DEPARTMENT OF TRANSPORTATION

Implementation of New Guidelines for Tightening Large Anchor Rods of Support Structures for Signs and Luminaires

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16. Abstract (Limit: 250 words)

Throughout the US, many state departments of transportation (DOTs) are experiencing issues with the loosening of anchor bolt nuts on overhead sign, luminaire, and traffic signal (SLTS) structures. Retightening loose nuts imposes a significant drain on state DOT resources. In addition, loosening of these nuts increases fatigue stresses on the anchor bolts, possibly increasing the risk of failure.

Loose anchor bolt nuts were recorded on both old and new structures, some immediately after installation. Even after retightening by Minnesota Department of Transportation (MnDOT) maintenance workers, anchor bolt nuts were found to come loose within two years. In a previous project, new retightening specifications were developed based on laboratory testing, field monitoring, surveys of current practices, and finite element modeling.

This project focused on implementation and evaluation of the proposed specifications from the previous project. Structural monitoring also continued on a previously instrumented overhead sign structure. Difficulties were discovered with the proposed procedures during implementation, including structure clearance, instruction clarity, and retightening timing. Overall, though, the proposed procedures were found to be effective in preventing loosening. Revisions to the specifications were suggested along with recommendations for further review to simplify the procedures through a future laboratory study.

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FINAL REPORT

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The work in this study would not have been possible without the instrumentation and construction that took place in the previous project by Connor Schaeffer.

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EXECUTIVE SUMMARY

This work was conducted for the Minnesota Department of Transportation (MnDOT) under the research project titled Implementation of New Guidelines for Tightening Large Anchor Rods of Support Structures for Signs and Luminaires. The research and report were completed by a team at Iowa State University.

MnDOT, along with numerous other state departments of transportation (DOTs), are finding that anchor bolt nuts are coming loose at a concerning rate for overhead signs, lighting, and traffic signal (SLTS) structures. Anchor bolts are critical to the structural stability of a structure, since, for MnDOT, they are the only connection to the foundation. Retightening loose nuts imposes a significant drain on state DOT resources. More important, the loosening of these nuts increases fatigue stresses on the anchor bolts, possibly increasing the risk of failure.

Loose anchor bolt nuts were recorded on both old and new structures, some immediately after installation. In addition, even after retightening by MnDOT maintenance personnel, some anchor bolt nuts have come loose within two years. The pre-tension or clamp force developed in anchor bolts during nut tightening is critical to keeping them sufficiently tight on the structure bases. Anchor bolts loosening after installation and maintenance suggested a deficiency in MnDOT's previous anchor bolt pre-tensioning procedures.

To alleviate the anchor bolt pre-tensioning limitations, new specifications were developed for a previous study titled Re-Tightening the Large Anchor Bolts of Support Structures for Signs and Luminaires. The new specifications were developed through laboratory testing, field monitoring, surveys of current practices, and finite element modeling.

This project focused on the implementation of the previously proposed specifications. For a specification to be effective, constructability is critical; if the procedures cannot feasibly be performed in the field, they will likely not be utilized to the fullest extent. Previously proposed specifications were attempted on a variety of MnDOT SLTS structures. Both new installation and maintenance practices were investigated. Monitoring on a previously instrumented in-field cantilevered overhead sign structure was also continued as part of this study.

During implementation, some difficulties were discovered with the proposed procedures. Clearance has been a critical aspect for many lighting and traffic signal structures; a wrench cannot be effectively placed inside the base to properly pre-tension the anchor bolts in many cases. During the pre-tensioning, individual steps from the specifications often needed clarification and tended to be difficult to follow for contractors. The proposed specifications also include a retightening torque after 48 hours to account for relaxation that was difficult to implement when contractor time and traffic control were considered. After investigating structures pre-tensioned with the new specifications, none had loose anchor bolt nuts, likely indicating that the new procedures were effective.

Overall, the proposed procedures were found to be effective, but sometimes difficult to perform and sometimes not feasible for certain SLTS structures. Revisions to the previously proposed specifications

were suggested along with recommendations for further review to simplify the procedures in a future laboratory study.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Across the United States, various state departments of transportation (DOTs) are finding that the base anchor rod nuts on critical support structures for traffic signals, overhead signs, and high mast light towers are coming loose. Retightening loose nuts imposes a significant drain on state DOT resources. In addition, the loosening of these nuts increases the failure risk of tall and overhanging structures.

In many of MnDOT's observed cases, anchor rod nuts were loose immediately after installation. Even after tightening by MnDOT personnel, it was found that anchor bolt nuts had consistently come loose just two years after retightening.

To alleviate the issue, new specifications were developed in a prior study. The new specifications were created around the importance of lubrication, bringing the nut to snug tight, turn-of-nut tightening, and tightening order.

After development in the laboratory, the newly recommended specifications still needed field verification to ensure constructability and in-service efficacy. If the specifications cannot be effectively implemented, anchor rod loosening will continue unabated.

1.2 REPORT ORGANIZATION

This report consists of multiple chapters, each focusing on a different aspect of the overall project. The basic content of each chapter follows:

- Chapter 2 contains a literature review of various anchor rod tightening properties along with a review of current specifications.
- Chapter 3 includes the results from implementation of the laboratory specifications. It is divided into implementation on overhead sign structures and on lighting and traffic signal structures given distinct differences in the two procedures.
- Chapter 4 summarizes the results of monitoring data from a cantilevered sign structure in Minneapolis, Minnesota.
- Chapter 5 brings all aspects of implementation together, recommending changes to the laboratory-developed specifications and providing concluding results.

1.3 BACKGROUND OF MNDOT TYPICAL ANCHOR ROD CONNECTIONS

To transfer forces on their overhead signs, lighting, and traffic signal (SLTS) structures to foundation bases, MnDOT employs double nut connections on anchor rods cast into a concrete foundation (Figure 1.3.1).

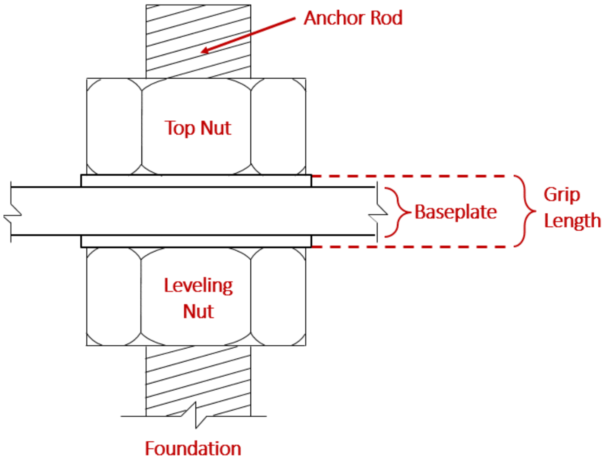
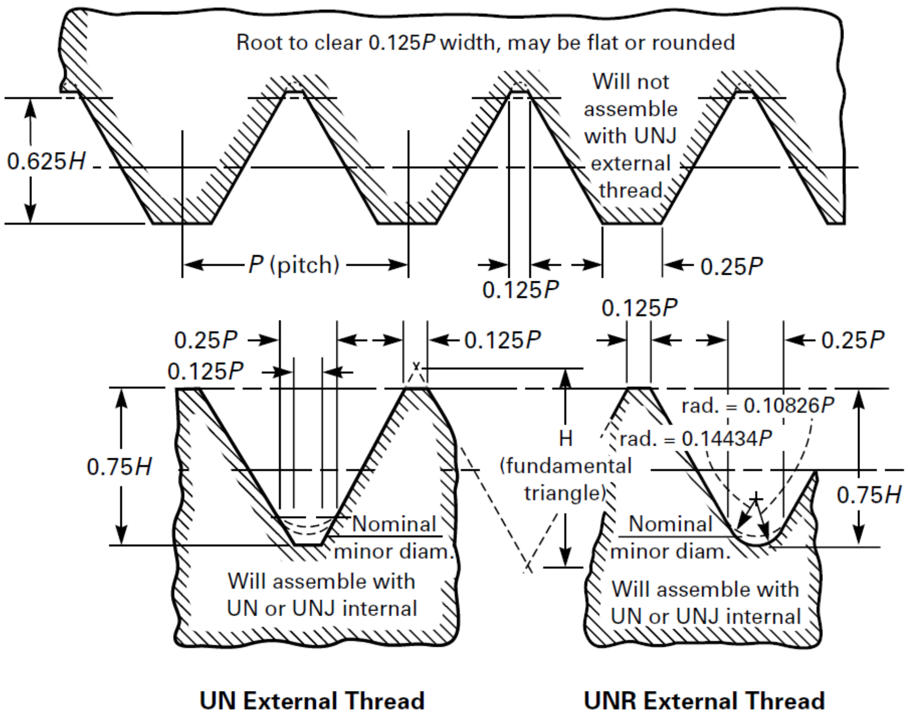


Figure 1.3.1 Typical double nut anchor rod connection

The connection is comprised of an anchor rod that clamps the baseplate of a structure with two nuts—commonly referred to as top and leveling. The leveling nut (on the bottom) is for leveling the structure before installation, and the top nuts are generally for tightening. Clamping force generated by tightening the top nut secures the baseplate of the structure in place. The thickness of the baseplate plus both top and bottom washers is referred to as the grip length, which is the length that the anchor bolt carries tension resulting from tightening plus external loads (dead load, wind load, etc.) during service.

1.3.1 Geometry

Typical anchor rod dimensions and materials are covered here before covering procedures. In the United States, the typical anchor rods utilized for SLTS structures adhere to the ASTM F1554-18 specification (ASTM 2014). Note that this specification differs from ASTM 325 and 490 for structural steel bolts. Anchor rods can be specified in three different yield grades: 36, 55, and 105 ksi. Of these, Grades 55 and 105 are most frequently used by MnDOT. Threads are cut or rolled according to ANSI/ASME B 1.1 Class 2A, as outlined in Figure 1.3.2.



ASME 2005

Figure 1.3.2 Typical anchor rod dimensions, UN threads

In addition, permanent grade identification is required on the ends of the anchor rods. As shown in Figure 1.3.3, marking can be completed with color coding or, if required, die stamped markings.

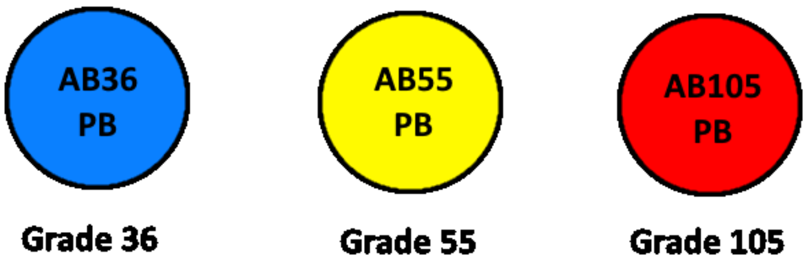
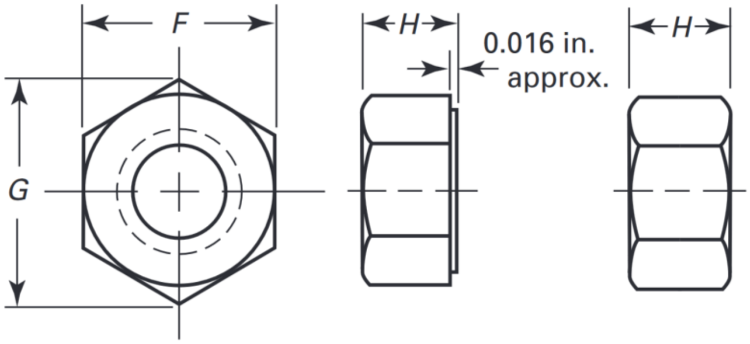


Figure 1.3.3 Typical anchor rod top coloring or stamped markings

As of 2018 construction specifications, MnDOT requires permanent markings (MnDOT 2018). Typical Nuts are ASTM A563 grade DH or A194 grade 2H Heavy Hex, which follows the dimensions of ANSI B1.1 Class 2B, as shown in Figure 1.3.4.



ASME 2010

Figure 1.3.4 Typical heavy hex nut dimension variables

Nuts have a proof load stress of 150 ksi (ASTM 2015 and 2005, ASME 2010). Finally, washers are specified to ASTM F436-18 (ASTM 2018).

1.4 SPECIFICATIONS FROM PREVIOUS RESEARCH PROJECT

This implementation project was based on a previous study funded by MnDOT titled Re-Tightening the Large Anchor Bolts of Support Structures for Signs and Luminaires (Chen et al., 2018). The previous project tested anchor rod tightening properties in the laboratory, instrumented an overhead sign for field monitoring, developed finite element models (FEMs) for numerical analysis, and developed new tightening specifications based on the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (LRFD – SLTS) 5.17.5.2 (2015).

The new specifications developed through the previous project were primarily based on AASHTO LRFD - SLTS 5.17.5.2, but with primary changes to torque, in addition to turn-of-nut verification, defining snug tight, and taking into account grip length. All three changes were a direct result of laboratory testing and literature review. By adding these three items, the new specifications aimed to take out inconsistency and better verify correct installation. The new specifications included an eight-step verification sheet, a table with the corresponding installation information (Table 1.1), and a table with wrench lengths for bringing nuts to snug tight. The eight steps are as follows:

1. Verify F1554 anchor bolt grade is as specified for the project. Verify nuts are ASTM A563 heavy hex and washers are F436.
2. Verify anchor bolts are clean and not damaged and plumb – not more than 1:40 slope or 1/4" in 10". (If bolts are out of plumb or damaged, contact project engineer.)
3. Lubricate anchor bolts with MnDOT-specified bridge grease (within 24 hours of tensioning) and turn nut down to foundation. Lubricate bearing surfaces of leveling nut and top nut prior to tightening.
4. Level leveling nuts – make sure nuts are less than one anchor bolt diameter from the foundation but no less than 1-1/4" for overhead (OH) signs.

5. Install structure with an F436 washer below and above baseplate and snug top nuts. When snugging, use snugging torque or maximum open-end wrench length on both the top nut and the leveling nut following the star pattern. Two cycles of snugging shall be performed prior to Step 6.
6. Perform turn-of-nut tightening. Mark the nuts and adjacent baseplate and turn the minimum required turn per appendix but do not exceed the verification torque.
7. Confirm verification torque was achieved, or continue to turn nut until verification torque is achieved.
8. Apply retightening torque 48 hours after initial tightening. The retightening torque is 110% of verification torque (1.1×T_v).

Table 1.1. Example of torque turn specification sheet with OH sign anchor bolts and grip lengths

Pole Type	Anchor Bolt Ø	Bolt Type (Galvanized to Spec. 3392)	Baseplate Thickness	Snug Torque (ft-lbs)	Rotation Beyond Snug	Verification Torque, T_v (ft-lbs)	Retightening Torque, T_r 48 Hours After Tightening
Type 5-7 Sign Truss	2-1/2 Inch	Type B Grade 55 Spec. 3385.2B	2 Inches	550	1/12	3,300	3,630

Table 1.1 is a shortened example of the new table provided for MnDOT specifications from the previous project. In the full table, there are 17 different types of structures and 22 different overall installation types. The full Table 1.1 that was provided to MnDOT was intended for contractors as a reference to find the correct values for a particular installation and to work through the eight steps defined above.

The previous project also completed a thorough literature review of current tightening practices along with a survey of various states' tightening procedures (Chen et al., 2018). Based on the prior study, 88% of states with tightening specifications used some form of turn of nut, with eight states lacking any specifications for tightening. Many states used multi-step specifications such as AASHTO LRFD - SLTS 5.17.5.2, going through lubrication, snug tight, and specified turns.

While states may not have common tightening procedures, one thing they did have in common was loose anchor rod nuts. Of 29 states, 80% reported having loose nuts on 1% to 90% of their structures with many states reporting that the deficiencies were due to contractor error and inconsistent practices. For the four states in the survey that reported no loose nuts on their structures, their procedures were different; however, two of them had fairly rigorous contractor verification and inspection to ensure proper pre-tension. Other states that reported loose nuts and subsequently implemented more rigid specifications experienced a decrease in "loosening" of the anchor rod connections but noted that the specifications were costly and time intensive to implement.

CHAPTER 2: LITERATURE REVIEW

This literature review focused primarily on bolted connections in SLTS structure bases. Where limited information was available for double nut connections in civil engineering applications, applicable research from the mechanical and aerospace engineering industries was utilized. In addition, the terms "bolt" and "anchor rod" are not used interchangeably unless discussing a fundamental property. The term "rod" refers to ASTM F1554 threaded rods, while the term "bolt" generally refers to bolts in structural steel connections (usually ASTM 325 or EN 14399) and not foundation connections. Finally, clamping force developed in threaded fastener connections is referred to as "pre-tension," since it is the same terminology as bolting specifications from the structural steel industry. Note that unlike concrete structures, "pre-tension" in this case refers more to the general case of pre-stressing, i.e., inducing a stress into a structure to resist applied loading, and not stressing the member before placement as is commonly used with precast, pre-tensioned, concrete beams.

2.1 IMPORTANCE OF AND BRIEF RESEARCH HISTORY

In the US, concerns about anchor rods in SLTS structures, and particularly cantilevered overhead sign structures (COSSs), arose in the late 1980s and 1990s. Around 1990, several states experienced collapses of COSSs with one recorded fatality (Culp et al. 1990, James et al. 1997, Kaczinski et al. 1998) During the 1990s, fatigue provisions for SLTS structures was studied and summarized in the National Cooperative Highway Research Program (NCHRP) Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Support Structures (Kaczinski et al. 1998). This research went into revising and writing the fatigue provisions in AASHTO LRFD – SLTS. The anchor rod tightening procedures in AASHTO LRFD - SLTS 5.17.5.2 were derived from the Federal Highway Administration's (FHWA's) anchor rod guidelines (Garlich and Thorkildsen 2005), which were derived from several other research projects (Till and Lefke 1994, Johns and Dexter 1998, Dexter and Ricker 2002).

In 2014, the Alaska Department of Transportation and Public Facilities (DOT&PF) looked into the loosening problem and found that the pre-tension loss was likely due to localized yielding of the anchor rods, but no conclusive evidence could be found (Hoisington and Hamel 2014). It is likely other states also experienced loosening before the investigation by Alaska.

Finally, in 2018, the previous study for this project was published (Chen et al. 2018). This study quantified tightening requirements from AASHTO and recommended tightening procedures to MnDOT for greater fatigue loosening resistance.

As far as the importance of proper pre-tensioning, or at least tensioning beyond snug tight, Kaczinski et al. (1998) notes that, when a connection loses pre-tension past the snug-tight condition, it will put more stress on surrounding anchor rods and can lead to wedging of the structure. These actions increase fatigue stress on anchor rods, reduce stiffness in the connection, and lead to failures within the grip length of anchor rods (Dien 1995). Garlich and Thorkildsen (2005) assert that: "When a pre-tensioned joint is subject to cyclic fatigue loads, it acts as if the pieces pressed together were actually monolithic (i.e., the bolts themselves feel only about 20% of the load range), with the majority of the load range transferred through the faying surfaces. When a bolted joint is not properly pre-tensioned, all the load is transferred through the bolts and they may quickly fail by fatigue." As long as a connection is beyond snug tight, there will be lower stresses on the anchor rods, and they will be less likely to fail in fatigue.

In addition to the fatigue loading issues, loose anchor rods present a serviceability problem (Hoisington and Hamel 2014, Chen et al. 2018, Phares et al. 2016). Loose anchor rod nuts cause state DOTs to expend resources on retightening and inspection, with the costs then passed on to the taxpayer.

2.2 ANCHOR ROD PRE-TENSIONING

The four primary methods for anchor rod pre-tensioning are angle-based, torque-based, direct pre-tensioning, and thermal methods. Direct pre-tensioning is generally achieved with a jack and is not covered due to the design and clearance limitations. Tightening can also be completed with a combination of torque and turn. In the aerospace and mechanical engineering industries, computerized wrenches are utilized in critical connections (Bickford 1997). These are also not discussed as many systems are proprietary and not widely used by contractors. Finally, thermal tensioning methods are not covered due to difficulties with field implementation.

2.2.1 Torque-Controlled Pre-Tensioning

The general governing equation for torque-controlled pre-tensioning is Equation 2.1, where *T* is the torque required to be applied to the connection, *F* is the final clamp or pre-tension force, *D* is the diameter of the anchor rod, and *K* is referred to as the "nut constant."

$$F = \frac{T}{KD} \tag{2.1}$$

As covered later in a general review of tightening specifications, almost all torque-controlled procedures depend on a variation of Equation 2.1 given the high degree of empiricism with torque-controlled pre-tensioning.

The nut factor, *K*, is empirical and highly variable. A brief list of variables on which the nut factor depends is presented by the Research Council on Structural Connections (RCSC) in their 2014 Specification for Structural Joints Using High-Strength Bolts as follows:

- Finish and tolerance on the bolt and nut threads
- Uniformity, degree, and condition of lubrication
- Shop or job-site conditions that contribute to dust and dirt or corrosion on the threads
- Friction that exists to a varying degree between the turned element (the nut face or bearing area of the bolt head) and the supporting surface
- Variability of the air supply parameters on impact wrenches that results from the length of air lines or number of wrenches operating from the same source
- Condition, lubrication, and power supply for the torque wrench, which may change within a work shift

- Repeatability of the performance of any wrench that senses or responds to the level of the applied torque

This list represents the known fact that many factors come into play with torque-controlled pre-tensioning. In most cases, it is recommended that nut factors be developed for specific individual installations or wrenches directly calibrated to desired pre-tension with a bolt calibration device. Additionally, many specifications have variations on *K* that are based primarily on frictional coefficients for a set type of bolt.

According to the RCSC, variations in final bolt pre-tensions can vary on the order of +/-40% when uncontrolled pre-tensioning with torque control is utilized (RCSC 2014). Bickford (1997), in An Introduction to the Design and Behavior of Bolted Joints*,* notes that “torque control of preload has obvious limitations and dangers, but in most cases, it will be the only practical or economical choice.” Bickford also asserts that “success in this case [bolt pre-tensioning], is not ‘preload accuracy’; it’s ‘joints which don’t fail.’” Both of these cases illustrate a generally agreed upon fact in the bolting community that torque control is easy and economical to use, but it is highly empirical, requiring proper verification and testing.

