Evaluation of Electro-Mechanical Impedance (EMI) for Structural Health Monitoring (SHM) of Post-Tensioned Ground Anchors

CLAYTON THURMER, JASON RAY, MATTHEW GLASSCOTT and BRIAN EICK

ABSTRACT

The US Army Corps of Engineers has demonstrated a need to monitor ground anchors within their large civil works portfolio in order to avoid structural damage to critical infrastructure. Ground anchors (ie, "tiebacks") are used for securing loose soil or rock by placing a tendon (such as seven wire strand) into a predrilled hole, pulling it into tension against an anchor plate or block, then typically grouting it into place. A common failure mode of these ground anchors is tendon degradation due to corrosion resulting in tension loss. However, the tendons are difficult to monitor due to embedment in material limiting visual inspection to exposed anchor plates, wedges, and strand ends. Furthermore, retrofitting sensors onto existing anchor installations is limited to the exposed components. Therefore, instrumentation is desired to detect and quantify corrosion and/or tension loss of the embedded tendon as part of a comprehensive Structural Health Monitoring (SHM) plan. An effort to evaluate instrumentation to this end was undertaken by the authors. A process for inducing accelerated corrosion of cable sections using additively manufactured corrosion cells was developed in order to facilitate a more time-efficient evaluation of sensing modalities' ability to detect corrosion induced material loss. Literature reveals that electro-mechanical impedance (EMI) using PZT (Lead zirconate titanate) patches (i.e. piezoelectric transducers) has been previously experimentally evaluated for both corrosion monitoring of steel components and cable tension respectively, although not concurrently. This paper presents an experimental methodology and laboratory results of corrosion detection and tension monitoring using PZT patches affixed to seven strand steel wire rope. Preliminary results from separate experiments indicate an ability to detect material loss due to corrosion and changes in tension using EMI.

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INTRODUCTION

Corrosion is a significant cause of failure of rock bolt style ground anchors [1]. Stress corrosion cracking (SCC) and pitting are accountable for 63% and 30% of failures respectively [2]. The SCC results from a high tensile stress occurring in a corrosive environment and manifests as brittle cracks on the metal surface [3]; whereas pitting is defined as the development of holes, or "pits", from localized metal loss due to the respective anode and cathode sizes [4]. Ground anchor corrosion reduces the capacity to carry load and diminishes the life expectancy of the ground support system [1] implying that monitoring and detection of corrosion of ground anchors is a pertinent endeavor. Therefore the US Army Corps of Engineers (USACE) has a need to detect corrosion of the seven cable strand widely used in their ground anchor applications. However, the tendons are difficult to monitor due to embedment in material limiting visual inspection to exposed anchor plates, wedges, and strand ends. Furthermore, retrofitting sensors and instruments to existing anchor installations is limited to the exposed components. Therefore, instrumentation is desired to detect and quantify corrosion and/or tension loss of the embedded tendon as part of a comprehensive Structural Health Monitoring (SHM) plan. An effort to evaluate sensors and instrumentation to this end was undertaken by the authors.

A review of relevant literature reveals a wealth of previous work. Song et al. provide a review of ground anchor monitoring techniques which includes discussion of piezoelectric transducer (PZT) electro-mechanical impedance (EMI) among other technologies, however, stranded cables are not addressed explicitly [1]. Meanwhile Na et al. provide a review of piezoelectric electro-mechanical impedance (EMI) for Structural Health Monitoring (SHM) of engineering structures where soil rock anchors are not addressed explicitly, however corrosion and damage detection of metallic structures is considered more broadly [5]. Using the EMI technique for SHM involves measuring the changes in electrical frequency response of a PZT sensor due to the changes in mechanical impedance of a connected engineering structure [5].

