TIMELINE

BESc (2007-2011)

- Undergraduate research position after 2\textsuperscript{nd} and 3\textsuperscript{rd} year with Professor Simonovic

MESc (2011-2012)

- Continuation of work in undergraduate research
TIMELINE

BC Hydro (2013-Present)
BRIDGE RIVER
LAJOIE DAM

BC Hydro (2013-Present)
DAM SAFETY

Do we need a new approach?
DAM SAFETY

BC Hydro Fleet

- All dams built between the early 1900s and 1985
- Many assets reaching end-of-life
- Major capital investment plan to renew generation infrastructure
- New methodology for risk assessment of dam systems required?
PROBABILISTIC RISK ASSESSMENT (PRA)

Current standard for dam safety analyses

- Events are assumed to be independent (e.g. flood, gate failure, landslide)
- Linear analysis using a chain of events
- Quantify the likelihood of identified failure modes
- No consideration of human factors (e.g. maintenance, design errors)
FAULT TREE ANALYSIS

A fault tree shows the interaction among system elements whose failure could lead to an undesired event.

Ref: G. Baecher
EVENT TREE ANALYSIS

An event tree graphically shows the logical sequence of events given the occurrence of a specific circumstance

Ref: G. Baecher
BOW-TIE MODEL

The bow-tie model is a method that can be used for risk management pertaining to a specific event (total or component failure). Key event causes and ways to prevent them are identified. Strategies for mitigation of the potential event outcomes are identified.

Ref: G. Baecher
BOW-TIE MODEL

Events, circumstances and scenarios

Undesirable event with the potential for harm or damage

HAZARDS

Engineering Activities

Maintenance Activities

Operations Activities

CONSEQUENCES

Harm to people and damage to assets and the environment
EXTREME EVENT ANALYSIS

Probable Maximum Earthquake

Probable Maximum Flood
PROBABILISTIC RISK ASSESSMENT (PRA)

Successes:

• Brainstorming of various failure modes
• Extreme load events and checks against design criteria
• Analysis of linear events

Observation:

• Many historical dam failures are caused by events which are well within the design envelope of the system
• Uncommon combination of common events
• Nonlinearities, feedbacks, component interactions in complex systems
• Lack of understanding of the system behaviour over time
TAUM SAUK, 2005

Pumped storage dam overtopping

- Gauge readings too low
- Back-up gauges located too high to indicate imminent failure
- No visual monitoring
- No overflow spillway

*Failure of SCADA (Supervisory control and data acquisition) systems and oversight of design engineers*

Ref: P. Regan, G. Baecher
SAYANO-SHUSHENSKAYA, 2009

Hydroelectric plant turbine failure

- Turbine operated in a “rough load zone” on several occasions
- Head cover bolt fatigue
- Inadequate maintenance or inspections?
- Lack of turbine shutoff valves and no backup power for intake gates

*Failure resulting from design omissions, operator oversight and inadequate maintenance or inspections*

Ref: P. Regan
FOLSOM DAM, 1995

Hydroelectric plant spillway gate failure

- Corrosion at the pin-hub interface increased the bending stress causing yielding of the strut
- Decreasing frequency of inspection, testing and maintenance
- Inadequate lubricant specifications
- Lack of sensors to measure force applied to move gate

* Failure resulting from increasing corrosion, inadequate maintenance and inspections, design omissions (lubricant, sensors)

Ref: G. Baecher
HISTORICAL DAM FAILURES

NOPPIKOSKI DAM, 1985
Hydroelectric plant dam breach

- High inflow event, not well forecasted
- Failure of spillway gate hoist
- Inability to access remote dam site to open additional gates
- Not able to activate emergency gate (lack of personnel/equipment on site)
- Lack of backup power supply
- Lack of staff to respond to crisis

*Failure resulting from design omissions and operational issues*

Ref: P. Regan, G. Baecher
A NEW APPROACH TO RELIABILITY ANALYSIS

Policy & plans  MANAGEMENT  Reports

Control Actions  STAFF  Data

Operations

Human operator  Displays  Controls  Sensors

Automated controller

Actuators

Performance indicators

Inputs

Operating system

Disturbances

Outputs

Current PRA

Adapted from Leveson, 2010, Baecher, 2014
A NEW APPROACH TO RELIABILITY ANALYSIS

Requirements:

- Nonlinear capabilities
- Assess combinations of loadings
- Design and construction errors
- Human factors (operational errors etc.)
- Uncertainties
- Disturbances
- Maintenance Activities
- Evolution of the system over time
SYSTEM DYNAMICS SIMULATION

Advantages:

• Simulation can be useful in showing how a system changes over time
• Nonlinearities can be simulated using feedback loops, stocks and flows
• Ability to represent non-physical system components
  • Operations
  • Maintenance
  • Budget
  • Information flow
  • Disturbances (eg. Flood events, earthquakes, landslides, debris buildup, forced outages, sabotage)
SYSTEM DYNAMICS SIMULATION

The basics:

- Stocks accumulate in value (eg. population)
- Flows describe the rate of change in the stock at a given time step (births, deaths)
- Auxiliary variables can be constants or equations which relate to other variables and help describe system behaviour (birth rate, death rate)
SYSTEM DYNAMICS SIMULATION

Model setup:

• Several sectors will be required to deal with different system aspects
  • Water-balance
  • Operations
  • Information flow (SCADA)
  • Disturbances
• System-of-systems approach?
• Sensitivity analysis required to deal with uncertainties
SYSTEM DYNAMICS SIMULATION

Water-Balance Sector:

- Physical structures which pass, store, or divert water for power production
- Component conditions (degradation, age)
- Component conditional reliability functions
- Site accessibility
- Back-up electrical systems and operational modes
SYSTEM DYNAMICS SIMULATION

Adapted from Leveson, 2010, Baecher, 2014
SYSTEM DYNAMICS SIMULATION

Operations Sector:

• Operational decisions (errors)
• Inflow forecast accuracy
• Maintenance budget
• Maintenance activities
• Local staff availability and qualifications
• Component priority (manufacturers maintenance recommendations, risk acceptance)
• Changing values (eg. environmental, regulatory, First Nations)
SYSTEM DYNAMICS SIMULATION

Adapted from Leveson, 2010, Baecher, 2014
SYSTEM DYNAMICS SIMULATION

Information Flow Sector:

• Accuracy and values from gauges measuring:
  • Reservoir level
  • Landslide movement
  • Embankment dam seepage
  • Penstock leakage
  • Forces on spillway gate hoists, etc.

• Gauge condition

• SCADA Systems (relay of sensory information to operators, alarms)

• Communication systems (microwave, radio, etc.)
SYSTEM DYNAMICS SIMULATION

Adapted from Leveson, 2010, Baecher, 2014
SYSTEM DYNAMICS SIMULATION

Disturbances Sector:

• Earthquakes
• Landslides
• Rockfalls
• Sinkholes
• Floods (stochastic timeseries input?)
• Forced outages (turbines, generators, electrical equipment, spillway gates, etc.)
• Debris buildup (affecting spillway capacity, ability to operate gates, ability to inspect dam face)
SYSTEM DYNAMICS SIMULATION

Adapted from Leveson, 2010, Baecher, 2014
SYSTEM DYNAMICS SIMULATION

Next steps in creation of a working example:

- Research partnership between BC Hydro and Western University (Civil Engineering)
- Application to NSERC’s Collaborative Research and Development grant program
- Development of theoretical foundations that will help quantify relationships in the system dynamics simulation model
- Application of simulation approach to BC Hydro’s Bridge River system
CONTEMPORARY DAM SAFETY

BRIDGE RIVER
RELIABILITY OF FLOW CONTROL SYSTEMS

Possible benefits of system dynamics modelling for flow control systems:

• Representation of extremely complex, nonlinear systems in a computational model

• Consideration of factors beyond physical structure of a system

• Identification of critical system components with respect to dam safety and overall system reliability

• Ability to test different system configurations to assist in decision making for capital upgrades

• Modeling of budget and staffing for sensitivity analysis of budget cuts

• Training of future system operators in a safe environment
RELIABILITY OF FLOW CONTROL SYSTEMS

Questions?