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LONG TERM MONITORING USING VIBRATING WIRE SENSORS

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ABSTRACT

The vibrating wire sensor is a simple mechanical device which uses the relationship between the tension in the wire, the wire mass and length, and its resonant frequency to determine strain. The only electrical parts of the sensor are a coil and permanent magnet assembly which are used to excite the wire and then to read the frequency of the current induced in the coil as the wire vibrates in the magnetic field. This simplicity of design affords the vibrating wire sensor excellent reliability, and the fact that the output is in the form of a frequency (as opposed to a voltage or resistance) allows the signal to be transmitted over long cables without degradation. Vibrating wire sensors can also provide excellent long term stability, i.e. not susceptible to drift. However, long term stability cannot be attributed to all vibrating wire sensors. It depends greatly on the way in which the wire is clamped in the body of the sensor and on the pre- and post-heat treating methods of the wire and sensor assembly itself. This paper describes the ways in which long term stability can be attained in vibrating wire sensors and discusses, with examples, how such sensors lend themselves to long term monitoring applications, even in difficult environments.

KEYWORDS

Vibrating wire, frequency, strain, reliability, drift, long term stability.

INTRODUCTION

Any successful long term monitoring project, whether it involves a bridge, building, dam, tunnel or foundation depends, to a great extent, on the reliability of the measurement system employed, particularly the sensors. Where sensors can be retrieved, checked and recalibrated, concerns generally only lie with the recalibration cycle itself, inasmuch as it should be undertaken in a timely manner, to minimize - and correct for any drift that is inherent in the sensors themselves. However, when sensors are buried in structures (such as dams, piled foundations or bridge decks) and retrieval is not possible, it is critical that the sensors do not drift, where drift is defined as the inherent tendency for the value returned by a repeated measurement to vary systematically over time when there is no variation in the parameter being measured.

THE ROLE OF INSTRUMENTATION IN STRUCTURAL MONITORING PROJETCS

The construction of a facility in or on soil or rock must take into account many uncertainties because the properties of these materials can change drastically over a very short distance. These changes may be due to natural geologic variations (sedimentary deposition cycles, faulting) or be man-made as a result of construction activities on the site. Additionally, consideration should also be given to any changes in loading that the facility might experience as a result of excessive rain or snowfall, earthquakes, strong winds etc. all of which contribute to produce substantial uncertainty in how the completed facility will perform during its lifetime. Further compounding these uncertainties is the potential for unexpected performance of the facility itself that may be caused by neighboring structures, utilities and people. Such occurrences of unexpected performance may delay the project, increase cost and lead to lengthy and expensive litigation.

Monitoring the construction, and adjacent structures, can provide us with quantitative information with respect to actual performance; where measured performance can be compared with predicted or expected performance, and where any differences can indicate uncertainties in design, and be evaluated to determine what they indicate for future performance. If, as a result, the anticipated future performance is unacceptable then changes or modifications (or remediation) can be implemented as a corrective measure (Marr 2007).
Many projects fail to get the full benefit of instrumentation because there is little or no provision for long term monitoring. Much value from instrumentation can come from long term readings, and not from getting

information in a short space of time which does not allow trends to be detected (Bromhead 2012). Long-term measurements are made over decades (10, 20, 30 or more years), and sometimes even over the lifetime of the facility. Long-term measurement systems track changes in the mechanical state of the structure and often the sensors are installed permanently at inaccessible locations where they cannot be replaced (or re-calibrated). As such it is critical that the sensors used be reliable, and do not drift over time; in this respect, properly constructed vibrating wire sensors are particularly well suited as will be discussed in the remainder of this paper.

WHAT IS A VIBRATING WIRE SENSOR?