EMI using PZT (Lead zirconate titanate) patches has been previously experimentally evaluated for both corrosion monitoring of steel components and cable tension respectively, although not concurrently. Li et al. show that material thickness can be observed using EMI with verification using finite element modeling [6]; however, their experimental specimens are not explicitly corroded to produce material loss. Ai et al. use EMI to monitor physical corrosion of a steel beam over 117 days [7], however a more rapid corrosive process is desired for time efficient experimental evaluation. In both efforts, the PZT is bonded directly to the flat sides of a rectangular prism shaped steel specimen. On the other hand, tension force monitoring using EMI has also been studied widely. Ryu et al. use a wearable interface device for force estimation on axially loaded members [8], while Huyhn et al. use an interface plate on tendon anchorages to measure the force [9]. These studies exemplify a trend to insert additional members between the PZT patch and the cable to facilitate use of EMI, including a variety of "smart" anchorages, which presents challenges for retrofit applications to the existing needs of USACE.

METHODOLOGY

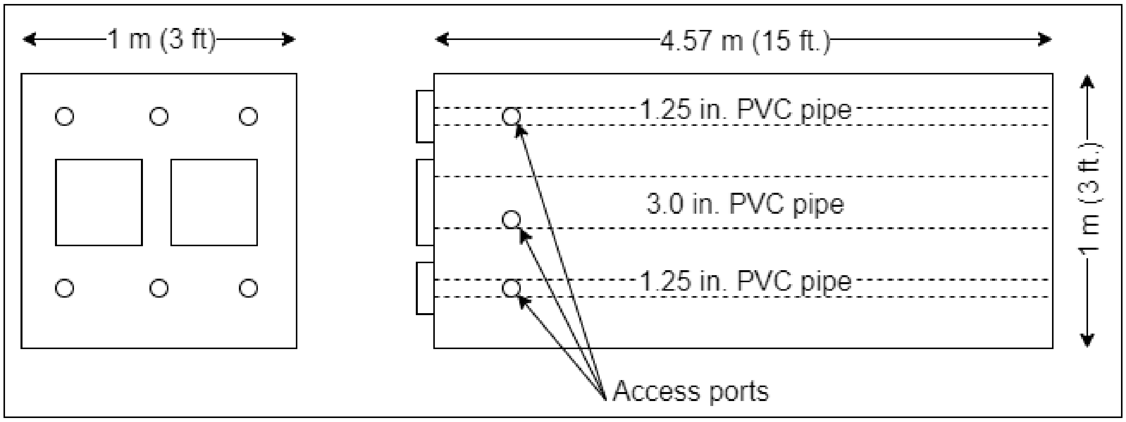

Figure 1. Schematic view of the tension testing apparatus.

The experiment required purpose built equipment. A tension apparatus was built in order to tension cables and corrode them. However, the corrosion process within the apparatus was inconsistent so an additional apparatus for accelerated corrosion was built. The EMI of the seven wire strand specimens was independently observed versus tension force and time exposed to corrosion. Concurrent experimentation of exposure to corrosion of the anchor under tension is left as future work.

Tension Apparatus

A testing apparatus was constructed to apply tension and facilitate the corrosion of multi-strand cables and a schematic is shown in Figure 1. [10] It is 4.57 m (15 ft.) long reinforced concrete and can support six single cables enclosed within six individual, 3.18 cm (1.25 in.) polyvinyl chloride (PVC) tubes and two seven cable assemblies enclosed within 7.6 cm (3 in.) PVC tubes. The test bed allows for stressing individual cables using a hydraulic ram-stressing machine up to their load-bearing capability, while being exposed to corrosive fluids by introducing those fluids directly into the tubes. Test ports are arranged on each of the larger tubes, one-third of the way down the length of the test bed. These provide access to the cable within the test bed and allow for observation of the cable's condition. However, the corrosion process in this apparatus has been inadequate for the desired experiments due to a slow and uncontrolled corrosive process within the tubes.