2.2.2 Angle/Turn-Controlled Pre-Tensioning

An angle- or turn-of-nut-based approach generally results in less final pre-tension scatter than torque (as noted by Bickford 1997, AASHTO 2015, James et al. 1997, Kulak 2002, and Fisher and Struik 1974, among others). Much of the uncertainty decrease is due to a yielding procedure, which is covered later in the specification review section. Unlike torque control, which is based primarily on force-controlled tightening, angle-based tightening is displacement-based. The turn process treats the threads on a rod as an inclined plane that is advanced as the nut is turned. As the threads are advanced, the anchor rod stretches a predetermined amount. Equation 2.2 is one relationship between turn and pre-tension force.

$$F = \frac{C\alpha P_i AE}{L} \tag{2.2}$$

Much like the torque-pre-tension equation, many different codes use different variables or coefficients, but the underlying displacement principle is the same.

In Equation 2.2, *F* is the final pre-tension or clamp force, *L* is the length of the bolt in the grip length, and *C* is a ratio of bolt stiffness to connection stiffness. *E* is Young’s modulus, P_i is the pitch factor (slope of the threads), and *A* is the tensile area of the fastener. Finally, *α* is the nut turn angle in ratio of a full turn (i.e., 1 is a full turn and 1/6 turn would be 0.1667).

For Equation 2.2 to be valid, the connection must be in firm contact, which is often referred to as the snug-tight condition. The pre-tension that is associated with snug tight is generally about 10% of the yield point of the anchor rod, and it is generally reached by an empirical method or a specified torque. Snug-tight is the initial condition for the anchor rod pre-tensioning with turn control. If the fastener is kept in the elastic range, there can be uncertainty from scatter in the snug-tight condition.

2.3 PRE-TENSION CONTROL AND VERIFICATION

Outside of approximating pre-tension with torque or turn control, there are several methods for verifying or checking pre-tension after installation. The technology in this section is primarily based on Investigation of High-Strength Bolt-Tightening Verification Techniques (Brent Phares et al. 2016) and An Introduction to the Design and Behavior of Bolted Joints (Bickford 1997). Both of these sources contain numerous other references, but for brevity's sake a summary is presented here.

The two methods of verifying pre-tension in this section are representative of accepted and field-implementable solutions for anchor rod pre-tension verification. Other methods that were investigated were strain gauges (vibrating wire, resistance, and optical), permanent load cells/sensing washers, acoustoelastic measurement, tension indicating rods, twist-off connectors, elongation measurement, and magnetic wave detection. These other options were not pursued further because implementation would not likely be feasible or cost effective for the current project. Additionally, many of the methods had more uncertainty than widely used standards.

2.3.1 Direct Tensile Indicating Washers

A relatively simple and accepted method of directly indicating tension in a bolted connection is with a direct tensile indicating (DTI) washer. Almost all bolting codes have a provision for DTI washers and there are several ASTM International standards for them. Traditional DTI washers have rounded, raised bumps or dimples on their surface. During pre-tensioning, the dimples plastically deform as they are compressed. Deformation increases the surface area of the dimples, requiring more load to deform further due to fundamental material properties.

To check the pre-tension, a feeler gauge is utilized to measure the gap between the DTI washer and the baseplate, which can then be correlated directly to the force required to flatten the DTI to its respective thickness. Additionally, DTIs can be calibrated with a known force to produce a specific pre-tension for a certain flattening. The error for these washers is about 10%, which is relatively low when compared to torque- or turn-controlled pre-tensioning. However, DTI installations require both contractor and inspector training on proper procedures and use of feeler gauges. Also, the clearances and design limitations of SLTS bases may limit the accessibility of DTI washer use.

There are also squirter-type DTIs that eject a colored polymer once the dimples are deformed to the specified pre-tension. This type of DTI must be specifically manufactured for one type of bolt and a single pre-tension. Although squirter-type DTIs make for easier installation and inspection, they are currently only produced for structural steel bolts and not for anchor rods.

2.3.2 Bolt/Rod Tension Calibrators

Bolt tension calibrators, while not part of the final installation, serve an important part of the anchor rod pre-tensioning process. In many specifications, if torque is used for pre-tensioning, a tension calibration of the installation will be required at least daily. Tension calibrators, themselves, are a sort of load cell, and commonly a hydraulic-based design.

The calibrators measure a given load and can be approximately correlated back to the torque required to tension the connection. They can also be used to calibrate DTI washers for a predetermined flattening in relation to a desired pre-tension force. Turn-of-nut calibration is somewhat limited, though, because the stiffness of the bolt calibrator will likely not match the true connection stiffness that it is supposed to be replicating. Error in the tension calibrators is in the range of 2–5%, but is not indicative of the final pre-tension accuracy since the tightening tools or measurement devices are being calibrated on it, and it does not remove the inherent inaccuracies with various tightening methods.

2.4 PRE-TENSION LOSS IN BOLTED AND ANCHOR ROD CONNECTIONS

Much like many other aspects of threaded fastener connections, there is a high level of uncertainty, empiricism, and disagreement when considering connection loosening mechanisms. In this review, an overview of losses is presented in two sub sections: service loading and relaxation. The service loading section covers pre-tension loss from fatigue and dynamic loads with a brief review of loosening theory. Relaxation covers stress loss from immediate and long-term relaxation of anchor rods.

2.4.1 Pre-Tension Losses from Service Loading

Much like anchor rod pre-stressing, pre-tension loss in threaded fastener connections is fairly empirical and difficult to accurately predict, with many confounding variables. Overall, there are generally three accepted loosening conditions: axial loading, transverse loading, and combined (Bickford 1997). In SLTS structures, the forces in the anchor rods are primarily axial. Base shear forces causing transverse loading on anchor rods also occurs to varying degrees in SLTS structures, but they generally are less than 10% of the axial forces induced.

While theories on loosening vary, they generally agree that proper pre-tension can prevent, or highly reduce, loosening, and that transverse loading is generally the most detrimental for bolted connections. Note that the majority of loosening research has been conducted on bolted connections, not double nut foundation rods, so extrapolation of results, especially from transverse loading, is approximate.

The majority of bolted connections in the structural steel and, for that matter, other industries are designed for fastening two or more pieces of material together. For this reason, a majority of testing and standard testing procedures are focused on the transverse loosening condition. In general, the majority of pre-tension loss in transverse loading appears to occur when the “slip” condition is reached (i.e., the frictional force holding the plates together is overcome by the applied load, making the plates slip). There are many theoretical causes for this loosening (Rodriguez Lopez et al. 2018, Bickford 1997, Jiang et al. 2003), but it is difficult to definitively prove any one theory. The Junker vibration tester (Junker 1969) is an accepted standard for testing the loosening behavior of bolted connections under transverse loading (DIN 2015).

Axial load loosening has also been studied to some degree, while not as intensely as transverse loosening. Most sources agree that, if a threaded fastener is pre-tensioned to 20% beyond the anticipated fatigue loading, there will be little to no loosening (Fisher and Struik 1974, Bickford 1997). In axial loading, for pre-tension loss, compression cycles will be the most damaging, since they can essentially remove the net pre-tension from the connection, resulting in less resistance to possible transverse shear loads and nut turning. The primary fatigue loosening mechanism of pure axial loading is generally theorized as localized plastic yielding of threaded connections, which decreases the elongation and pre-tension of the fastener (Hoisington and Hamel 2014, Bickford 1997). In a study of high mast light towers (HMLTs) in Alaska, local plastic yielding was the primary loosening mechanism cited (Hoisington and Hamel 2014).

2.4.2 Pre-Tension Losses from Relaxation

Much like other materials under constant loading, there will be some degree of immediate and long-term relaxation and creep for anchor rods after pre-tensioning. The AASHTO LRFD – SLTS currently recommends that connections are retightened 48 hours after original pre-tensioning. From several sources (Fisher and Struik 1974, Bickford 1997, Yang and Dewolf 1999, Nijgh 2016, Till and Lefke 1994), total preload loss for high strength bolts will be in the range of 5 to 50%, depending on many factors. Additionally, pre-tension loss is a time-dependent process and generally follows a log-power pattern no matter the degree of loss.

One major source of loss stems from the thickness of the galvanized coating (Yang and Dewolf 1999). After 42 days, Yang and Dewolf found that the total relaxation of 7/8" A325 high-strength bolts was about 5% for uncoated bolts and 20% for bolts with a 20 mil (0.020 in.) galvanized coating.

Embedment of the galvanizing surfaces is also a critical factor along with the grip length and bolt diameter (Nijgh 2016). Nijgh found that a lower grip-length to bolt-diameter ratio, which is typical of MnDOT double nut connections, led to greater pre-tension losses. This behavior was due to the increased stiffness of the bolts and higher pre-tension levels, leading to increased plate embedment and creep. Retightening for anchor rods is generally recommended in the first 2 to 5 days, which represent approximately 90% of the total lifespan pre-tension losses due to the power distribution of loss (Munse 1967, Fisher and Struik 1974, Yang and Dewolf 1999). Overall, pre-tension loss likely occurs primarily due to creep and relaxation of the surface finish, which may be exacerbated due to the high pre-tension forces used in MnDOT's SLTS structure connection geometry.

2.5 IMPLEMENTATION STUDIES AND INTERVIEWS

While there are many theoretical and laboratory-tested high-strength anchor rod pre-tensioning tests, far fewer field implementation studies exist on which to base the specifications. Previous studies often completed state and industry interviews for an inventory of anchor rod and bolt pre-tensioning practices (James et al. 1997, Chen et al. 2018, Hoisington and Hamel 2014). In the previous Phase I research study for this project (Chen et al. 2018), the researchers found that procedures varied widely from state to state, most states experienced loose nuts, and many states believed that a lack of quality assurance/quality control (QA/QC) during the original installation was the primary reason for the loosening. Both James et al. (1997) and Phares et al. (2016) received similar responses from both industry and state DOTs, respectively.

An interesting quote from Phares et al. regarding a response to their survey, from the Alaska DOT&PF, was: “Bolts not being torqued to the correct tension requirements or not at all. In this case, the entire splice is checked with the manual torque wrench. (This is not required by the Alaska DOT&PF specification. This is something I have adopted as a deterrent for a contractor not doing their QC prior to my inspectors doing the spot checks… the contractor’s personnel are more likely to make sure all the bolts are torqued.)”

Most literature also agrees that proper pre-tensioning of large-diameter, high-strength anchor rods is not feasible without a hydraulic torque wrench, regardless of whether torque- or tension-controlled pre-tensioning is used (Hoisington and Hamel 2014, Garlich and Thorkildsen 2005). Finally, the difficulty with documentation of installations with a few anchor rods is noted by Garlich and Thorkildsen’s 2005 FHWA report: “In addition, unless a contractor is erecting a group of sign structures, only a few high strength bolts may be needed. Where the quantity of fasteners is small, it may not be realistic to expect the same bolt documentation and testing as would be provided on a steel bridge erection project.” Note that this report is referring to anchor rods of SLTS structures even though “bolt” terminology is used. When all of the previous interviews and field experience are considered, significant difficulties are seen in communicating and implementing an effective anchor rod pre-tensioning specification.

2.6 MECHANICS OF PRE-TENSIONED DOUBLE NUT CONNECTIONS

As briefly discussed in the turn-of-nut tightening section, the total displacement is based on C, or the ratio of rod to baseplate stiffness. The stresses and strains in anchor rods depend both on the baseplate and the anchor rod and can be modeled as a set of springs in parallel (Culpepper 2009). This concept is illustrated in Figure 2.6.1 with k_b representing the baseplate stiffness and k_r representing the rod stiffness.

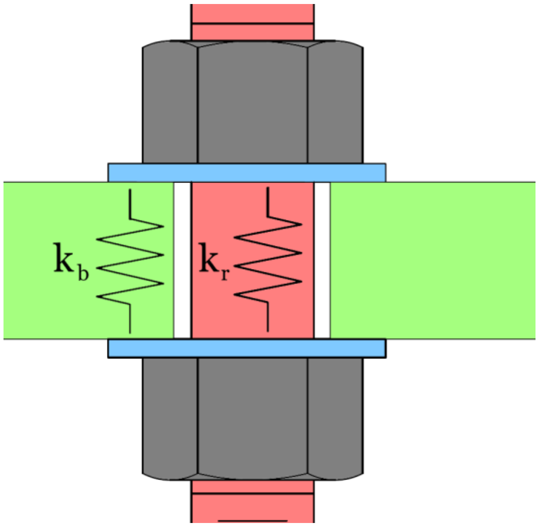


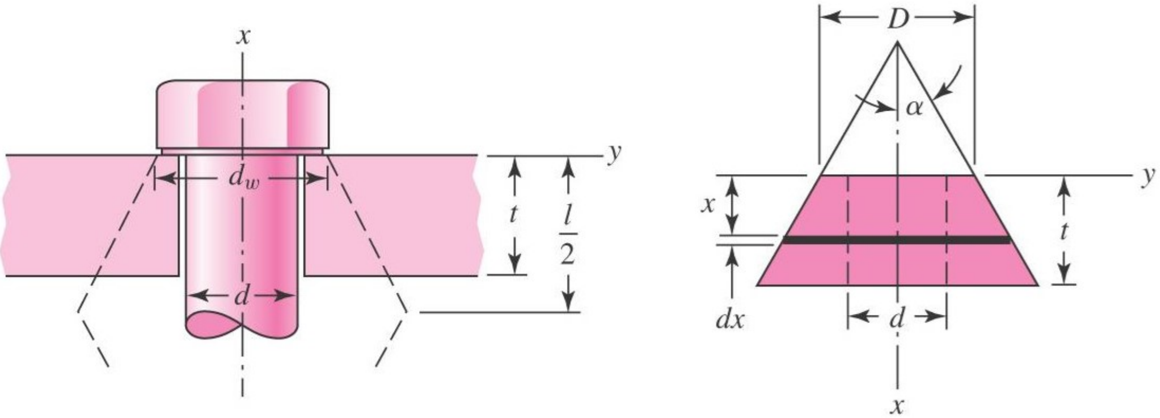
Figure 2.6.1 Double nut connection stiffness

The stiffness of the anchor rod is simply calculated with Equation 2.3 from mechanics of materials.

$$k_r = \frac{A_t E}{l_t} \tag{2.3}$$

In Equation 2.3, A_t is the tensile area of the anchor rod, E is Young's modulus, and l_t is the grip length plus 1 thread into the nut.

Stiffness of the plate must be calculated considering the stiffness distribution in the baseplate, which can be approximated as a cone, called a frusta, extending out from the exterior of the washer (Budynas et al. 2015). For a typical bolt, the stress distribution and variables are shown in Figure 2.6.2.



Budynas et al. 2015

Figure 2.6.2 Stress distribution of a typical half bolt connection

To adapt this model for a double nut connection, *t* would be taken as ½ of the baseplate thickness with 1 washer thickness included, and l_t would be ½ of the total grip length plus 1 thread into the nut. The aspect ratio of the stress distribution is taken as 30 degrees since this compares closely to FEM analysis (Budynas et al. 2015).

In the case of this derivation, the stiffness of the washers is included in the frusta, since they have approximately the same Young's modulus. With the washer included, the flat dimension of the heavy hex nut then becomes the *D* or *dw* (refer to Figure 2.6.2 for typical dimensions) (ASME 2010). Note that this formula does not take into account the galvanized coating due to complex creep and relaxation impacts.

Baseplate stiffness, K_b, can be found by integrating the half frustum area as outlined in Equations 2.4 (integration), 2.5 (unit area of frusta), 2.6 (integration to find displacement from applied *P*), and 2.7 (individual frusta thickness). Note that *P* is the pre-tension force and *E* is Young's modulus.

$$d\delta = \frac{Pdx}{EA} \tag{2.4}$$

$$A = \pi(x\tan\alpha + \frac{D+d}{2})(x\tan\alpha + \frac{D+d}{2}) \tag{2.5}$$

$$\delta = \frac{P}{\pi E}\int_0^t \frac{1}{(\tan\alpha + \frac{D+d}{2})(x\tan\alpha + \frac{D+d}{2})}dx \tag{2.6}$$

$$k = \frac{P}{\delta} = \frac{\pi E d \tan\alpha}{\ln\frac{(2t\tan\alpha + D - d)(D + d)}{(2t\tan\alpha + D + d)(D - d)}} \tag{2.7}$$

Since the connection is symmetric, the two stiffnesses can be added in series, and the variables from the connection can be substituted in, giving Equation 2.8 for the baseplate stiffness.

$$k_b = \frac{\pi E d \tan\alpha}{2\ln\frac{(l\tan\alpha + d_w - d)(d_w + d)}{(l\tan\alpha + d_w + d)(d_w - d)}} \tag{2.8}$$

Using Hooke's Law for springs in parallel, the stiffness constant, *C*, can then be found, as shown in Equation 2.9.

$$C = \frac{k_r}{k_r + k_b} \tag{2.9}$$

C is the proportion of the total external load that will be transferred through the bolted connection grip length. For example, in a double nut connection, if *C*=0.2, the pre-tensioned interior anchor rod grip length forces would be approximately 20% of the forces transferred from the structure to the baseplate through the standoff anchor rod distance.

Looking into the mechanics of the anchor rods brings up an interesting observation. In a typical slip critical pre-tensioning application, in structural steel, a bolt acts purely as a fastener, clamping two structural members together. In SLTS structures, the anchor rods are acting as both a fastener and a structural member.

With a structural tension connection, the primary fatigue loosening mechanism is from compression cycles on the bolts, which only occurs when the structural members are in compression. Tension, in a typical axial structural steel connection, will increase the preload in the anchor rod and, unless plastic yielding takes place, likely have minimal impact on a well-designed connection. With anchor rods though, both the tension and compression forces will have an impact on the loosening of the structure. Compressive forces will loosen the top nuts, while tensile forces will theoretically loosen the leveling nuts, possibly imparting increased damaging fatigue cycles on the connection.

2.7 NATIONAL AND INTERNATIONAL BOLT PRE-TENSIONING SPECIFICATIONS

The review of specifications primarily focuses on standards in the US, but also covers procedures used around the world. Materials and hardware dimensions are only reviewed giving imperial sized connections.

2.7.1 American Association of State Highway and Transportation Officials (AASHTO)

In the US, the current prevailing specification for pre-tensioning high strength anchor rods in SLTS structures is AASHTO LRFD – SLTS 15.6.3, which states: "All anchor bolts shall be adequately tightened to prevent loosening of nuts and to reduce the susceptibility to fatigue damage. Anchor bolts in double-nut connections shall be pre-tensioned. Anchor bolts in single-nut connections shall be tightened to at least one half of the pre-tensioned condition. Anchor preload shall not be considered in design." (AASHTO

2015). All pre-tensioning procedures are in the commentary section of the same specification and are primarily based off of Garlich and Thorkildsen (2005), with considerations from other references.

Keeping tightening practices in the commentary is likely wise of AASHTO, since specific procedures can be difficult to implement and leaves options open for individual states, which have a wide variety of SLTS bases. The AASHTO commentary tightening steps are based on a turn-of-nut procedure with a torque verification at the end and a recommended 48-hour retightening torque to account for creep in the galvanizing surface. Anchor rods are pre-tensioned to 0.5 Fy for Grade 36 rods and 0.6 Fy for 55 and 105 rods. Turn of nut is completed based on the grade and diameter of an anchor rod, as shown in Table 2.7.1.

Table 2.7.1. AASHTO top nut rotation for turn-of-nut specification

Anchor Bolt	**Nut Rotation beyond Snug-Tight**	
Diameter	**F1554 Grade 36**	**F1554 Grades 55 and 105, A449, A615, and A706 Grade 60**
≤$1^1/_2$ in.	1/6 turn	1/3 turn
>$1^1/_2$ in.	1/12 turn	1/6 turn

Notes: Nut rotation is relative to anchor bolt. The tolerance is plus 20 degrees ($^1/_{18}$ turn). Applicable only to double-nut moment connections. Use a beveled washer if the nut is not in firm contact with the base plate or if the outer face of the base plate is sloped more than 1:40.
Source: AASHTO 2015

Torque verification is completed using a derivation of the previously described processes using a nut factor, *K*, of 0.12. Additionally, AASHTO provides an option to use DTI washers conforming to ASTM F2437 for grade 55 and 105 anchor rods. AASHTO recommends that DTI washers be used on the leveling nuts to ensure proper pre-tension throughout the connection.

2.7.2 Other US Structural Connection Pre-Tensioning Standards

Besides those from AASHTO, the American Institute of Steel Construction (AISC) and the RCSC have the leading structural bolting procedures in the US. Since most AISC procedures are based on those from the RCSC, the RCSC specification is primarily covered here. The RCSC specification sets a minimum required bolt pre-tension, which unlike AASHTO, is 0.7 of the minimum bolt tensile strength. The RCSC allows for four different pre-tensioning techniques: turn-of-nut, calibrated wrench (torque), twist-off control bolts, and DTI washers. The RCSC notes that there is no method preference as long as the procedures are performed according to the specification, although turn-of-nut is indicated as more accurate. Twist-off specifications are not covered in this review since they are not applicable to foundation anchor rods.

The RCSC procedure for all pre-tension methods is inherently more accurate due to the degree of pre-tension; since bolts reach the upper inelastic portion of the stress-strain curve using the RCSC specification/procedures, the pre-tension values do not change linearly with increased turns or torques, which results in less pre-tension scatter (Fisher and Struik 1974, Bickford 1997).

The AISC and RCSC turn-of-nut specification is shown in Table 2.7.2 and is based on the bolt length and slope of the connection.