A vibrating wire sensor comprises a mechanical assembly (a tensioned steel wire permanently mounted inside the sensor body), a means of electromagnetic excitation to vibrate the wire and a measurement system to measure the frequency of the wire vibration (Figure 1). In use, the vibrating wire is set into transverse vibration by a short pulse of current, generated in the measurement instrument, which passes through the electromagnetic excitation (coil) located near the midpoint of the wire, and which sets the wire vibrating at its resonant frequency until it stops due to dampening. As the wire oscillates in the magnetic field of the electromagnetic coil (the same coil used to excite the sensor) it creates a small alternating current, whose amplitude drops as the oscillation dampens, and which travels at the sensor (vibrating wire) frequency, via a cable, to the measurement system. In the measurement system a pulse counter measures the time for a given number of cycles (zero crossings) and a microprocessor converts the period (the time for one cycle) into a corresponding frequency. The square of this frequency is proportional to the parameter (strain, pressure, temperature etc) being measured. Recent developments in vibrating wire measurements now include the ability to measure frequencies using spectral analysis techniques, rather than using time based methods. The spectral analysis method offers significant advantages and is discussed in more detail later.

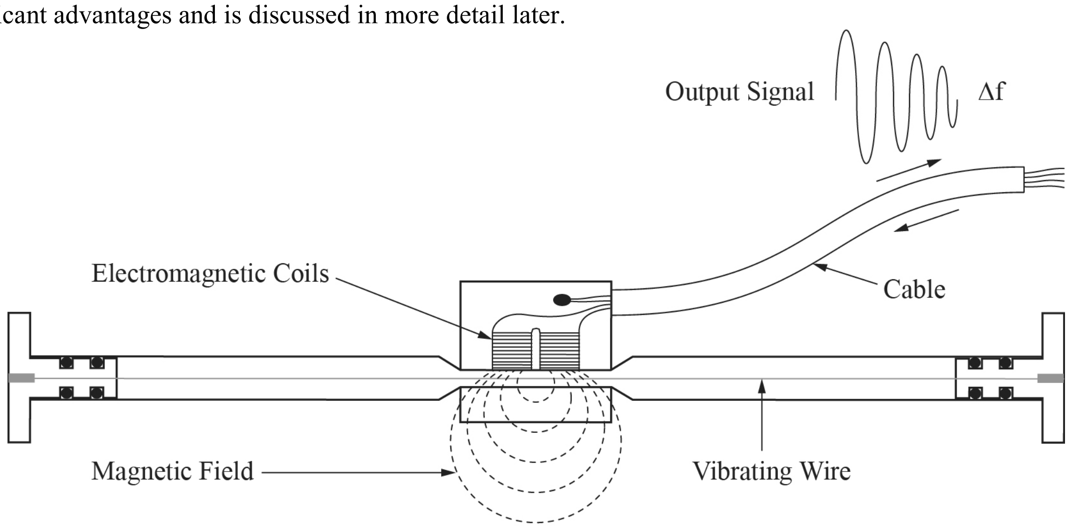

Figure 1. Vibrating Wire Strain Gage

How Does the Vibrating Wire Sensor Measure Strain?

The law relating tension to frequency is given as

$$F = 1/2L\sqrt{\sigma / \rho} \tag{1}$$

Where F is the natural frequency of vibration, L is the length of the wire, σ is the stress in the wire and ρ is the density of the wire.

And Hooke's Law is given as

$$E = \sigma / \varepsilon \tag{2}$$

Where E = Young's Modulus, σ is stress and ε is strain

Combining (1) and (2) gives

$$F = k\sqrt{\varepsilon} \tag{3}$$

Where $k = 1/2L\sqrt{AE/\rho}$ and from which the change in strain can be shown as

$$\Delta\varepsilon = k\,(F_1^2 - F_0^2) \tag{4}$$

History of Vibrating Wire Sensors

The earliest recorded account using a plucked, stretched string (wire) to measure deformation was in 1888 in Italy, by Pietro Cardani (1858-1924), a professor at the University of Palermo. It is reported that he plucked the wire manually using a small pair a tweezers and determined the frequency by ear with a stroboscope. Using this technique he was able to measure deformations with an accuracy of approximately 0.003mm. The next documented account is found in US Patent No. 633,471, dated September 10th, 1899 where Edward McGarvey of Bellefonte, Pennsylvania patented a Weight and Pressure Indicator in which the weight of coal carts could be determined using the resonant frequency of a support cable and a fulcrum coupled to a secondary, shorter wire and fulcrum which vibrated in unison.

