Quantitative Risk Assessment of Underground Pipelines with a Focus on Probability Estimation

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• Independent engineering, consulting and testing services
• Not-for-Profit subsidiary of Alberta Innovates
• Self-sustaining, fee-for-service operation
• In operation since 1984
Making Pipelines Safer

- Large-scale Destructive Testing
- Technology Evaluation
- Advanced Design Methods
- Quantitative Risk Assessment
- Risk and Reliability Based Integrity Management

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Why Consider Risk?

• Can provide an objective and consistent basis for assessing, managing and demonstrating pipeline performance

• Actions based on risk considerations reflect both likelihood of failure and potential consequences

• Applicable to new design and integrity management of existing pipelines
  – Presentation focus on application to integrity management
Why Quantitative Risk?

• Available approaches
  – Qualitative methods
    • Characterize risk by a descriptive value or index
    • Best suited to threat identification and risk ranking
  – Quantitative methods
    • Characterize risk as the expected value of a measurable consequence parameter
    • More objective basis for decision making
      – Better suited to determining if a system is safe enough
      – Better suited to determining what actions are required and when
High profile incidents have led stakeholders to demand better pipeline performance. Quantitative analysis methods are being embraced to more objectively, consistently and defensibly address pipeline risk.
Quantitative Risk Analysis (QRA)

• Given the basic definition of risk

Risk = Probability x Consequence

• QRA requires

  – Quantitative failure probability or failure frequency estimates
    • Distinction by failure cause to identify dominant threats and targeted remediation action
    • Distinction by failure mode (leak versus rupture) to acknowledge consequence differences

  – Quantitative failure consequence estimates
    • Consideration of public safety impact \( \leftarrow \) for toxic or flammable gas and liquid lines
    • Consideration of environmental impact \( \leftarrow \) for lines transporting persistent hazardous liquids
    • Consideration of financial impact \( \leftarrow \) direct and indirect costs
• Quantitative analysis options
  
  – Statistical methods
    • Estimates developed from evaluation of past pipeline performance
    • Various historical incident data sets available
  
  – Reliability-based methods
    • Estimates developed from pipeline and ROW attributes
    • Various approaches available including structural reliability methods
• **Approach**
  – Collect historical data on previous pipeline failures
  – Use historical data as basis for probability estimates

• **Data sources**
  – Proprietary operator data
  – Industry data in public domain
    • US: US Department of Transportation (USDOT / PHMSA)
    • Canada: National Energy Board (NEB) | Canadian Energy Pipeline Association (CEPA)
    • Europe: European Gas Pipeline Incident Group (EGIG)
      UK Onshore Pipeline Operators Association (UKOPA)
      CONservation of Clean Air and Water in Europe (CONCAWE)
Example – Statistical Approach

Calculate annual probability of corrosion rupture for section of natural gas pipeline

• Given incident database
  – Data on 100,000 km of gas transmission lines
  – 50 corrosion failures recorded in last 5 years
  – 10% of corrosion failures were ruptures

• Solution
  – Annual failure rate = number of incidents / system exposure = 50 / (100,000 x 5) = 1 x 10^{-4} per km-yr
  – Annual rupture rate = 0.1 x 1 x 10^{-4} per km-yr = 1 x 10^{-5} per km-yr

• Key assumption
  – Historical average is representative of pipeline performance in the future

• Possible concerns
  – How are failure rate estimates affected by:
    • pipeline age and condition
    • operating stress level
    • integrity management actions taken
Comments on Statistical Methods

• Advantages
  – Simple
  – Credible (based on real data)

• Limitations
  – Generally not very pipeline-specific
    • Data sets do not support subdivision by key pipeline attributes
    • No link between failure rate and maintenance actions
  – Ignores systematic changes in pipeline condition
    • Cannot account for time-dependent deterioration
Reliability-based Methods

• Approach

– Develop failure prediction models that define the sets of conditions that can lead to failure

– Use structural reliability methods where appropriate to combine deterministic models with input uncertainties to estimate probability (or frequency) of failure for individual threats

POF = P(R < L)

Requires formal characterization of the uncertainties in the applied load and the available resistance for each damage or deterioration mechanism
Uncertainties Inherent in the Probability Estimation Process

• Random variations → Loads imposed on the line
  – Internal pressure
  – Third party impact force

• Measurement uncertainty → Pipe properties and line condition
  – Joint-by-joint yield strength & fracture toughness
  – Number and size of defects
  – Defect growth rates

