clean soil for backfilling the holes around new or recently inspected anchor shafts, though even then it is possible that bacterial-infected waters could seep back into the soil around the anchor shafts and cause accelerated corrosion.

- ***Proximity to utilities and structures:*** Site owners who have tower sites that are nearby or adjacent to other utilities or infrastructure must also be cognizant of how those neighbouring utilities and structures can affect corrosion of pivotal below-grade components such as anchor shafts. These include, but are not limited to:
  - *Electrical sub-stations*: The proximity of a nearby electrical sub-station could potentially result in increased electrical currents passing through a tower site's soil – including the soil around the anchor shafts – potentially increasing corrosion rates in below-grade components. Depending on the type of substation, below-grade anchor shafts could be subject to dissimilar metal corrosion if the tower is continuous with the sub-station grounding, or stray current interference (specifically if a high-voltage DC sub-station).
  - *Pipelines and oil and gas facilities:* Tower sites in close proximity to bitumen, natural gas or other pipelines – or other oil and gas facilities – may also be susceptible to accelerated corrosion of below-grade components as those pipelines and facilities are typically cathodically protected, and these protection systems can create stray currents. As a result, nearby below-grade metal components – such as anchor shafts – may be subject to stray current interference, significantly increasing the rate of corrosion on those components. This applies to both above-ground and buried pipelines as well as other oil and gas facilities, and any site within 60 meters of a pipeline or facility is considered to be at particular risk of being

Images 18-20: Proximity to Utilities and Structures that Can Cause Accelerated Corrosion

Buried steel anchor shafts in proximity to electrical or oil and gas infrastructure may be susceptible to accelerated corrosion. (Courtesy of CBC) exposed to conditions that could increase corrosion of buried steel anchor shafts.

- *Power lines:* Much like electrical sub-stations, buried power cables can also be a significant source of stray currents, and can cause accelerated corrosion rates in nearby anchor shafts as a result. Fortunately, this is only the case with buried power lines, and does not apply to overhead/aerial lines. Because the amount of current passing through buried power lines can differ dramatically, there is no general “safe distance” from buried power lines at which site owners can assume buried anchor shafts would not be affected by stray currents.

- ***Proximity to structures with below-grade metallic components:*** Nearby structures with below-grade metal components can also affect the flow of underground electrical currents below tower sites. Depending on the type(s) of metal used in any nearby below-grade structural components, steel anchor shafts may effectively serve as an anode to those metal components, should they become continuous, potentially increasing anchor shaft corrosion significantly. Continuity with other below-grade steel infrastructure, such as building piles, could potentially result in an increased load on the anchor shafts’ cathodic protection system, resulting in that system depleting at an accelerated rate, and potentially reducing the amount of protection the system provides to the anchor shafts.

Site Characteristics that Can Affect Below-Grade Corrosion

Soil resistivity and salt content

Risk of saturation

pH levels

Ground radials

Biotic factors

Proximity to utilities and structures

Proximity to structures with below-grade metallic components

- ***Proximity to populated areas:*** While proximity to a populated area will not necessarily increase the rate of corrosion of below-grade anchor shafts, site owners should be aware of the potentially deadly result of a tower collapse in or around a populated area. This alone may be cause to justify additional inspections. Additionally, it should also be noted that sites that are nearby populated areas may also be more prone to human-caused factors that can affect soil resistivity and corrosion rates.

- ***Critical/important infrastructure:*** Finally, it cannot be ignored that site owners may also want to prioritize site inspections based on the importance of the tower and its role in maintaining critical lines of communications. Needless to say, no client wants to lose access to critical communications as a result of a tower failure, and it is reasonable to expect that site owners may take extra precautions – including priority or more frequent inspections – to protect critical communications infrastructure against potential hazards including anchor shaft corrosion, among others.

