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ASOCIACIÓN DE EMPRESAS DE PETRÓLEO, GAS Y ENERGÍA RENOVABLE DE AMÉRICA LATINA Y EL CARIBE

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Risk Assessment and Cost Benefit Analysis for Pipelines Buried in Slow-Moving Landslides

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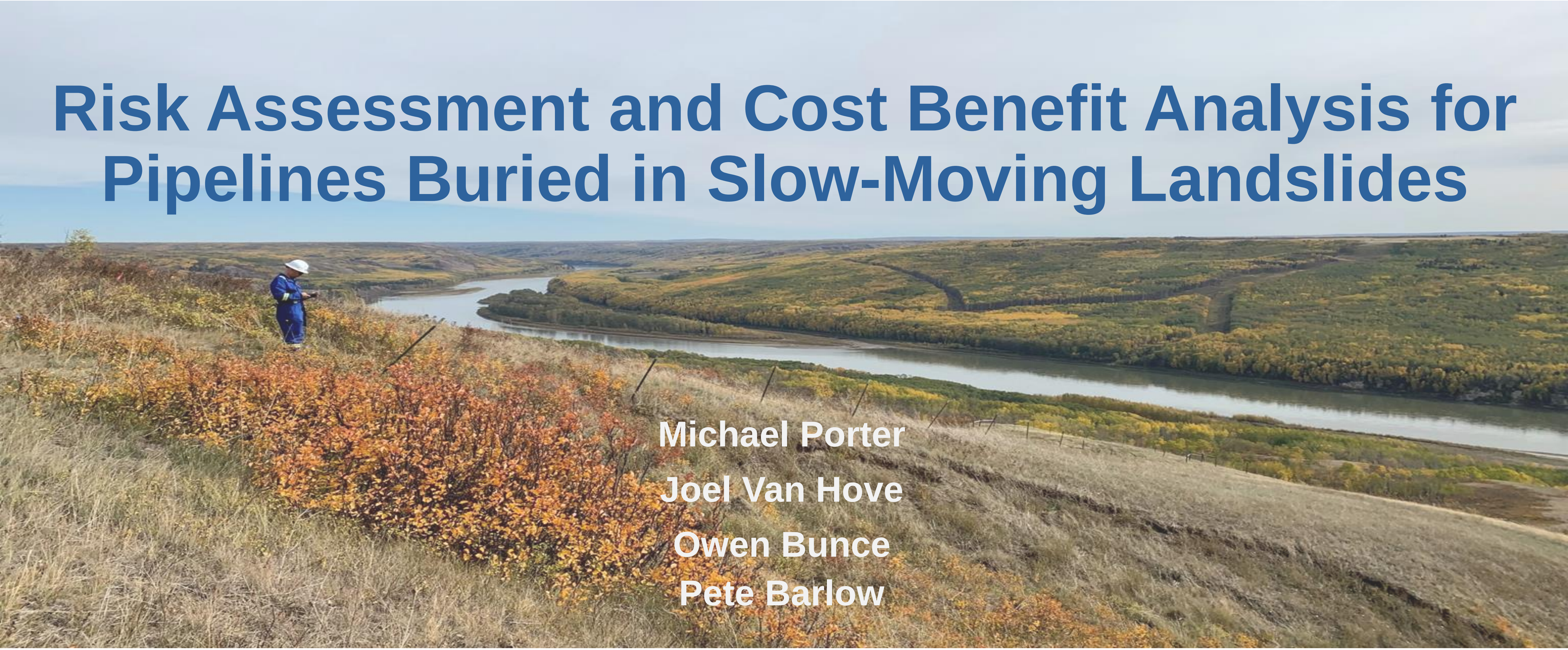
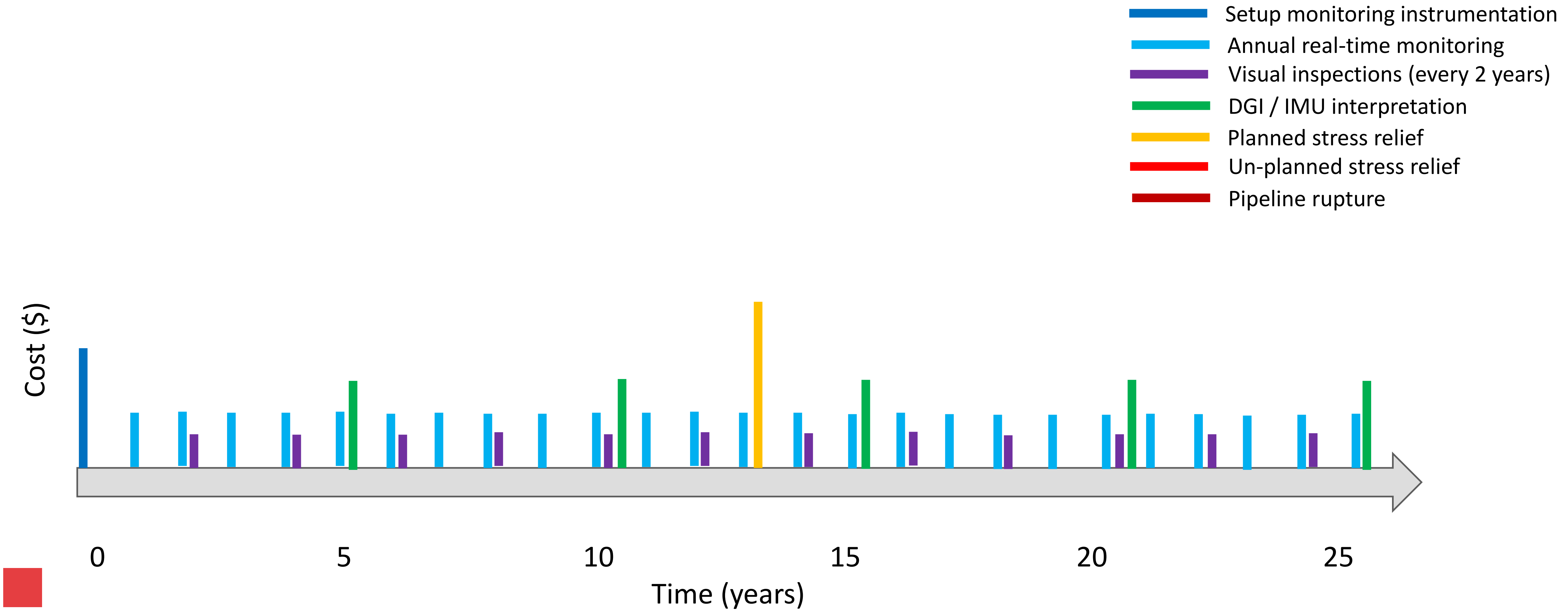
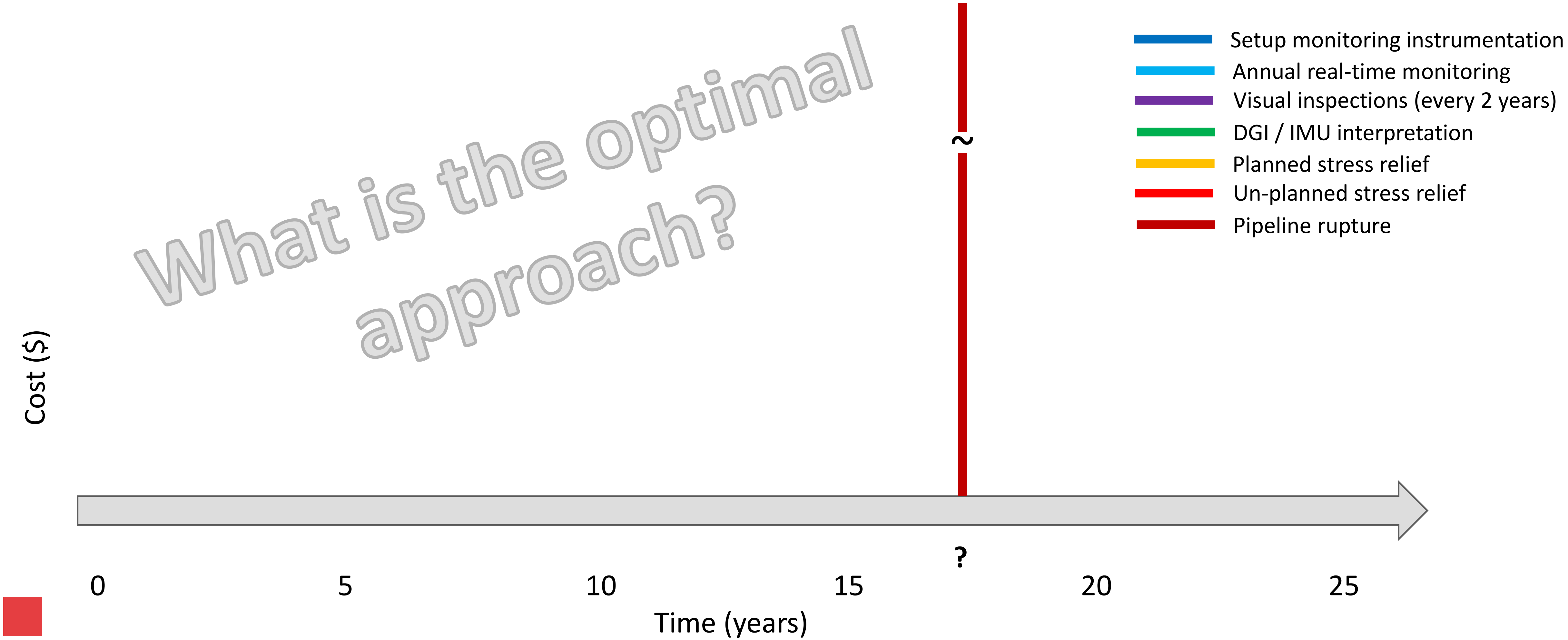