• Model uncertainty → Pipe behavior under loads
  – Burst capacity at corrosion defect
  – Dent-gouge failure susceptibility
  – Tensile capacity of girth welds
Reliability Model Chosen Depends on the Type of Threat

• Consider management of **progressive (time dependent) damage**
  – Determine existing damage severity
    • Find and size existing defects
  – Assess anticipated behavior over time
    • Estimate rate of defect growth and assess time for defects to become failure critical
    – Manage integrity through periodic inspection and remediation or proof-testing

• Examples include corrosion and cracking
  – Consider metal loss corrosion
Probability Estimation

• Corrosion – example of a time dependent damage mechanism

\[
\text{Failure rate (per km-yr)} = \text{No. defects (per km)} \times \text{Probability of failure per defect (per yr)}
\]

• Considerations in developing failure rate estimate
  – Identifying and characterizing defect population
    • Assumed number of features and feature sizes should reflect the probability of detection and sizing accuracy of inspection method
  – Estimating probability of failure over time ↓ structural reliability model
    • Failure predictions should reflect uncertainties in: defect sizes and growth rates, variability in pipe properties, and accuracy of the failure prediction model
  – Considering impact of maintenance
    • Effects of defect remediation, re-inspection interval and modified operating conditions should be reflected in probability estimates
Probability Estimation Process

- Select deterministic failure prediction models (consider leak and burst separately)
- Characterize parameter uncertainties using probability distributions
- Calculate failure probability using standard techniques (e.g. simulation)

Example for corrosion

- Operating pressure
- Material property & dimension data
- Inspection data
- Defect characteristics
- Model uncertainties
- Defect growth parameters
- Failure probability as function of time
• Obtain pipeline failure rate versus time

*based on risk considerations that reflect failure consequences
Impact of Maintenance

• Mitigation philosophy
  – Find and eliminate significant defects before they reach critical size

• Maintenance options, e.g.
  – In-line Inspection (ILI) and selective repair
  – Hydrostatic testing

• Maintenance impact
  – Eliminate contribution to failure probability from defects removed
• Obtain pipeline failure rate versus time – accounting for maintenance

*based on risk considerations that reflect consequences
Reliability Model Depends on the Type of Threat

• Consider management of **random (time independent) damage**
  – Determine likelihood of damaging event occurrence
    • Characterize event frequency
  – Assess anticipated pipeline response to event
    • Characterize the damage tolerance of pipeline
  – Manage integrity through control of event likelihood or potential for failure given an event

• Examples include mechanical damage and sudden ground movement
  – Consider mechanical damage
Probability Estimation

• Mechanical damage – example of time independent damage

\[
\text{Failure rate (per mi-yr)} = \text{Hit frequency (per km-yr)} \times \text{Probability of failure given hit}
\]

• Considerations in developing failure rate estimate
  – Estimating hit frequency
    • Likelihood of having excavation activity and effectiveness of damage prevention measures should be reflected in hit frequency estimate
  – Estimating failure probability given a hit
    • Failure probability given line hit should reflect: uncertainty in damage caused by contact, variability in pipe properties, and accuracy of failure prediction model
  – Considering impact of maintenance
    • Effect of changes in damage prevention measures or modified operating conditions should be reflected in probability estimates
Assessment Approach

- Calculate equipment impact failure probability

Hit Frequency
(inductive logic model – fault tree)

Failure given Hit
(structural reliability models for puncture or dent-gouge)
Simplified fault tree model - to illustrate concept

- Excavation to pipeline location
  - Construction activity
  - Inadequate cover or protection
- Contractor fails to avoid pipeline
  - Contractor unaware of pipeline
    - Inadequate markings
    - Inadequate one-call system
  - Contractor ignores warnings
- Operator ROW patrols fail to detect activity
  - Interval between patrols too long
  - Patrol fails to detect activity

Basic event probabilities (depend on line attributes)
Calibrated using historical data and engineering models
Actual fault tree model required - more complex

Model reflects effect on hit frequency of a range of system attributes and damage prevention measures, including:

- land use and presence of crossings
- depth of burial
- one call system type
- dig notification requirement
- dig notification response
- public awareness level
- right-of-way indication
- alignment markers - explicit signage
- alignment markers - above ground
- alignment markers - buried
- surveillance method / interval
- mechanical protection
• Mitigation philosophy
  – Reduce potential for line hits

• Maintenance option examples
  – ROW condition enhancement
  – Increased signage/markers
  – Public awareness improvements
  – Increase burial depth
  – Introduce mechanical protection

• Maintenance impact
  – Reduce hit frequency → proportionate reduction in failure probability
Effect of Damage Management