Table 2.7.2. Nut rotation from snug-tight condition for turn-of-nut pretensioning[a, b]

Bolt Length[c]	Disposition of Outer Faces of Bolted Parts		
	Both faces normal to bolt axis	One face normal to bolt axis, other sloped not more than 1:20[d]	Both faces sloped not more than 1:20 from normal to bolt axis[d]
Not more than *4d*[b]	½ turn	½ turn	% turn
More than *4d*[b] but not more than *8d*[b]	½ turn	% turn	% turn
More than *8d*[b] but not more than *12d*[b]	% turn	% turn	1 turn

[a] Nut rotation is relative to bolt regardless of the element (nut or bolt) being turned. For all required nut rotations, the tolerance is plus 60 degrees (¼ turn) and minus 30 degrees.

[b] Applicable only to joints in which all material within the grip is steel.

[c] When the bolt length exceeds 12 db, the required nut rotation shall be determined by actual testing in a suitable tension calibrator that simulates the conditions of solidly fitting steel.

[d] Beveled washer not used.

Source: RCSC 2014

The snug-tight condition is defined as "firm" contact between the structural members being connected. In Table 2.7.2, the sloped connection details could likely be negated, since SLTS structure anchor rods should not be installed past 1:40 out of plumb.

For calibrated wrench (torque-based) installations, the RCSC requires that wrenches and connectors be calibrated with a bolt tension calibrator to meet the minimum pre-tensions daily under any of the following conditions:

- When the lot of any component of the fastener assembly is changed
- When the lot of any component of the fastener assembly is relubricated
- When significant differences are noted in the surface condition of the bolt threads, nuts, or washers
- When any major component of the wrench including lubrication, hose, and air supply are altered.

While this may seem a fairly intensive specification, for the number of bolts in structural erections and to ensure the accuracy of pre-tension, it is commonly viewed as fairly reasonable.

Finally, the RCSC allows for DTI installations according to ASTM F959. Note this is a different standard than the DTIs for anchor rods and can also include indicating, or "squirter" type, DTIs that provide correct pre-tension by ejecting a colored polymer when correctly pre-tensioned.

2.7.3 State Special Provisions

The previous project (Chen et al. 2018) covered different state practices for anchor rod pre-tensioning and found a wide variety of procedures. Some states specified torque, while others used turn-of-nut, some used DTI verification, and three left the nuts at snug-tight. For the 42 states that were found to have specifications online, 37 of them used turn-of-nut with the majority being based on AASHTO recommendations. As discussed in Chen et al. 2018, some states inspected installations after or during installations and had requirements similar to those from the RCSC.

Also from the previous project, states that specified minimum pre-tensions and had rigorous verification techniques appeared to have less of an issue with under pre-tensioned anchor rods. In addition, many of these states left the tightening method up to the contractor, requiring verification through a bolt tension calibrator. These verification techniques were often fairly draining on resources, and a couple of states conceded that the techniques are not always followed and that inspection after installation is difficult (Chen et al. 2018).

2.7.4 European Practices

European practices are generally based on EN 1090-2: Technical Requirements for the Execution of Steel Structures (CEN 2018). EN 1090-2, much like standards from the AISC and RCSC, specifies structural bolts be pre-tensioned to 0.7 of the minimum tensile strength of the bolt. Pre-tension can be induced with a torque method, a combined torque-turn method, DTIs, or twist-off fasteners. The Eurocode also uses a k class for each pre-tensioning method to designate the calibration and testing required for the installation. K0 is least rigorous with no requirement. K1 is the next most rigorous with an approximate range of nut factors for the fasteners tested by the manufacturer. Finally, K2 is the most rigorous with a mean test value for the nut factor required along with the standard deviation (DIN 2006). K2 also requires wrench calibration and certain fastener storage on site.

Torque control in EN 1090-2 requires K2 fasteners and is performed in three steps. The first step is snugging the installation. Second is 75% of the maximum toque. Lastly, 110% torque is applied. The 110% is to account for the immediate relaxation.

The combined method uses the first step of the torque method followed by the nut turns specified in Table 2.7.3.

Table 2.7.3. Standard Eurocode turns

Total nominal thickness *t* of parts to be connected (including all packs and washers) ***d*** **= bolt diameter**	**Further rotation to be applied, during the second step of tightening**	
	Degrees	**Part turn**
$t < 2d$	60	1/6
$2d \leq t < 6d$	90	1/4
$6d \leq t \leq 10d$	120	1/3

Where the surface under the bolt head or nut (allowing for taper washers, if used) is not perpendicular to the bolt axis, the required angle of rotation should be determined by testing.
Source: CEN 2018

The combined method is a K1 class. The turns are based only on the grip length and require testing for any angled installations.

2.7.5 Other Country Practices

Most other countries around the world have adopted a version of the Eurocode or RCSC specifications.

2.8 CONCLUDING POINTS

- There are many accepted and proven procedures for accurate and repeatable anchor rod pre-tensioning in addition to the ones recommended in the previous study (Chen et al. 2018).
- While many states may have sufficient specifications, without proper communication and verification techniques, it is likely that they are not being implemented or that they are being ignored by contractors in the field.
- Pre-tension loss from loading can generally be negated with proper pre-tensioning force; however, there are many uncertainties with both torque- and turn-controlled anchor rod pre-tensioning.
- Relaxation and creep pre-tension loss have potentially greater impact than fatigue for MnDOT's connections.
- Error in both torque- and turn-controlled pre-tensioning can be minimized with proper procedures.
- There is an acceptable range of error in pre-tensioning between plastic yielding and approximately snug tight (about 10% yield) when there is little recorded impact on fatigue resistance.

Considering both the literature and the previous project, it is likely that successful anchor rod tightening specifications need to be effective, constructible, and verifiable. An effective specification would ensure the proper anchor rod pre-tensioning force, so that the SLTS structure will not loosen over its lifespan. Constructability is also a major key, ensuring that the specification is able to be implemented in the field. Finally, the procedures need to be verified to check on proper installation, motivate contractors to properly perform the tightening, and provide a record for asset management.

CHAPTER 3: IMPLEMENTATION OF PROPOSED PROCEDURES FROM PREVIOUS PROJECT

This chapter is divided into four sections: Methodology, Overhead Signs Structures, Lighting and Traffic Signal Structures, and Concluding Points. The Overhead Sign Structures and Lighting and Traffic Signal Structures sections are each split into two subsections for Installation and Maintenance procedures.

3.1 METHODOLOGY

Implementation of the specifications proposed through the previous project was designed to refine the processes in the field and ensure the constructability of both maintenance and installation procedures. All of the steps in the process followed the flowchart in the Burati et al. (2003) FHWA report.

For this project, training of technicians and iteration of the specification took place. To assist with implementation, videos, handouts, and QA/QC sheets were created referring to the new specifications. Multiple site visits were scheduled with MnDOT assistance for both overhead signs and lighting structures. The installation processes were specified to follow the new specification delivered to MnDOT through the previous project (Chen et al. 2018).

Before any maintenance on the structure, the connection is checked for inadequate clamping force by striking two opposite edges of the top and leveling washer with a pick (Figure 3.1.1).

Figure 3.1.1 Checking for clamping force in connection

If the washer moves, it indicates there is not sufficient clamping or pre-tension force in the connection. If washers were found with inadequate tension, a modified installation procedure was used as follows: Instead of snugging the nuts in two steps, nuts were taken off one at a time, lubricated with the specified grease, and turned back down to snug tight before repeating the procedure with the next nut. When following this procedure, it was important to only remove one nut at a time to ensure the structure was sufficiently clamped to the base at all times and therefore stable. After all nuts were snug tight, the normal specification procedure could be followed (Steps 6–8).

In addition to the modified maintenance procedure, instructional materials were developed to train technicians on the new specifications, following the procedure in Burati et al. (2003). Videos on the new specifications, overhead signs, and lighting structure installation were created based on installation experience and posted to the MnDOT website. The installation specification sheet for contractors was also uploaded for reference when installing new structures. Procedures for maintenance were sent to MnDOT, and maintenance personnel worked with the researchers to train on the new procedures.

For both overhead signs and lighting structures, the maintenance clamping force check with a pointed hammer has a couple of underlying inaccuracies. Control of force applied to the washer is difficult, as every worker will strike the edge of the washer with different magnitudes of force and at different angles. Also, there will be varying frictional coefficients between the washer and nut due to weathering. Finally, the washer could be pushed up against the anchor rod when striking, possibly not moving even when the connection is inadequately tensioned. Even with the inherent inaccuracies, this method presents a relatively simple and effective way of checking the clamping force in a connection.

Garlich and Thorkildsen (2005) checked for nut looseness also with a hammer, but by hitting the nuts and listening for a “dull” noise. While this method is effective for finding loose nuts, according to Garlich and Thorkildsen, it cannot differentiate between the snug-tight and pre-tensioned condition of the rod. In addition, in many older and unlubricated installations, the nuts could be rusted or corroded to the anchor rod, making it seem like the nut is still tight, but not tensioned. With both of the methods, there is significant subjectivity, but they remain a simple and fast solution to investigate whether there is any pre-tension in the anchor rod.

The notation for referring to anchor rod numbers is based on traffic direction. Facing traffic perpendicularly, numbering starts at the top left anchor rod and goes around clockwise. Figure 3.1.2 illustrates an example for a 12-rod structure.

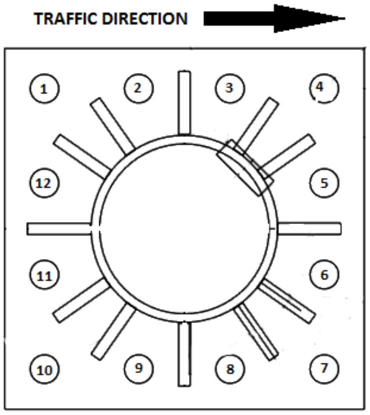


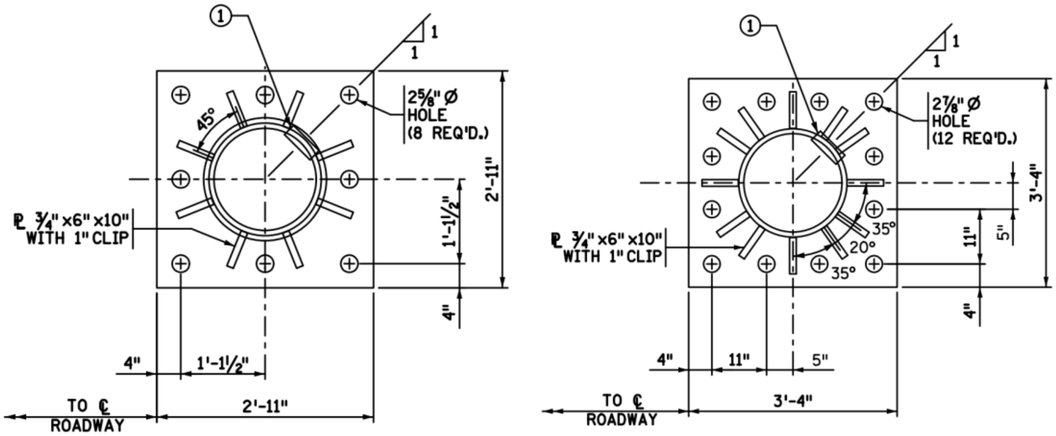
Figure 3.1.2 Example of anchor rod numbering notation on a 12-rod baseplate

3.2 OVERHEAD SIGN STRUCTURES

3.2.1 Installation

3.2.1.1 Installation Observation – 10/24/2018 and 10/25/2018

The first step of the implementation project consisted of observing the installation of two overhead sign structures on October 24 and 25, 2018. One of the structures was a cantilevered structure (OH 280-023) with a MnDOT Type B, 8-2 1/4" diameter anchor rod baseplate (Figure 3.2.1 left). The other was a sign truss (OH 94-689) with two MnDOT Type A, 12-2 1/2" diameter anchor rod baseplates (Figure 3.2.1 right).



MnDOT 2019

Figure 3.2.1 MnDOT Type B OH sign base (left) and MnDOT Type A OH sign base (right)

Grade 55 anchor rods were used in both installations. Both of the structures were installed by Global Specialty Contractors of Eagan, Minnesota. Both structures were installed at night due to traffic control requirements. Before the installation of the posts, the leveling nuts were leveled as illustrated in Figure 3.2.2.

Figure 3.2.2 Leveling nuts on sign truss structure (left) and final installation of COSS out of plumb (right)

Figure 3.2.2 (left) illustrates the leveling process on the full truss sign structure. The leveling procedure proceeded without any issues.

On OH 280-023, the cantilevered sign, more difficulties arose while leveling. The majority of the issues originated from a couple of the anchor rods that were out of plumb, but within the 1:40 limit. Figure 3.2.2 (right) illustrates that, even with the leveling efforts, the final installation on the COSS was slightly out of plumb. In addition to leveling the structure, standoff distances were also verified.

After leveling, the installation and placement of the sign structure, anchor rods, washers, and nuts could be lubricated. In the contractor's previous experience, only the anchor rods were lubricated, which would result in significantly greater friction while tightening. A copper anti-seize spray was used as the lubricant for the installation. While this was not the MnDOT-specified lubricant, spray copper anti-seize has a nut factor approximately the same as the approved lubricant, so it is possible that the pre-tension force that developed in the anchor rods was still sufficient to prevent loosening. Figure 3.2.3 (left) and (right) shows the lubricated anchor rod connection and the lubricant used, respectively.

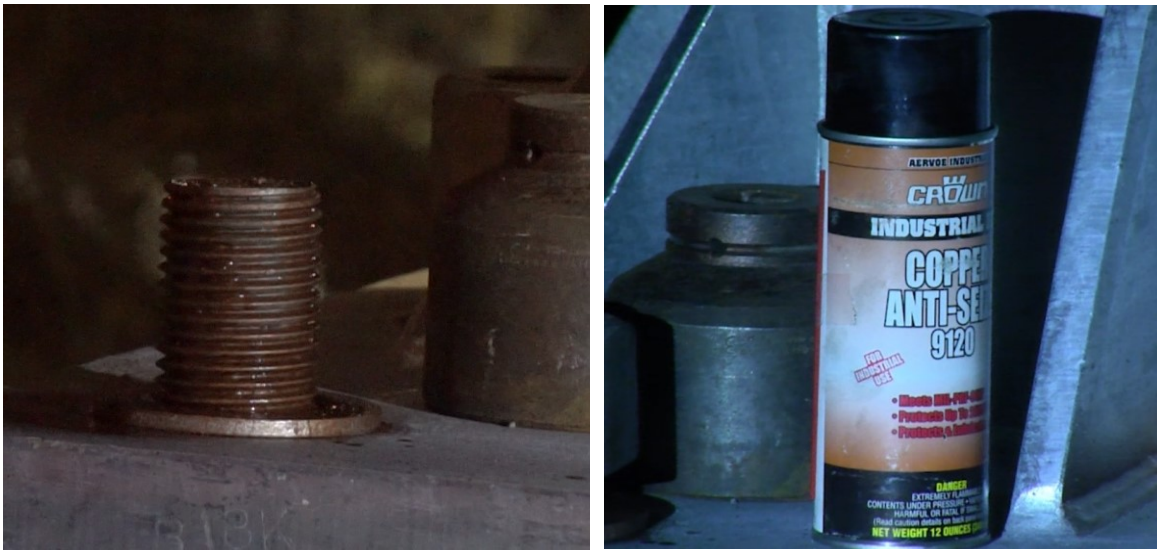


Figure 3.2.3 Lubricated anchor rod connection (left) and lubricant utilized (right)

After lubrication, the leveling nuts were approximately snugged with a pipe wrench (Figure 3.2.4 left).

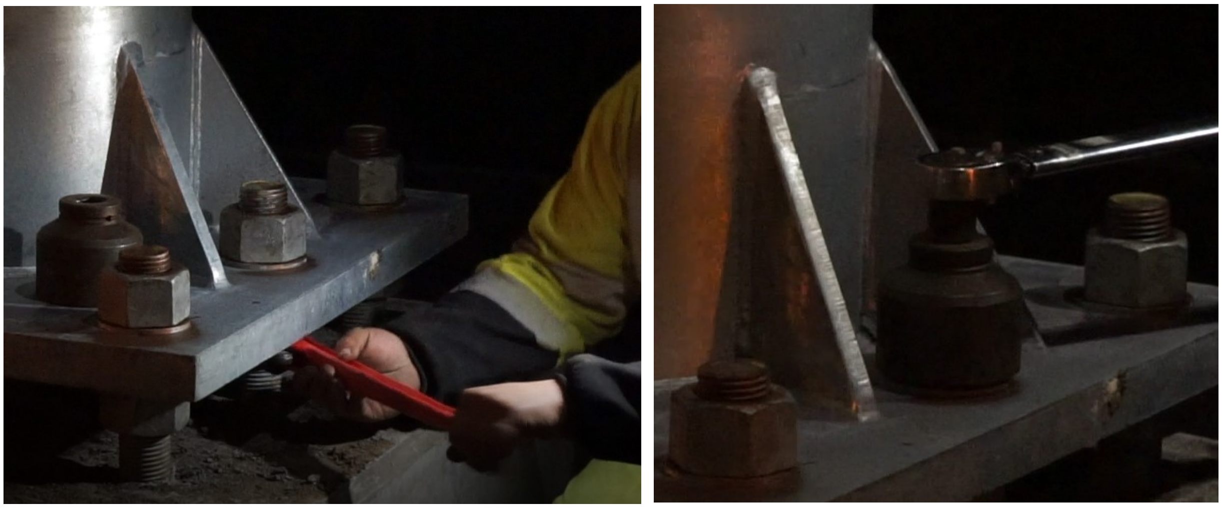


Figure 3.2.4 Tightening leveling nuts with pipe wrench (left) and snugging top nuts with a calibrated wrench (right)

A pipe wrench, while not ideal, was utilized due to clearance issues; also, a large enough open-ended, calibrated wrench was not available during the installation. After snugging the bottom nuts, the top nuts were brought to snug tight in two steps using a calibrated wrench (Figure 3.2.4 right). For both steps and all following tightening steps, a star tightening pattern was utilized to ensure stresses were equally distributed in the anchor rod connections. The star pattern was new to the contractor but was followed after letting them know the significance of the step.

After snug-tightening, the contractor marked each rod and nut as reference for the turn-of-nut tightening (Figure 3.2.5 left).

Figure 3.2.5 Marking each rod and nut as reference for the turn-of-nut tightening (left) and tightening using a hydraulic wrench (right)

Anchor rods were pre-tensioned in two steps of 1/24 turn each for a full rotation of 1/12. After full application of the specified turns, the verification torque was applied to each rod. For the tightening steps, a hydraulic wrench was required due to the high torque required to achieve the turns (Figure 3.2.5 right).

After all of the steps were completed, both the contractor and inspector signed the verification form to ensure the quality of the entire new tightening process. Note that this form was signed before the 48-hour retightening torque was applied, and it was implied that the 48-hour retightening torque would be applied.

Overall, the contractors commented that the specifications were straightforward and fairly easy to follow. The only deviation from the specification was the lubrication type, and slight out-of-plumb installation of OH 280-023. For the lubrication specification, in this case, the grease is not for removals in case of a knock down like with breakaway pole bases, so if the nut factor with a different lubricant is sufficient, it is possibly acceptable to use it. Further laboratory research on the specific impact that lubrication has on the nut factor will need to be investigated.

3.2.1.2 Pre-Tension Loss Check at Various Installation Sites

Nine months after installation of both the OH sign structures, they were checked again to ensure that no nuts had come loose. Additionally, four additional OH sign structures that had been subsequently installed were also inspected. The nuts were checked with the typical procedure of striking washers with a hammer. Table 3.2.1 outlines the structures inspected, the year installed, and any notes on the inspection.

Table 3.2.1. New procedure installation inspection summary

Structure	Structure Type	Month/Year Installed	Inspection Date	Inspection Notes
OH MN 36-090	OH Cantilever	5/2019	10/2019	No Loose Nuts
OH I-94-688	OH Cantilever	10/2018	10/2019	No Loose Nuts
OH I-94-689	OH Sign Truss	10/2018	7/2019	No Loose Nuts
OH I-35-318	OH Sign Truss	4/2019	10/2019	No Loose Nuts, #5 out of plumb
OH 280-023	OH Cantilever	10/2018	7/2019	No Loose Nuts, #8 out of plumb
OH MN 51-013*	OH Cantilever	8/2017	7/2019	No Loose Nuts

*Monitoring structure was approximately installed with AASHTO turn-of-nut procedures

Of the six structures investigated in Table 3.2.1, none had loose top nuts, and the only defects found were out-of-plumb anchor rods on two of the structures. The time between installation and inspection ranged from two years to around 4 months. OH I-35-318 and OH MN 36-090 were installed in early 2019, according to MnDOT, and show that the contractors are learning and implementing the new procedures well, since they were installed without any guidance from the research team.

During July 2019, both of the OH sign structures observed in October of 2018 were inspected to ensure that no nuts had come loose with the new procedures. The full-span truss sign I-94-689 was found to have no loose nuts after checking both the top and leveling nuts. On the COSS OH 280-023, all of the nuts were tight, but, after inspection of the leveling nuts, it was found that nut 8 was slightly angled with the rod itself out of plumb (Figure 3.2.6), likely causing the issue.

Figure 3.2.6 Out-of-plumb anchor rod on COSS OH 280-023

When further investigated, it was discovered that the leveling of this particular installation took about 30 minutes and the final installation was slightly out of plumb as shown previously in Figure 3.2.2. The decreased clamping force in connection #8 of this structure may cause additional stresses in the surrounding anchor rods and could be inspected on an increased schedule as a case study.

In October 2018, three additional overhead signs that were installed with the new procedures were inspected. While more signs were installed than inspected, these three were visited given accessibility. All three of the signs had sufficient pre-tension in the anchor rods, but rod #5 on OH I-35-318 was slightly out of plumb. In Figure 3.2.7 (left), the leveling washer of rod #5 appeared to have space between it and the baseplate when compared to Figure 3.2.7 (right), which is rod #8 on the same structure. Note that the space between the washer and the nut is due to the geometry of the nut.

