CITY OF SEATTLE'S APPROACH TO BRIDGE LONG TERM MONITORING

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Abstract

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. Because of visible degradation induced by earthquakes along with age-related and load rating considerations, SDOT has implemented an electronic monitoring program with data feedback to a central location on several of their bridges. This paper describes the evaluation process to set up this program. The paper also describes considerations for selection and analysis of data collection. Description of monitoring system selection and specifications are included.

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
- To monitor chang[1]e over time

All of the structures currently being monitored were built with reinforced concrete. The structures have either known defects or have been administratively load rated. Cracks in relatively critical locations have been found during visual inspections. On some structures, these cracks have been present for many years. But, with only manual methods being used for measuring crack widths, is has been difficult to determine if they are growing significantly over time, or how much they may just be opening and closing just as a function of temperature fluctuations of the structures.

By installing a relatively inexpensive monitoring system on the structures with known structural defects or low load ratings, SDOT will be able to quantify whether or not the degradation is getting significantly worse over time. One important feature of the monitoring systems is that if any of the parameters that are being monitored exceeds

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reasonable limits, the system will automatically send an alarm to SDOT's pager network so that an inspector can immediately be dispatched to assess the situation.

Each monitoring system is composed of four major components; the Sensors, the Data Logger, and the Communications Interface with the Centralized Data Collection and a Data Display / Data Base. Sensors routinely used are strain gages, displacement gages (crack gages), tilt meters, and temperature probes. Depending on the structure and the goal of the instrumentation plan, the various sensors are routed to an on-site Data Logger where they are read, processed, and the data stored. At a predetermined time, or on demand, the Centralized Collection PC located in SDOT's offices, calls the data loggers and uploads the data. Graphic display software makes it easy to see changes over time, sudden movement or movement as a function of temperature. SDOT is now monitoring five bridges, and will installing three more systems in the near future.

This paper will outline the rationale for developing a long term monitoring program, discuss how a structure may qualify for the program, discuss decisions about what type of data would be valuable and how to get that data.

The need for a monitoring program

The Seattle Department of Transportation realized the need for a monitoring program in the year 2000. Several questions arose such as what was the goal of a bridge monitoring program? What bridges are we going to monitor? What specially are we going to monitor? How are we going to monitor? All these questions and issues were evaluated and reviewed. It was determined that bridges that were administratively load rated ; bridges with low load ratings and bridges with structural defects that could not be posted without significant inconvenience to the public, would all be candidates. At the same time, we wanted to be assured that if there was further decline of the structure we would be able to track and document the changes. Another need was to monitor defects such as shear cracks, to look for a change or a possible failure over time. Public safety of the traveling public was the primary concern of the program.

Factors to be considered

When making plans for a long term monitoring system some of the factors to be considered are:

1. How long do we want to monitor the structure? It could be for a week, a month or for years. This relates to if there is a need to monitor change over time or if the need is a snapshot. Crack monitoring would be an example of the need for a long range program or change over time. Short term monitoring is usually related to a specific event e.g. a local landslide.
2. What type of data do we want and how much data do we want to collect? More data is not always better. Data should be directly related to the answers of number

one above. It should be clear and reliable and aid in decisions or policies concerning the bridge.

3. How will the data be used? Collecting data for the sake of getting it or because the data would be interesting, does not necessarily serve the purpose of the program goal. Data needs to directly support critical decisions or policy regarding the structure.
4. Data management from onsite storage, collection, processing, display and reporting. Data management should be as easy and automatic as possible. Data should be able to be read from the source in "Real Time" by connecting to the bridge site and automatically collected. The data storage and retrieval database should enable the user to view data in a graphic format from any time period.
5. What are the initial costs? What are costs for maintenance and the costs associated with data management. There are two basic approaches when developing a bridge monitoring system. The first is the proprietary black box that is attached to the bridge with some software at the office. This type of system relies heavily on support from the manufacturer. The second is to assemble a system using off the shelf items. This system is usually more flexible and can be used in many situations. Local staff can be trained to design, program, install and monitor and repair the system. If the system is in need of some type of repair, trained staff could respond quickly. Because each system uses the same components, a small inventory of on hand parts would mean the downtime is kept to a minimum.