Management Cost – Very Proactive



Management Cost – Purely Reactive



Risk-informed Decision Making

An approach to achieving objectives while balancing costs and benefits in the face of uncertainty

Examples:

- Clarifying decision-making processes
- Selecting preferred options
- Optimizing solutions
- Prioritizing resources to reduce uncertainty and manage risk
- Emergency preparedness & contingency planning
- Comparing calculated probability of failure or risk against tolerance criteria

Cost Benefit Analysis & Lifecycle Cost

- Methods of weighing the expected costs and benefits of options
- For decisions about landslide risk management:
  - Cost of planned management effort (e.g. inspections, monitoring, slope maintenance, pipeline maintenance, re-routes)?
  - Expected cost of the residual risk (pipe damage, unplanned outage, pipe rupture)?

Lifecycle cost = present value of residual risk + present value of risk management effort

Expected Cost of Residual Risk

- Probability x Consequence = Expected Annual Risk Cost
  - Included as annual costs in the cash flow model for lifecycle cost
  - “Easy” if probability is expected to remain constaint over design life

Buried Pipe + Moving Landslide = Complex Dynamic System

- Landslide condition state may change

Current Movement Rate → Speed Up? / Stay the Same? / Slow Down?

- Pipeline condition state will change if the landslide moves
  - No Strain → Elastic Strain → Plastic Strain → Loss of Containment

Lifecycle Costs for Infrastructure Crossing Slow-moving Landslides

1. Define a set of *Asset Condition States* & costs that can be linked to landslide velocity or total landslide displacement
2. Modify a common landslide velocity classification system so that *Landslide Velocity Classes* can be treated as Markov Model condition states
3. Develop *Markov Chain Models* to predict landslide velocity class probability distributions for a range of *Landslide Behavior Types*
4. Use *Monte Carlo Simulation* to estimate the annual probabilities of landslide displacements exceeding the asset condition state thresholds
5. Predict annual costs (maintenance & management effort; event-based costs) over the asset design life, and determine *Present Value of Lifecycle Cost*

Pipeline Condition States & Costs (1)

- Annual costs would occur every year if an inspection, monitoring and maintenance program was in place (States A, B, and C)
- If detected, a transition to State D would trigger emergency actions that would include reverting the pipe back to a better condition state (a one-time event cost)
- A transition to State F would result in realization of failure costs (also a one-time event cost)

TABLE 3. PIPELINE CONDITION STATES AND TYPICAL ACTIONS AND COSTS FOR LIFECYCLE COST MODELLING

Condition State	Description	Typical Actions if Condition State is Known	Typical Annual or Event Cost
A	No definitive evidence of pipe strain	Infrequent visual inspection or aerial patrol	<$1k/yr
B	Strain well below plastic limit	Visual inspection and IMU	$1k to $10k/yr
C	Strain approaching plastic limit	Frequent inspections and IMU; detailed investigation; planned strain relief	$10k to $1M/yr
D	Strain exceeding plastic limit	Pipe shut-in; slope stabilization; emergency strain relief; re-route	$1M to $10M (event cost)
F	Loss of containment	Service outage; cleanup and repair; emergency strain relief; slope stabilization; re-route	>$10M (event cost)

Landslide Velocity Classes (2)

Modified from Cruden and Varnes (1996)

Defined in terms of an annual displacement (m) at a location of interest (total displacement over a cycle of seasons)

Estimated from field reconnaissance, remote sensing, instrumentation

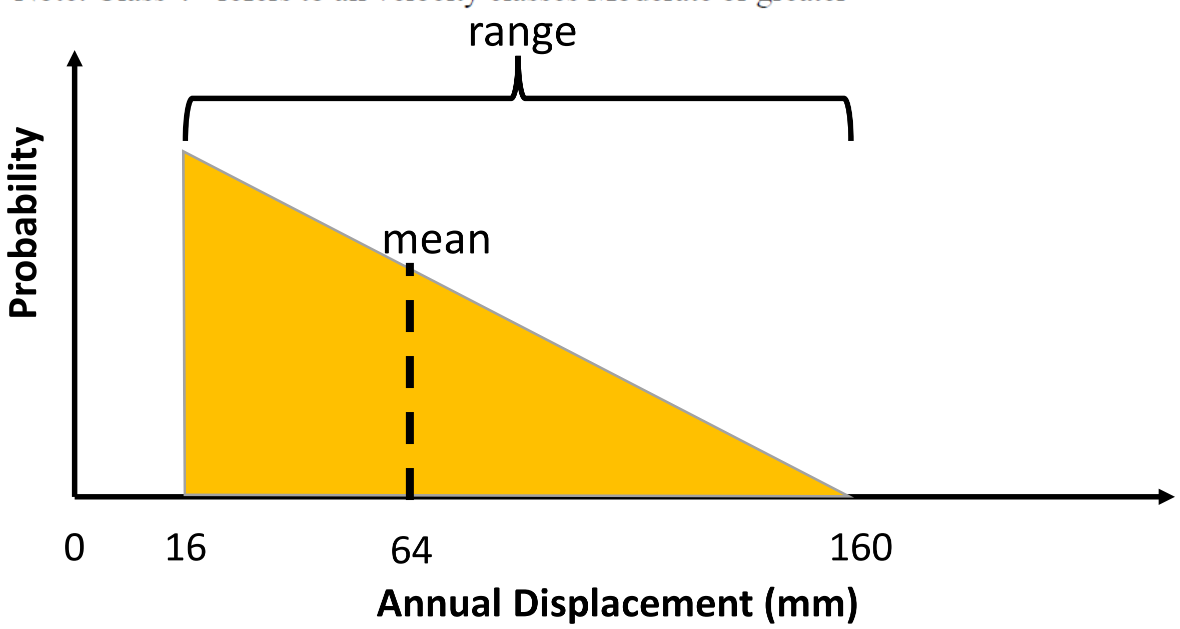
Class 4+ includes any annual displacement exceeding 16 m

