Subtopics

• Why instrument and monitor?

• Modern tools for monitoring

• Automation of monitoring

• Some observations
Reasons to Monitor of Infrastructure

1. Show that performance is safe and acceptable.
2. Provide a warning of an impending failure or unsafe condition.
3. Reveal unknowns and aid use of the Observational Method.
4. Evaluate contractor’s means and methods.
5. Control construction or operations.
6. Minimize damage to adjacent structures.
7. Inform stakeholders.
8. Satisfy regulators.
10. Improve performance and advance state-of-knowledge.
Uncertainties and Unknowns → Risk

- Subsurface conditions and geo-material complexity
- Loads
- Parameters
- Prediction methods
- Construction methods and results
- Actual performance

Very few engineering disciplines have to deal with as much uncertainty as we have in infrastructure. We use performance monitoring to show us when these uncertainties might lead to negative impacts so we can take action as soon as needed.
Reason to Monitor Performance

• To help client monitor and manage risks.

• Value of performance monitoring is better understood by clients when the benefits of performance monitoring are explained as a means to identify emerging risk so it can be managed.
World Trade Center Reconstruction, Manhattan

Purpose of the monitoring: Ensure slurry wall and subway box do not move too much.
World Trade Center Monitoring

Settlements of #1 Subway

Graph showing settlements over various points and dates.
Why monitor performance?

TO LOWER OPERATIONAL RISK

- **RISK** = Probability of Failure * Consequences
  - Good monitoring can reduce probability of failure.
  - Good monitoring can reduce consequences by giving early notice to remediate.
    - Loss of life
    - Damage to other property
    - Loss of facility
    - Costs to mitigate and repair
    - Delays
    - Cost of litigation
    - Damage to reputation
Why monitor performance?

To manage anything you must measure Key Performance Indicators (KPIs). Monitoring is an important component of Active Risk Management.

**Figure 1: Circle of Risk Management**

- **IDENTIFY** - Establish the components of risk
- **ACCESS** - Determine the likelihood of each risk element and the consequences
- **PLAN** - Define strategies to minimize likelihood and control consequences
- **MONITOR** - Measure anything that can indicate risk, evaluate the results and update the risk assessment
- **CONTROL** - Take action to reduce risk at every opportunity.
Horizontal movement
> $\frac{3}{4}''$ triggered review
> 1.5” stopped work
Significant sources of risk

- Collapse of one or more major structures adjacent to the excavations due to failure of the support system.
- Major damage to structures due to failure of excavation support system.
- Architectural damage to historic structures along the alignment.
- Claims by contractors for costly construction delays caused by damage to adjacent structures or stoppage of work.
CA/T Instrumentation Program

• Estimate of risk without monitoring = $550 million plus potential for significant loss of life and injury.

• At completion of construction amount paid to repairs of damages = $9M

• Total cost of monitoring program = $60M

• Monitoring program potentially saved the project $500M in avoided risk costs.
Measuring Performance
Great equipment available to measure field performance reliably and quickly.
Deformation - Distance change by laser

- Measurement range - 0.2 to 200 m
- Typical accuracy $\pm 1.5$ mm (SD)
- Measurement time 0.6 to 4 sec
- Hundreds of targets per ATS
- Remotely controllable
- Use for automated monitoring and alarming
- Minimizes disruption to building occupants
Instrumentation Program:

- 294 Resistance strain gages
  - 6 on each member, logged at regular intervals of 5min to 1hr, as well as high speed data collection
- 130 Vibrating Wire strain gages
- 3 Automated Total Stations (AMTS)
  - Typ. 3-5 prisms on each pier/bent
- GPS reference and control points
- 21 Seismograph geophones
  - Installed on critical pier/bent footing and surrounding structures

Sakonnet River Bridge, RI
Cause for Alarm:

- Sheet piling within 15’ of existing Bent 2 South Column
- AMTS data taken every 5-15 min showed settlement of column reaching 0.5”

AMTS data showing settlement of Bent 2 South Column during sheet piling
Deformation - Distance change by GPS