Figure 3.2.7 Gap between baseplate and washer #5 out of plumb (left) and bolt #8 plumb for reference (right)

When striking the washer on rod #5, it was not found to be loose, so the perceived gap may have been due to manufacturing tolerances or concavity caused by embedment.

The rest of the installations completed without observation by the research team were in good condition. As an example of an ideal structure, OH I-94-688 was installed exactly to specification, even with the turn-of-nut marks still visible on the nuts (Figure 3.2.8).

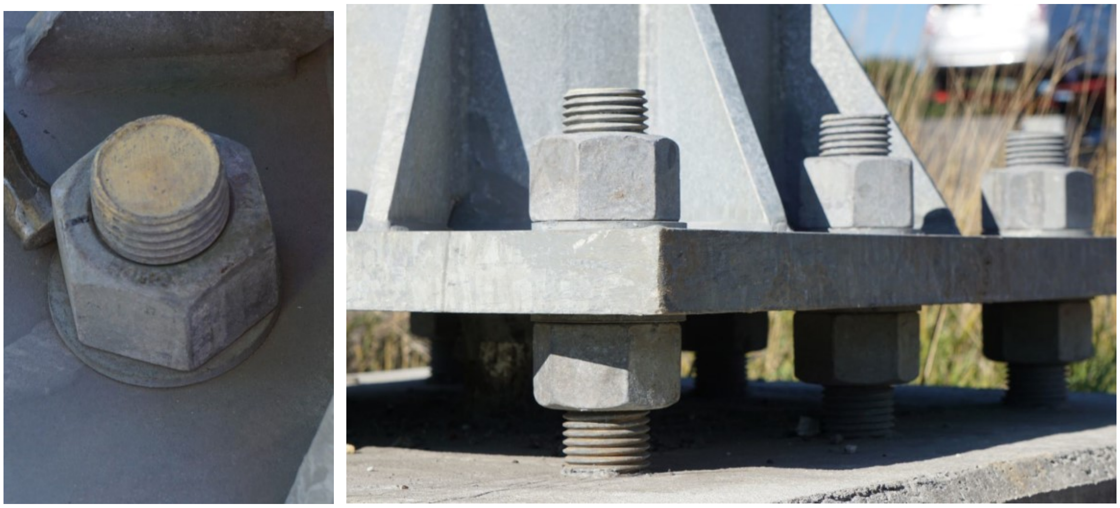


Figure 3.2.8 Turn-of-nut marks on nut (left) and baseplate of OH I-94-688 (right)

The successful installations indicate that the contractors are following the new specifications fairly well; however, knowing exact torques, lubricant, and the tightening pattern used is not possible when inspecting the structure months or years after installation.

Of all existing structures, the monitoring one, OH MN 51-013, is interesting due to the fact that it was tightened using AASHTO turn-of-nut procedures. In the first phase of this study (Chen et al. 2018), the anchor rods for this structure were pre-tensioned with 1/6 turn of nut using AASHTO procedures. This resulted in bringing the anchor rods to 70% of their yield strength, as they were mistaken as grade 105, not 55, during pre-tensioning. Although the final pre-tension is higher than expected, there has been little to no loosening of the monitoring structure. This may indicate that the pre-tension loss in connections may not be from the AASHTO procedures themselves but more so the implementation and inspection.

3.2.2 Maintenance

3.2.2.1 Existing Condition Inspections

For a comparison to the new installations and to get an approximate idea to the extent of the difficulties with maintaining existing structures, eight structures that were previously installed and maintained were inspected for looseness in the fall of 2019. Inspections were completed in the typical manner of striking the washer with a pick type hammer and observing if the washer moved.

From Table 3.2.2, it is clear that the old procedures were resulting in loose nuts on in-place structures.

Table 3.2.2. Loose nuts on inspected existing structures

Structure	Structure Type	Loose Nuts (Shaded)											
		1	2	3	4	5	6	7	8	9	10	11	12
I-94-601 EB	OH Sign Truss												
I-94-602 EB	OH Sign Truss	X	X	X					X	X	X		
I-94-608 EB	OH Sign Truss			X									
I-94-608 WB	OH Sign Truss												
I-94-606 WB	OH Sign Truss							X				X	X
I-494-153 EB	OH Sign Truss*	X		X				X	X				
I-494-199 EB	OH Cantilever												
I-494-188 EB	OH Cantilever	X	X	X	X	X							X

X=loose nuts
*Legacy design of four rod groups on two sides (8x2)

Noting markings on the structures, the I-94 structures were all retightened in 2015, and the I-494 structures were retightened in 2014. This indicates that, in the past 5 years, about half of the retightened signs re-loosened when the old maintenance procedures were followed.

The variability and weather impacts on pre-tension can also be observed through differences in the Iowa State University (ISU) inspections and the MnDOT inspections for the I-494 structures. Many of the structures that were investigated by the research team had been previously inspected by MnDOT. On many of the structures, separate inspection reports came to different conclusions regarding the anchor rods. On I-494-153, two more loose nuts were discovered compared to the MnDOT inspection. On I-494-199, the MnDOT inspection found three loose nut pairs where the ISU inspection found none. Finally, six loose nut pairs were found with the ISU inspection of I-494-188 while the MnDOT inspection found five.

Note that the MnDOT inspections indicated the number of loose anchor rods, but not the individual rods that were loose, so there could be further differences besides the number of anchor rods with significant pre-tension loss.

Discrepancies between the two inspections may be due to weather changes, further loosening of the anchor rods, or differences in striking techniques. MnDOT inspections were performed in mid-August, and the ISU inspections were performed in mid-October. Temperatures for the inspections differed by approximately 20°F, which would correspond to a theoretical temperature-induced differential stress of approximately 3.5 ksi. Temperature shrinkage may have stressed the bolts on I-494-199 enough so that the ISU inspection in the colder month of October did not observe any loose nuts, contrary to the MnDOT inspection in August of the same year.

As for the other two I-494 structures, they may have lost more pre-tension in the anchor rods, or, inherently, there may have been inaccuracies with the pre-tension checking method. Since the washers are struck with a hammer to check pre-tension, the results are somewhat subjective and dependent on speed of the strike and washer position on the structure. One inspector may strike the washers with more force than another. Additionally, if a washer is hitting the anchor rod, it will not move as much when struck, possibly resulting in a false recording.

The results in Table 3.2.2 may also indicate that nuts come loose in groups. Although the sample size is small, most of the observed loose nuts are next to each other. This behavior would make sense, as when one nut comes loose, more stress is put on the surrounding ones. Observations in numerical models from Phase I also support the theory that the anchor rod nuts come loose in groups. If the connections are put into compression, this may shake the nut loose and be amplified as more nuts get loosened.

Conditions were also noted during inspections of the existing signs. For most, the installations were fairly new and in good condition. The I-494-153 sign truss structure was in slightly worse condition than the other observed structures and is an older design as indicated by the 8x2 rod layout pattern. Figure 3.2.9 shows the standoff distance issues that were found during inspection.

Figure 3.2.9 Large standoff distance on I-494-153 structure

On this structure, the standoff distance was about twice the specification of the one-bolt diameter. Both Dexter and Ricker 2002 (NCHRP) and Hosch (2015) found that increased standoff distance significantly increases the fatigue loading on the anchor bolts. In addition to the fatigue from the standoff distance, Dexter and Ricker found that having connections under sung tight increases fatigue loading on bolts due to wedging of the baseplate. With these two factors coupled, the anchor rods on this structure were likely undergoing far greater fatigue loading than a comparable, correctly installed structure.

3.2.2.2 Maintenance Observations

On July 11, 2019, modified maintenance procedures were implemented on existing MnDOT full-span overhead structures. Overall, five structures were tightened, with two using the new specifications and the other two tightened to 3,650 ft-lbs of torque (due to no rods being loose). Due to traffic control concerns and the structures already being installed, the inspection and maintenance procedures were modified to the following sequence:

1. Check both top and leveling washers for looseness by striking with a hammer on two sides.
2. Take off nuts individually, lubricate, and bring to snug tight in a single star pattern. Ensure that only one nut at a time is removed, lubricated, and snugged.
3. Bring to 50% verification torque (*Tv*) in a star pattern.
4. Bring to 110% *Tv* in a star pattern.

Snug tight had to be completed in one step, one nut at a time, to ensure the structure was effectively anchored to the base. Removing all of the anchor rod nuts at once could result in collapse of the structure, so it was critical that this step was performed one nut at a time.

Turn of nut was not utilized at the request of MnDOT personnel due to uncertainties about the existing conditions and to avoid yielding the anchor rods. Reference turn-of-nut marks were used for verification of torque and to understand approximate torque-turn relationships in maintenance conditions.

The rods were immediately brought to 110% *Tv* in two star patterns. This was done due to feedback that it was unrealistic to come back 48 hours after tightening and would put a significant drain on resources, especially for difficult-to-reach locations that require traffic control. In addition, several sources (Fisher and Struik 1974, Bickford 1997, James et al. 1997, Phares et al. 2016) indicate that the immediate 110% will result in less final uncertainty than other tightening factors such as varying nut factors, tool error, torque-controlled pre-tensioning, and differential tightening.

Maintenance notes for each structure following their inspection processes throughout the day (July 11, 2019) follow. The increasing or decreasing notation refers to the side of the highway that the structures were on. Increasing indicates that traffic is traveling toward the structure, while decreasing indicates that traffic is traveling away from the structure.

I-94-601 (INCREASING SIDE) – FIGURE 3.2.10

Figure 3.2.10 I-94-601 Base

Inspection and maintenance on this structure went from 7:20 a.m. to 8:05 a.m. All of the nuts were checked for looseness, with none found to be loose. Because none of the nuts were loose, all were torqued in a single star pattern to 110% *Tv*. Nut 3 was the only one that turned slightly. It was also found that the gauge on the pump was zeroed at 300 psi, so all pressures had 300 psi added to them. The maintenance procedure was not used on this sign because all nuts were tight, and it was desired to establish a baseline for the new specifications for future inspections to compare the procedures performed.

I-94-602 (INCREASING SIDE) – FIGURE 3.2.11

Inspection and maintenance for this structure took longer than the first, due to the new procedure being used. While striking the washers, concerns were voiced by MnDOT maintenance personnel about whether a washer was pushed up against the rod, so it would likely be beneficial to strike opposite sides of the washer when checking for looseness, as demonstrated in Figure 3.2.11 (right).

Figure 3.2.11 Full truss OH sign I-94-602 (left) and inspecting rod pre-tension force (right)

After inspection, nuts 1, 2, 3, 8, 9, and 10 were found to be loose, so the new procedure was used for retightening. While taking off the nuts, it was discovered that many were rusty or corroded on the interior of the threads. The condition of the threads was likely due to chlorides from deicing salt infiltrating through small gaps, but was somewhat unexpected considering that the threads are completely covered by the nuts and washers. Rod 10 was found to be out of plumb (Figure 3.2.12), which led to a much higher turn-of-nut value than expected that possibly did not develop the full tension in the rod.

Figure 3.2.12 Rod 10 out of plumb and misaligned

I-94-608 (INCREASING SIDE) – FIGURE 3.2.13

Only one rod, #3, was found to be loose, but the procedure was still followed to take all of the nuts off and lubricate to reset the installation. Much like the previous structure, rod threads were fairly corroded on the inside of the nut (Figure 3.2.13 left).

Figure 3.2.13 General condition of anchor rods (left) and sample turn-of-nut verification (right)

Turn of nut was also measured to compare the specified torque to the "required" turn-of-nut values (Figure 3.2.13 right).

During this inspection, it was found that snugging the nuts with a torque wrench significantly increased the efficiency of the process, because it removed the need to switch the reaction arm of the hydraulic wrench for every rod, as required during initial snugging. The increased efficiency led to this inspection and maintenance taking half an hour less than the first structure. In addition, lubricating the top threads of the rod before loosening lowered the torque demand; before this, many nuts would take greater than 110% *Tv* to remove due to friction in the threads.

I-94-608 (DECREASING SIDE) – FIGURE 3.2.14

On this structure none of the washers moved when struck, so it served as another control variable where all of the nuts were brought to 110% *Tv* in a star pattern. In Figure 3.2.14 (left), the post has a tag marking the designation and a C-15 marking painted on.

Figure 3.2.14 I-94-608 Post (left) and 1/12 turn on nut #8 (#2 in star pattern) (right)

The C-15 marking indicates that the structure was retightened in 2015. Before tightening, all of the nuts were marked where they started so turn measurements could be taken. Overall, three nuts turned: 8, 10, and 11. Of these three, nut 8 turned the most at about 1/12 of a rotation, shown in Figure 3.2.14 (right). The 1/12 turn on rod 3 may indicate that it was approximately sung tight, since 1/12 is the specified turn for full pre-stressing. Due to lubrication conditions though, there is a greater likelihood that the leveling nuts for the nuts that turned were not snugged up against the baseplate and that the turns were more a result of straining the entire anchor rod to “pull” the leveling nut snug to the baseplate.

I-94-606 (DECREASING SIDE) – FIGURE 3.2.15

On this structure, nuts 7, 11, and 12 were found to be loose and rod 8 was missing a top washer (Figure 3.2.15 left).

Figure 3.2.15 Missing washer on rod 8 (left) and excessive turn of nut on rod 11 (right)

For the procedure on this base, nuts were immediately brought from snug tight to 110% *Tv* in a star pattern to investigate if the half step could be eliminated for efficiency. For this structure, skipping the half step enabled the procedure to be completed 15–20 minutes faster than it took on the previous processes. However, future inspections will need to document if skipping this step negatively impacts the fatigue resistance of the pre-tensioned connections. On the east side of the structure, many of the nut turns were far greater than expected, at about three times the specified amount. As shown in Figure 3.2.15 (right), nut 11 turned 3/12 from snug, a full 300% of the AASHTO specification.

OVERHEAD SIGN MAINTENANCE SUMMARY

Table 3.2.3 shows the turn-of-nut value achieved at final torque.

Table 3.2.3. Final turn-of-nut values and Inspection and maintenance time

Structure	**Final Nut Turns**												**Time (min)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
I-94-601 EB*	0	0	1/24	0	0	0	0	0	0	0	0	0	45
I-94-602 EB	3/24	3/12	x	1/6	3/24	1/12	1/12	1/12	1/6	3/12	x	1/6	120
I-94-608 EB	1/12	1/24	1/12	1/12	1/6	1/6	3/24	1/12	1/6	x	1/12	1/12	90
I-94-608 WB*	0	0	0	0	0	0	0	1/12	0	1/24	1/24	0	25
I-94-606 WB	3/12	1/12	1/12	x	1/12	3/24	1/6	3/24	1/6	1/12	3/12	3/12	70

*No washers moved during inspection, so full retightening maintenance procedure was not used

Note that for I-94-601 EB and I-94-608 WB, the retightening procedure was not used, so the values are for reference only. The boxes are shaded according to how far off from the specified turn of 1/12 they were. The farthest observed, 3/12, is red, with closer values approaching green at the specified 1/12 of a turn. Boxes with an x indicate that the turn was not recorded for that nut.

It is likely that the new procedure will add about 30 to 60 minutes to the maintenance of each structure. From the results in Table 3.2.3, the inspection and maintenance times decreased as the day progressed for respective procedures. With the control procedure of only tightening, the procedure was completed 20 minutes faster, likely due to a learning process concerning the steps and tooling. With the new procedures, inspection and maintenance time was improved by approximately 30 minutes after each experience. The improvement was attributed to learning and finding quicker procedures as the day progressed.

Maintenance times were completed with a three-person crew. The procedure could likely be done with two people to cut down on labor and vehicles required on site, but may increase the duration of time to complete maintenance. Additionally, it is unlikely that the new procedures will take less than 60 minutes to complete when traffic control, travel, and other considerations are averaged out for all structures.

Turn of nut may not be reliable for existing maintenance/correlate well with torque. Table 3.2.3 shows that of the structures that the procedure was used on, and 40% achieved the specified turn-of-nut value. Since the connections were pre-tensioned to 110% of the required torque, it is possible that the turn values could be higher, but even when considering the 3/24 turns, only 56% of the nuts reached the specification. 15% of the nuts turned triple the AASHTO required value. From calculations, the 300% turn would indicate yielding of the rod; however, considering the torque value used, it is unlikely that the rods yielded, especially with the less-than-ideal lubrication conditions.

Many factors could play into the excessive turn-of-nut values. One major factor could be the tightness or level of the leveling nuts. If the leveling nuts are slightly loose, or lower than the surrounding nuts, the grip distance would be increased to where the rod is fixed in the concrete. This condition strains the entire anchor rod until the leveling nut is pulled up to the baseplate during pre-tensioning. Another reason for the increased turns could be that the galvanizing finish on the existing washers or anchor rods is slightly deforming. Finally, the rods may not be completely level, which increases the grip distance and results in stress concentrations in the connection.

Due to many existing unknown factors, it is likely that taking the nuts off, lubricating, and using torque will provide greater accuracy in final tensions when compared to turn of nut. In addition, the torque spec would likely prevent under tightening since only one nut out of all in the new procedure turned under 1/12.

Lubrication and taking off nuts is critical to “reset” the installation. If only torque is used for maintenance, it is critical that each nut is taken off, lubricated, and replaced at snug tight. As observed, every nut that was removed had rust and corrosion within the threads, even though no interior threads were exposed to the elements. To remove loose nuts (i.e., ones without pre-tension left in the connection), sometimes 100–150% of the tightening torque was required due to friction, indicating the impact that friction has on an installation. Without cleaning and re-lubrication, there is no way to effectively know the existing conditions and friction in the connection, so any sort of tightening, be it turn-of-nut or torque, is effectively guesswork.

3.3 LIGHTING AND TRAFFIC SIGNAL STRUCTURES

3.3.1 Installation

3.3.1.1 Light Pole Installation Observation

On October 29, 2019, researchers visited the installation of a 9-40 ft stainless steel light pole on a construction project in Mendota Heights, Minnesota, located in the northeast quadrant of the TH 110 and TH 35E east junction. The pole base had a 15" bolt circle and was set on a MnDOT Design E concrete foundation consisting of four Type B, Grade 55, 1" diameter anchor rods in accordance with MnDOT Specification 3385.

The installation process followed the new procedures. First, the installation was verified, ensuring that the correct anchor rods, nuts, and washers were being used for the project. The rods, nuts, and washers on this particular project were checked to be Type B, Grade 55, 1" diameter anchor rods in accordance with MnDOT Specification 3385. The specific requirements included the following:

- Four 1" diameter anchor rods, projecting at least 3 5/8" and no more than 4" from the top of the foundation
- Eight 1" diameter nuts
- Eight standard ASTM F436 washers
- Four ½" thick washers (no longer required by the pole manufacturer)

The contractor lubricated the bearing surfaces of the leveling nuts and washers and the threads of the anchor rods. As the leveling nuts were turned down onto the anchor rods, the inside threads of the nuts were also lubricated, as shown in Figure 3.3.1 (left).

Figure 3.3.1 Placing leveling nuts (left) and verifying standoff distance (right)

After the leveling nuts were turned down onto the anchor rods, the contractor adjusted each leveling nut to the required standoff distance (Figure 3.3.1 right). The standoff distance is either specified by the manufacturer or the MnDOT typical standoff distance of less than one anchor rod diameter.

The contractor used a level to level the leveling nuts (Figure 3.3.2 left).

Figure 3.3.2 Leveling process (left) and improper lubrication of leveling nuts (right)

Once leveled, the contractor lubricated the top and bottom surfaces of the ½" thick washers and placed them on top of the leveling nuts (Figure 3.3.2 right). Note that lubrication of the washers on the nonbearing surfaces is a deviation from the specification requiring lubrication of bearing surface nuts and washers. This may result in less clamping friction between the double nut moment connection and the baseplate. Additionally, the lubricant used was a deviation from the specification, using a brush-on copper anti-seize, instead of the MnDOT-specified Bridge Grease.

The light pole was then lifted via crane and guided onto foundation anchor rods. Washers were placed on top of the pole baseplate. The bearing surfaces of the washers and top nuts were lubricated, and the top nuts were turned down by hand onto the anchor rods making contact with the washers.

Next, two cycles of snug tightening were completed in a star pattern sequence. The top nuts were tightened to the snug-tight condition first, followed by the snug-tight condition of the leveling nuts. The contractor had the option of using either a 12" long offset wrench made by the pole manufacturer, a 12" long open-end and closed-end wrench, or a torque wrench set to 50 ft-lbs. For the first cycle, the contractor utilized the manufacturer’s 12" long offset wrench to bring the leveling and top nuts to a snug-tight condition, as shown in Figure 3.3.3.

Figure 3.3.3 Snugging top nuts (left) and snugging leveling nuts (right)

The top nuts were then marked to visualize the turn of nut needed. The new specifications required 1/18 of a turn for proper pre-tension in these anchor rods. According to the proposed tightening specification, this step should be performed over two 1/36 turn steps.

The turn of nut was accomplished using the closed-end wrench on the top nuts. The contractor found it difficult to achieve these turns, not due to tension from turning the nuts, but rather because of lack of space inside the pole base to use the closed-end wrench and not being able to see the required 1/18th turn marks inside the pole base.

Figure 3.3.4 (left to right) shows examples of one nut before, at a second step, and after the contractor completed turn-of-nut pre-tensioning, respectively.

Figure 3.3.4 Nut turns at initial, second step, and final values (left to right)

The limited clearances are fairly apparent in Figure 3.3.4 with almost no turn visual from the initial to second step. Also note the fine sand particles in Figure 3.3.4 (right). To prevent contamination of the anti-seize lubricant on anchor rod and nut threads and the bearing surfaces of nuts and washers, debris inside poles should likely be removed before installation.

The last step, shown in Figure 3.3.5, required the contractor to use a torque wrench set to 200 ft-lbs.

Figure 3.3.5 Applying verification torque

The contractor applied the set torque wrench to the top nuts, tightening in two cycles. Lastly, the contractor is required to apply a retightening torque to the top nuts 48 hours after installation. The contractor can use the same torque wrench, this time set to 110% of the verification torque, 220 ft-lbs. The contractor should apply the retightening torque in two cycles.