4.4 Tower/Anode Age

The final major factors for tower owners to consider when attempting to identify towers at risk of anchor shaft corrosion is the age of the tower as well as the age of the active anodes on each of the tower's anchor shafts. With regards to tower age, this information is primarily useful for determining whether a tower could potentially have been built without a cathodic protection system, as many Canadian guy towers were designed before the use of anodes was a standard industry practice. Site owners should assume that towers built before 1995 do not have cathodic protection systems installed unless there is evidence indicating otherwise, and should prioritize these towers for anchor shaft inspections. Notably, even towers built since 1995 may have below-grade anchors shafts that are not protected through the use of anodes, and it should never be assumed that any tower has cathodic protection until this is confirmed.

Anode materials have different rates of deterioration or consumption when discharging a given current from the anode surface in a specific environment. Therefore, the life of an anode is primarily determined by the anode material and size, as well as the current output. The design of anode systems should always consider both the current requirement and the system design life. Generally, most professionally designed cathodic protection systems are designed to last approximately 20 years, though this expected lifetime can be reduced significantly in some circumstances.

Notably, cathodic protection systems installed on Canadian communications towers have often taken a "cookie-cutter" approach to anode installation that did not properly consider the expected lifespan of the anode. As such, in some circumstances, the anode lifespan may be significantly less.

5.0 How to Investigate Towers at Risk

After Canadian tower owners utilize the information in Section 4 of this document to evaluate their site portfolios and identify any guyed tower sites that are at high risk of anchor shaft corrosion, it is incumbent that they begin inspecting those towers to determine whether they are affected by any such corrosion, and whether they are still safe to climb.

There are two primary methods of anchor shaft inspection that can be used to determine if a tower is – or might be – affected by anchor shaft corrosion: surface inspections and dig-to-blog inspections. A brief overview of each is as follows:

5.1 Surface Inspection

Pre-climb surface inspections represent the simplest form of anchor shaft monitoring and should be completed on every guyed tower before climbing begins. Advanced surface inspections that examine the first 24 inches of below-grade anchor shaft should also be completed on each guyed tower at least once during every four-year inspection cycle. Importantly, any inspections that require digging down more than 24 inches must first be approved by a qualified engineer, who must examine whether the tower will require temporary anchorage during the procedure.

While daily pre-climb surface inspections are primarily geared towards identifying other potential hazards that do not relate to anchor shaft corrosion, corrosion must still be considered during any such inspection. These basic surface inspections can be useful for identifying above-grade corrosion that may indicate that the tower is a safety hazard, and can – in some cases – provide indication of any anchors that are submerged in water and may be at greater risk of below-grade corrosion. Unfortunately, it is also possible for below-grade anchors to be submerged in water without any apparent evidence on the surface. Any sign of actual corrosion should be taken seriously, and will likely require further investigation before the tower can be declared safe to climb, though not all surface rust detected on an anchor shaft will necessarily be cause for immediate concern.

Image 21: Surface Inspections

Surface inspections require crews to unearth the top 24 inches of the below-grade anchor shaft to identify any visible signs of corrosion. Any inspections that require digging down more than 24 inches must first be approved by a qualified engineer.

Importantly, a surface inspection alone is never sufficient to determine the safety of a tower with absolute confidence, as anchor shaft corrosion is often more likely to occur on below-grade lengths of the shaft than above-grade portions. Areas of the shaft just below the surface can be exposed to a higher oxygen concentration, making the first two or three feet below-grade one of two parts of an anchor shaft that can be particularly corrosion prone (along with the location at which the anchor shaft enters a below-grade concrete block, if applicable).

At least once during each four-year inspection cycle, each guyed tower anchor should be subject to a more detailed corrosion analysis such as an advanced surface inspection that examines the first 24 inches of the shaft below grade. To complete these inspections, contractors will dig down 24 inches or more around each anchor shaft – though never more than one shaft at a time – to inspect for signs of corrosion.[1] If there are any signs of corrosion on a shaft, the crew should then measure the material loss caused by corrosion at the most corroded portion of the cross-sectional to determine the extent of the issue. Any material loss should be reviewed by a competent person to determine whether further action may be required to reinforce or replace the anchor. Notably, these detailed surface inspections are not necessarily required if a more efficient means of determining if corrosion is present on the below-grade shaft, such as through mechanical testing.

[1] Please note that most provinces require crews to contact provincial authorities before digging more than 12 inches around a tower structure.