- Measurement range - unlimited
- Typical accuracy ±1 mm (SD)
- Measurement time 0.1 to 10 sec
- No moving parts.
- Use for automated monitoring and alarming
- Minimizes disruptions to occupants to read
Washington DOT Floating Bridge
Multipoint Integrated Sensors
Slope Monitoring

Filter [t, z] = [0, 3], Ref-Far, Dir = [1-564]/564 Frames

A = f(AZ) Relative to Frame 1

2008-06-30 20:08:22 >> 2008-09-28 16:53:00 UTC

Abs(Displacement) vs. time

Polyfit n = 5
z = -15.90 ft
z = -119.07 ft

0
500
1000
1500
2000
time, hrs (mm/dd)
Why monitor in real time?

– Failure can occur rapidly with little visible warning, even for an excavation that has been stable for years.

Global instability – shear slide in few hours to weeks

Internal instability – internal erosion – piping
  - few hours to years

Other – soil/structural failure - sudden to years

– Failure may be avoided using preventative actions, if we have adequate warning.

– Consequences can be reduced significantly if we have a reliable warning.

– With real-time monitoring we are better able to connect cause and effect.
Web-based monitoring

– Deliver evaluated data to those with need to know, rapidly in form it can be quickly evaluated and responded to.

– Enabling technologies include:
  • Low cost, high speed computers
  • Ubiquitous, low cost communications devices
  • High data transmission rates
  • Reliable, remote data loggers
Web-based, Real-Time Remote Monitoring

Web Enabled Settings

Internet

Off-site User

from sensor to screen

iSitecentral.com
Web-based monitoring

– Components include:
  • Sensors
  • Signal-to-digital converter
  • Communications device
  • Communications NETWORK
  • Server
  • Internet
  • User device with Internet accessibility

– Systems are more complex and require more skill sets than manual approaches
Wireless monitoring

- Transferring commands and data without a wire, i.e. radio frequency signals.
Communications for automation

• Serial to modem/landline
• Serial to modem/cell phone
• Serial to modem/satellite
• Serial to radio
• Serial to Ethernet
• Serial to WiFi
• Radio
• Ethernet
• WiFi
Wireless monitoring

• Advantages
  – No time spent running wire
  – Cover long distances and areas where it would be difficult to run cables
  – No time spent maintaining cables during changing site conditions
  – Faster to install
  – Avoid possible union issues
  – Possibility for multiple paths for data transmission
Wireless monitoring

• Pitfalls
  – Range as spec’d is not often reality- depends on system components and terrain
  – Interference
    • Problematic to identify
    • Can change through the duration of installation due to new installations
    • System management requires time to diagnose
  – Technically challenging to integrate with other technologies
  – Distributed power needs (no single power location)
  – Bandwidth- depends on what you are collecting. Need to size throughput carefully so as not to lose data
  – Reliability- systems need capabilities to reboot and reconnect to avoid radio lock-ups that occur
Antennae

Omni-directional
- Height is everything
- Line of sight where possible
- Communication is only as good as connectors, cables and antenna
- Height is everything

Directional
One channel data logger
Remote data logger
Self contained, Plug-and-Work™ technology

Options for vibrating wire, piezo-resistive, and strain gage sensors

Options for landline, CDMA and GSM cell modems, satellite phone
Remote wireless installation
Wireless communications

Satellite modem
Cell modem - IP
Radio
CPU
A-D and lightning protection
A vision - iLevee
Four Use Cases:

1. Normal Operations and Maintenance (O&M);
2. Pre-Event;
3. During Event; and
4. Post Event.

Each use case is developed to have features and tools useful for flood protection management before, during or after a storm event, as well as normal operations.
Monitoring Global Stability of Levee/Floodwall In-Place Inclinometer/Tiltmeter/GPS

LPV 148 (Site 4) Installation

Intelligent Levees

Extensometer (other side of wall)

Solar Panel

GPS Antenna

Tiltmeter (in enclosure)

Datalogger Enclosure (with GPS receiver, cell modem, datalogger)

Extensometer (in enclosure)

In-Place Inclinometers (below ground surface)
17th ST. CANAL INSTALLATION

Fiber optic cable installation in levee embankment

Fiber optic installation on floodwall
17TH ST. CANAL MONITORING - FIBER OPTIC DISTRIBUTED STRAIN SENSORS

Construction induced strain
Web-based monitoring

What the Client Wants

• Reliability
• Real-time
• Secure Access
• Simple Format
• Response time
• Early warning
• Easy access
• Control of the information
• “Everything is ok.”
The future of monitoring is the Web and handheld devices.