In speaking with the contractor, it seemed as though there were three main areas of the new tightening procedure that differed the most from old tightening specifications, as follows:

- Areas of lubrication on nuts and washers differed from past procedures. Much like during the installation of the overhead sign, the contractor was only used to lubricating the threads of the anchor rod. While this would ensure that the inside faying surfaces of the nuts were lubricated, critical surfaces would be left unlubricated (top surface of the leveling nut, bottom and top surfaces of the washers, and bottom of the top nut). In addition, unneeded surfaces like the leveling nut washers were lubricated, which could decrease friction in the baseplate connection, requiring less shear force to induce a slip condition to the double nut connections.
- In past tightening methods, the contractor tightened the bottom nut using the turn-of-nut required, rather than the top nut. Additionally, a verification torque was not applied after the turn of nut.
- The contractor completed only one round of tightening for snug and turn-of-nut tightening, rather than two rounds.

Overall, the tightening of anchor rods in light pole structures revealed serious constructability issues. Unlike overhead signs, the nuts are in very tight spaces, and effectively tightening them can be difficult with certain equipment. Additionally, accurate turn-of-nut measurement is difficult within the base, especially with conduit and wiring also installed.

3.3.1.2 Light Pole Installation Procedure Test

For 50’ tall light poles, with 1 ¼" diameter, Grade 55, anchor rods, the recommended specifications called for 400 ft-lbs of torque and nearly 600 ft-lbs for steel screw-in type foundations. After the field experience, concerns were raised about clearances and the capability of achieving higher torque inside the limited base space. This installation was primarily for demonstration purposes for torque, so angle measurements were not recorded.

On December 20, 2019, the pole manufacturer, Millerbernd Manufacturing Company of Winsted, Minnesota, hosted a schematic demonstration with River City Electric of River Falls, Wisconsin. The demonstration was to show that the required pre-tensioning torque could be achieved within the base constraints and to practice the tightening specifications.

The Grade 55 anchor rods were welded onto a steel plate for demonstration purposes. The initial installation was done correctly, without lubrication on the top of the leveling nut washers, as shown in Figure 3.3.6 (left).

Figure 3.3.6 Correctly installed leveling nuts and washers (left) and leveling installation (right)

Figure 3.3.6 (right) illustrates correct leveling procedures performed on the installation. After leveling, the base was placed, and all required surfaces were lubricated with the specified grease, as shown in Figure 3.3.7 (left).

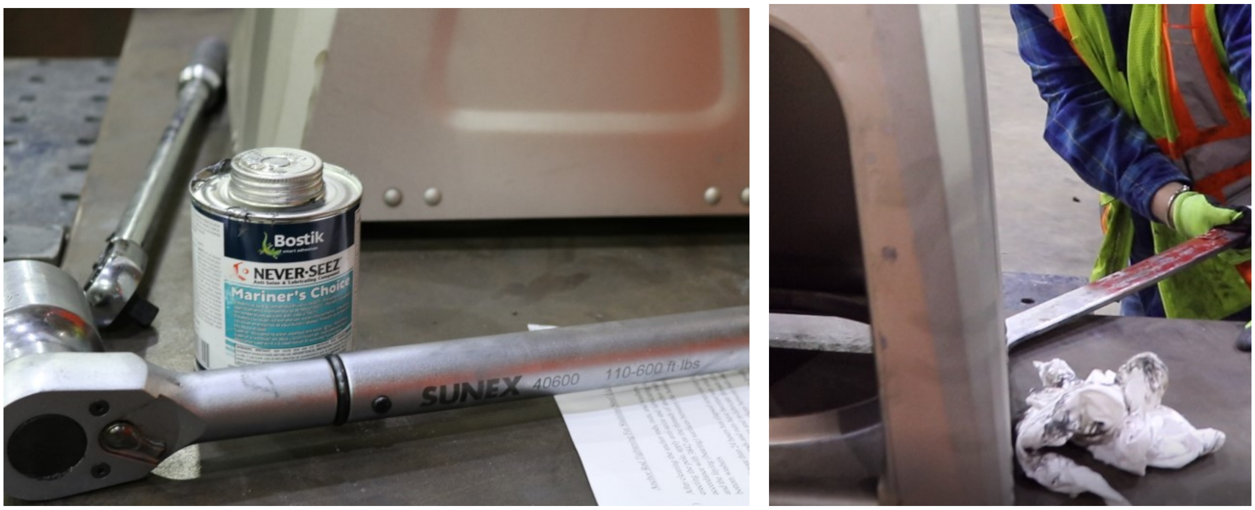


Figure 3.3.7 Calibrated torque wrenches and specified grease (left) and snug tightening leveling nuts (right)

Top nuts were then brought to snug tight using 50 ft-lbs of torque applied with the calibrated wrench shown in the background of Figure 3.3.7 (left); the calibrated torque wrench in the foreground was used for the second and final torque. The leveling nuts were snugged with an open-ended wrench, as shown in Figure 3.3.7 (right), which works well for the process, but was held past the 12" specified snugging distance for 1 ¼" diameter anchor rods. In addition, the star pattern was not followed, so some differential stresses may have been induced.

Finally, the anchor rods were immediately stressed to the full 400 ft-lbs in one step with a calibrated torque wrench (Figure 3.3.8).

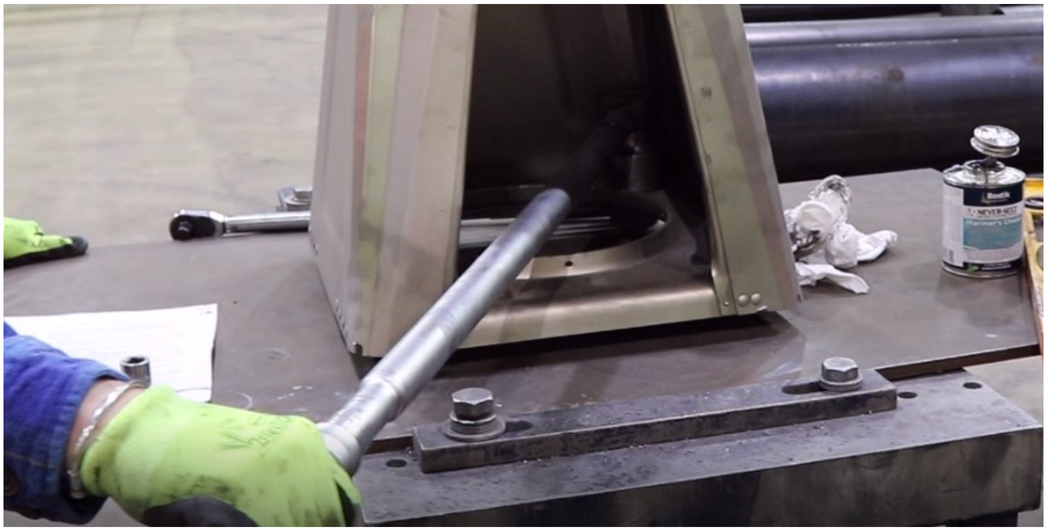


Figure 3.3.8 Final verification torque on the structure installation

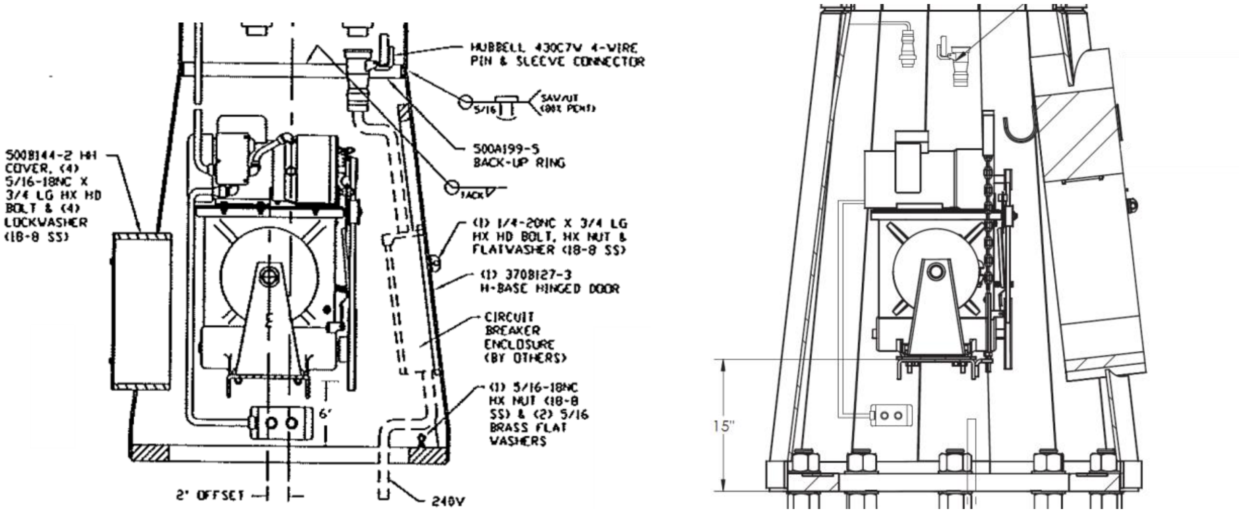
The contractor then reapplied the verification torque as the last step. This deviation from the specification indicates that the procedures should likely have a half-torque step, or better clarify the two steps. The star pattern was applied per the new procedures.

Overall, the contractor found the specifications fairly easy to follow and recommended that the steps be separated individually, instead of two steps for each specified torque or turn. In addition, the torque-controlled pre-tensioning was far preferred over turn-of-nut due to the limited visibility in light pole bases (personal interview with Mark Draper, foreman for River City Electric, December 20, 2019).

3.3.1.3 High Mast Light Tower Installation

Over the time period that the study was taking place, an HMLT installation using a hydraulic torque wrench was not able to be observed. HMLTs are fairly specialized lighting structures, and new installations are not routine. Although no installations with the low-profile hydraulic torque wrench were directly observed, the clearances were modeled using computer-aided design and drafting (CADD), and conclusions were drawn based on field experiences.

For a general overview of HMLT bases, Figure 3.3.9 illustrates the interior view of the MnDOT legacy HMLT base design and the new HMLT base design.



Millerbernd 2019

Figure 3.3.9 Legacy HMLT base design (left) and revised current HMLT base design (right)

Note that the interior anchor rod design is preferred by MnDOT for increased fatigue performance and to protect anchor rods from the elements. The winch assembly in the base is utilized for raising and lowering the luminaries at the top of structure during maintenance. Between the legacy and current designs, the major changes to improve clearance were raising the winch assembly up 9", making the maintenance openings larger, and increasing the distance of the wall to the anchor rods. While these were not the only changes made, they were the ones that improved the accessibility the most.

Additionally, when comparing the two drawings, the clearance improvements of the updated design are fairly clear. While pre-tensioning of the anchor rods can be completed from the leveling nuts, this operation is not desired if possible. Any turning of the leveling nuts can bring the installation out of plumb. Also, an open-ended wrench is required for tensioning the leveling nuts. Due to the relatively significant torque required for the proper pre-tension, open-ended wrenches run into clearance issues between the foundation and baseplate of HMLTs due to their required thicknesses.

On the single observed HMLT installation, the tower anchor rods were pre-tensioned to snug tight with a calibrated manual wrench. It was intended that the HMLT anchor rods would be fully pre-tensioned at a later date using a hydraulic torque wrench. The manual wrench worked fairly well in the updated base, especially with the raised winch detail. As shown in Figure 3.3.10, clearance was limited when torqueing the nuts closest to the door and required a fairly fine-toothed socket wrench to tighten.

Figure 3.3.10 Manual wrench installation tightening of HMLT anchor rods

The manual wrench worked sufficiently for bringing the nuts to snug tight; however, it cannot generate enough force to reach the required torque necessary to properly pre-tension HMLT anchor rods. Clearances for the hydraulic wrench were schematically investigated using CADD.

The limiting clearance area for the hydraulic torque wrench was due to the sloped inner sidewall of the HMLT base. In both the existing new and old base designs, this proved to be an issue. Primarily, the clearance problems were observed on nuts that were next to each other, likely indicating that the tolerances in the baseplate holes contributed to the inability to place the hydraulic wrench, moving some nuts closer to the tower wall and others farther away. Working with the manufacturer, the base clearances were increased by an inch to help with installation, which is greater than any of the clearance issues experienced in the field. It is likely that the low-clearance hydraulic wrench will work in the redesigned bases.

3.3.2 Maintenance

Maintenance work on lighting and traffic signal structures focused on traffic signal poles and HMLT structures due to the limiting clearances and high torque required for proper pre-tensioning. Most of the effort was put toward finding a feasible maintenance option for the existing HMLTs since clearances inside the legacy bases is a limiting factor for pre-stressing.

3.3.2.1 Traffic Signal Mast Arm Pole

The maintenance procedures were investigated on a Type PA traffic signal pole installation. The signal mast arm pole that was retightened is located at the northeast corner of the T-section of County Road 14 (34th Street North and Century Avenue North in Oakdale, Minnesota) and MN 120. This pole was the only one retightened as a proof of concept for clearance. Preliminary CADD drawings (Figure 3.3.11) indicated sufficient clearance, but the condition needed to be further investigated in the field.

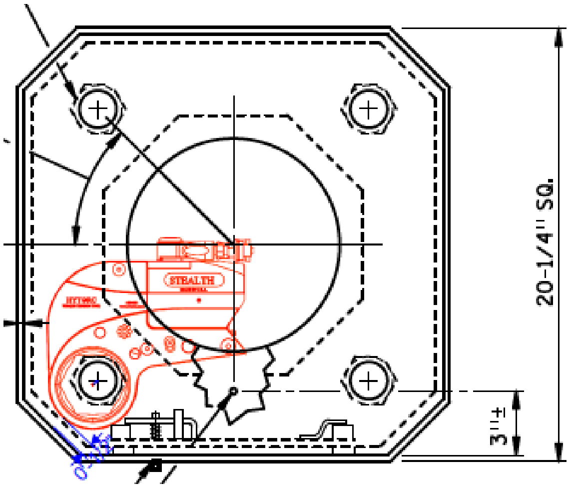


Figure 3.3.11 CADD modeled hydraulic wrench clearances

Much like the OH sign structures, the installation procedure was modified for maintenance operations. The major difference between the OH sign and traffic signal mast pole maintenance was that the nuts were immediately brought to the 100% verification torque without a half step. The procedure was modified because the limited clearances make it difficult and far slower to maneuver the wrench around in the base. The maintenance procedure is as follows:

1. Take off the nuts, lubricate, and bring to snug tight in a single star pattern.
2. Bring the nuts to 100% verification torque in star pattern.

When checking the looseness of the nuts by striking with a hammer, it was discovered that clearance issues did not allow for accurate measurement of the clamping force in the connection. In lieu of striking with a hammer, the approximate torque required to loosen all nuts was measured. Starting with the first nut, the wrench was set at 1,500 ft-lbs and easily loosened the nut, and the next three nuts came loose at about 800 ft-lbs, which indicates that all of the connections were likely torqued to no more than 800 ft-lbs during initial installation. After loosening the nuts, it was found that the anchor rods were lubricated with what appeared to be the specified grease (Figure 3.3.12 left).

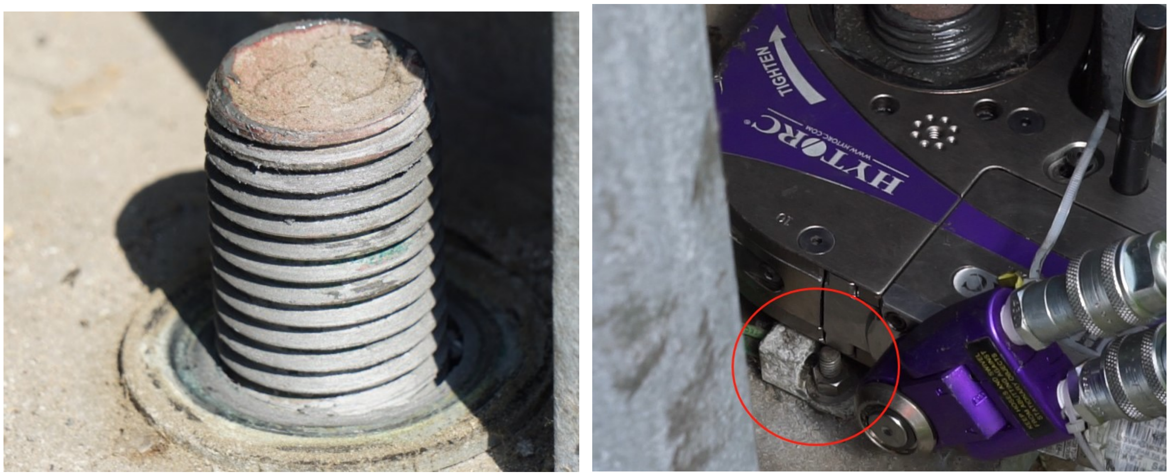


Figure 3.3.12 Previously lubricated anchor rod (left) and clearance with ground lug (right)

This was surprising given lubrication was not specified for installation when these poles were built, so the contractor must have had prior nut tightening experience. The installation was also fairly new (circa 2015), so not much weathering had taken place. After removal, each nut was lubricated and brought to snug tight. The final snug tight was slightly higher than the specification due to the minimum torque on the wrench, but for pure torque installation, the initial snug value does not impact the final pre-tensions greatly.

Turn of nut for this installation was not utilized due to the small clearances. One issue found while retightening the nuts was that the ground wire connection prevented the wrench from being placed on the baseplate of the structure for the front nuts, as shown in Figure 3.3.12 (right).

The wrench was still able to tighten the nuts, but care was needed to prevent wedging or pinching when using the wrench placed on top of the ground wire. The ground connection could also be loosened to help with clearance (3.3.13 right).

Figure 3.3.13 Galvinizing dimples on washer (left) and moved grounding wire (right)

It is also important for safety that the fuses for the signals are pulled before maintenance. Finally, Figure 3.3.12 (left) details dimples in the galvanized surface of the washers. These could possibly add to relaxation losses and deform during tightening.

3.3.2.2 HMLT Tightening Procedures

Existing HMLT structures presented the limiting situation for effective anchor rod pre-tensioning. Hydraulic torque wrenches are required for turning the top nuts when tightening anchor rods on HMLTs because of the high torque values necessary to tension Grade 105 anchor rods. Manual wrenches cannot meet the required torque values to properly tighten the anchor rods. A bolt jacking solution was not chosen due to clearances inside the base design and the fact that jacking the entire structure up would be difficult. The same clearance issues limited the use of gear drive wrenches.

Three different methods were attempted for re-pre-tensioning existing HMLT bases: HYTORC hydraulic wrench, Millerbernd designed J Wrench, and a slug wrench.

HYTORC STEALTH 4 HYDRAULIC TORQUE WRENCH ASSESSMENT

July through December 2019, the HYTORC low profile Stealth 4 hydraulic torque wrench with a HYTORC Vector hydraulic pump was assessed for maintaining anchor rod connections on existing structures. The maintenance sequence was modified from the original tightening specifications intended for new installations, as follows:

1. Take off the nuts one at a time, lubricate threads of nuts and anchors and the bearing surfaces of nuts and washers, install F436 washers where washers were not originally used, and bring to snug torque in a single star tightening pattern. Ensure that only one nut at a time is removed, lubricated, and snugged.
2. Bring to 100% *Tv* in a star tightening pattern.

Due to all nuts being snug torqued during the initial stage, it is recommended not to perform this procedure on windy days.

In regards to the changes, snug torque was completed in one step to ensure the structure was effectively anchored to the base. The turn-of-nut step was not utilized due to uncertainties about the existing conditions, to avoid yielding the anchor rods, and because of limited accessibility. Final tightening for the anchor rods were immediately brought to 100% *Tv*.

HMLT S09A 2 – HYTORC WRENCH

This HMLT located on I-494 near the Wakota Bridge crossing over the Mississippi river is a legacy design structure shown in Figure 3.3.14 (left).

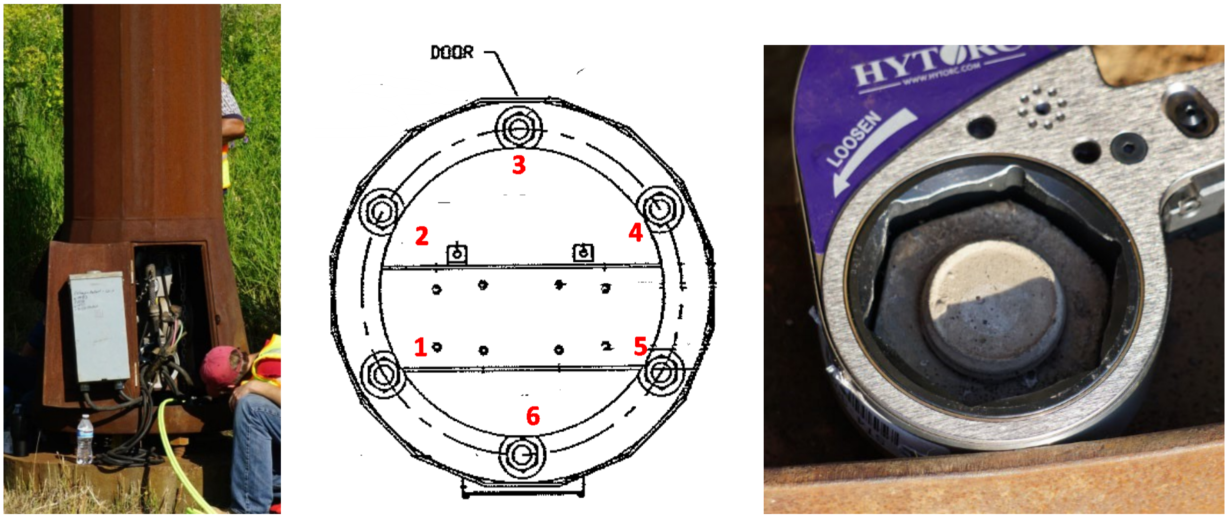


Figure 3.3.14 S09A 2 legacy base design (left), anchor rod numbering (center), and wrench clearance issues (right)

Figure 3.3.14 (center) shows assigned numbering of the anchor rods. For removal and retightening, the hydraulic torque wrench could only be placed on nuts 4 and 6. The wrench would likely fit onto the top nuts once in place; however, the lack of sufficient clearance between the taper of the sidewall and the top nuts make it infeasible for the wrench to get past the taper and onto the top nuts. Figure 3.3.14 (right) shows that the wrench fits on the nut, but would have to be forced past the taper of the sidewall and would be fairly difficult to remove.