<u>After considering the above factors, SDOT selected these requirements for a long term bridge monitoring system:</u>

1. The system must be able to record slow changes over time due to loading and environmental effects. This calls for sensors that are not prone to drift and some type of data display and data base that can graph the readings. The system also needs to detect and report sudden movements in the structure.
2. Structure temperature readings and individual sensor temperatures are important when monitoring changes in the structures behavior.
3. The on site system must be robust and be able to operate in a self sufficient manner. The data logger must automatically collect data from the sensors, examine the raw data for errors, and notify owner of any out of tolerance readings.
4. The process of processing raw data and summarize the results is another requirement of the on site data logger.
5. The on site data logger must be accessible from the "Main Office" so the data can be collected and any configuration changes to the logger be uploaded.
6. The on site system, must stand alone separate from the main data collector. Alarms must be able to be relayed to key personnel regardless of the state of the data collection PC.

7. Data storage must be in a database format. The need to review historical data is very important to track change over time.

Considering the needs of the City of Seattle these types of sensors were selected for its bridge monitoring program:

1. Vibrating wire crack gages
2. Vibrating wire tilt meters
3. Vibrating wire strain gages
4. Temperature sensors

It is important that the selected gages be a reliable simple technology with low drift. Low drift is very important for detecting change over a long period of time. Because a structure is dynamic with changes in temperatures, temperature sensors should be installed in the structure. If the structure is large, several temperature probes may be needed. Each sensor should have a thermistor for reading and recording local temperature. Gages that have direct sunlight on them during part of the day may need to be compensated. Covers should be installed over all the sensors. There are two reasons a cover is necessary; one being protection from the elements and possible vandals, the other has to do with the temperature of the structure compared to the temperature of the gage. The coefficient of expansion due to temperature is very close between the steel wire in the vibrating wire gage and the concrete (or steel) structure. If the gage is covered, it will tend to be a similar temperature as the structure, making gage / temperature drift a non issue.

The advantage of a vibrating wire gage over more conventional electrical resistance (or semiconductor) types lies mainly in the use of a frequency, rather than a voltage, as the output from a gage. A very basic overview of a vibrating wire gage would be to stretch a steel wire between two fixed points that are mounted to the bridge. Deformations in the bridge (cracks, strains or tilts) will cause these two points to move relative to one another, thus altering the tension in the steel wire. The tension is then measured by plucking the wire and measuring the induced resonant frequency of vibration using an electromagnetic coil. Frequencies may be transmitted over long cable lengths without appreciable degradation caused by variations in cable resistance, contact resistance, or leakage to ground. This provides a very stable gage that is required for long term monitoring.

Dataloggers

The dataloggers are the very backbone of the system. When considering a datalogger, many points must be examined.

1. Power requirements for the data logger, not only voltage but current also must be considered. Alternating current power sources may not be available readily at the

bridge. SDOT's system runs on 9.6 – 16 volts direct current and draws only 1.3 ma quiescent, and 13 ma when processing. Between measurement routines the processor goes into the quiescent mode, conserving power. The power options for our dataloggers then are 120 VAC using a power supply, Solar panels or even a car battery for temporary monitoring. A battery backup should be used in case of power outages or low voltage from the solar panel.

2. The data logger communication options should be as versatile as possible. Systems that may be used are short haul MODEM, radio, hard wired phone line, cellular phone or satellite. A RS232 port should also be available for in field direct connects.
3. The number of sensors the datalogger can handle should be as high as possible. SDOT's largest number on one structure is thirty two. A number as high as one hundred twenty eight should be possible on one datalogger.
4. Internal memory should be at least 2 M. A temporary monitoring system may be required that would involve collecting data from on site, 2 M of memory can store months of data depending on the number of sensors.
5. Analog type inputs are necessary for standard voltage loop sensors.
6. External digital I/O ports for discreet contact closures may be necessary.
7. The datalogger must have a conditioner for the vibrating wire gages

When selecting a datalogger for use in a long term monitoring program it would serve you well if the unit was designed to operate in a field environment. Every opportunity should be taken to protect the datalogger from the environment but, heat, cold and humidity must be considered.