This was followed, in 1928, by work in Russia, by Davidenkoff, and in France, by Andre Coyne. It is fair to say that Coyne's work was pivotal in commercializing vibrating wire sensors. Having embraced the concept, in 1930 he went on to make the first installations of vibrating wire sensors at Bromme Dam. Then, in 1931, he patented a vibrating wire strain gage, and in 1947 founded Telemac, who manufactured vibrating wire sensors on a commercial basis. Then followed developments in Germany (Maihak); the UK, at the Building Research Station and Road Research Laboratories (Gage Technique); and in Norway at the Norwegian Geotechnical Institute (Geonor). Today vibrating wire sensors are manufactured in several countries.

Reliability of Vibrating Wire Sensors

(Bordes and Debreuille 1985) defined the reliability of vibrating wire sensors as comprising the physical durability of the sensor, enabling it to perform reliably for years after the installation, and its time-stability, that it experiences no zero drift, such that any reading at any time can be referred to the same datum. While durability is relatively easy to understand and quantify, time-stability is more difficult to determine unless there is access to years and years of historical data taken under controlled conditions.

Even if there are no historical data on which the time-stability can be proven, it is still possible to assess the intrinsic quality of vibrating wire instruments by looking at the factors and mechanisms that affect time-stability (aka long term stability). Basically there are two factors affecting the long term stability of vibrating wire sensors; the first involves changes in the vibrating wire itself, and the second is the way in which the wire is fastened in the sensor itself.

Tests (Bordes and Debreuille 1985; McRae and Simmonds 1991; DiBiaggio 2003) have shown that if the stress in the vibrating wire is kept below 30% of it yield strength then zero drift is minimal (1% FS after 27 years) and where wire stress is between 13% -15% of yield strength zero drift is insignificant (0.1% FS after 27 years). Another factor which may change the vibrating wire and affect its long term stability is if it experiences some form of micro-corrosion reducing its diameter and mass and which would result in an increase in its resonant frequency. Some manufacturers have minimized the likelihood of this occurring by evacuating the sensor cavity or by filling it with an inert gas like nitrogen.

One of the most important details influencing performance of a vibrating wire sensor is the fixation of the wire at its ends, i.e., the way in which the wire is clamped or gripped to hold it in place and the quality of the assembly at that point of fixation. Poorly designed end fixations may not be watertight and can act as stress concentrations which may lead to irrecoverable strain (drift) in the wire. The techniques used by manufacturers to fix the vibrating wire in place in the sensor are generally proprietary and so their effectiveness can only be proven by long term testing under controlled conditions.

Another factor, greatly influencing the long term stability, is for vibrating wire sensors to be subjected to an aging process during manufacture, to allow time for strain hardening of the components and fixation points and the relaxation of any internal stresses that result from the manufacturing process itself. The aging process can be accelerated by cyclic loading/unloading or, as is more commonly adopted, by exposure to elevated temperatures for specific periods of time (Bordes and Debreuille 1985; McRae and Simmonds 1991; Choquet *et al.* 1999)

ATTRIBUTES OF VIBRATING WIRE SENSORS

Long Term Stability

The output of a vibrating wire of a certain length is fully dependent on the parameter to be measured, which in this case is the tension in the wire. Such sensors have advantages over comparable analogue types inasmuch as the signal is totally time dependent and can be measured directly in digital systems. As mentioned above, well made resonant (vibrating wire) sensors can exhibit excellent long term stability, a highly desirable feature, attributed to the fact that the mechanical vibrations of the sensing element (the vibrating wire) depends primarily on its mechanical properties and not on any electrical circuits, whose function is only to excite the wire and measure the output signal. Long term stability is critical where sensors are buried and inaccessible and re-calibration (or verification) is not possible.