The taper of the structure wall was found to be the primary clearance issue as outlined in Figure 3.3.15 (left).

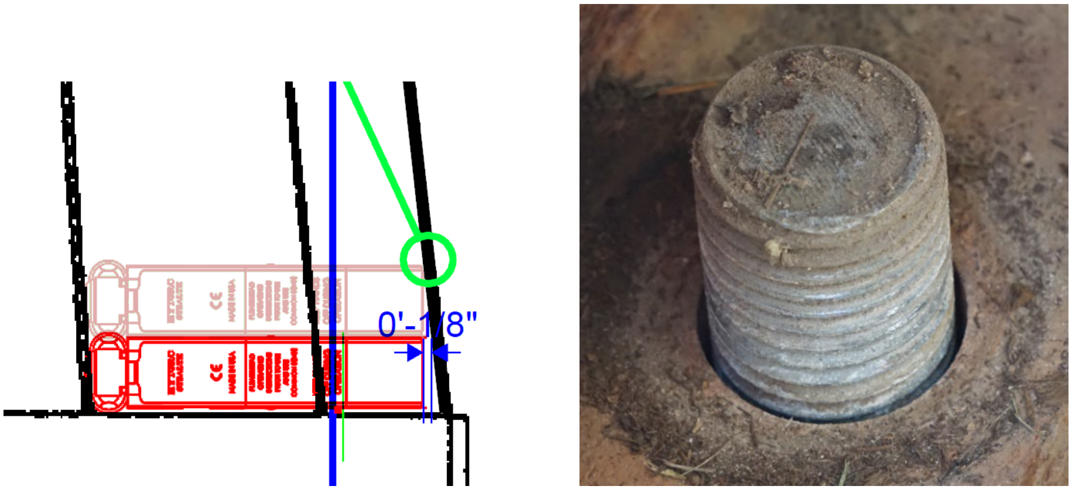


Figure 3.3.15 Wrench clearance issues (left) and anchor rod condition (right)

This limiting taper was improved in the current HMLT base designs. On the two top nuts that were taken off, galvanization was in fair condition with minimal rust or corrosion (Figure 3.3.15 right). Since this HMLT is not directly next to the road, the structure is exposed to less chloride exposure from chemicals used in snow and ice removal, unlike many OH sign structures. In addition, the top nuts are enclosed in the HMLT base and consequently not fully exposed to the elements and corrosive chemicals.

HMLT A14E 4 – HYTORC WRENCH

This HMLT is located at the I-94 and I-494 interchange near Maple Grove, Minnesota. The structure has a newer eight-rod pattern and a larger base design than the legacy HMLT base at the Wakota Bridge. Note that this HMLT base design has slightly smaller clearances than the current design previously outlined in Figure 3.3.9.

This base was an intermediate design between the legacy base and the current design partially due to the findings of this project. In the intermediate base design, the hydraulic wrench experienced wedging against the sidewalls due to the sidewall taper, although to a lesser degree. Compared to the legacy design, a greater number of top nuts on this newer HMLT base design were accessible for re-tensioning. Referencing Figure 3.3.16 (left), only nuts 6 and 7 were not able to be retightened.

Figure 3.3.16 Rod numbering (left), checking washers for looseness (center), and prior copper anti seize lubrication on rod (right)

Before loosening, the leveling nuts were checked for tightness (Figure 3.3.16 center) and none were found to be loose. Because the striking had to be completed on the leveling nuts, this may not be an ideal indicator of clamping force.

The new procedure was attempted on the structure to investigate the feasibility of the new design even though no nuts appeared to be loose. While loosening the nuts, lubricant from the initial installation was present (Figure 3.3.16 right).

Because the nuts were lubricated during the initial installation, a tightening torque value could be approximated based on the loosening torque. All of the top nuts came loose at about 1,000 ft-lbs of torque. It’s likely that the bottom nuts were torqued to a maximum of 1,500 ft-lbs. This torque value would match up with the DOT’s observations of the contractor using a 10' long breaker bar over the handle of a pipe wrench to turn the bottom nuts tight. While the original installation likely used far less than the required torque value, it does show that the clamping force can be transferred relatively well by only tensioning the leveling nuts.

HMLT TW06A 1 - HYTORC WRENCH STACK SOCKET ATTACHMENT

To alleviate clearance issues, the hydraulic torque wrench manufacturer recommended a socket attachment fitted to the wrench. Although the socket raises the wrench higher into the taper of the HMLT, it also allows for a smaller diameter wrench head to be used on the top nuts, therefore positioning the wrench farther away from the taper. Figure 3.3.17 illustrates the hydraulic torque wrench with the stack socket attached.

Figure 3.3.17 HYTORC Stealth 4 hydraulic wrench with stack socket

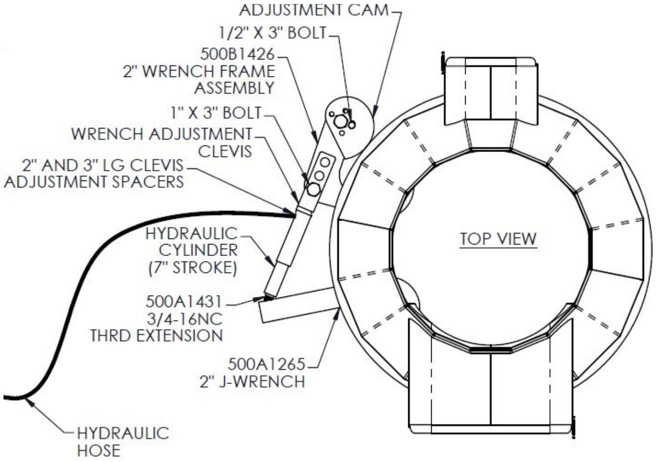
Note that the piston and hoses that power the wrench are unattached. Clearances with the stack socket are improved from using the wrench alone, but there were still a couple wedging issues, especially when the anchor rod protrusions extended beyond the top nuts, lifting the stack socket up into the base sidewall, as shown in Figure 3.3.18 (right).

Figure 3.3.18 Wedging on door frame (left) and socket raised into wall by nut protrusion (right)

Note that unlike many socket wrenches, the stack socket partially covers the nut, as shown in Figure 3.3.17 (left). As shown in Figure 3.3.18 (left), the stack socket does not work on the top nuts that are centered at the access door openings found on existing older structures. The edge of the door opening has an increased inward bend compared to the rest of the HMLT base. This inward bend results in binding on the socket and on the original wrench as shown in Figure 3.3.18 (left). The stack socket was not tested on the new HMLT base designs, but it is fairly likely that it would work since the new bases are larger and the clearances on the smaller legacy bases were close for the stack socket fitting.

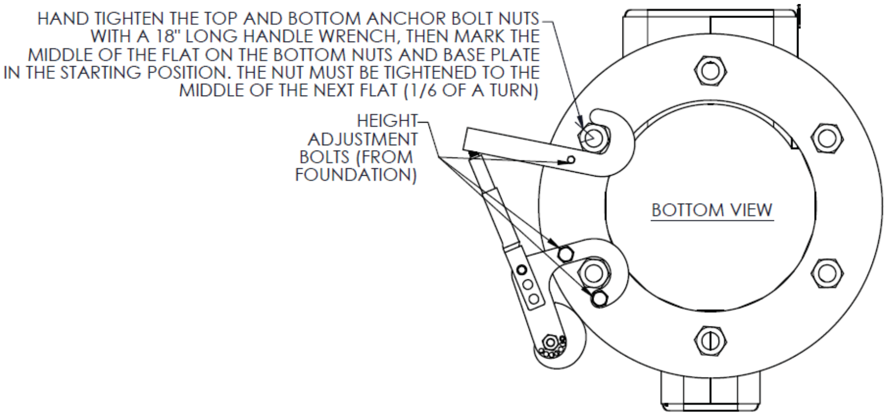
MILLERBERND J WRENCH FIELD TESTING

Millerbernd, the HMLT manufacturer, designed and produced a hydraulic wrench for tightening the bottom nuts as detailed in Figure 3.3.19 and 3.3.20.



Millerbernd 2019

Figure 3.3.19 Top view of Millerbernd wrench operation



Millerbernd 2019

Figure 3.3.20 Bottom view of Millerbernd wrench operation

The wrench frame assembly uses a hydraulic jack to rotate the J wrench, which turns the bottom nuts tight. The wrench frame reacts off an adjacent bottom nut and the outside of the base sidewall. In this configuration, the reaction bottom nut is a theoretical pinned connection, and the wall reaction is a theoretical roller connection. Adjustment of the Millerbernd wrench is completed by adjusting the cam in the back of the wrench frame against the wall of the HMLT. As torqueing takes place, the hydraulic jack extends, rotating around the mounting bolt on the wrench frame to maintain contact with the J wrench. A 10,000 psi electric hydraulic pump powers the hydraulic cylinder.

During operation of the Millerbernd wrench, MnDOT staff noted several limitations. Neither a pressure gauge nor calibration were provided with the wrench assembly. While the plans indicate 1/6 of a turn, this specification may not be valid for maintenance on existing HMLTs and could result in damage to the wrench with the torque required to turn existing nuts to the required pre-tension. Additionally, if a contractor failed to use turn-of-nut, they may assume that the wrench is calibrated for the correct torque values on the nuts and overstress the frame, as observed by MnDOT workers.

Clearance under HMLT bases was also a defined limitation according to MnDOT personnel. Due to the thickness of the J wrench and existing conditions of in-place high mast tower foundations, such as: limited standoff distances, short anchor rod projections, embedded bottom nuts in the concrete foundation tops, and interference with electrical conduits, the J wrench could only be placed on a limited number of HMLT anchorages.

While a contractor was using the Millerbernd wrench, the frame of the wrench bent. Yielding appeared to occur primarily in the tensile controlled region of the frame at one of the leveling screw holes (Figure 3.3.21).

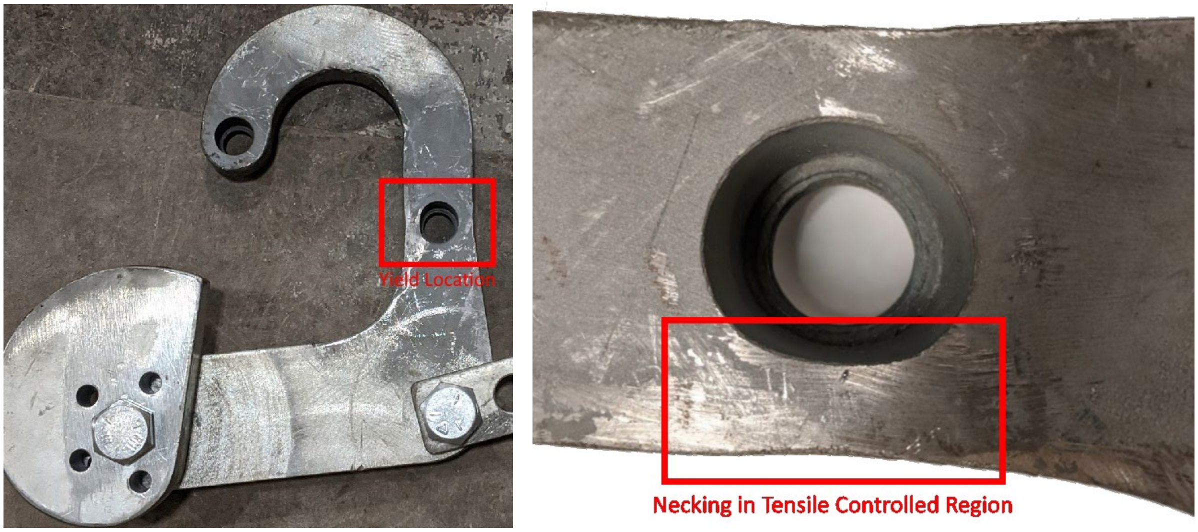


Figure 3.3.21 Yield location (left) and necking detail (right)

The yielded region surface differences from the edge of the leveling hole to the edge of the wrench were measured with a dial indicator (Figures 3.3.22).

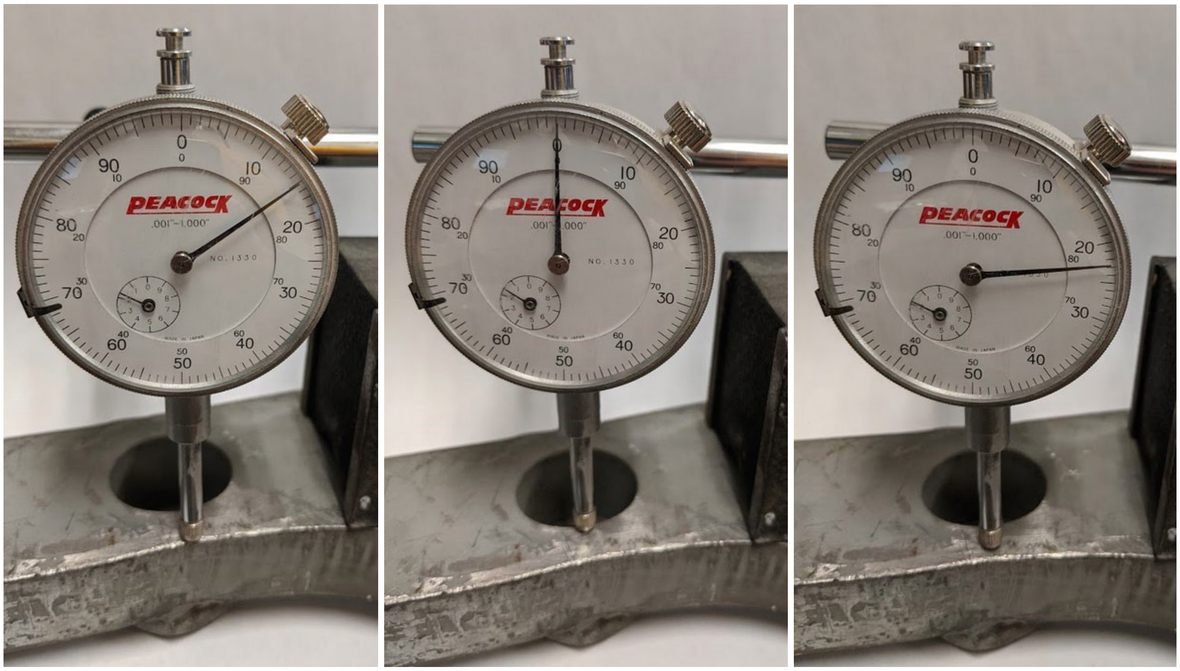


Figure 3.3.22 Distance measurement at hole edge, high point, frame edge (from left to right)

Near the edge of the hole, there was a 0.023" difference from the high spot of the region; toward the edge, there was a 0.008" difference, which approximately matched the rest of the wrench. The decrease in the cross sectional area near the hole likely indicates that the yielding was primarily due to stress concentrations. The galvanized coating makes any repairs on the current wrench difficult.

The movement range of the Millerbernd wrench was modeled in CADD (Figure 3.3.23) to determine the range of operating angles and any associated geometric constraints.

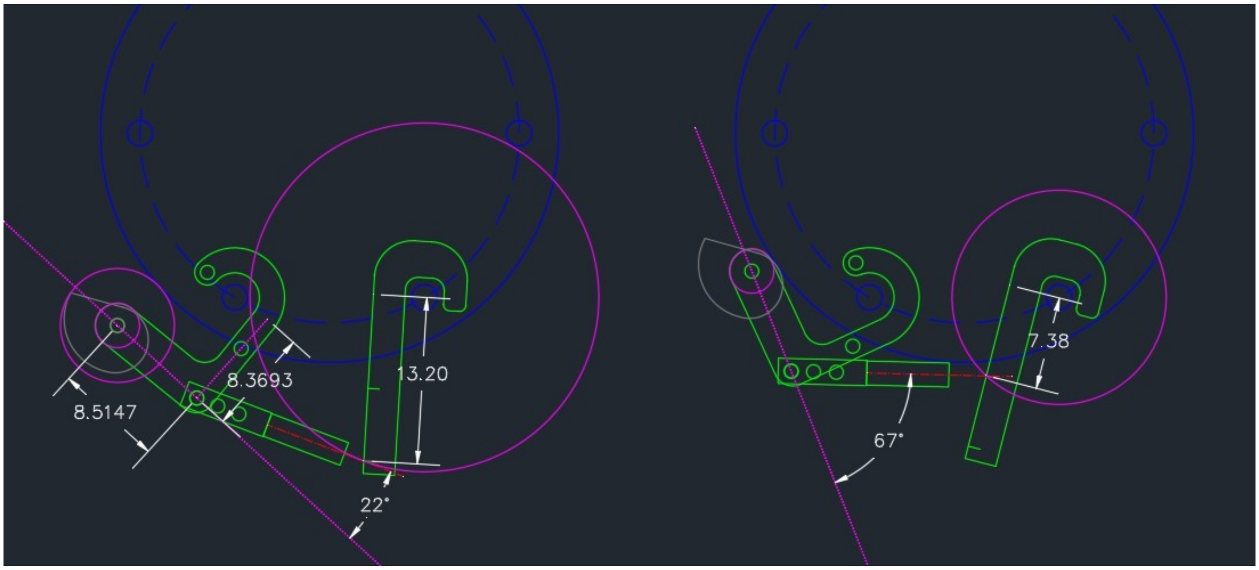


Figure 3.3.23 CADD model of Millerbernd wrench geometry and operations

The wrench was modeled on the older base design to investigate the limits for maintenance purposes. It was found that the operating angle range of the wrench was 22 to 67 degrees from the plane between the back cam and clevis holes. The 22-degree operating angle occurred with full cam extension and on the furthest J wrench slot. The 67-degree operating angle occurred with the minimum cam extension and on the closest J wrench slot.

The wrench frame was analyzed as a simply supported moment frame/lever with the cam end acting as the roller and the bolted connection end acting as a pin. While these assumptions are idealized, they can give an approximate idea of the internal forces in the wrench frame. The steel grade in all wrench parts was assumed to be grade 50, since it is the same as the HMLT structures that Millerbernd produces. An FEM was considered for analysis, but with the mesh size required to model stress concentrations and the time required to create the model, it was decided that using empirical relationships on a simplified model would be sufficient. Table 3.3.1 indicates the maximum operating force to yield the wrench frame.

Table 3.3.1. Wrench frame forces at hole section for 5,500 lb force, Fy 50 ksi, and varying operation angles

Pj angle (deg)	Fj angle (rad)	Ve (lb)	Me (lb")	σ Edge (ksi)	σ Interior (ksi)
22	0.38397	5099.511	16675.4	37.9611	50.14101
27	0.47124	4900.536	16024.75	37.05437	49.3622
32	0.55851	4664.265	15252.15	35.86562	48.20772
37	0.64577	4392.495	14363.46	34.40392	46.68634
42	0.73304	4087.297	13365.46	32.68038	44.80965
47	0.8203	3750.991	12265.74	30.70812	42.59194
52	0.90757	3386.138	11072.67	28.50216	40.05007
57	0.99484	2995.515	9795.333	26.07928	37.2034
62	1.0821	2582.094	8443.446	23.45792	34.07359
67	1.16937	2149.021	7027.299	20.65803	30.68446

Source ASTM A572

Table 3.3.2 indicates the minimum and maximum possible torque that could be applied to the nut from the J wrench.

Table 3.3.2. Pressure, force, torque, required thickness limitations, and frame factor of safety of 2

Bore ID (in): 1.13 (Enerpac RC55)
Max Lever Length (in): 13.2
Min Lever Length (in): 7.210338 (7.4*cos(13deg)
Wrench Thickness F.S. (in): 2

Pressure (psi)	Force (lbs)	Min Torque (ft-lbs)	Max Torque (ft-lbs)	Req. J Wrench Thk. (in)	Current Frame F.S.
500	501.4375	301	552	0.25	11.0
1000	1002.875	603	1103	0.51	5.5
1500	1504.312	904	1655	0.76	3.7
2000	2005.75	1205	2206	1.02	2.7
2500	2507.187	1506	2758	1.27	2.2
2600	2607.475	1567	2868	1.32	2.1
2700	2707.762	1627	2979	1.37	2.0
2800	2808.05	1687	3089	1.42	2.0
2900	2908.337	1748	3199	1.47	1.9
3000	3008.625	1808	3309	1.53	1.8
3100	3108.912	1868	3420	1.58	1.8
3200	3209.2	1928	3530	1.63	1.7
3300	3309.487	1989	3640	1.68	1.7
3400	3409.775	2049	3751	1.73	1.6
3500	3510.062	2109	3861	1.78	1.6
4000	4011.5	2410	4413	2.03	1.4
4500	4512.937	2712	4964	2.29	1.2
5000	5014.375	3013	5516	2.54	1.1
5500	5515.812	3314	6067	2.80	1.0
6000	6017.249	3616	6619	3.05	0.9
6500	6518.687	3917	7171	3.30	0.8

Table 3.3.2 also indicates the required thickness of the J wrench for a given torque value with an included factor of safety of 2 and the factor of safety on the frame with the applied force.

Note that Tables 3.3.1 and 3.3.2 are from a simplified analysis of the members without torsional, strain hardening, or intensive stress concentration impacts considered. While conservative assumptions were made during analysis, the failure values at a factor of safety of 1 should likely not be approached to avoid further damage to the current Millerbernd wrench frame. Note that Table 3.3.2 shows a theoretical pressure-torque relationship and has not been directly calibrated.