5.2 Dig-to-Block Inspection

Because surface inspections cannot provide reliable evidence that below-grade anchor shafts are unaffected by corrosion, a more thorough – and more costly – “dig-to-block” inspection may be required to determine the safety of guy towers, especially high-risk towers. In fact, a dig-to-block inspection is the only known way to verify the integrity of below-grade anchor shafts on most existing guy towers.

Dig-to-block inspections are completed by removing the soil from around the below-grade anchor shafts to reveal the entire length of each anchor shaft, one at a time. Once the anchor shaft if exposed all the way down to the block, workers can clean the shaft and visually inspect it for corrosion. If corrosion is detected anywhere on the anchor shaft, the crew must then determine whether the corrosion is within acceptable safety parameters. U.S.-based site owner Crown Castle has developed a “corrosion severity index” that can be used to determine whether partially corroded anchor shafts are likely to pose a risk.

Because dig-to-block inspections necessarily require the removal of soil that is pivotal to the engineered integrity of the tower, these inspections must be engineered procedures and should never proceed without the express approval of the site-owner and/or client. Temporary anchorage may be required to ensure the safety of the tower during a dig-to-block inspection, and a qualified engineer must consider all of the factors that can affect stability and the load on the tower when deciding whether to install temporary anchorage for each individual anchor that will be inspected. After considering the design analysis, current loading and risk communication provided by the contractor, the qualified engineer can suggest whether temporary anchorage should be used. Due to the costly nature of providing temporary anchorage, however, the site-owner/client must make the decision whether to proceed. Corroded anchor shafts can fail during a dig-to-block inspection, and temporary anchorage is strongly recommended when excavating any soil around anchor shafts that are suspected of already being corroded.

Image 22-24: Dig-to-Block Inspections

Dig-to-block inspections require inspectors to unearth the soil around the anchor shaft all the way down to the concrete block, and to measure the shaft at its most corroded portion. *(Courtesy of AnchorGuard)*

6.0 Going Forward Designs

Canadian towers owners should always refer to the latest CSA S37 standard for minimum corrosion protection requirements for below-grade steel anchor shafts. CSA S37 currently requires that "all anchorage steel located below grade should be hot dip galvanized" and that "anchorage steel located below grade and not encase in concrete have corrosion protection in addition to galvanizing." Each of the methods outlined in Section 4.2 of this document are acceptable additional protective measures, including: concrete encasement, cathodic protection and painting/taping. The standard also adds that protective coatings (such as paint/tape) must remain "crack-free and not become brittle or fluid over the anticipated service temperature range" and that they remain "chemically stable, non-reactive with adjacent materials, and impervious to moisture."[2]

Absent any additional, specific instructions from CSA S37, it is primarily up to each tower owner to determine what type(s) of corrosion protection they want to apply to their below-grade anchor shafts. That said, STAC recommends that the following considerations be taken into account:

- ***Avoid dissimilar metals:*** Be aware of situations where engineering plans call for use of dissimilar metals, or where below-grade dissimilar metals may already exist in other nearby structures. In particular, pay attention to any nearby metals that are more noble than the steel anchor shafts, or which have a more electropositive potential. Sites that call for use of copper grounding may be particularly prone to the type of accelerated corrosion issue linked to dissimilar metals.

- ***Over-design:*** One advantage site owners have is the ability to over-design certain tower components, including the corrosion protection systems or even the anchor shafts themselves, thus increasing their ability to stave off corrosion. This can be achieved by going above and beyond the minimum requirements (as per S37), such as by creating larger concrete encasements or by using larger than necessary anodes, for example, or by utilizing multiple protective measures in combination with each other. Anchor shafts can also be over-designed, so to speak, through the use of additional steel on the cross-sectional portion of the shaft. In this way, tower engineers can account for the anchor shaft to lose some of its steel to corrosion over time without affecting its structural integrity.

- ***Use monitoring tools and techniques on cathodic protection systems:*** There are also several cost-efficient tools that can help ensure the continued structural integrity of below-grade anchor shafts by facilitating the monitoring of anode conditions without requiring a physical examination of the buried anodes through a costly dig-to-block excavation.