Signal Transmission over Long Cables

The reliability of any instrument system includes the signal transmission reliability or susceptibility to interference. Transmission of data from most vibrating wire sensors requires only two wires. (Tunbridge and Oien 1989). The information in the signals to and from the sensor includes only the frequency component, and while the amplitude of this oscillation may decrease the frequency is not altered, and signals can be transmitted over long cable lengths. The author is aware of vibrating wire pressure transducers, from his company, working well over cable lengths in excess of 1.5 km, while Tunbridge, at the Norwegian Geotechnical Institute, reports an experience with a cable 10km in length where reliable signals were obtained without the need for amplification or conditioning.

Cable Splicing

Because the signal from the vibrating wire sensor is in the form of a frequency it is not influenced by cable effects such as resistance changes brought about by temperature fluctuations, moisture intrusion etc. Consequently, cut or severed cables can be quickly and easily repaired (or lengthened) without compromising the measurement signal itself and with minimal “downtime” in reading frequency. Such a feature can be of great benefit on construction sites where cables are sometimes damaged by the actions of plant and or labour, and where data is required on a real time basis as a means of construction control.

Robustness

Because there are no internal electronics, other than the electromagnetic coil used to excite the wire, and by carefully selecting materials and using techniques that are both generally available and proprietary, vibrating wire sensors can be constructed to be mechanically and corrosion resistant, and capable of long term use in highly aggressive environments. By the same token, vibrating wire sensors more easily lend themselves to modification for use in environments subject to temperature extremes. Vibrating wire sensors have been manufactured and successfully used in cryogenic environments at temperatures down to -196°C (LPG storage facilities) and in elevated regimes up to +250°C (tar sand oil recovery applications) (Simmonds 2003)

FACTORS AFFECTING VIBRATING WIRE SENSORS

Electrical Interference (Noise)

Signals from vibrating wire sensors can be influenced by electromagnetic noise produced by various causes (adjacent high voltage sources, radio interference etc) which can be picked up by the cable conductors. Such interference can usually be prevented using 100% shielded twisted pairs of conductors with a bare copper wire draining any induced currents on the shield to ground. However, recent advances in the precision of frequency measurement techniques now permit the analysis of the vibrating wire’s response directly as a function of frequency, rather than indirectly through a measurement of time (period). Such spectral analysis techniques are able to easily discriminate the dominant, resonant vibrating wire frequency component from any accompanying sources of electrical noise and, at the same time, provide a measurement precision one order of magnitude greater than measurements made using the more classical time domain analysis techniques. Readings taken using this approach are independent of noise unless the noise has a frequency content equal to that of the vibrating wire.

Temperature Sensitivity

The vibrating wire in a vibrating wire sensor is made from high strength steel and has a certain temperature dependency proportional to its thermal coefficient of expansion. As such, it is possible that changes in temperature can cause changes in output that are not related to changes in the structure or the material in which the sensor is installed. Fortunately the mechanical properties of the vibrating wire are well known, including its thermal coefficient thus allowing temperature corrections to be made. In cases where the vibrating wire is contained inside a transducer housing (as in a pressure transducer for example) the sensor can be tested where the output is measured at varying temperatures, thus allowing a thermal correction factor to be determined.

Damage by Lightning

As with any electrical sensor, vibrating wire sensors can be damaged by voltage surges from lightning strikes. A direct hit strike on a cable or sensor will be totally destructive or incur irreparable damage. Most of the damage caused during electrical storms occurs as a result of induced voltages in the sensor cables. This said, vibrating wire sensors can be protected from induced voltages using gas discharge tubes installed across the electromagnetic coil in the sensor and connected to ground, while dataloggers at the readout end of the cables can be protected using spark gaps and or multistage surge protection devices comprising gas discharge tubes, tranzorbs and inductors.