Accelerated Corrosion

A process to rapidly corrode the seven cable strand was used for more time efficient experimentation. Corrosion is an electro-chemical process which occurs when a potential gradient forms between two metal contacts and electrons migrate from the cathode (at higher potential) to the anode (at lower potential) through solution. Molecules are reduced (gain electrons) at the cathode and are oxidized (lose electrons) at the anode resulting in mass loss from the anode itself. The corrosion flow cell was designed as two cylinders, the outer cylinder (solid) with a length of 91.5 mm (3.6 in.) and a radius of 57 mm (2.24 in.), and the inner cylinder (hole) with a length of 50 mm (1.97 in.) and a radius of 44 mm (1.73 in.). Two through-holes, 8.5 mm (0.33 in.) radius, were integrated to allow the cell to be fitted around a section of seven wire strand and caulked into place. Two holes were drilled in the top and bottom of the unit to act as the inlet and outlet for solution flow. Importantly, the hole drilled in the top is perpendicular to the plane in order to ensure the cell fills completely with liquid. The hole in the bottom half was drilled at 35° to the plane to allow the cell to rest on a flat surface. Flexible Tygon tubes (Compagnie de Saint-Gobain S.A., La Défense, Courbevoie, France), 6.35 mm (0.25 in.) outside diameter by 3.175 mm (0.125 in.) inside diameter, and 3 m (10 ft.) long were fitted to the holes and sealed in place with epoxy resin. To complete the circuit for the corrosion process occurring at the seven-strand cable (anode), a 7.62 cm (3 in.) steel nail was inserted into the top half through a drilled hole and connected to a Scotchbright (3M, Maplewood, MN USA) stainless steel metal scrubber within the corrosion flow cell, acting as the cathode. The high surface area of the stainless-steel scrubber helps lower the junction resistance of the corrosion cell and facilitates higher current magnitudes. A 55-gallon drum was used as a reservoir to contain the corrosion matrix (5% sodium chloride, NaCl, in tap water). The pH of the solution was approximately seven, which promotes the formation of iron hydroxide colloids during the corrosion process. A 10 µm filter bag (Pentair, London, United Kingdom) was installed in the 55-gallon drum in order to filter the effluent from the outlet in order to remove the colloids from the corrosion matrix and keep the solution clean of larger corrosion fragments which might clog the pumps. A submersible 12 VDC pump model MARCH-0893-0030-0200 (March Pumps, Glenview, IL USA) was used to control flow rate of the corrosion matrix into the corrosion flow cell. This pump is chemical resistant and brushless (which is necessary considering the corrosive nature of the solution), and has a tunable flow rate depending on the DC power applied. The pumps were operated at a flow rate correlated to a 0.5 Amp current using a BK Precision power supply (B&K Precision, Yorba Linda, CA USA). A 6 Amp, 20 Volt BK Precision DC power supply was used in order to precisely control the corrosion process. The negative lead was connected to the cathode (nail on the outside of the corrosion cell) and the positive lead was connected directly to the seven-strand cable. The power supply was then set to deliver 6.000 A continuously, which generally required a 9-20 V. Notably, the voltage can fluctuate as the surface area of the corroding surface decreases, but if the current remains constant, the process may be calibrated by evaluating the mass loss (reduction in cable diameter) as a function of corrosion time-frame. Figure 2 shows the layout of the additively manufactured accelerated corrosion cell shown as two pieces with test specimen and experimental PZT patch locations.

Experiment Design

Three different PZT patches (STEINER & MARTINS, INC. Davenport, FL USA) were acquired for the experiment (with resonant frequency noted): SMD10T2R111WL (215 kHz), SMD07T02R412WL (300 kHz), and SMD05T04R111WL (450 kHz). Importantly, only units with wire leads included were chosen due to experienced difficulty attaching leads. Each of the three options were respectively affixed to 30.48 cm (12 in.) lengths of seven wire strand at the cut cable end (roughly to the central strand) and along the length of the section (to a single exterior strand). Cyanoacrylate glue (Loctite, Westlake, OH USA) was used to affix the PZT patches to the cables. Similarly, the PZT