Each velocity class represented by a range, mean, and assumed left-triangular probability density function

TABLE 1. MODIFIED LANDSLIDE VELOCITY CLASSIFICATION AFTER CRUDEN AND VARNES [3]

Class	Description	Typical velocity	Proposed annual displacement criteria (m)	Proposed mean annual displacement (m)
7	Extremely rapid	>5 m/sec		
6	Very rapid	>3 m/min		
5	Rapid	>1.8 m/hr		
4+	Moderate	>13 m/mo	>16	64
3	Slow	>1.6 m/yr	>1.6	6.4
2b	Very slow	>160 mm/yr	>0.16	0.64
2a	Very slow	>16 mm/yr	>0.016	0.064
1	Extremely slow	<16 mm/yr	>0	0.005
0	Dormant	0 mm/yr	0	0

Note: Class 4+ refers to all velocity classes Moderate or greater

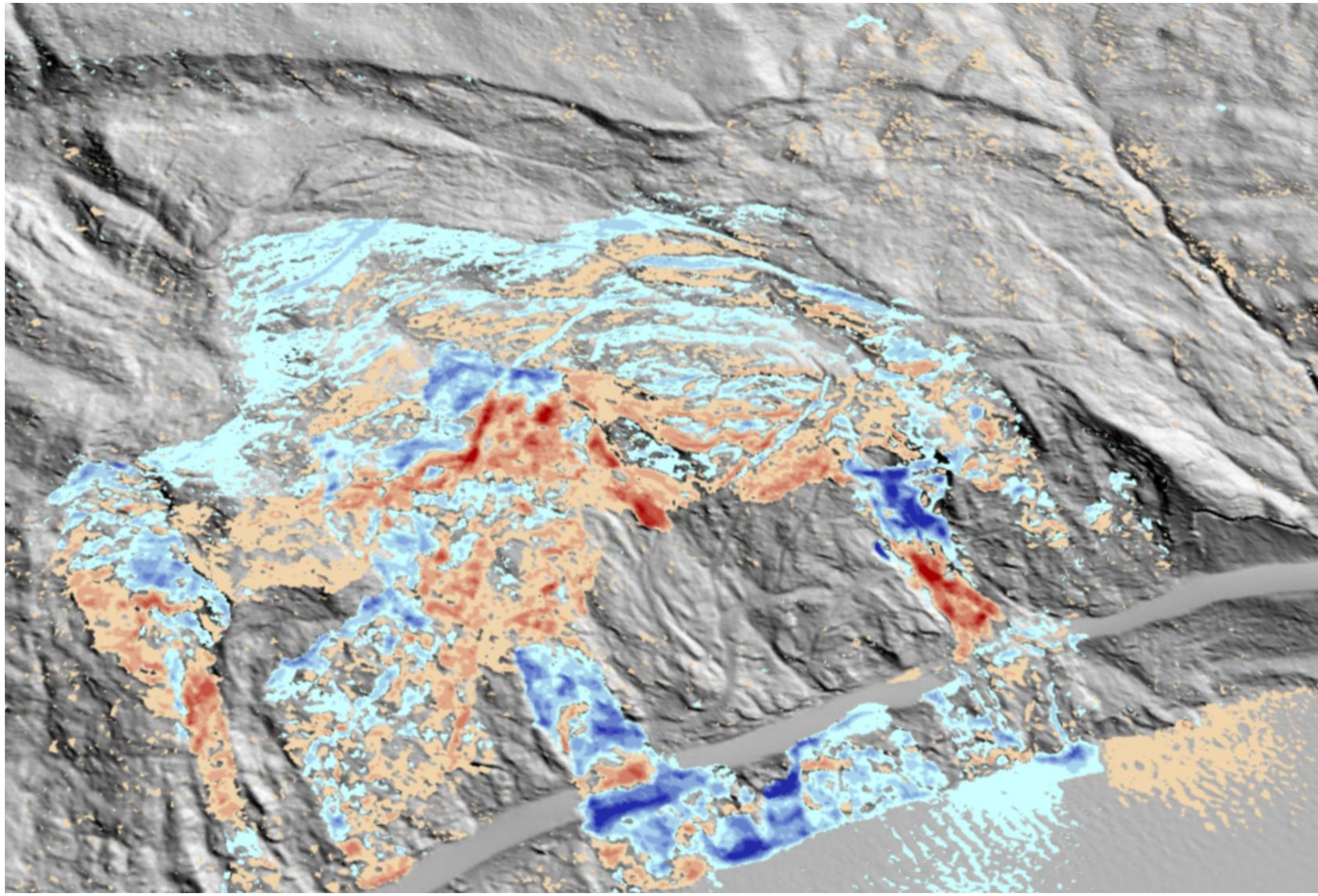


Predicting Displacement of a Slow-moving Landslides (3)

Slope geometry can change as a result of *slide movement*, surface erosion, toe erosion, human activity

Cohesion and angle of friction can change in response to *progressive failure*, weathering, changes in soil moisture, changes in *slide movement rate*

Porewater pressure can change in response to changes in rainfall, snow accumulation & melt, evapotranspiration (e.g. timber harvesting, forest fire), *formation of tension cracks and sag ponds, internal shearing*, external loads



Need a Probabilistic Model

Markov Chain models generate a velocity class probability distribution for each model timestep (3)

$$[\,P_0, P_1, P_{2a}, P_{2b}, P_3, P_{4+}\,] \times \begin{bmatrix} \text{Matrix of} \\ \text{Transition} \\ \text{Probabilities} \end{bmatrix}^n = [\,P_0, P_1, P_{2a}, P_{2b}, P_3, P_{4+}\,]$$

Initial Velocity Class Probability Distribution

Transition Matrix

Velocity Class Probability Distribution after 'n' timesteps