Dynamic Measurements

Standard, single coil vibrating wire sensors using the pluck and read method are not suitable for tracking dynamic measurements. Typically they are read at rates around 1 Hz (depending on wire length and frequency). However, so called autoresonant versions are available which are capable of making dynamic measurements. They incorporate two electromagnetic coils (a drive coil and a pick-up coil) in a feedback loop system and provide a continuous output at the sensor frequency. These early versions suffered certain drawbacks as the amplitude of vibration had to be controlled to achieve a stable output, and the outputs were unstable over lengthy cables. At the Norwegian Geotechnical Institute, to overcome these problems, controlled oscillator circuits were incorporated which stabilized the output by regulating the applied voltage, limiting the excitation current, and filtering and amplifying the output signal from the sensor (DiBiagio 2003)

The abovementioned sensors, while capable of providing dynamic outputs, were more costly to manufacture and, by incorporating electrical circuits (albeit minor in size and complexity) were slightly more susceptible to failure. As a result some manufacturers designed dynamic interfaces that are capable of obtaining a dynamic response from the more common and less costly single coil (pluck and read) vibrating wire sensors. Of these dynamic vibrating wire interfaces, in the author’s opinion, the most exciting development comes from Campbell Scientific Inc. Utah, USA who recently introduced the CDM-VW300 Series. This device, which incorporates the spectral analysis measurement technique mentioned previously, keeps the vibrating wire oscillating by injecting energy into the oscillation at precisely the right frequency and at the correct phase. Using the CDM-VW300 interface, standard single coil vibrating wire sensors can be used to collect both static and dynamic data (between 20Hz and 333Hz depending on gage frequencies and acceptable noise levels) with the same high precision and long-term stability that was previously limited to static measurements. It also opens up the opportunity to use vibrating wire sensors for measurements that have previously been the domain of other technologies such as resistive foil strain gages (Cornelsen and Jacobsen 2012).

Wire Fatigue

In any mechanical system which oscillates there is always concern with respect to fatigue type failure. With vibrating wire sensors, this would be of particular concern with autoresonant versions, or with standard versions connected to a dynamic vibrating wire analyzer. However, testing, on vibrating wire sensors continuously vibrated over a 27 year period, at the Norwegian Geotechnical Institute (DiBiagio, E 2003), has shown that not only does fatigue failure not occur, but also that drift is minimal (<0.02% FS/year) even on sensors where the wire stress is at 20% of yield strength.

Non-Linear Output

The output from the vibrating wire sensor is in the form of a frequency which changes in a non-linear way over its measuring range, thus making data reduction somewhat complex. However, by squaring the frequency output values, data reduction can be achieved using linear regression techniques with accuracies on the order of +/-

0.2% FS. Where higher accuracies are required, polynomial expressions can be developed which allow accuracies of +/-0.1% FS or better to be attained.

Advances in State of the Art

Vibrating wire instrument manufacturers who might consider using new manufacturing processes and or different materials must keep in mind that any changes they might implement may require requisite periods of time to verify the long term stability of any new design. Fortunately, recent developments in materials and methods, along with stringent quality control programs contribute to accelerating the verification of such technological advances (Bordes and Debreuille 1985).

VIBRATING WIRE SENSOR TYPES

The vibrating wire concept can be used to manufacture a variety of different sensor types for various structural and geotechnical monitoring applications. Most manufacturers' designs are constructed from stainless steel (or other corrosion resistant alloys and materials), and are waterproof with all internal components sealed using O-rings.

Strain Gages

In its simplest form the vibrating wire can be used to construct a strain gage in which the wire is clamped between two end blocks. Gage lengths can vary between 50mm and 1.00m, and with various designs which allow for use on steel, fibreglass, rock, timber, geogrids and in cement, grout, concrete and soil. High temperature versions are also available for use in asphalt and spun concrete piles. Vibrating wire strain gages can also be used as the sensing element in compression and tension load cells, instrumented rebars and bolts, and in cantilevered displacement transducers.