Model reflects effect on hit frequency of a range of system attributes and damage prevention measures, including:

- land use and presence of crossings
- depth of burial
- one call system type
- dig notification requirement
- dig notification response
- public awareness level  \(\Leftarrow\) Improve awareness
- right-of-way indication  \(\Leftarrow\) Enhance indication
- alignment markers - explicit signage
- alignment markers - above ground
- alignment markers - buried
- surveillance method / interval
- mechanical protection
Effect of Damage Management

- Attribute changes affect basic event probabilities
  - change hit frequency
  - change failure rate

<table>
<thead>
<tr>
<th>Right-of-way Indication</th>
<th>Public Awareness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below average</td>
</tr>
<tr>
<td>None</td>
<td>1.0</td>
</tr>
<tr>
<td>Intermittent and/or very limited indication</td>
<td>0.87</td>
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<tr>
<td>Continuous but limited indication</td>
<td>0.47</td>
</tr>
<tr>
<td>Continuous and highly indicative</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Probability that ROW indicators are not recognized
Effect of Damage Management

• Example: from C-FER fault tree model
Comments on Consequence Estimation

• Considerations
  – Safety, Environment and Cost

Population effects dominated by short term impact of flammable or toxic gas or liquid product releases

Environmental impact dominated by longer term impact of persistent liquid product releases

- Product Release Rate
  - Fireball → Jet fire
  - Pool fire
  - Vapour cloud fire
  - Vapour cloud explosion
  - Toxic or asphyxiating vapour cloud

- Measures of Safety Impact
  - Chance of casualty
  - Number of casualties

- Effective Release Volume
  - Product Toxicity
  - Volume Released
  - Environment Sensitivity or Importance
  - A measure of Environmental and Socioeconomic Impact

Product Release Rate

Population effects dominated by short term impact of flammable or toxic gas or liquid product releases

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Risk Management

• Obtain pipeline risk versus time \( \leftarrow \) calculate over sliding evaluation length
  – Determine required action

Risk Thresholds
Safety:
- Individual risk of fatality
- F-N Curve (expected no. fatalities)
Environment:
- Expected release volume*
  *volume adjusted for spill impact

Criteria currently under review for possible inclusion in CSA Z662 - 2023
Risk Evaluation of Linear Systems

• Key considerations

– Some integrity threats are concentrated at explicit locations
  • Locations are known (e.g. corrosion defects found during inspection)
  • Best evaluated as discrete, location-specific probability → units: per year

– Some integrity threats are distributed along pipeline length
  • Locations not known (e.g. future mechanical damage, corrosion defects not found)
  • Best evaluated as failure rate or distributed probability → units: per km-yr

What is required is the aggregated probability or average failure rate over a relevant length

\[ P_f = P_d + \frac{1}{L_e} \sum_{i=1}^{n} P_{fi} \]
Evaluation Length Considerations

• Example: safety implications of natural gas pipeline

*Interaction Length* is segment length with potential to affect dwelling occupants
- level of safety risk exposure depends on aggregated failure probability from all active threats within IL
Evaluation Length Considerations

• Example: environmental implications of liquid product pipeline

*Interaction Length* is segment length with potential to impact river
- level of environmental risk exposure depends on aggregated failure probability from all active threats within IL
Pipeline risk should be evaluated over a sliding evaluation length. In many situations, the appropriate evaluation length equals the hazard interaction length. The appropriate evaluation length depends on:
- The risk measure being evaluated
- Various pipeline and right-of-way attributes
Quantitative Risk Assessment - Summary

• Benefits of Quantitative Risk Assessment (QRA)
  – An objective and consistent basis for assessing pipeline operating risk

• Added benefits of QRA employing structural reliability methods
  – Better able to reflect line-specific factors including impact of maintenance actions
  – Framework for consideration of all significant sources of uncertainty
  – Sound basis for decision making
    • What actions are required
    • When action is required
Comments on Quantitative Risk Assessment Using Structural Reliability Methods

• Feasibility
  – Structural reliability methods and models for specific pipeline integrity threats have been under development for more than 20 years
    • Various Joint Industry Research Programs
    • PRCI Research → C-FER’s Reliability Based Design and Assessment (RBDA) process
    • Reliability models directly applicable in risk assessment
  – Many models in public domain, e.g. Annex O of CSA Z662

• Validity
  – Model development activities have included extensive calibration and validation exercises
    • Models have been used to hindcast historical failure rates for the existing North American pipeline network – agreement shown to be good