  Reference cells (or "reference electrodes") are specially designed electrodes that have a stable and well-known electrode potential, allowing corrosion engineers to take potential measurements on buried structures. These potential measurements are then used to indicate whether or not a structure has adequate cathodic protection. Cathodic protection potentials are typically described in terms of

[2] CSA S37 – Annex F … but maybe also elsewhere that isn't an Annex?

mV with respect to a $Cu:CuSO_4$ reference electrode (CSE) and measurements taken with respect to other references are usually converted.

This is achieved most easily when the reference cell is installed within a test head (or "test station"), which allows crews to monitor a buried cathodic protection system's performance, including the protection level, the anode life, the operation of the anode(s) and corrosion rates. Notably, these performance measurements can also be taken without the presence of a test head, but only if the anode connection is both accessible and can be disconnected. Anodes that cannot be disconnected, or where the connection is inaccessible, can cause issues with obtaining accurate potential measurements. While some assessments of cathodic protection systems can be made in these cases, the assessment will not provide accurate quantitative data.

Because buried reference cells provide a more accurate picture of the cathodic protection across the anchor shaft as a whole, it is recommended that those installing reference cells install them at approximately half the depth of bottom of the anchor shaft.

"Coupons" are another tool that can be used to evaluate a cathodic protection system's performance by measuring its "instant-OFF potential." This process allows crews to measure the polarized potential of the structure without interrupting the anode, allowing them to determine if the anchor shafts are receiving adequate cathodic protection and determine if a structure may be at risk. Coupons can also be disconnected from the cathodic protection system in order to assess the "depolarized" potential of the structure.

Finally, an corrosion rate probe is another option to site owners that can be installed along with a cathodic protection system to measure the system's performance. While a corrosion rate probe, such as an ER probe, is the only type of device capable of determining the actual corrosion rate a structure is experiencing in millimeters per year – they are most pertinent to sites that are expected to be subject to accelerated corrosion.

Remote monitoring of any of the installed cathodic protection monitoring equipment is possible and will facilitate more regular measurements. As with ER Probes, remote monitoring is most pertinent to sites that are expected to be subject to accelerated corrosion.

- ***Use an impressed current cathodic protection system:*** Impressed current cathodic protection systems utilize DC power to force a relatively inert anode to become more electronegative and thereby protecting the cathode (in this case, the tower anchor shafts). The DC power may be supplied by a variety of methods, but is most often supplied by a transformer rectifier, which takes AC power and rectifies it to a DC output. Impressed current systems may be more economical for cathodic protection when the current requirement for the site is high or when the site's soil resistivity is high, both of which may make the use of galvanic anodes impractical.

Annex: STAC Recommended Anchor Shaft Inspection Priority Matrix

The matrix on the next two pages was designed to assist communications tower owners assess the relative urgency of recommended anchor shaft inspections for each guyed tower in their inventory. Importantly, there may be additional considerations not accounted for in this matrix that may justify increasing the inspection priority for individual or groups of towers.

Though this matrix was developed in consultation with corrosion engineers and communications tower industry experts, it cannot determine that a tower's anchor shafts have not been subjected to excessive corrosion that could cause structural instability. STAC strongly recommends that all site owners develop their own programs to ensure the structural integrity of their infrastructure and sites.

Note: STAC Members can also download a Microsoft Excel version of the STAC Recommended Anchor Shaft Inspection Priority Matrix at https://members.stacouncil.ca/stac-recommended-anchor-shaft-inspection-priority-matrix/. Please contact info@stacouncil.ca to inquire about access to the STAC Members Website.

Instructions for Use

1. Identify the requisite characteristics of each guyed tower for assessment (eg: soil conditions and environment, corrosion protection, grounding system, etc …)

2. Identify where each pair of characteristics intersect in the matrix and record the indicated ""score"" at each appropriate field.

3. Add the score from each recorded field for each tower and divide the total by the number of fields recorded for that tower to determine the average score for each tower.

4. Compare the average score of each tower assessed. Towers should be prioritized for anchor shaft inspections from highest average score to lowest, with the following general guidelines in mind for each average score range:
   - 1-2: low priority
   - 2-3: moderate priority
   - 3-4: high priority
   - 4-5: urgent

5. Review each tower with an average score of 3 or lower for any individual combination of characteristics that score 4 or 5, which could necessitate an increased priority for inspection than indicated by the average score.