Displacement Transducers

In a displacement transducer the vibrating wire is connected in series with a tension spring made from a heat treated steel or other alloy (for optimum stability) and a moving shaft (Figure 2). The tension spring allows the shaft to travel and measure displacements over lengths well beyond that achievable with the strain gage alone. Displacements between 3mm and 350mm are possible with standard designs and up to 3.00m with designs incorporating pulleys and lead screws. Displacement transducers are commonly used as crackmeters (on rock and concrete), jointmeters (in mass concrete), as strain gages (in highly plastic materials such as geogrids) and as the sensing element in multipoint borehole extensometers.

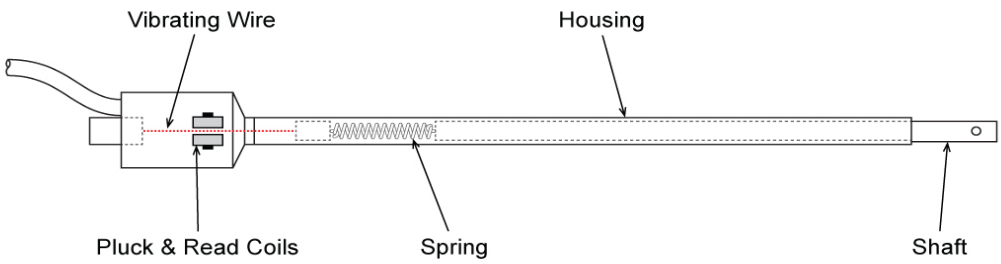

Figure 2. Vibrating wire displacement transducer

Temperature Sensors

By clamping the vibrating wire inside a metal tube with a thermal coefficient of expansion totally different to that of the vibrating wire itself, it is possible to construct a sensitive (+/-0.035°C) temperature sensor. Such sensors are well suited for use in highly aggressive environments and can simplify data acquisition system designs where all the other measurements (strain, pressure, load etc) are made using vibrating wire sensors. Similarly, to maintain a uniformity of measurement methods, vibrating wire temperature sensors can also be installed inside a common housing as used for piezometers, load cells or extensometers etc.

Pressure Transducers

In a pressure transducer one end of the vibrating wire is attached to the back side of a sensitive flexible diaphragm with the other end of the wire clamped to a stable point of fixture at a location opposite to the diaphragm. (Figure 3). Pressure acting on the diaphragm causes it to deflect, in a concave fashion (albeit miniscule), and so changes (reduces) the tension (and frequency) in the vibrating wire. Conversely, any negative pressures acting on the diaphragm will result in a concave deflection and increasing wire tension (higher frequency). Pressure transducers form the basis of vibrating wire piezometers (for water level and pore pressure measurements), and are also used in pressure cells (to measure soil pressures and concrete stresses) and in settlement systems (for measurements of soil consolidation or ground heave).

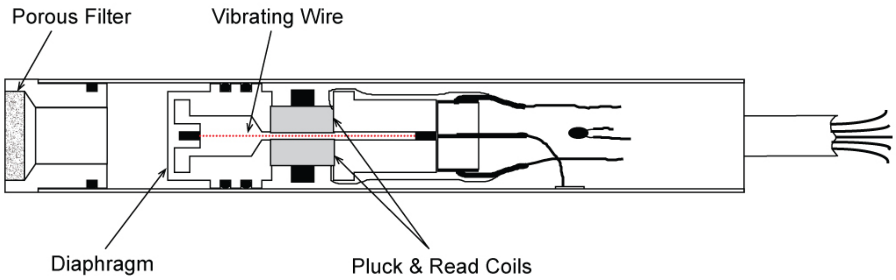

Figure 3. Vibrating wire piezometer

Tiltmeters

By attaching a vibrating wire to a weight suspended off centre beneath a flexible hinge, a very sensitive tiltmeter can be constructed. In its simplest form the design is rather delicate and sensitive to damage by shock. However, by incorporating frictionless bearings, (which utilize internal flat crossed springs–trapped in a cylindrical housing to provide precise rotation with low hysteresis and no frictional losses), the tiltmeter becomes much more rugged and capable to withstand the rigours of normal operation and handling. The tiltmeter can be used in standalone form to measure the rotation of buildings, bridge piers or structural members, or it can be assembled in series, with connecting rods and wheel assemblies as an in-place inclinometer which, connected to a datalogger, can provide a real time monitoring for any impending slope or excavation failure.