The challenge is to boil large quantities of information from different sources down to what is needed in format that is immediately useful.

The ultimate challenge is using the measurements to provide more perceived value:

- Warnings of unexpected or degrading performance
- Comfort and confidence
- Process improvement
- Reduce risk
Useful reports – 4 hour update

From: Alerts@iSiteCentral.com
Sent: Wednesday, March 06, 2013 12:05 AM
To: Marr, Allen
Subject: Notification(Willow)

Summary of Instrumentation Alert Status at 03-06-2013 00:00:13

<table>
<thead>
<tr>
<th>Sensor Name</th>
<th>Reading Time</th>
<th>Reading Value</th>
<th>Unit</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Alert Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-05-08XI</td>
<td>2013-03-05 02:00:00</td>
<td>0.2543</td>
<td>inches</td>
<td>--</td>
<td>0.25</td>
<td>Caution</td>
</tr>
<tr>
<td>I-06-07XI</td>
<td>2013-03-05 02:00:00</td>
<td>0.3003</td>
<td>inches</td>
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<td>0.25</td>
<td>Caution</td>
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<tr>
<td>P-26-s</td>
<td>2013-03-05 22:30:43</td>
<td>583.09</td>
<td>Elevation (ft)</td>
<td>--</td>
<td>580</td>
<td>Caution</td>
</tr>
<tr>
<td>P-28-s</td>
<td>2013-03-05 22:30:28</td>
<td>577.3</td>
<td>Elevation (ft)</td>
<td>--</td>
<td>575</td>
<td>Caution</td>
</tr>
<tr>
<td>RA-21 _ForceAvg</td>
<td>2013-03-05 21:44:00</td>
<td>30</td>
<td>Force (Kips)</td>
<td>31.2</td>
<td>--</td>
<td>Take Action</td>
</tr>
<tr>
<td>RA-23 _ForceAvg</td>
<td>2013-03-05 21:44:00</td>
<td>29.3</td>
<td>Force (Kips)</td>
<td>29.4</td>
<td>--</td>
<td>Take Action</td>
</tr>
<tr>
<td>RA-24 _ForceAvg</td>
<td>2013-03-05 21:38:00</td>
<td>31.4</td>
<td>Force (Kips)</td>
<td>31.8</td>
<td>--</td>
<td>Take Action</td>
</tr>
<tr>
<td>SM16 - Z_Calc</td>
<td>2013-03-05 18:40:00</td>
<td>-1.6475</td>
<td>inches</td>
<td>-1</td>
<td>--</td>
<td>Caution</td>
</tr>
<tr>
<td>SM18 - Z_Calc</td>
<td>2013-03-05 18:50:00</td>
<td>-1.7542</td>
<td>inches</td>
<td>-1</td>
<td>--</td>
<td>Caution</td>
</tr>
<tr>
<td>SM-RF-13 -Y_Calc</td>
<td>2013-03-05 19:49:00</td>
<td>0.58321</td>
<td>Displacement (inches)</td>
<td>-0.5</td>
<td>0.5</td>
<td>Caution</td>
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<tr>
<td>SM-RF-22 -Z_Calc</td>
<td>2013-03-05 22:29:00</td>
<td>-0.79575</td>
<td>Displacement (inches)</td>
<td>-0.75</td>
<td>--</td>
<td>Take Action</td>
</tr>
</tbody>
</table>
Performance Monitoring

Biweekly (left) and Daily (Right) I&M Reports
Data and information management system

Universal Data Management System

- Sensors
  - Environmental
  - Load
  - Tilt
  - Stress
  - Piezo
  - Geomatics
  - Vibration

- Site Information
  - Construction Activities
  - Field Observations
  - Reports
  - Photos

- Management System
  - Available 24/7
  - Secure Access
  - Multiple Users
  - Daily Backup
  - Dual-system synchronization ensuring 99.99% uptime
  - 3rd Party monitoring

- Users
  - Regulators
  - Contractors
  - 3rd Parties
  - Owners

- Anytime Access via Remote Devices
  - Auto-generated PDF Reports
  - Web based Charts & Graphs
  - Alarms
Message Board

Dewatering well inside Cell 1 on 10/28/2013 3:02:17 PM
Dewatering well inside Cell 1 went down last week. It will be replaced tomorrow.