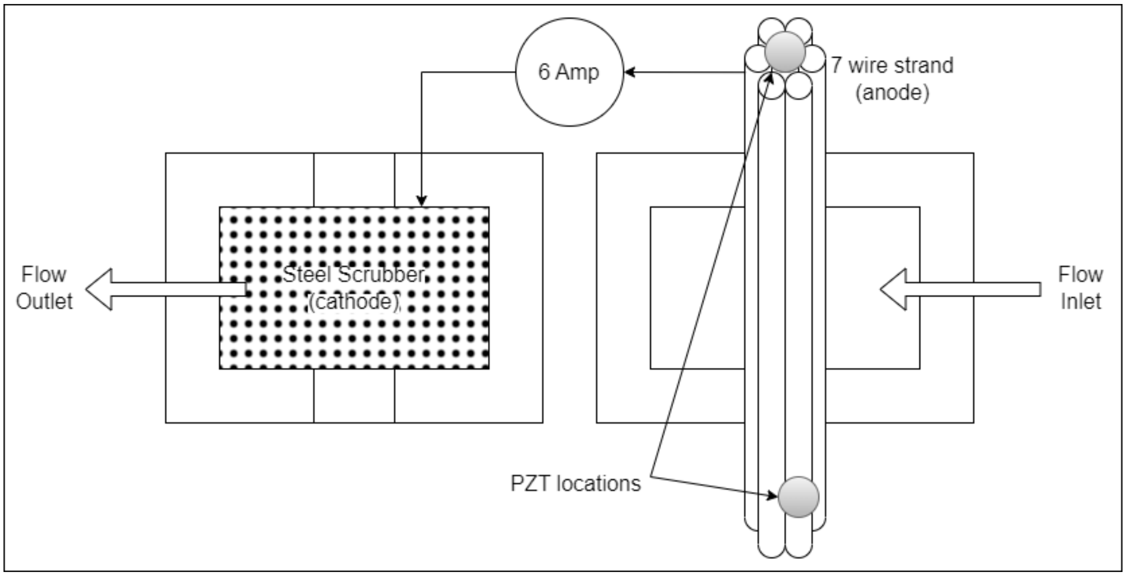

Figure 2. Layout of the additively manufactured accelerated corrosion cell shown as two pieces with test specimen and experimental PZT patch locations.

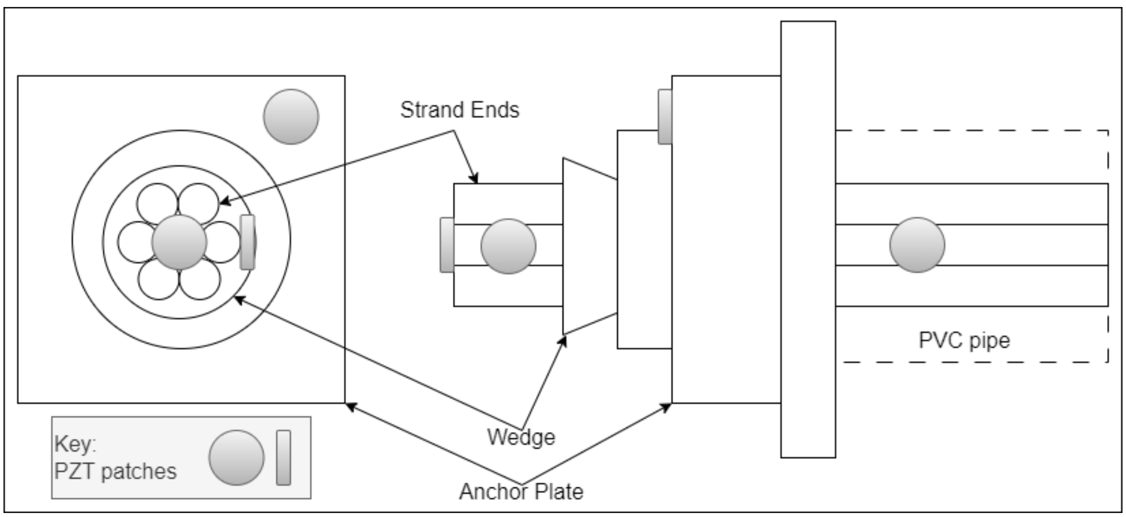

Figure 3. Schematic view of the placement of PZT patches for experimentation using the tension apparatus.

patched were affixed to the test apparatus, including the exposed cable ends, the anchor ends, and along the cable within the apparatus. Figure 3 shows the placement of PZT patches for experimentation using the tension apparatus.