Force Transducers

Probably the purest form of vibrating wire sensor, the force transducer simply comprises a cylindrical weight suspended from its radial centre point by the vibrating wire itself. In use the cylindrical weight hangs in water (or a water-antifreeze mix) which rises (or falls) over the length of the cylinder and in so doing the buoyancy effect changes it's specific mass and thus the tension (frequency) in the vibrating wire. The design is virtually free from temperature effects, the reason being that although changes in temperature, might change the wire length very slightly, they do not change the tension in the wire. Thus the force transducer design lends itself extremely well for highly sensitive measurements of seepage (in weirs and flumes) and in closed interconnected systems for multipoint or differential settlement measurements (where settlements as small as 0.025mm can be reliably monitored).

LONG-TERM MONITORING CASE HISTORIES USING VIBRATING WIRE SENSORS

Star City Bridge, WV., USA

The Star City Bridge near Morgantown, West Virginia, USA is heavily instrumented with a variety of sensors that record the response of bridge elements to dynamic and static loading configurations. The bridge is 1004 ft long over 4 spans consisting of a light-weight-design concrete deck supported by steel girders. The sensory system was installed while the second phase of the bridge was still under construction in 2003-2004. Data are being recorded every 20 minutes through six data loggers placed along the bridge and provide continuous monitoring of the performance of the bridge since construction. Long term response parameters are monitored through a variety of sensors manufactured by Geokon Inc. based on vibrating wire technology: 200 weldable strain gages are installed on the steel girders to record both shear and bending stresses as well as straining actions in the diaphragm members, 105 embedment strain gages measure the tri-axial state of strain in the concrete deck, 42 instrumented rebars continuously record the forces in reinforcing steel, 56 embedment crack meters record the initiation and propagation of any concrete cracks the deck, and 2 displacement transducers record the overall expansion and contraction of the bridge ends relative to the abutments due to seasonal and daily temperature changes, and 439 thermistors provide an overall thermal map of the concrete deck temperature and record temperature data for the sensors thermal compensation (Shoukry, Riad and William 2005)

Long-Term Bridge Monitoring in Seattle WA., USA

The City of Seattle is located on Puget Sound in the Northwest corner of the U.S. The Seattle Department of Transportation (SDOT) is responsible for evaluating and maintaining 149 bridges in the City of Seattle. Thirty four of these structures are 70 years old or older with an average age of all bridges being 54 years old. Seattle is also located in an active seismic area; with the latest earthquake of magnitude 6.8 (Richter) was in February of 2001. Because of visible degradation induced by earthquakes along with age-related and load rating considerations, SDOT has implemented a monitoring program on several of their bridges. The goals of the program are: to monitor known structural defects such as cracks or tilt, to monitor critical members in an administratively load rated bridge and to monitor changes over time. After considering the above factors, SDOT selected vibrating wire crack gages, vibrating wire tilt meters, vibrating wire strain gages and temperature sensors as the basis for a long term bridge monitoring system (Anderson and Thorarinsson 2009)

Instrumentation Program for Boston Red Line Subway Tunnel MA., USA

An Immersed Tube Tunnel (ITT) was placed in a dredged corridor across the Fort Point Channel in Boston, MA. Construction was complicated by the existence of active Red Line Subway Tunnels (RLT) located beneath the channel and about 1.8 meters below the base of the ITT. Geotechnical and structural investigations, and numerical studies, were performed to evaluate the impacts on the RLT. Of particular concern was the danger of the RLT floating upwards as the cover above it was removed. Pilot programs were conducted to select instruments for monitoring settlement, heave, joint opening, and water flow into the RLT. An open channel type liquid level system 1310 m long with 125 vibrating wire settlement sensors was installed to monitor settlements, and more than 700 vibrating wire strain gages and crackmeters were attached to the concrete liner surface using a novel epoxy bonding technique. An Automated Data Acquisition System (ADAS) monitored all the sensors for more than three years (Feldman *et al.* 1999)