Proper programming of the data logger is crucial to get the data results that match the goals of the project. A basic program can be written and used on many structures with only minor changes. Field crews can be trained to make these minor changes, insert calibration factors and alarm values. Developing this type of program makes startup of a new site relatively easy to do. Troubleshooting the program becomes easier because all sites are basically the same. Of course there will always be exceptions and the new site will not perform as needed unless a special program is used. In this case programming should be easy to understand and perform.

Data collection and communications

At the main office, a desk top PC can be used as the data collector. The data collection software must have these functions:

1. Communicate with the dataloggers through which ever mode they require (hard wired phone, cell phone, radio, satellite)
2. Have an automatic collection routine that can be custom configured to collect the latest data from the logger at any time interval. Each site must be able to have its own interval time, that is to say, one site may need to have its data collected every two hours, while another site may only need its data collected every month. The

system must also know to collect only the added data since the last collection. The old data stays in logger in case it needs to be retrieved; the memory in the logger should act as a FIFO (first in first out) type memory.

3. Data for each site should be saved to a unique folder on a remote drive that is backed up regularly.
4. Data should be stored in a CSV (comma separated value) format. In this format it makes it easy to display special graphs using a spread sheet program.
5. A collection history window makes it easier to see what sites have been collected and when. It will also flag any communications problems that may have occurred.
6. Within the communications package there should be a method of calling the remote data logger. The advantage of this is to be able to view data from the logger in "Real Time". All sensors should be able to read in the raw value and Delta value, in numbers and graphically. Being able to do this makes it easy to check alarms, or troubleshoot any problems. The online ability also makes it possible to change alarm set points, or any other set point within the program. While online with the logger, uploading a new or changed program should be possible. One word of caution, if there is a need to change the program or to halt the program the old initial readings of the sensors should be recorded first. The reason is, when the program restarts, it changes the initial readings. Changing the initial readings will reset all the sensor delta readings to zero. Because one of the primary reasons for a long term monitoring program is change over time, resetting the sensors would defeat that goal. After the program is updated, or restarted it should be possible to send the logger the old initial readings. This will result with seamless delta readings. If the initial readings are not recorded before the reset, they are gone forever unless they are included in the routine data upload. It is good practice to record the initial readings for each site when the logger is started.

<u>Internal and external alarms</u>

As mentioned previously alarms that are generated from the datalogger would be considered an external alarm. What that means is that a sensor has two set points for the delta reading alarm, a high reading and a low reading. If either set point are exceeded the logger has the ability to dial a pager and send a numeric page (usually a number signifying what bridge). It is good practice to qualify the alarms by programming in a time that the gage must be out of tolerance before alarming. Consider latching the alarms, so that if the alarm condition changes back to normal it is easy to see which sensor went out of range. In the program, it is also a good idea to have the ability to shut off or ignore the alarms on individual sensors, that way if a sensor fails it would not keep sending in nuisance alarms.

Internal alarms are a secondary alarm system that originates from collected data on the data collection PC. A graphic screen shows each sensor, it's high and low alarm setting, it's current delta reading (as of last data collect), and if it is in alarm or not. An alarm Wav file can be assigned to any active alarm and for playing on the data PC. The purpose of the secondary alarm system is any sensor on any bridge can be quickly scanned for alarm status.

Programming

Programming of the datalogger is usually unique to the type of datalogger. Since there are many types of dataloggers and many ways to achieve the program goals specific details of programming will not be included.

There are some features that make logger management and troubleshooting easier.

1. Program notes and comments should be able to be written directly on the program. This enables easier troubleshooting and helps keep track of program upgrades.
2. Using comments and the ability to comment sections out of the program. Provides one flexible program and can be altered for many structures. Simple editing (commenting out) tailors the program for the specific site.

