Use of Performance Monitoring to Manage Risks for Infrastructure

Presented to:       Kansas Section
                    ASCE Geo-Institute

Presented by:      W. Allen Marr, PhD, PE, NAE
                    Founder and CEO of Geocomp

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Roadmap for the next hour

- Why do we instrument and monitor?
- Some recent developments in I&M technologies
- Some illustrative applications
- Components of an effective I&M program
<table>
<thead>
<tr>
<th>Reason</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indicate impending failure.</td>
</tr>
<tr>
<td>2</td>
<td>Provide a warning of unacceptable performance.</td>
</tr>
<tr>
<td>3</td>
<td>Reveal unknowns.</td>
</tr>
<tr>
<td>4</td>
<td>Evaluate critical design assumptions.</td>
</tr>
<tr>
<td>5</td>
<td>Assess contractor’s means and methods of construction.</td>
</tr>
<tr>
<td>6</td>
<td>Minimize damage to existing structures during construction.</td>
</tr>
<tr>
<td>7</td>
<td>Control construction to avoid performance problems.</td>
</tr>
<tr>
<td>8</td>
<td>Control operations to avoid performance problems.</td>
</tr>
<tr>
<td>9</td>
<td>Devise remedial measures to fix problems.</td>
</tr>
<tr>
<td>10</td>
<td>Improve performance to meet desired goals.</td>
</tr>
<tr>
<td>11</td>
<td>Advance state-of-knowledge.</td>
</tr>
<tr>
<td>12</td>
<td>Show change in performance over time to predict future conditions.</td>
</tr>
<tr>
<td>14</td>
<td>Be a good neighbor and inform stakeholders.</td>
</tr>
<tr>
<td>15</td>
<td>Comply with regulatory and/or governance guidelines.</td>
</tr>
<tr>
<td>16</td>
<td>Reduce litigation associated with claims and failure.</td>
</tr>
<tr>
<td>17</td>
<td>Show that facility is performing well.</td>
</tr>
</tbody>
</table>

From Marr 2007 ASCE GSP 175
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
Uncertainties and Unknowns >> Risk

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

Very few engineering disciplines have to deal with as much uncertainty as we have in our underground work.

We use performance monitoring to show us when these uncertainties might lead to negative impacts so we can take action as soon as needed.
Why monitor performance?

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

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Figure 1: Circle of Risk Management
# Cycle of Active Risk Management

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDENTIFY</td>
<td>Establish the components of risk.</td>
</tr>
<tr>
<td>ASSESS</td>
<td>Determine the likelihood of each risk element and the consequences.</td>
</tr>
<tr>
<td>PLAN</td>
<td>Define strategies to minimize likelihood and control consequences.</td>
</tr>
<tr>
<td>MONITOR</td>
<td>Measure things that can indicate and quantify risk, evaluate results and update the risk assessment.</td>
</tr>
<tr>
<td>CONTROL</td>
<td>Take action to reduce risk at every opportunity.</td>
</tr>
<tr>
<td>REASSESS</td>
<td>Periodically review and update risk elements and action plans.</td>
</tr>
</tbody>
</table>

**Instrument – Monitor - Mitigate**
Consequences can be serious

Singapore

Dulles
One killed, two trapped
PANYNJ - World Trade Center Reconstruction
World Trade Center Monitoring

Settlements of #1 Subway

- East beams 01/29/09 (since Feb 07)
- East beams 01/28/09 (since Feb 07)
- West beams 01/23/09 (since Feb 07)
- West beams 01/22/09 (since Feb 07)
• Consequences can be expensive.
  small slope failure because contractor dug too deep

• Contractor filed claim for $12,000,000 damages from delays

• Contractor awarded $6,000,000 by Review Board with no knowledge of soil mechanics.
Risk – a great communications tool that owners, construction managers, contractors and engineers conceptually understand.

- Factor of safety = 1.3 means what to an owner?
- A probability of massive stability failure of 1 in 30 will get everyone’s attention.