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STAC Recommended Anchor Shaft Inspection Priority Matrix (v. 1.1)

Structure, Tower & Antenna Council
Conseil des structures, pylônes et antennes

		Soil Conditions and Environment			Corrosion Protection					
		Close to source of stray currents	Corrosive soil conditions	Non-corrosive soil conditions	No known protection	Galvanized anchors, no other known protection	Galvanized anchors, use of bitumen coating	Galvanized anchors, concrete encasement	Galvanized anchors, use of galvanic anodes	Impressed current cathodic protection system (rectifiers, etc ...)
Soil Conditions and Environment	Close to source of stray currents				5	5	4	4	3	3
	Corrosive soil conditions				5	4	3	3	3	1
	Non-corrosive soil conditions				4	3	2	2	1	1
Corrosion Protection	No known protection	5	5	4						
	Galvanized anchors, no other known protection	5	4	3						
	Galvanized anchors, use of bitumen coating	4	3	2						
	Galvanized anchors, concrete encasement	4	3	2						
	Galvanized anchors, use of galvanic anodes	3	3	1						
	Impressed current cathodic protection system (rectifiers, etc ...)	3	1	1						
Grounding System	Copper grounding	4	4	3	5	4	3	3	2	1
	No copper grounding	2	2	1	4	3	2	2	1	1
Tower Age	Built before 1995	5	5	5	5	5	4	4	3	1
	>20 years old	5	5	4	5	5	4	4	2	1
	>15 years old	5	4	3	4*	4*	3	3	2	1
	>10 years old	4	3	2	4*	4*	3	3	2	1
	> 4 years old	3	2	1	3*	3*	2	2	1	1
	> 1 year old	2	1	1	2*	1*	1	1	1	1
Last Anchor Inspection	No recorded inspection*	5	5	5	5	5	5	5	5	5
	> 4 years ago*	5	5	5	5	5	4	3	3	3
	< 4 years ago	4	4	3	4	3	1	1	1	1
	< 2 years ago	3	2	1	4	2	1	1	1	1
	Continuous remote monitoring of anchor shafts***	1	1	1	4	1	1	1	1	1
Galvanic Anode Age (23 lbs.)	> 20 years old	5	5	4	N/A	N/A	N/A	N/A	5	N/A
	> 10 years old	5	4	3	N/A	N/A	N/A	N/A	3	N/A
	< 10 years old	3	2	1	N/A	N/A	N/A	N/A	1	N/A
Anode Connection	No visual or measured confirmation	5	5	2	N/A	N/A	N/A	N/A	5	5
	Visual or measured confirmation	3	2	1	N/A	N/A	N/A	N/A	1	1
Anode Capacity	< 50% of original capacity at last measurement	5	3	2	N/A	N/A	N/A	N/A	3	3
	> 50% of original capacity at last measurement**	3	2	1	N/A	N/A	N/A	N/A	1	1

**This chart only relates to towers built in accordance with CSA S37*

*** Measured loss of less than 50% of an anode's capacity after 20 years could be indicative of unreliable data.*

**** Continuous remote monitoring assumes monitoring demonstrates protective potentials*

Please note - this is a living document and will be updated as appropriate. STAC is continuously seeking feedback on this document and requests that all comments or concerns be sent to info@stacouncil.ca