Problem with I-4 on 10/9/2013 9:25:38 AM
There is a problem with inclinometer 4 (I-4) readings. We are currently investigating the issue.
Initial evaluations indicated that this could be due to the GAS unit malfunctioning.

Alert on 8/27/2013 10:56:25 AM
Inclinometer 1 (INCL-01) exhibited a spike in the AM. We are continuing to monitor this sensor and will invalidate the faulty
Performance State

• **Normal** – performance is within the design parameters with no anomalous behavior and no indicators of undesirable performance and is expected to remain in this state for the near future.

• **Caution** – performance is outside the range expected in the design, or anomalous behavior not anticipated in the design is occurring, or an indicator of undesirable performance is occurring at an increasing rate.

• **Alert** – performance is in a range where safety of the dam is in question, or performance is deteriorating and not controllable.
<table>
<thead>
<tr>
<th>ACTION STATE</th>
<th>DESCRIPTION</th>
<th>RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORMAL - GREEN</td>
<td>Observations and measurement indicate expected and acceptable values</td>
<td>Continue inspection, monitoring, and maintenance program.</td>
</tr>
<tr>
<td>CAUTION - YELLOW</td>
<td>One or more indicators of performance are above expected values</td>
<td>Review the data for reliability. Meet with Evaluation Team to decide what to do. Inform all involved parties of the current condition and the recommended plan of action. Take steps to reduce chance that reading will exceed the Limit Level.</td>
</tr>
<tr>
<td>ALERT - RED</td>
<td>One or more indicators are above the Limit Levels established for each instrument.</td>
<td>Inform all parties to stop any work in affected area. Implement contingency plan. Develop safe steps to proceed.</td>
</tr>
</tbody>
</table>
Guidance for success

• Every instrument should have a purpose – answer a question or quantify an unknown
• I&M should follow a systematic approach
• All details of the systematic approach must be followed.
• Alert levels and action plans must be developed and used.
• Contingency plans must exist for failure modes that have potential for large consequences.
Steps of a Systematic Approach

1. Identify what questions need answering.
2. Identify what measurements can and should be made.
3. Design appropriate monitoring system.
4. Plan installation, calibration, maintenance and data management.
5. Prepare and update budget.
6. Procure, test, install and verify instruments.
7. Calibrate and maintain instruments and readouts.
8. Collect, process and evaluate data.
9. Interpret and report results quickly.
10. Take action when required. (adapted from Dunnicliff.)
Automatic with readings several times per day.

- Detect sudden changes quickly.
- Better detect and define trends early for more accurate interpretation of data.
- Detect daily and seasonal changes due to environmental effects so:
  - These effects help show data are valid
  - These periodic changes can be defined and removed from the data to better see the primary changes.
- More data that are reliable and believable creates a higher degree of confidence in the information so quick action can be taken.
Web-based monitoring

– Deliver evaluated data to those with need to know, rapidly in form it can be quickly evaluated and responded to.

– Enabling technologies include:
  • Low cost, high speed computers
  • Ubiquitous, low cost communications devices
  • High data transmission rates
  • Reliable, remote data loggers

– This is undoubtedly one area of big change over next 20 years.
Conclusions

• Heavy civil construction involves substantial risk due to uncertainties and unknowns.
• Effective monitoring programs can help reduce risk and save money.
• Effective monitoring programs need to be real-time.
• New technologies (computers, communications, sensors) make real-time monitoring technically and economically feasible.
• Success requires systematic approach with a dedicated team.
• Contingency plans and their timely implementation are essential for success.