“Perhaps the main advantage of using statistical methods is that the element of judgment is expressed as a numerical probability, and so forms a consistent and rational basis for comparisons of all kinds of data.” Lumb (1968)
How much can I reduce risk with an effective Instrumentation-Monitoring-Mitigation program

- Risk assessments taking into account effects of I-M-M on probability of failure (Marr USSD 2015):

<table>
<thead>
<tr>
<th>Case</th>
<th>Probability Detect</th>
<th>Probability of Remedial Success</th>
<th>Probability of Failure</th>
<th>Reduction Factor for Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No detection</td>
<td>None</td>
<td>1.0</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.75</td>
<td>1.33</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.19</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>0.95</td>
<td>0.098</td>
<td>10.2</td>
</tr>
<tr>
<td>4</td>
<td>0.995</td>
<td>0.995</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>0.995</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>0.995</td>
<td>0.5</td>
<td>0.50</td>
<td>2</td>
</tr>
</tbody>
</table>
Key Points

An effective Instrumentation - Monitoring – Mitigation program can help manage and reduce risk by 10 to 100 times.

Conditions change with time. Effective risk management may require I-M-M throughout the life of the facility, especially structures like dams, levees and impoundments.
Technological Innovations in I & M

- Sensors and Electronics
- Installation and Maintenance
- Communications Hardware
- Data and Information Management
Deformation - Distance change by Robotic Total Station

- Measurement range - 0.2 to 200 m
- Typical accuracy ±1 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
Comparison Between AMTS and Manual Survey
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
Why do we use RTS and dGPS?

- Very accurate and repeatable to a couple of mm in x, y and z, if operated properly.
  - More accurate and repeatable than manual surveys.
- Can function remotely in all kinds of situations.
- Can provide measurements several times a day.
- Can transmit data via network for immediate consumption.
- A RTS can monitor dozens of points for very little added cost.
- A dGPS can work for years with no maintenance.
- Can be set up and made operational within hours.
In place inclinometers

Reliably measure deflections to 1 mm.
I-20 at Vicksburg
• Displacement moves away from river as the river level rises and towards the river as the river recedes
Multipoint Integrated MEMS tilt sensors
Wed 17 September 2008
(WB road closed; detoured on EB lanes)

Fri 26 September 2008

Dussenbock, MnDOT
Distributed sensor fiber optic technologies
Slot cutting on top of floodwall

A slot is cut on top of the wall for installation of the fiber optic distributed strain and temperature sensor.
Installation and maintenance

• Drilling remains expensive but has become somewhat more efficient with more drillers experienced at installing instrumentation into borings.

• Maintenance remains a challenge with biggest problem being to protect the instruments from damage. -- Enforce contract clauses that he who destroys pays for the replacement.
Protecting Instrumentation from People and the Environment
Installation and maintenance

- Grouted in place sensors
- Multiple sensors in the same borehole.

Vogtle Nuclear Station Units 3 and 4
Grouted in-place piezometers

Pore pressures are almost never hydrostatic!
Why monitor in real time?

– Failure can occur rapidly with little visible warning, even for a dam that has functioned well for many 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.
Dataloggers

• Resolution
  – 12 bit – one part in 4096
  – 16 bit – one part in 65,536
  – 24 bit - one part in 16,777,216

• Precision
  – 12 bit – one part in 2,000
  – 16 bit – one part in 16,000
  – 24 bit - one part in 130,000

• Frequency
  – Up to 10,000 samples per second or more

• Cost
  – $100 to $200 per channel roughly
Communications

• 20 years ago
  – Send technician to field to read and record data in a field book
  – Reduce data with a calculator and plot by hand.
  – Copy plot and mail to end user.

• Today
  – Wireless connection from the sensor to a screen located anywhere in the world (or on the moon) 24 x 7 for less than $0.10 per reading.
Wireless communications

- Satellite modem
- Cell modem - IP
- Radio
- CPU
- A-D and lightening protection
Data and information management

• Hard drive disk storage - $100 per terabyte
• Storage cost for one year of data from sensor read every hour is $0.0000001.
• Unlimited storage in the “Cloud” at $3.95 per month.
• Annual storage of data and related information is essentially $0.
• More metadata will be stored to help evaluate the data.