Long-Term Stability of a Backfilled Room-and-Pillar Test Section at the Buick Mine, MO., USA

Rock mechanics instruments have been providing data in a backfilled room-and-pillar test section of the Buick Mine near Boss, MO, USA for nearly 16 years. They demonstrate that backfill improves long-term underground safety by supporting the mine roof and maintaining the strength of support pillars. These instruments, installed to monitor stability of the test section during mining of remnant ore pillars, were read for an additional 13.7 years after mining was completed to monitor long-term stability. Borehole extensometers equipped with vibrating wire displacement transducers and vibrating wire biaxial stressmeters were installed in the pillars and abutments. Extensometers were also installed in the mine roof. Vibrating wire embedment strain gauges and vibrating wire earth pressure cells were placed in the cemented backfill The purpose of these instruments, was to monitor short- and long-term stability, record stress redistribution to pillars during mining, provide input to validate a numeric model, and calculate rock mass modulus and strength. Vibrating wire transducers were used in this study because of their proven longevity, stability, and minimal zero drift over long time periods (Tesarik *et al.* 2008)

Monitoring the A1 Motorway, Piekary Silesia, Pyrzowice, Poland

Between 2009 and 2010 more than 28,000 sensors were installed over a 100,000m^2 area to monitor vertical displacements and geogrid deformations that could be brought about by subsidence where a new motorway construction crosses an area of near surface, poorly mapped, abandoned mine workings. The instrumentation comprised 2,541 horizontal extensometers, equipped with vibrating wire displacement transducers, 12,706 vibrating wire displacement transducers with custom clamps for measurement of geogrid deformation, 25 vibrating wire settlement sensors, 30 vibrating wire instrumented rebars and 15,247 temperature sensors. Vibrating wire instruments were selected as the sensors of choice as monitoring is required to take place for more than 30 years (NeoStrain, Krakow, Poland 2010)

Tsankov Kamak Double Curved Concrete Arch Dam, Rhodopes Mountains, Bulgaria

A new dam in Bulgaria, Tsankov Kamak HPP, was under construction between 2006 and 2011. The dam employs a double curved concrete arch construction, with a height above lowest foundation of 130.5m. The crest length is 480m and the reservoir will contain 110 million cu. meter of water. The main power plant is located some distance along the cascade valley, but a small generating station of 1.12 MW is contained inside the dam. The scope of the instrumentation was mostly developed from designer studies, which analyzed the potential failure modes, defined the monitoring parameters and the measurement program. From these specifications, more than 300 instruments were identified, 200 of which were installed during the construction phase. The instruments included 30 vibrating wire strain gage rosettes (5 x 6 gages), 20 pressure cells, 66 vibrating wire jointmeters, 18 x 3-position borehole extensometers (each with vibrating wire displacement transducers), 20 vibrating wire piezometers, 12 pendulum systems, 6 vibrating wire seepage weir monitors a seismic monitoring system and a weather station all connected to a data acquisition system providing data for visualization over the internet (Brehe *et al.* 2011)

CONCLUSIONS

A very important factor in selecting the appropriate measurement technology in any Structural Health Monitoring or geotechnical monitoring project is to consider the environment in which the corresponding sensors are to be installed; the length of time of the measurement program and the suitability of the selected sensors to operate reliably throughout the duration of the measurement program. While a comprehensive SHM program will include sensors based on different technologies (likely including the latest MEMS and fibre-optic offerings, connected in wireless mesh networks and with data instantly available over the internet) it will often be required that certain measurements be made at locations that are inaccessible after construction, and over extended periods of time. In this respect, this paper proposes that well-made vibrating wire sensors should be the sensors of choice, and supports this contention with various case histories that show the successful use of vibrating wire sensors in a variety of applications and over long periods of use.

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