Grounding Systems		Tower Age						Last Anchor Inspection					Galvanic Anode Age (23 lbs.)			Anode Connection		Anode Capacity	
Copper grounding	No copper grounding	Built before 1995	>20 years old	>15 years old	>10 years old	> 4 years old	> 1 year old	No recorded inspection	> 4 years ago	< 4 years ago	< 2 years ago	Continuous remote monitoring of anchor shafts***	> 20 years old	> 10 years old	< 10 years old	No visual or measured confirmation	Visual or measured confirmation	< 50% of original capacity at last measurement	> 50% of original capacity at last measurement**
4	2	5	5	5	4	3	2	5	5	4	3	1	5	5	3	5	3	5	3
4	2	5	5	4	3	2	1	5	5	4	2	1	5	4	2	5	2	3	2
3	1	5	4	3	2	1	1	5	5	3	1	1	4	3	1	2	1	2	1
5	3	5	5	4*	4*	3*	2*	5	5	4	4	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	2	5	5	4*	4*	3*	1*	5	5	3	2	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	1	4	4	3	3	2	1	5	4	1	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	1	4	4	3	3	2	1	5	3	1	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1	1	3	2	2	2	1	1	5	3	1	1	1	5	3	1	5	1	3	1
1	1	1	1	1	1	1	1	5	3	1	1	1	N/A	N/A	N/A	5	1	3	1
		3	3	3	3	3	2	5	5	4	3	1	5	4	2	4	2	4	1
		1	1	1	1	1	1	3	2	1	1	1	4	2	1	2	1	2	1
3	1							5	5	3	2	1	5	4	1	5	1	5	2
3	1							5	5	3	2	1	5	4	1	5	1	4	1
3	1							5	5	2	1	1	N/A	3	1	4	1	3	1
3	1							5	5	1	1	1	N/A	3	1	3	1	3	1
3	1							5	5	1	1	1	N/A	N/A	1	2	1	4	1
2	1							1	N/A	1	1	1	N/A	N/A	1	2	1	5	1
5	3	5	5	5	5	5	1						5	5	4	5	N/A	N/A	N/A
5	2	5	5	5	5	5	N/A						5	5	3	5	3	5	3
4	1	3	3	2	1	1	1						4	3	1	4	1	4	1
3	1	2	2	1	1	1	1						2	2	1	3	1	2	1
1	1	1	1	1	1	1	1						1	1	1	1	1	1	1
5	4	5	5	N/A	N/A	N/A	N/A	5	5	4	2	1				5	3	5	4**
4	2	4	4	3	3	N/A	N/A	5	5	3	2	1				4	2	3	1
2	1	1	1	1	1	1	1	4	3	1	1	1				2	1	3	1
4	2	5	5	4	3	2	2	5	5	4	3	1	5	4	2			4	1
2	1	1	1	1	1	1	1	N/A	3	1	1	1	3	2	1			2	1
4	2	5	4	3	3	4	5	N/A	5	4	2	1	5	3	3	4	2		
2	1	1	1	1	1	1	1	N/A	3	1	1	1	4**	1	1	1	1		

Glossary

Note: All definitions are copied from the [NACE International "Glossary of Terms" webpage], unless otherwise specified.

Activity/active metals	A collective name for the metals that react strongly or quickly with other sub0073tances *(Definition courtesy of the University of Illinois.)*
Adequate cathodic protection	Cathodic protection such that the potential of the structure satisfies one (or more) of the NACE SP0169 (2013) criteria; cathodic protection levels under which corrosion is effectively mitigated *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Anode	The electrode of an electrochemical cell at which oxidation occurs. (Electrons flow away from the anode in the external circuit. It is usually the electrode where corrosion occurs and metal ions enter solution.)
Bituminous coating	An asphalt or coal-tar compound used to provide a protective coating for a surface.
Cathode	The electrode of an electrochemical cell at which reduction is the principal reaction.(Electrons flow toward the cathode in the external circuit.)
Cathodic polarization	(1) The change of electrode potential caused by a cathodic current flowing across the electrode/electrolyte interface. (2) A forced active(negative) shift in electrode potential. [See polarization.]
Cathodic protection	A technique to reduce the corrosion rate of a metal surface by making that surface the cathode of an electrochemical cell.
Conductivity	(1) A measure of the ability of a material to conduct an electric charge. (2) The current transferred across a material (e.g., coating) per unit area per unit potential gradient. (Conductivity is the reciprocal of resistivity.)
Copper /copper sulfate reference electrode (CSE)	A reference electrode composed of a pure copper rod in a saturated copper sulfate solution. This is the most commonly used type of reference electrode. [See reference electrode.] *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*