Looking into Table 3.3.1, the suspected failure mode from visual inspection and measurements was confirmed. For the stress at the interior of the hole, there is an empirical multiplier of 2.05 due to stress concentrations (Hibbeler 2017). While the flexural stresses are not at maximum at the edge of the hole, the stress concentration multiplier is enough to offset the difference, resulting in yielding at a 5,500 lb load from the hydraulic jack at a 22-degree operating angle. It is likely the contractor using the wrench applied approximately 6,000-8,000 lbs of force or 3,600-8,800 lb-ft of torque to yield the wrench frame. An exact value cannot be determined without knowing the exact configuration the wrench was in when it was damaged. Although these torque values are over the required value for lubricated HMLT structures, it is likely in an unlubricated case that these torque values could be reached to achieve the required turns. The contractor that yielded the wrench also did not have a maximum operating pressure for the tool and may have been mistaken on the calibration, resulting in the yielding.

In Table 3.3.2, the theoretical pressure and torque curves are compared to the minimum thickness of the J wrench and the factor of safety on the current wrench frame. The factor of safety on the frame is taken at an operation angle of 22 degrees, which results in the maximum torque values. All of the minimum torque values occur at operation angles between 41 and 67 degrees. Therefore, the closest slot on the J wrench will result in inefficient tightening. The factor of safety could be calibrated for the minimum torque values with lower angles; however, the closer slot on the J wrench results in higher axial forces for the same tightening torque. If the furthest slot in the J wrench is used, there is also less variability in the maximum torque values because the contact angle between the J wrench and the jack is closer to 90 degrees. Although the maximum torque of 2,980 ft-lbs is less than required, it should still sufficiently tension existing HMLT structures to prevent nut loosening. The minimum thickness for the J wrench with the current wrench frame could be 1.37", which is 0.4" and could help with the clearance issues encountered during maintenance. The reduced thickness of the J wrench would make the factor of safety the same for the whole Millerbernd wrench assembly if a factor of safety of 2 is desired.

MILLERBERND J WRENCH FIELD ANALYSIS

After analysis, the Millerbernd wrench was tested in the field. Figure 3.3.24 shows the wrench set up for operation in the in the closest setting, and Figure 3.3.25 show the setup in the farthest setting.

Figure 3.3.24 Millerbernd wrench operation at closest setting

Figure 3.3.25 Millerbernd wrench operation at farthest setting

Much like the HYTORC hydraulic torque wrench, there were also clearance issues with the Millerbernd wrench, for both the wrench frame and the J wrench. The wrench frame could only be placed on four of the six bottom nuts due to the electrical conduit placement in the foundation as shown in Figure 3.3.26 (left).

Figure 3.3.26 Clearance Issues with conduit placement (left) and with foundation finishing (right)

The J wrench itself was only able to service one of the six bottom nuts. The location of the electrical conduit and the thickness of the wrench affected the placement of the J wrench. If the J wrench was milled down ½", it could fit under the same nuts as the wrench frame; however, the thickness presented a challenge with the concrete finishing on the foundation being rough, as shown in Figure 3.3.26 (right).

Because of the design limitations, the Millerbernd wrench may not be the ideal option for maintenance on HMLTs. Further discussions with Millerbernd indicated that they no longer intended to produce the wrench, so it will likely not be used for subsequent installations.

SLUG WRENCH

MnDOT’s Electrical Services Section (ESS) currently uses a slug wrench, which is a wrench that is placed on the leveling nuts and struck with a 16 pound sledge hammer to re-tension HMLT structures from the leveling nuts. Slug or striking wrenches generally result in a pre-tension error of approximately 50% (Garlich and Thorkildsen 2005), and it is unlikely that they would reach the full 60% yield pre-tension with the full effort of a worker. However, the MnDOT slug wrench was investigated at HMLT TW06A 1 at the I-35 and TH 280 interchange. This HMLT is the older base design with a six-bolt pattern, and it is the same one that the Millerbernd wrench and the HYTORC stack socket were investigated against previous to this. Figure 3.3.27 (left) and (right) summarize the turn results of the tightening procedure and the method used, respectively.

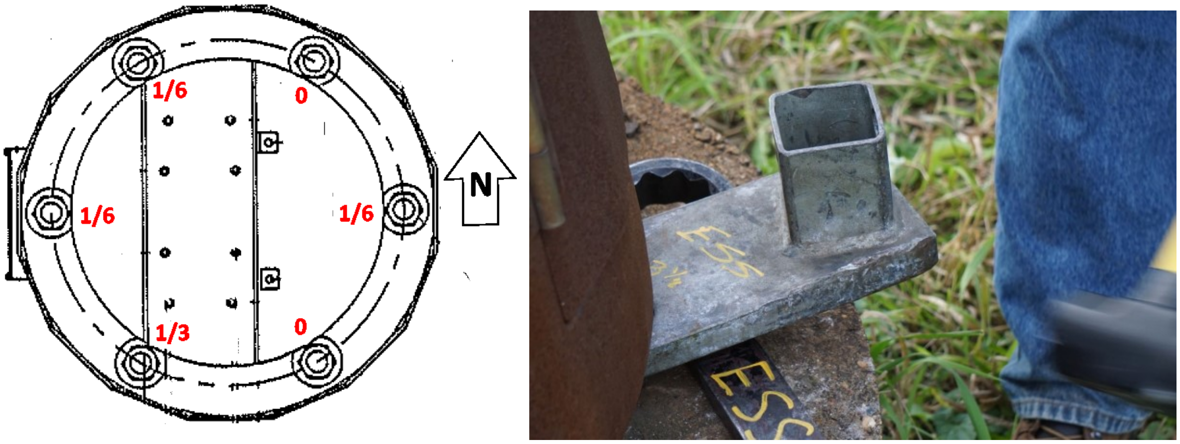


Figure 3.3.27 Final nut turns from original position (left) and striking wrench use (right)

The retightening process on the leveling nuts consisted of two steps, first breaking a nut loose in the opposite direction, then retightening up against the baseplate. This was performed for each nut individually with the MnDOT ESS slug wrench.

The first breaking loose step was used to make sure that the nut could be chased back up the bolt. The ESS closed spanner was used to prop up the slug wrench while striking due to the standoff distance. It may be beneficial for maintenance personnel to have varying sizes of plate steel with them if this method is used, to smoothly prop up the slug wrench.

All of the nuts were turned as far as they would go with the full amount of energy that could be put into the slug wrench. Full tightening strength was used, because it is unlikely enough energy could be put into the nut from this setup to yield the anchor bolt, considering the unlubricated condition. Figure 3.3.27 left shows the final turns achieved from the starting position of each nut on the HMLT base. Two of the six nuts could not be broken loose and were assumed to either be sufficiently pre-tensioned or rusted in place.

Of the four remaining nuts, three turned 1/6th of a turn and one turned 1/3rd of a turn. The turn values are fairly excessive, even from what was calculated, possibly indicating that they were initially torqued less than expected. If the slug wrench option is further pursued as a maintenance option for HMLTs, more research will be put into the maximum energy that can be achieved with a slug wrench, more wrench options, and a refined procedure for the handbook.

Maintenance serviceability may be improved with further iterations of the hydraulic torque wrench designs. In addition to the clearance issues on current HMLTs, MnDOT maintenance workers expressed concerns about bringing all of the required equipment to some light towers in remote locations, especially since the pump for the HYTORC wrench requires fairly constant voltage for accuracy. Field experience demonstrated that the pump sometimes struggled to operate using a generator and would not run off vehicle inverters. One of the MnDOT workers noted a transformer that plugs into the HMLT power outlet could be an option, but would result in high amperages after the voltage reduction.

Overall, the hydraulic wrenches that can be used for maintenance will likely not be able to service every nut on every post and are fairly difficult/frustrating to operate in the close quarters of the older base design. For maintenance, the slug wrench may be the best option for HMLTs with the older base design. If a very low clearance jack was used, the post could be jacked up to the proper pre-tension and the leveling nuts tightened, but finding a low enough clearance jack is unlikely.

3.4 CONCLUDING POINTS

- **Clearances in structures presented difficulties with following turn-of-nut specifications**

  With lighting and traffic signal structures, there were significant difficulties implementing the turn-of-nut specification due to clearance issues within the post bases. On OH sign structures, both the turn-of-nut and torque procedures were fairly straightforward. It would likely to be beneficial to separate the procedures into overhead sign and lighting/traffic signal categories.

- **The clarity of specifications could be improved**

  In many cases, there were miscommunications on the procedure steps, lubrication, torque, and turns. It is likely that the specification could be simplified with more illustrated figures of the steps. The different specification deviations should also be investigated to estimate the effect they have on the final anchor rod pre-tension scatter.

- **Maintenance and new installations likely need different specifications**

  Performing maintenance retightening on structures presented different challenges and required several different approaches when compared to new installations. It would likely be beneficial to further subdivide the specification between maintenance and installation procedures.

- **Appears new procedures work for overhead sign structures**

  After inspection of six OH sign structures, it appears that the new procedures are performing well and no under pre-tensioned anchor rods were recorded.

- **48-hour retightening torque is difficult to perform**

In both installation and maintenance, retightening connections after 48 hours presents a drain on resources and should be investigated further to estimate its effect on pre-tension loss.

CHAPTER 4: OVERHEAD SIGN MONITORING RESULTS

4.1 METHODOLOGY

4.1.1 Specimen and Instrumentation

4.1.1.1 Setup

The instrumented sign was a cantilevered OH sign structure in Rosedale, Minnesota, shown in Figure 4.1.1 (left).

Figure 4.1.1 Instrumented sign post (left) and data logger cabinet (right)

Installation and instrumentation took place in August 2017. The post and anchor rods were instrumented with three wire resistance strain gauges. On the post, eight 6 mm temperature-compensated foil strain gauges produced by Tokyo Sokki Kenkyujo Co., Ltd. were affixed. The anchor rods were bored 4 ½" down into the approximate grip length and instrumented with a bolt strain gauge series BTM 6 mm produced by the same company. In addition, an R. M. Young Company 05103V wind monitor was fixed to the top of the sign structure. The anchor rods were Grade 55, 2 ¼" diameter, and the post was a MnDOT Type 4 with a Type A base (MnDOT n.d.). A Campbell Scientific data logger (Figure 4.1.1 right) was utilized for data collection with a sampling rate of 100 Hz. For more information on the installation, see the previous study (Chen et al. 2018).

Figure 4.1.2 shows a simplified elevation view of the structure with dimensions and a section of the roadway as shown from the decreasing, southbound direction on the roadway.

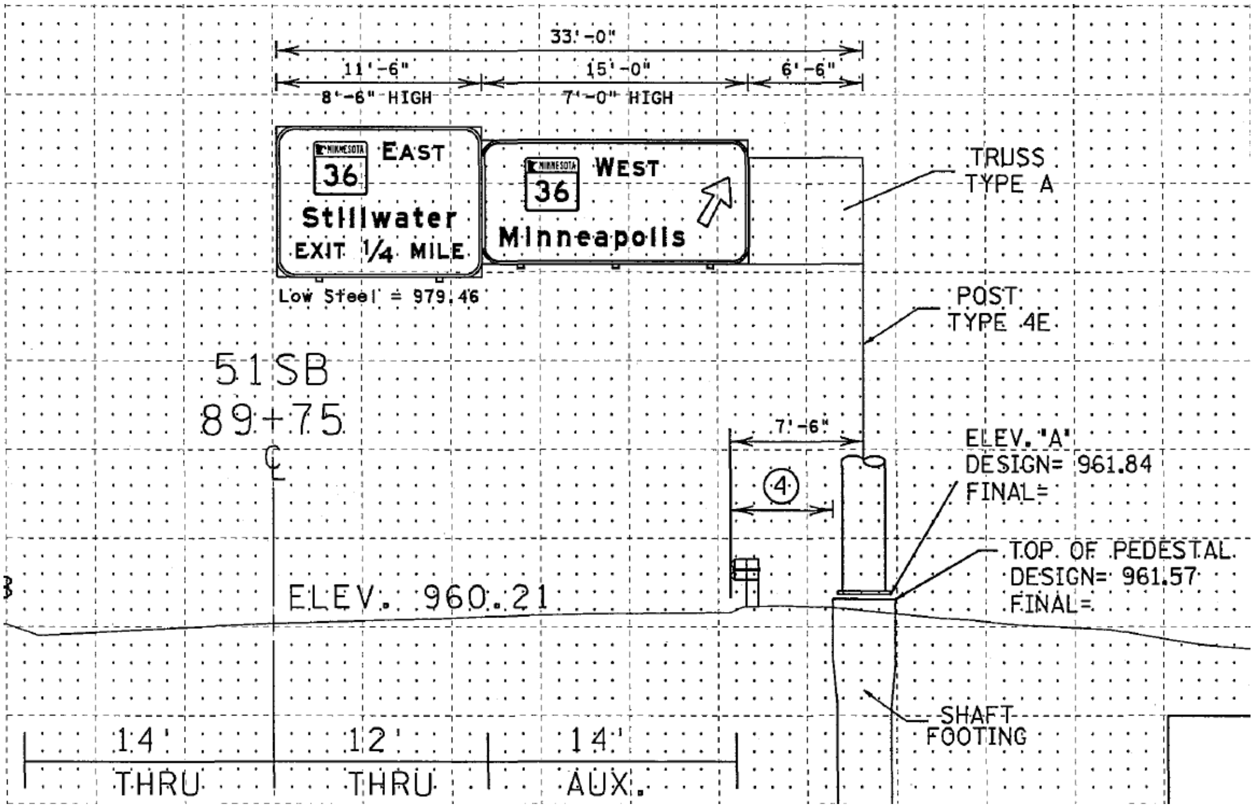


Figure 4.1.2 Elevation of sign structure from southbound travel

Figure 4.1.3 shows reference locations for all gauges with an elevation and plan view of the post base.

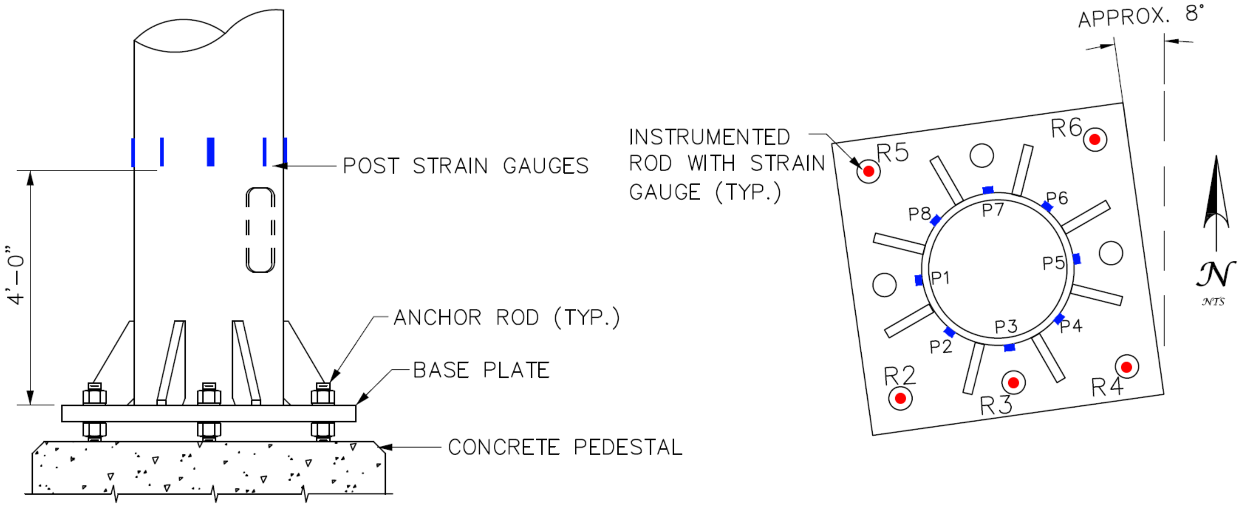


Figure 4.1.3 Lower post instrumentation elevation view (left) and post base instrumentation plan view (right)

For specific dimensions, see MnDOT Standard Plan 5-297.764 (MnDOT 2019).

4.1.1.2 Data Collection History

An effective structural monitoring system must be continuously kept up and is often constrained by environmental factors. This was true with data collection on the instrumented post in Minneapolis. Oftentimes, maintenance could not be completed due to winter weather and other factors.

The sign data collection system was installed in August 2017 with the data from that year reported in the Phase I report (Chen et al. 2018). As of July 2018, only bolts 2 and 3 were still transmitting data, likely due to intrusion of water into the other gauges. The gauges could not be replaced in the fall and winter due to weather constraints. In September and October of 2018, the data were corrupt due to an issue with the logger.

In mid-April through early May 2019, the data logger failed leading to missed data for parts of those months. Finally, in July 2019, the broken strain gauges were replaced in the field; however, the strain gauge in bolt 3 began to drift after the others were replaced, and it stopped working completely in early August 2019. This could have been due to a wiring problem in the cabinet after adjusting the other bolts.

In late January 2020 through early February 2020, the power supply to the logger shorted out and three weeks of data were lost due to inaccessibility of the site.

4.1.2 Data Processing and Derivation

For processing, computer code developed by the research team was utilized for more efficient data processing due to the data being collected continuously at 100 Hz for the past two and a half years. The computer code was based on ASTM E1049-85 (ASTM 2017), which is the rainflow counting method for fatigue stress cycles.

After rainflow counting was completed, a lognormal probability density function curve was fitted to a histogram of the rainflow counts for each day, and the equivalent stress range was found by taking the third moment of the function as outlined by Lassen and Recho (2006) in Fatigue Life Analyses of Welded Structures.

Using a log normal PDF was chosen over Miner's rule due to it being able to more effectively model the probability of occurrences than Miner's cumulative damage method. After processing, the equivalent stress range for all anchor rods ended up being close to 0.5 ksi. This value is far lower than the AASHTO constant amplitude life limit of 7 ksi. However, after further research into the equivalent stress range concept, Miner's method was deemed unsuitable for investigating pre-tension loss for anchor rod connections.

To understand why an equivalent stress range for anchor rod pre-tension loss is unsuitable, it is helpful to first understand a simplified derivation of a typical equivalent stress range damage fraction and the general design S-N curves. For a more in depth derivation, refer to Miner's original paper (Miner 1945). For both the Miner and other equivalent stress range concepts, they are dependent on empirical fatigue tests for specific details. This is in order to derive a damage fraction, as illustrated in Equation 4.1.

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C \tag{4.1}$$

In Equation 4.1, n_i is the number of cycles applied at a specific stress, N_i is the number of cycles to failure at a specific stress, and C is the damage fraction. If C is equal to 1, the detail has failed in theory. Equation 4.1 approximately quantifies the lifespan of a detail that is taken up from a specific stress range. Each stress range count and the corresponding damage fraction can then be summed to approximate if a certain detail has failed. Even if a probabilistic model is used, it is still dependent on an empirically derived damage fraction for determining equivalent stress ranges.

The unsuitability of the accepted fatigue damage concept for pre-tension loss arises from both the definition of fatigue damage and the empirically derived damage fraction. Firstly, the definition of fatigue damage is fairly binary; a detail is fractured or it is not. Whether it is complete failure, crack propagation, or crack initiation, fatigue damage is defined. For pre-tension loss, it is a little more difficult to define, and possibly complete loss of pre-tension or a loss of a defined interval of strain could be utilized, but there are no existing fatigue tests that are performed in that manner. Even if a “failure” pre-tension is defined, an S-N curve for each pre-tension would be required since the number of cycles at a certain stress range would also be dependent on the initial pre-tension force. Empirical derivation of such F-S-N curves would likely be difficult when considering the number of confounding variables, and especially pre-tension accuracy and long-term relaxation. The rainflow counting results from the anchor bolts and post are presented in the Concluding Points section of this chapter. From the rainflow plots, laboratory testing cycles were derived to approximate field conditions and monitor possible fatigue losses from the new procedures.

4.2 DATA

4.2.1 Climate

Since the focus of this project was primarily the stress in the anchor rods, climate data focused on the long-term seasonal changes in anchor rod forces. To investigate long-term changes in the anchor rods, a daily average was taken for each day in the dataset. An average was chosen due to various daily temperature differentials, and these data would adequately represent anchor rod behavior over a long time period.

Throughout the year, anchor rods experienced, approximately, a 10 ksi stress differential from the summer to winter months. This is likely due to thermally induced stresses from expansion and contraction. Long-term rod stresses also match up approximately with a theoretical daily temperature-induced stress based on material properties. Figures 4.2.1 and 4.2.2 illustrate the long-term anchor rod stresses and theoretical temperature-induced stresses for half of the monitoring period each.