Data display / data base

With any monitor program it is necessary to be able to display the data in an easy to read format. Graphing the data has been found to be the easiest method. Some considerations when selecting graphing options are:

1. Alias ability, which is the ability to rename a sensor for graphing, is a useful option. An example would be a crack sensor that is in the second bent, third girder, in the program may be called "DVal_2-1". Not very useful information when looking a graph. With alias ability in the graph the sensor could be renamed "Bent 2, Girder 3, Crack Gage". A much clearer way to show data. You may know what DVal_2-1 means but I would bet others will not.
2. Each sensor should be able to be displayed in an appropriate engineering unit.
3. When setting up the graphing, if only one or two structures are being monitored with only a small handful of sensors keeping the graph screens straight is not a problem. As your system grows, attention must be paid to how your screens are organized. The way the SDOT system is organized each bridge is a book, within the book is a chapter. A chapter may have several themes, or graphs. There may be as many as 6 graphs on the screen. Then there are pages or individual graphs. In this way data graphs are clear.
4. Graph Y (engineering units) axis should be able to be preset or automatic.
5. Graph X (time) axis should easily be able to be varied. The SDOT system can be varied from one hour to one year. It may seem odd to have one year of data on a screen but for overall change over time at a quick glance, it is a useful tool.

6. The database for the collected data makes easy work of data review. The SDOT system has a data robot that looks at the collected data from the bridges every two minutes. If there is new data in the files it is imported into a database. What this enables you to do is to rapidly look at historical data graphically. A couple quick clicks on a calendar retrieve the data for that time period, be it two days or two years ago.

When starting a long term monitoring program planning for the results that you need to make decisions is key. This paper is only a very brief overview of considerations.

Components of the SDOT Long Term Monitoring System

The following is a list of components and sources. This in no way should be considered as the only way or only product to achieve monitoring goals. This is an only a list of components used in the SDOT system.

Gages and Accessories

Vibrating Wire Crack Gages
Geokon Model 4420

Vibrating Wire Stain Transducers
Geokon Model VSM-4000

Vibrating Wire Tiltmeter
Geokon Model 6350

Geokon Inc.
Lebanon, NH
www.geokon.com

Bridge Diagnostics Inc.
Boulder, CO
http://www.bridgetest.com/

Data Cable
Temperature Probes
Gage covers

Bridge Diagnostics Inc.
Boulder, CO
http://www.bridgetest.com/

Dataloggers and Accessories

Datalogger
Campbell Scientific CR10X

Multiplexers
Campbell Scientific AM 16/32

Vibrating Wire Conditioner
Campbell Scientific AVW1

Power supplies / Solar panels
Campbell Scientific (Model numbers depend on application)