• Cost lies in
  – Effort to retrieve the desired information
  – Effort to interpret that information into something meaningful and useful.
Putting the pieces together
3D Plan
SECTION 5A AT I-5 (11/15/2012)
Movement of the Exposed Rock Face During Excavation
INCL-05-AA-Inc, Inclinometer Incremental, Downstream at Toe of Slope

- 02/23/2013 02:00:00
- 03/05/2013 02:00:00
- 02/28/2013 02:00:00

Elevation (ft), top of rock = 558 ft, top of casing = 562.5

Away from excavation: Displacement (in) towards excavation
Dyna Force Sensors to Measure Force in Tendons

![Diagram showing force measurement data over time with warning lines for caution and take action.]
RA-21 (Dyna Force Sensors on Rock Anchor 21)

- LS-RA-21-Dyna 1
- LS-RA-21-Dyna 2
- LS-RA-21-Dyna 3
- LS-RA-21-Average
- RA-21 _ForceAvg
- RA-21-1_Force
- RA-21-2_Force

Dyna 3 Not Functioning

Force [kips]

Date

11/1 12:00 AM
12/1 12:00 AM
1/1 12:00 AM
3/1 12:00 AM

RA-21 Lockoff Avg
Cautions
Take Action

02/18/2012
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>
<td>--</td>
<td>0.25</td>
<td>Caution</td>
</tr>
<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-R-A-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>
</tr>
<tr>
<td>SM-R-A-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>
Useful reports - Daily report

<table>
<thead>
<tr>
<th>Alert Level</th>
<th>Response Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caution</td>
<td>Monitor daily for additional movement.</td>
</tr>
<tr>
<td>Caution</td>
<td>Monitor daily for additional movement.</td>
</tr>
<tr>
<td>Caution</td>
<td>Preparing to submit revised threshold and limit values request based on modified slope stability analyses.</td>
</tr>
<tr>
<td>Caution</td>
<td>Preparing to submit revised threshold and limit values request for review based on modified slope stability analyses.</td>
</tr>
<tr>
<td>Take Action</td>
<td>Carrying out fault stabilization plan. Current anchor load is stable and sufficient to support existing condition. Anchors will be reanalyzed or re-stressed prior to closing flood gate.</td>
</tr>
<tr>
<td>Take Action</td>
<td>Awaiting reply for request to adjust alert levels on anchors.</td>
</tr>
<tr>
<td>Take Action</td>
<td>Requested modification to Alert Levels to adjust data entries in iSiteCentral.</td>
</tr>
<tr>
<td>Caution</td>
<td>Monitor daily for additional movement.</td>
</tr>
<tr>
<td>Caution</td>
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<tr>
<td>Take Action</td>
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</tr>
</tbody>
</table>

Levels, with the following exceptions:

<table>
<thead>
<tr>
<th>Limit</th>
<th>Alert Level</th>
<th>Response Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Caution</td>
<td>Monitor daily for additional movement.</td>
</tr>
<tr>
<td>5</td>
<td>Caution</td>
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</tr>
<tr>
<td>0</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Take Action</td>
<td>Monitor daily for additional movement.</td>
<td></td>
</tr>
</tbody>
</table>
The monitoring system – extensive array of strain gages on structural members, seismographs, and automated total station monitoring.

AMTS system comprised of:
• 3 fixed AMTS instruments (Leica TCA1800/1201)
• 4 dGPS station locations for additional system referential control
• 4-6 prismatic targets on each existing pier

The need: A new $120 million, 3,160-ft-long, 4-lane bridge built along an alignment located immediately south of the existing bridge, which will remain in operation during construction. Extensive earthwork and deep piled foundations for new pier to potentially disturb existing bridge structure and foundations.
Sakonnet River Bridge Replacement

- dGPS station – Leica GPS, spread-spectrum radio, Solar engine
- Leica total station – mounting enclosure with solar engine adjacent to disused railway
Active Risk Monitoring: Structural Response to Construction and Mitigation activities

1. On 10/14/09 the South Column of existing Bent 2 suddenly moved.
   - Engineers monitoring response identify sudden change;
   - AMTS data collection frequency increased to once every 10 min – showed the column continued to settle.
   - Investigation into the cause found contractor installed small, temporary pile very close to the existing pier that was not on the construction drawings.