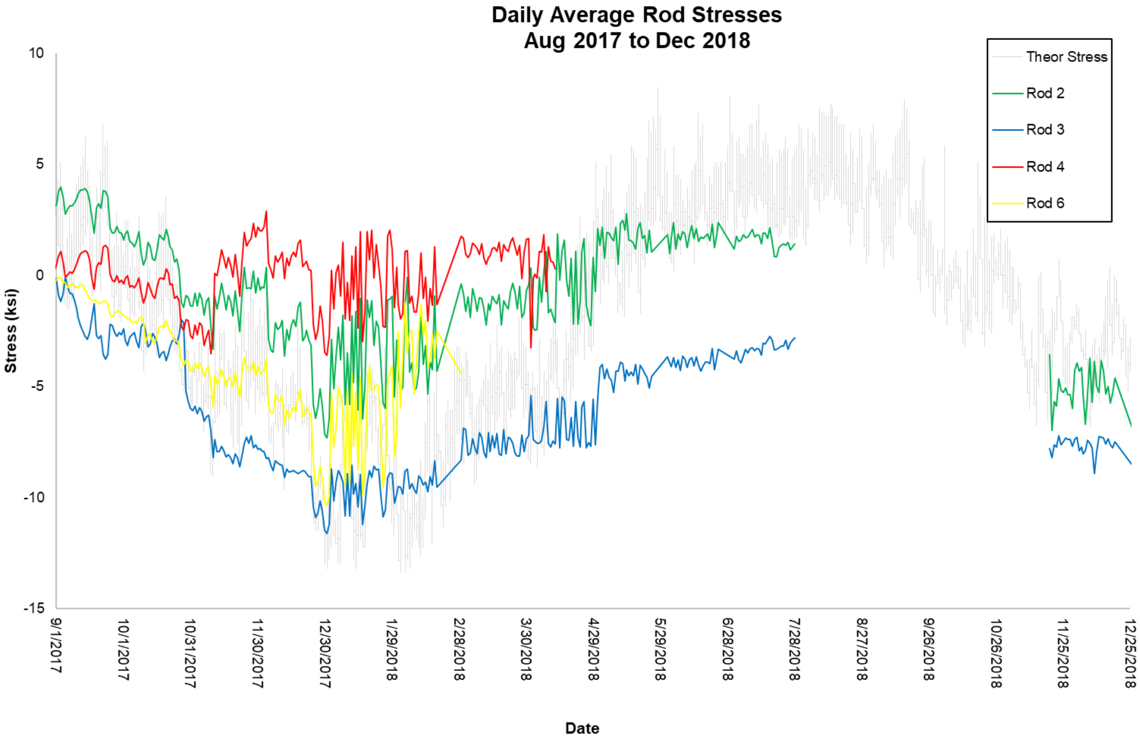


Figure 4.2.1 Long-term anchor rod stresses 8/2017–12/2018

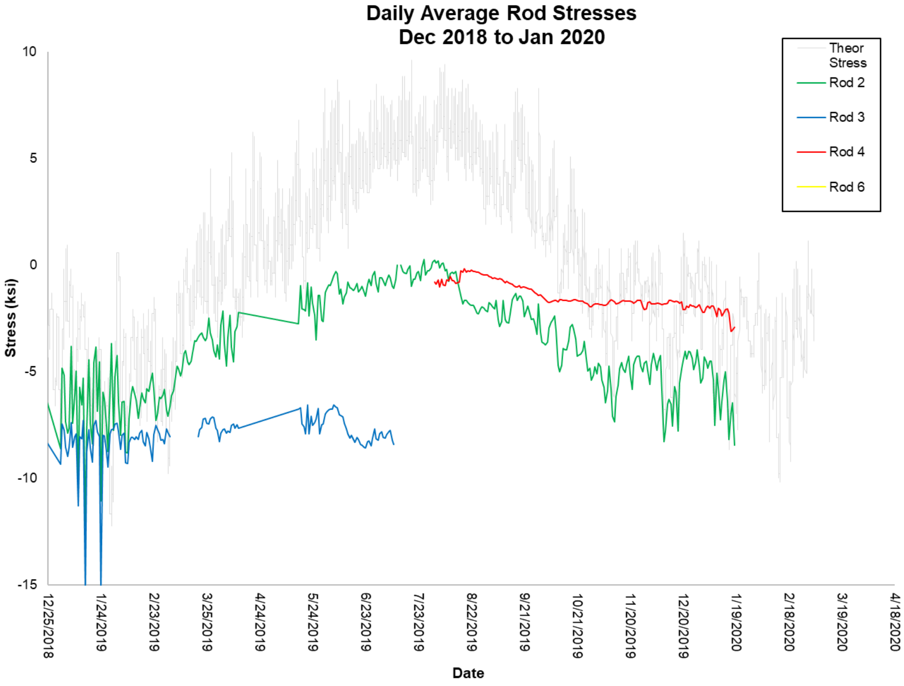


Figure 4.2.2 Long-term anchor rod stresses 12/2018–1/2020

For clarity, data are not included when anchor rod gauges failed. Another observation from the long-term rod stresses is that there is greater scatter in winter months and many gauges were observed to fail during this time period. It is hypothesized that the scatter is likely from snow and ice accumulating on the anchor rod gauges in addition to snow impacting gauges when a plow passed the installation. Enforcing this theory is the fact that all of the north facing gauges, which coincided with rods 5 and 6, failed first during the winter of 2017–18. The north facing part of the pole received the greatest snow impact from snowplows and likely resulted in premature failure of the rod-mounted gauges. Finally, the rod strain data does appear to drift away from the theoretical data. While this behavior could be due to relaxation or pre-tension loss, it is also likely that the resistance gauges are drifting over a long period of time and needs to be tested further in a laboratory environment to confirm any long-term loosening impacts.

4.2.2 Rainflow Curves

Rainflow counting N-S curves were developed for both the post gauges and the anchor rod gauges. *N* is the number or count of cycles, and *S* represents the stress or strain range. Figure 4.2.3 shows the N-S curve for the post gauges with 1 microstrain bins, and Figure 4.2.4 shows the N-S curve, in 0.925 ksi stress bins, for the anchor rod gauges that functioned the full year in 2018.

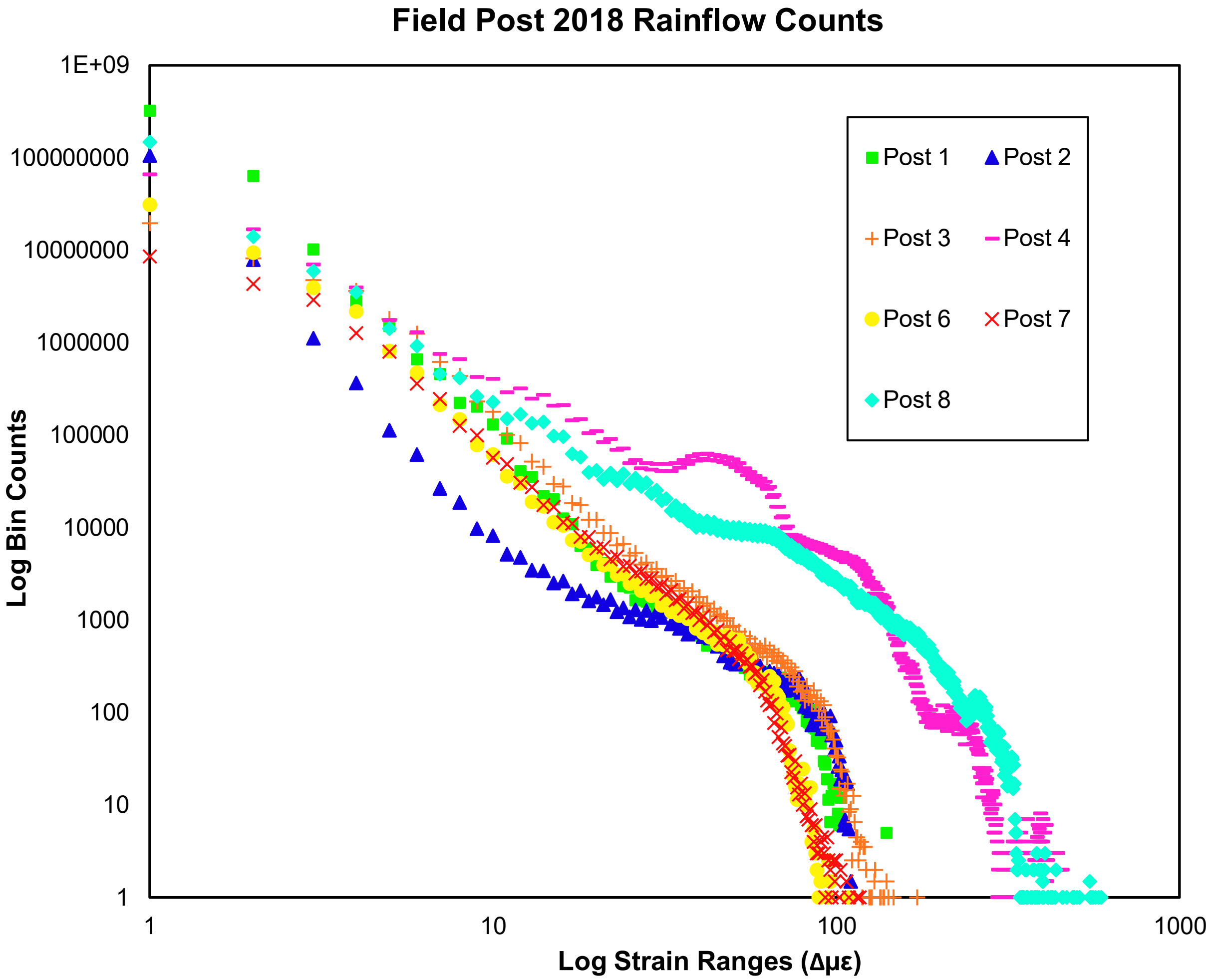


Figure 4.2.3 Field N-S curve for post stresses

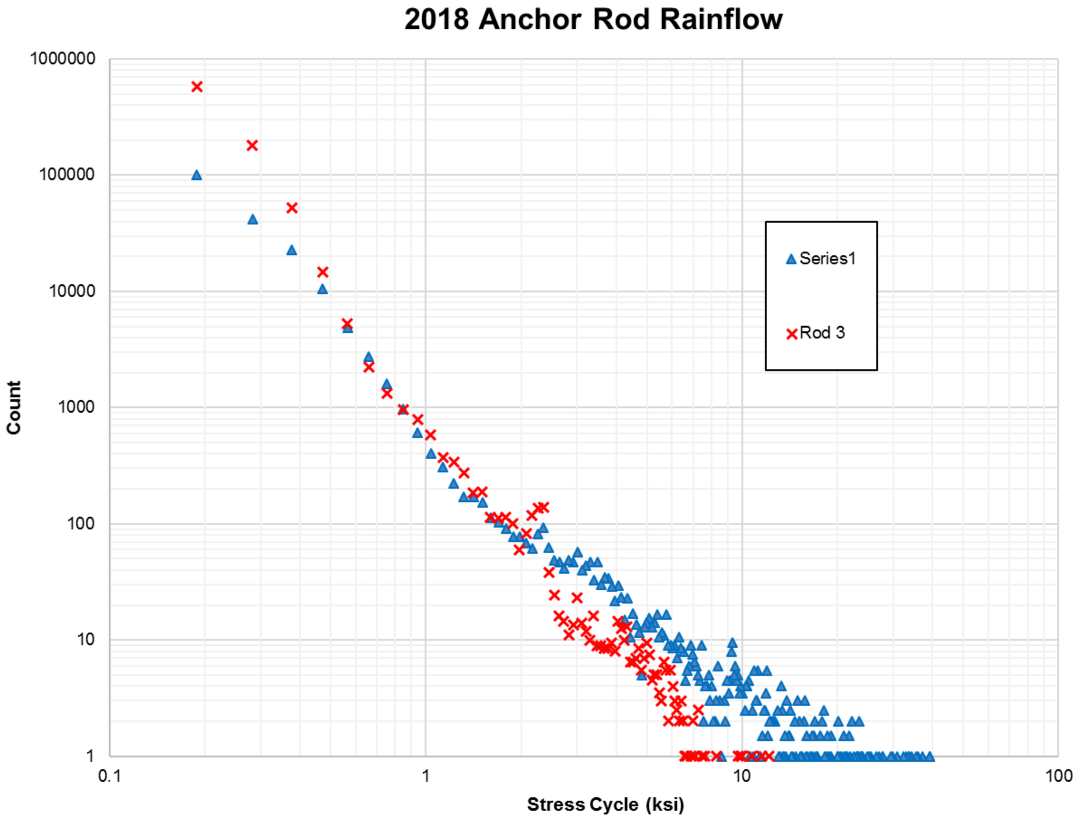


Figure 4.2.4 Field N-S curve for post stresses

Note that these plots are not S-N curves empirically derived for design purposes and instead represent the direct field stresses on the monitoring structure. Field N-S curves are generally represented in histograms, but for brevity and clarity, bins for multiple gauges are represented by points in Figures 4.2.3 and 4.2.4. Each point represents the maximum of its respective bin.

In Figure 4.2.3, the rainflow count of post strains for the maximum observed stresses were in post gauges 8 and 4 at approximately 600με. Gauges 4 and 8 were on opposite sides of the monitoring post, so it makes sense that they would both be maximum. Interestingly though, the two maximum gauges are not perpendicular with the sign/road direction and are closer to 45 degrees from perpendicular to the sign. Galloping or vortex shedding could be the reasoning for these results, or possibly the sign's natural frequency is in that direction. All other strain gauges experienced a maximum of about 100 με.

In addition to the post N-S curve, one was also constructed for the anchor rod stresses, shown in Figure 4.2.4 on a log-log plot. Both of the anchor rods that illustrated long-term stability, 2 and 3, were plotted, since the data for some of the other anchor rods were questionable. Rod 3 experienced a maximum stress differential of 10 ksi and rod 2 experienced a maximum stress differential of 40 ksi. However, there are a couple of additional confounding variables involved with the anchor rod gauges than with the post gauges.

As discussed in the previous Climate section, snowplows and snow likely had an impact on the gauges, likely disturbing the tops of the connections, which have shown to be sensitive to disturbances. Figure 4.2.5, taken with the structure monitoring camera, shows snow and ice on the gauges in late February 2020.

Figure 4.2.5 Snow and ice piled on anchor rod gauges

All of the large stress cycles were experienced during winter months. A 40 ksi stress reversal of rod 2 would also be unexpected given it was an exterior anchor rod. Previous experience in Phase I demonstrated that exterior anchor rods, like rod 2, are subjected to less stress than interior rods, like rod 3.

4.3 CONCLUDING POINTS

- Long-term monitoring of anchor rods shows, approximately, a 10 ksi seasonal differential stress due to differential temperature impacts.
- Overall, this change would be enough to loosen anchor rods if tightened with the old specification of 480 ft-lbs. The differential may also play into long-term pre-tension loss, but the impact has yet to be definitively observed.
- There is downward drift in the anchor rod strain gauges of the sign structure.
- The downward drift may be pre-tension loss through relaxation or fatigue, but it is more likely that it is due to long-term drift of the resistance strain gauges. When rod gauge 3 failed in August 2019, the wires were stripped and it was found that they were corroded, which would impact the total resistance of the connection. Additionally, the post gauges, which are not in a pre-tensioned state,

also have a slight downward drift, but it is difficult to make comparisons between the two given they are different sizes and types of resistance strain gauges.

- It may be more reliable to base laboratory testing on the forces that the post exerts on the anchor rods due to the reliability and number of functioning anchor rod gauges.
- For laboratory testing, it would likely be better to model the testing procedure off the forces that the post undergoes and therefore transfers to the anchor rods, instead of the anchor rods themselves, due to the level of uncertainty with the anchor rod gauges.
- Anchor rods have not lost significant pre-tension over the past two and a half years.
- Looking into the long-term data and after field inspections, it appears that the connections have remained sufficiently pre-tensioned over two and a half years, which is better than MnDOT's previous experience. The connections were also pre-tensioned with AASHTO turn of nut, which may indicate that the current specification is sufficient, but could just use improvement with its implementation and inspection.

CHAPTER 5: CONCLUSIONS AND RECCOMMENDED IMPROVEMENTS TO TIGHTENING PROCEDURES

5.1 CONCLUSIONS

After reviewing the literature, previous laboratory testing, results from implementation, and the field post monitoring data, it is likely that the majority of the problem with anchor rod pre-tension loss is not the result of procedures but has to do with their constructability. For connections to retain pre-tension, tensioning procedures need to be effective, constructible, and verifiable.

In implementation, the two major areas of improvement to the specifications can be summarized as specification clarity and error control. For future laboratory testing, the goal will be to understand and minimize error while simplifying procedures, so efficiency and efficacy can be balanced. Field loading will also be replicated to further understand the impact that fatigue has on loosening connections and new procedure performance.

5.2 RECOMMENDED CHANGES TO MNDOT TIGHTENING PROCEDURES

5.2.1 Specification Clarity

5.2.1.1 Separation of Overhead Sign and Lighting/Traffic Signal Specifications

Because of the inherent differences in bases of overhead signs and traffic signal/lighting structures, it would likely be beneficial to separate the specifications. Separation of the specifications would increase the clarity of each and allow for focusing on some of the more nuanced aspects of each structure type. For overhead signs, turn-of-nut specification and torque could be used for a sort of double verification as intended by the Phase I recommended procedures. In the pre-tensioning steps for lighting and traffic signal structures, the specifications could focus on clearance issues and the quality of torque control. In addition, the contractors for each type of structure vary a lot, and many lighting structures may be installed by an electrical contractor that may not have the same structural experience as an overhead sign contractor.

5.2.1.2 Create Maintenance Procedures

In addition to separating the specifications, it would likely be beneficial to create maintenance procedures for both overhead signs and traffic signal/lighting structures. Since maintenance procedures differ greatly from installation, it would likely benefit MnDOT maintenance personnel to have a set of procedures to which they could refer. Special care also must be taken during maintenance to ensure that the structure remains stable while anchor rods are serviced.

5.2.1.3 Verify Lubrication Areas

With both overhead sign and light pole installations, contractors expressed uncertainty concerning the exact areas to lubricate besides anchor rods. Contractors often needed specific instructions on which areas needed to be lubricated on the nuts and washers. The current language in the installation record does not clearly state the surfaces needing lubrication, and a graphic should possibly be created illustrating proper lubrication areas.

5.2.1.4 Specify Steps in Logical Manner

Most contractors also had never utilized two rounds of tightening to complete snugging, turn or nut, and verification. Language utilized in the specification needs to clearly state when two rounds of tightening are needed. In addition, if the contractor is utilizing a torque wrench, it must be clarified that, with two rounds of tightening, the required torque is not to be cut in half.

The relationship between turn-of-nut and verification torque should also be clarified. Verification torque should be considered the “final” tightening value. Even if certain turn-of-nut angles cannot be accomplished, the contractor should proceed to the verification torque required.

Finally, for smaller diameter anchor rods, contractors generally do not consider over-tightening, and yielding, of the anchor rods. At times, the contractor wants to utilize two hands to tighten the nuts. However, to prevent yielding, the new specification instructs that the nut should be tightened using one hand. “Yanking” on the nut should not be encouraged. Contractors do not have a good understanding of the yield strength of smaller diameter bolts of lower grades.

Each required step should likely be laid out as an individual torque or turn in a table so they can be logically followed one at a time without having to go back and forth with half torques. In addition, it may be beneficial to add some descriptions to the steps to explain why they are important to follow for contractors.

5.2.2 Error Control

5.2.2.1 48-Hour Retightening Torque

Currently, one of the AASHTO-recommended procedures is to retighten connections after 48 hours to 110% of verification torque. This retightening is supposed to account for creep due to galvanizing and minimize initial relaxation losses. In practice though, the 48-hour retightening torque is likely seldom followed, was not recorded on any of the installation structures, and was not used during maintenance due to the resources required, especially for structures installed in the medians of arterial highways. Although it is difficult to perform, concerns about losses are still valid (Bickford, 1997; Fisher & Struik, 1974; Yang & Dewolf, 1999). Laboratory testing should be performed to investigate the impact on final pre-tension forces if connections are initially pre-tensioned to 110% torque instead of after 48 hours.

5.2.2.2 Lubrication

Throughout implementation, contractors generally did not use the specified MnDOT bridge grease on installations. The majority of lubricants, though, were a sort of anti-seize compound, and research into the literature indicated that the nut factor was comparable to the specified grease regardless. However, since there will be some variance in the lubricity, it is important to investigate the impact that a deviation from the specification may have on the connection and how strict enforcement should be.

5.2.2.3 Specification Simplification

Fewer steps than currently specified could likely be used. In all of the maintenance and most of the installations, steps were skipped when bringing nuts to snug tight and with the verification torque. The reasoning for the steps was to prevent differential stresses in the bolts; however, doing two steps at snug and two steps at verification may not be proportional enough to cause major differentials in bolt stresses compared to taking bolts from snug to fully tightened. The impact of these steps can be further investigated. In addition, clarity of the specification could likely be increased by removing the snug-tight terminology given that many contractors connote it to mean hand-tight. Alternatively, a 20%, 60%, and 110% torque or turn terminology could be used to communicate more effectively.

5.2.2.4 Existing HMLT Installation and Maintenance

With the revised design clearances, the HYTORC low-profile stealth series hydraulic torque wrench should work on new HMLT installations. The wrench was very close to fitting on the newer base design at the Maple Grove site (A14E 4). With the stack socket attachment, the wrench nearly worked on the older base design and was far easier to place. Contractors may want to consider using the stack socket attachment during installations for easier placement and removal of the hydraulic torque wrench.

On in-place HMLT structures, though, the only feasible retightening option would likely be a slug type wrench, since both hydraulic wrench options encountered significant difficulties. During a next phase, a tightening maintenance procedure can be developed for HMLTs based on turns with a slug-type wrench.

5.2.2.5 Torque-Only Specification for Lighting and Traffic Signal Structures

During all of the installations and maintenance experiences with traffic signals and lighting structures, turn or nut was difficult to perform, or not even attempted. In the next phase of this work, the error of only using a torque specification can be investigated, since some previous literature maintains it was not reliable. The benefits of having slightly more error with torque-controlled pre-tensioning likely would outweigh the limitations of attempting turn of nut in smaller diameter anchor rods and in enclosed spaces.

5.3 LABORATORY TESTING AND NUMERICAL MODELING RECOMMENDATIONS

5.3.1 Error and Impact from Simplified Procedures

As covered in the Specification Clarity section, there are several areas of simplification to the procedures; however, simplifications must be balanced with efficacy to ensure that anchor rods will still retain pre-tension throughout their lives and an acceptable amount of pre-tension scatter is achieved. The two main investigation areas will be the impact of a torque-only specification, error from using different lubricants, and 48-hour pre-tension losses. All of the laboratory results can then be compared with the literature and revisions recommended to the specification.

The fatigue resistance of the new procedures can also be tested and compared to the field monitoring structure. This will assist in verification of the field data to investigate strain drift and any possible fatigue loosening of the connections to develop a servicing lifespan.

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