Campbell Scientific
Logan UT
http://www.campbellsci.com/index.cfm

Bridge Diagnostics Inc.
Boulder, CO
http://www.bridgetest.com/

Software

Data Collection and Programming
LoggeNet

Campbell Scientific
Logan UT
http://www.campbellsci.com/index.cfm

Bridge Diagnostics Inc.
Boulder, CO
http://www.bridgetest.com/

Database and Display
Vista Data Vision

Vista Engineering
Reykjavik
Iceland

http://www.vistadatavision.com/

Resources

Geokon Inc.
Lebanon, NH
www.geokon.com

Bridge Diagnostics Inc.
Boulder, CO
http://www.bridgetest.com/

Campbell Scientific

Logan UT
http://www.campbellsci.com/index.cfm

Vista Engineering
Reykjavik
Iceland

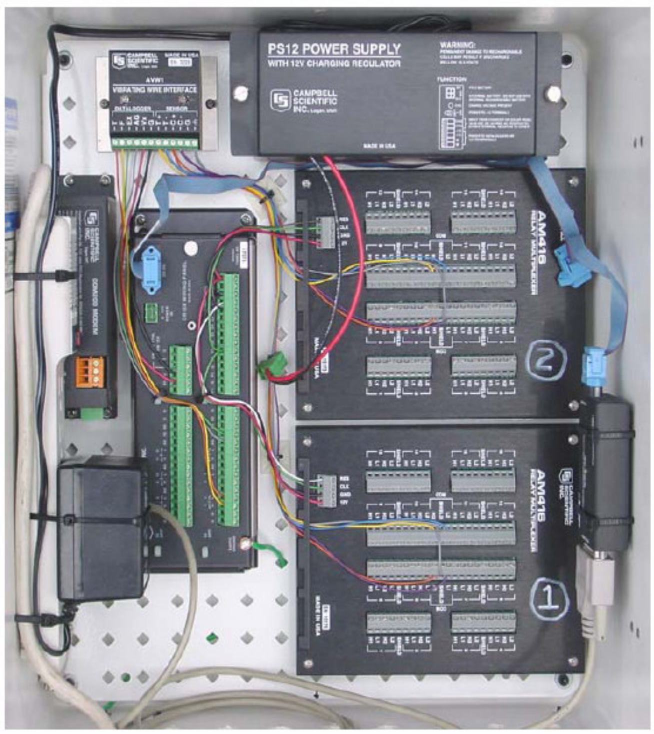
http://www.vistadatavision.com/

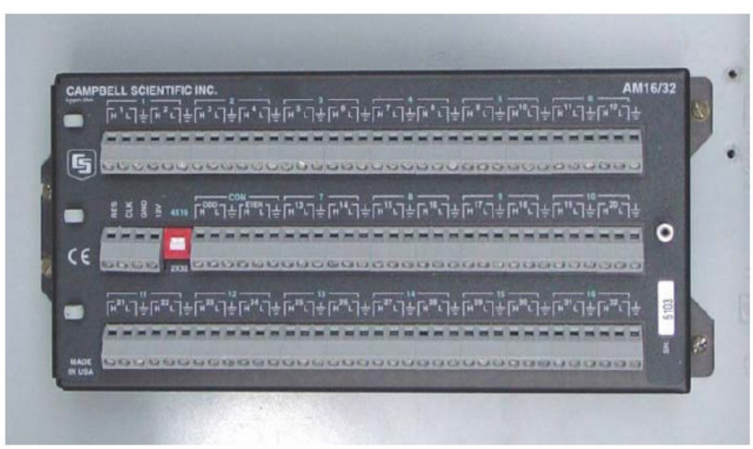
Appendix

Setting Up the BDI Structural Monitoring System

The following general guidelines should be followed while using the BDI Structural Monitoring System after the sensors have been installed on the test structure. The BDI-SMS has been designed to be as easy to use as possible, however, careful notes and several photographs should be taken by the user during the entire testing operation to help when questions arise in the data reduction phase.

The datalogger and associated hardware is typically supplied in a weather-resistant fiberglass enclosure as shown below. The particular system shown is designed to handle 32 Geokon Vibrating Wire (VW) sensors which can consist of any combination of strain gages, crackmeters, tiltmeters, and others. In the configuration shown below, all 32 sensor cables must be routed to this unit so they can mounted to the two multiplexers (via screw lugs) shown. Another possible configuration consists of mounting one or more of the multiplexers in remote locations away from the logger as shown in the second photo.





This second configuration of using remote multiplexers can significantly reduce the amount of cable required for installation as just one specialized cable needs to run from the logger to the remote mux, rather than running 16 instrumentation cables back to the logger.

TRACKING SENSOR LOCATIONS AND CHANNEL NUMBERS: *Accuracy in this operation is very important because if data is taken, but it is not known which sensor it came from, it will be useless*. Each SMS will be supplied with one or more multiplexers (muxes) as shown below that use screw lugs for attaching the sensor wires.

One phase of the cable installation process will be to ensure that the sensor cables are labeled properly before being inserted into any conduit and run to the datalogger. Otherwise, a great deal of time will be spent trying to determine which cable belongs to which gage.

The channel numbers 1 through 16 are listed directly on the mux, with each channel accepting four wires from each Vibrating Wire (VW) sensor as follows:

Red – H (odd)
Black – L (odd)
Green – H (even)
White – L (even)
Shield (ground)

For example, under Channel 1, there is a "1" or "odd" channel and a "2" or "even" channel. It is very important strip the wires back approximately ¼" and to ensure that the screw lug is bearing directly on the bare wire and NOT on the insulation. Furthermore, the lugs should be fairly tight to ensure a good connection.