The EMI technique is typically applied in range of 30-400 kHz [7]. The frequency response of the samples was tested using the IET/QUADTECH 7600 PLUS PRECISION LCR METER (EIT, Rosalyn Heights, NY USA), a laboratory grade spectrum analyzer. Spikes in the spectrum were observed and, if necessary, the targeted frequency range was narrowed. Once the range of interest was determined, the interrogation was transitioned to the EVAL-AD5933EB (Anaolog Devices, Wilmington, MA USA). This is a low-SWaPC (low size, weight, power, and cost) impedance analyzer that is commonly

TABLE I. PARAMETERS FOR EXPERIMENT

Test	PZT patch	Location	Test Range	Spectrum
Tension 1	SMD10T2R111WL	anchor head	0-5000 psi	250-275 kHz
Tension 2	SMD10T2R111WL	30 cm from anchor	0-5000 psi	240-290 kHz
Corrosion 1	SMD07T02R412WL	cut end	0-8 hours	450-550 kHz
Corrosion 2	SMD10T2R111WL	cut end	0-6 hours	250-300 kHz
Corrosion 3	SMD10T2R111WL	5 cm from cut end	0-6 hours	225-275 kHz

used for EMI [5] and has potential to be integrated into wireless SHM systems [11]. Importantly, however, an appropriate resistor value must be calculated for the desired frequency range and inserted into the device ports [12]. Following a preliminary investigation of the samples, five tests were determined to complete as shown in the Table I. Due to limitations of the testing apparatus, the measurement of corrosion and tension force with EMI was explored separately, although initially it was desired to explore these concurrently. For corrosion testing, the specimen was placed in the corrosion cell and corroded continuously for several hours. The EMI was recorded every hour until complete, when the corroded specimen was removed from the cell and measured for material loss. For the tension testing, a 4.57+ m (15+ ft.) specimen was placed in the tension apparatus and stressed using a hydraulic ram stressing machine. The EMI was measured at every 1000 psi increment.

RESULTS AND DISCUSSION

Regarding tension, considerable difficulty was encountered when mounting the PZT patch to the external components that would be needed for a retrofit SHM system in the USACE portfolio, such as the anchorage and cut cable ends. Part of the challenge is the inability to select an appropriate frequency range containing a spike available for tracking. The spike encountered in these experiments was near the resonance of the PZT patch itself. Consideration was given to adding a so-called PZT interface (additional materials between the PZT patch and the anchorage), such as [9], but this was considered beyond the scope of this initial effort. Ultimately, the test “Tension 1” was ambiguous and did not produce a measurable shift in the EMI throughout the entire tension regime. On the other hand, the test “Tension 2” showed clear and approximately linear shift leftward as the tension was increased as shown in Figure 4. Interestingly this result is opposite of the rightward shift expected from [8]. Furthermore, placement of the sensor on the internal cable would only be appropriate for new installations, and is not relevant for the retrofit needed in the USACE portfolio.

Regarding corrosion, the flow cell method was efficient at corroding the seven wire strand but the encasement of the specimen within the cell limited the meaningful observation of material loss to only the beginning and end of the test regime. Challenges on mounting the PZT patch to the sides of the round strands was also limiting. Placing the PZT patch on the center of the cut end largely focused the contact to the central strand, whereas mounting along the length of the strand limited the contact to an external strand. The tests with centrally mounted PZT patches were ambiguous, however the