Corrosion	The deterioration of a material, usually a metal, that results from a chemical or electrochemical reaction with its environment.
Corrosion rate(s)	The time rate of change of corrosion. (It is typically expressed as mass loss per unit area per unit time, penetration per unit time, etc.)
Corrosion rate probe	A monitoring device that is connected to a structure and placed in the electrolyte, and used to directly measure corrosion rates. One common type is an Electrical Resistance (ER) corrosion probe. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Depolarization	The loss of polarization. [See polarization.] *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Depolarized potential	The free corroding potential of a metal after cathodic protection is removed. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Electrically continuous	A circuit has continuity when there is a continuous path for electricity to flow through the circuit (free from open circuit conditions); for example a fence tied into station grounding would be electrically continuous with all other structures tied into the grounding. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Electrolytic path	The path through the electrolyte in the corrosion cell that allows the ions to flow between the anode and cathode. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Electronic path	The path inside the metal in the corrosion cell that allows electrons to flow between the anode and cathode. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Ferrous	Metals composed of, relating to, or containing iron. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Galvanic/sacrificial anode	A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.
Galvanic corrosion	Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

Galvanic series	A list of metals and alloys arranged according to their corrosion potentials in a given environment.
Galvanizing/galvanic coating	A [hot-dip] coating of zinc on steel that contains an interfacial interdiffusion layer of zinc and iron, forming a metallurgical bond at the steel surface.
Instant-OFF potential	The polarized half-cell potential of an electrode taken immediately after the cathodic protection current is stopped, which closely approximates the potential without IR drop (i.e., the polarized potential) when the current was on.
Microbial corrosion/micro biologically influenced corrosion (MIC)	Corrosion affected by the presence or activity, or both, of microorganisms.
NACE International	NACE International is a not-for-profit professional organization for the corrosion control industry whose mission is to "[equip] society to protect people, assets and the environment from the adverse effects of corrosion." *(Definition courtesy of Wikipedia.)*
Noble metals	Metals with standard electrode potential more positive than that of hydrogen.
Oxidation	(1) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a material that is exposed to an oxidizing gas at elevated temperatures.
Polarization	The change from the corrosion potential as a result of current flow across the electrode/electrolyte interface.
Polarized potential	(1) (general use) the potential across the electrode/electrolyte interface that is the sum of the corrosion potential and the applied polarization. (2)(cathodic protection use) the potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.
Porosity	The quality or state of being porous; (porous = *a* : permeable to fluids *b* : permeable to outside influences)
Potential / structure-to-electrolyte potential	The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference

	to an electrode in contact with the electrolyte.
Qualified engineer	A licensed engineer habilitated to practice in a specific province. This practice is regulated under a system of licensing administered by a self-regulated engineering association in each province, such as OIQ in Quebec, PEO in Ontario or APEGA in Alberta. In Canada, the designation "professional engineer" can only be used by licensed engineers and the practice of engineering is protected in law and strictly enforced in all provinces. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Rectifier/transformer rectifier (TR)	A device for converting alternating current into direct current, and for transforming the voltage. *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*
Reduction	Gain of electrons by a constituent of a chemical reaction.
Reference cells/reference electrodes	An electrode having a stable and reproducible potential, which is used in the measurement of other electrode potentials.
Resistivity / soil resistivity	The electrical resistance between opposite faces of a unit cube of material.
Stray current interference	In cathodic protection, the term interference refers to electrical interference as opposed to physical or chemical interference. Hence interference can be defined as any detectable electrical disturbance on a structure caused by a stray current, which can cause accelerated corrosion at the discharge location. See also: stray currents. *(Definition courtesy of NACE)*
Stray currents	Current flowing through paths other than the intended circuit.
Sulfate reducing bacteria (SRB)	A category of microorganisms involved in the MIC. SRB is one of the most important microbes for anaerobic corrosion of buried steel structures in soils. SRB can remove molecular hydrogen from the cathode, leading to cathodic depolarization of the metal surface. Iron sulfide or scale by SRB is accumulated on surfaces of metals, which accelerates corrosion rates locally. See also: Microbial corrosion/micro biologically influenced corrosion (MIC). *(Definition courtesy of the STAC Anchor Shaft Corrosion Project Team.)*