2. On 10/28/09 – after 0.5” of settlement was recorded, the construction contractor was required in initiate their action plan and jack the pier back into position.
APM Tunnel Extension at Hartsfield-Jackson International Airport
Cox Tower 1 - Atlanta, GA

- Two 12-story towers for the Cox Technical Expansion required 390’ by 420’ by 35’ deep excavations through saturated residual soils.
- The support of excavation walls consisted of soldier piles with wood lagging and 3 rows of tieback anchors.
- Geocomp monitored lateral movements and settlement of the support of excavation walls using a robotic total station and 65 prisms.
- Nearly 9” of lateral movement into the excavation and 11” of settlement was experienced at one point next to a major road.
Cox Tower 1 - Atlanta, GA
Cox Tower 1 - Atlanta, GA

Diagram showing:
- Foundation backfilled with soil
- 4th Level tie-back stressed
- Excavation of Tower Crane Foundation
- 1st Row Tiebacks Stressed
- 2-1/2" Rain event

Graphs showing:
- Easting Displacement (ft.)
- Height Displacement (ft.)

Data and Information must be processed, i.e. evaluated and interpreted

- Information must be timely.
- Information must accurately describe the performance state.
- Information must reach the decision makers.
- Prompt action is required when indicated.
Integrating data and context

Universal Data Management System

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

Equipment Information
- TBM
- AMTS

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
- Operators
- Contractors
- Owners
- 3rd Parties

Anytime Access via Remote Devices
- Auto-generated PDF Reports
- Web-based Charts & Graphs
- Alarms
Mobile Apps for data consumption and action
Mobile Apps for data collection and diagnostics
Automation 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.
### Table 7-2: Performance monitoring Action States

<table>
<thead>
<tr>
<th>ACTION STATE</th>
<th>DESCRIPTION</th>
<th>RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NORMAL – PERFORMANCE AS EXPECTED</strong></td>
<td></td>
<td></td>
</tr>
<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><strong>THRESHOLD LEVEL</strong></td>
<td></td>
<td></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><strong>LIMIT LEVEL</strong></td>
<td></td>
<td></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>
Key Elements of Effective Performance Monitoring

- People
- Training
- Technology
- Systematic approach
- Organizational Structure
- Contingency Planning
- Emergency Preparedness
- Documentation
- Maintenance
Key Points

Performance monitoring provides a very effective way to control risk on a project.

To be effective, Performance monitoring should:
• consist of **visual surveillance** and monitoring with **instrumentation**;
• be **designed** to help identify, manage and reduce risk;
• be developed and executed in a **systematic way**;
• have an **action plan** ready to implement when monitoring indicates it is needed
# Adding Action to Visual Inspections

<table>
<thead>
<tr>
<th>Performance Indicators</th>
<th>Why Significant</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unexpected settlement</td>
<td>Decreasing freeboard means less flood protection.</td>
<td>Alert if settlement is accelerating for no known reason or different than past patterns; otherwise, Caution.</td>
</tr>
<tr>
<td>Differential movement horizontally or vertically</td>
<td>Dam not performing uniformly; cracks could be developing.</td>
<td>Alert if rate of movement is accelerating or different than past patterns for no known reason; otherwise, Caution.</td>
</tr>
<tr>
<td>Cracking in transverse direction</td>
<td>Cracks extending to below water level in dam can initiate a breach.</td>
<td>Alert if more than 0.5 inches wide and increasing daily; otherwise, Caution if not deeper than half of the freeboard or 5 ft, whichever is less and not increasing.</td>
</tr>
<tr>
<td>Cracking in longitudinal direction</td>
<td>Cracks running parallel to axis of dam may indicate shear strains occurring in the upstream or downstream slope or within the foundation.</td>
<td>Alert if more than 0.5 inches wide with differential settlement across the crack and increasing daily; otherwise, Caution.</td>
</tr>
<tr>
<td>Structure is unexpectedly moving differently than</td>
<td>Might indicate loss soil at depth, undermining of the structure, or slippage of soil</td>
<td>Alert if recent and increasing daily. Caution if long-term at constant rate without immediate threat.</td>
</tr>
</tbody>
</table>
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.)
Data and Information must be processed, i.e. evaluated and interpreted

• Evaluate
  – Are the data correct and believable?
  – Is the information valid and complete?
  – What steps are needed in improve quality of the data?

• Interpret
  – What do the data mean?
  – What is the cause and effect?
  – What are the implications of the data?
  – What actions are required?
Recommended I-M-M-M Practices

• Every instrument should have a purpose. It should help answer an important question.
• Selection, installation and operation of an I&M program should follow a systematic approach.
• All details of a systematic approach are important.
• Alert Levels should be established for each instrument.
• Contingency plans must exist and be used.
• Visual observations are equally important. (cameras and video.)