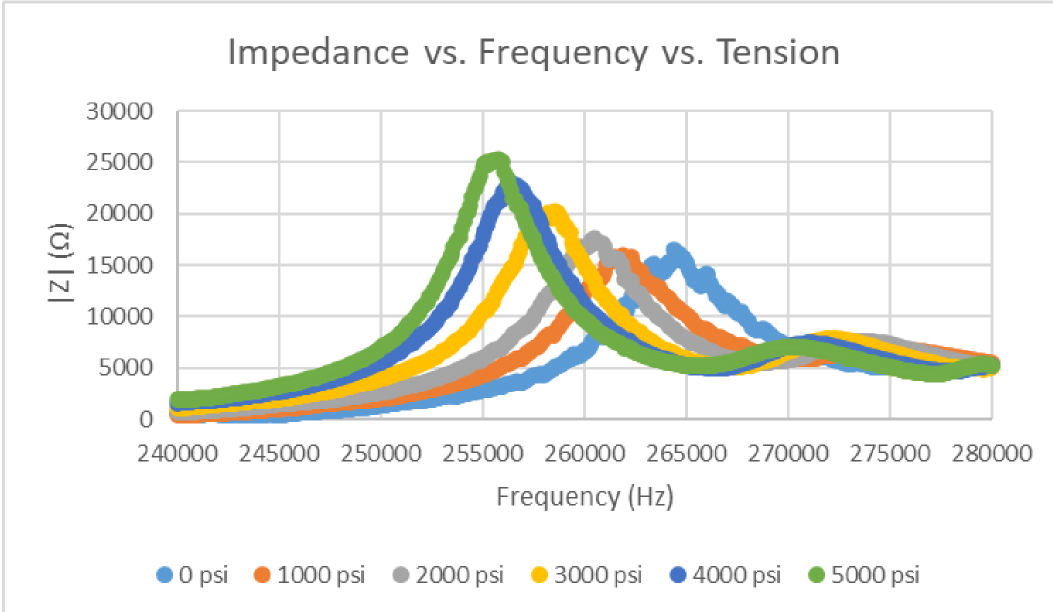

Figure 4. Results of the test "Tension 2" showing a leftward shift of the peak as tension is increased.

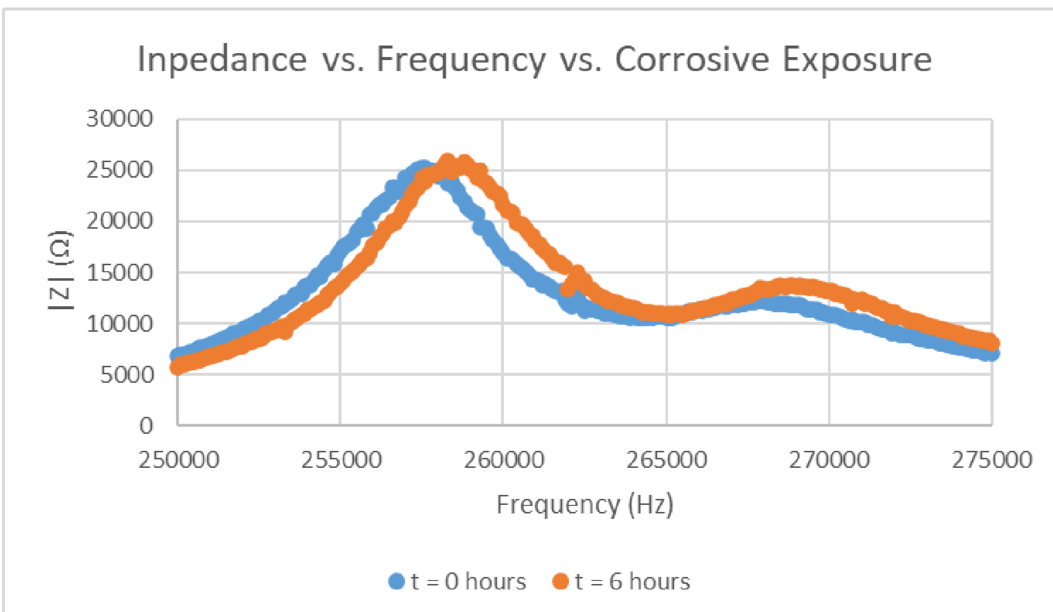

Figure 5. Results of the test "Corrosion 3" showing a rightward shift of the peak as corrosive exposure time is increased.

test "Corrosion 3" with PZT patch mounted lengthwise showed a noticeable shift rightward throughout the corrosion regime as shown in Figure 5. During this test, the strand with PZT patch was entirely corroded through. Interestingly, this rightward shift is also opposite of that observed in [7].

CONCLUDING REMARKS

A methodology was presented to evaluate the effectiveness of EMI for SHM of seven wire strand used in ground anchors. Preliminary results show that both corrosion and tension can be observed in seperate experiments. Additional testing is needed to align the results with literature, including the possible use of interface materials between the PZT patch and the cable for more consistent attachment and peak tracking. Pending future works, EMI based SHM may be useful to USACE for ground anchors within their civil works portfolio.

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