It is very important to note which sensor is hooked into which channel so that the proper calibrations factors can be applied in the SMS software. It's best to group types of sensors together as this makes software configuration much easier. For example, VW strain gages should be in a group, followed by a group of crackmeters, and then a group of tiltmeters. It turns out that the VW strain gages all have basically the same calibration factors, while the cal factor for each crackmeter and tiltmeter are significantly different.

The alternative to our portable systems are the more permanently-installed systems. While these systems can still be removed and re-used on other structures, it will take a little more time for disassembly and re-assembly. The primary difference between these and the portable SMS systems is that the sensor cables in these systems are run through a hole in the SMS housing and attached directly to the SMS multiplexers with screw-type lugs.

Usually, the supplied software will already be configured for particular sensors in particular channels. However, if something changes for one reason or another, it can be easily reconfigured. Either refer to the supplied software manual or contact BDI.

EXTENSION CABLES: There is no practical length limit with the VW sensors as signals can be easily transmitted for more than a kilometer on the standard extension cable. On the Portable SMS systems, the extension cables are all the same type and vary only in length. They can therefore be plugged between any sensor and any receptacle on the logger housing. Each extension cable has a designation label (and its length) printed on each end. In order to obtain the information required for data reduction, be sure to record the sensor number, the extension cable number, and the SMS channel number that the extension cable is plugged into. The software then keeps track only of channel numbers. While reducing data, it is up to the user to correlate the channel numbers with their corresponding sensors.

POWER: The system has a built-in rechargeable battery that, ideally, should at all times be connected via the provided power outlet cord to 110V AC. The AC power will provide a constant trickle charge to the system battery and eliminate any power difficulties. If AC power is not available at the site, depending on the number of sensors, sample rate, and the frequency of other functions such as data downloading, the system battery should last approximately one week from a fully-charged condition. As a backup for this situation, the system should be powered by a 12V deep-cycle automobile battery and changed on a regular basis. One of the data channels (see Software Guide) records the system's battery voltage level and should be checked each time the data is downloaded. If the level is approaching 12.0 volts, then the battery should be either recharged via AC power or the deep-cycle battery replaced. Another option is a solar panel that will trickle charge the power supply battery during daylight hours.

DOWNLOADING DATA: A serial cable that mates the back of a portable PC has been provided. Follow the instructions outlined in the Software Guide in order to download data, change programs, or otherwise communicate with the data logger. On most systems, a modem is also installed that will accept a standard R-11 phone line jack. Data is then downloaded via telephone lines from a remote computer.

GROUND THE SYSTEM. If the system is to be placed where it is possible that lightning will strike in the vicinity, it is good practice to ground the data logger using the brass lug located on the bottom of the fiberglass cabinet. A heavy copper wire should be run to a suitable ground.

KEEP CABINET AND CONNECTORS DRY. If the cable connectors are going to be exposed to weather, they need to be protected to insure that they do not get wet. Using water-proofed connectors is cost-prohibitive, therefore, usually a small amount of tape and plastic (such as a kitchen bag) are often used. Often, several connectors can be "bunched" together and one piece of plastic used. This technique is sufficient for shorter-term monitoring situations (less than a few months). While most of the cabinet is water-resistant, the bottom panel that accepts the sensor connectors needs to be kept out of the weather so that the electronic signals do not become shorted. The more permanent SMS systems are better suited for inclement weather because the extension cables will usually be spliced at the sensor end and encased in waterproof material, and the other end is terminated in the SMS cabinet.

ROUTING CABLES: If there are several long cables of similar length to be run, time can often be saved by grouping them in bundles of four or six and wrapping them in zip ties along their length before going to the field. Also, since the system is often used where construction is ongoing, it is a good idea to bundle wires along a safe path and periodically tie them together to keep people from tripping over "loops".

REQUIRED TOOLS AND OTHER SUPPLIES: It is recommended that a well-equipped tool kit be assembled before installing the system in the field. In addition to the tools and supplies described in the instructions for installing particular sensors, the installation will require tape measures, wrenches, a hammer, clean rags, screwdrivers, various grinders (AC power and/or battery-operated), zip ties, duct tape, flashlights, extension cords, power generator, spare gasoline, and other miscellaneous items. It is also recommended that spares of most everything listed above be obtained as often tools will get lost or broken in the field.