After many timesteps these models converge on a limiting state probability distribution (long-term average)

TABLE 2. PROPOSED LANDSLIDE BEHAVIOR TYPES AND CHARACTERISTICS FOR PRE-EXISTING SLOW-MOVING LANDSLIDES

Behavior Type	Type A	Type B	Type C	Type D	Type E
Typical geology	Relatively intact shales, mudstones	Relatively intact shales, mudstones, residual soils, over-consolidated glacial deposits	Relatively intact glacial deposits, colluvium derived from shales, mudstones, residual soil and glacial deposits	Colluvium derived from shales, mudstones, residual soil and glacial deposits	Colluvium derived from shales, mudstones, residual soil and glacial deposits
Typical failure mechanism	Translational block slides and spreads	Translational block slides and spreads	Translational block slides and spreads, rotational slides, complex earth slides-earth flows	Translational slides, rotational slides, earth flows, complex earth slides-earth flows	Translational slides, rotational slides, earth flows, complex earth slides-earth flows
Typical inclination of basal shear surface	Sub-horizontal (0 to 5 degrees)	Sub-horizontal (0 to 5 degrees)	Similar to the residual friction angle	Similar to the residual friction angle	Sub-parallel to the ground surface
Typical toe condition	No toe erosion	Toe erosion usually absent	Toe erosion may be active	Toe erosion often active	Toe erosion almost always active
Long-term annual probability of Class 4+ velocities	1 in 80,000	1 in 17,000	1 in 3,000	1 in 750	1 in 250
Assumed limiting state velocity class distribution; (assumed average annual displacement for each velocity class in brackets)					
0 (0 m)	79.2%	52.2%	32.6%	19.1%	12.0%
1 (0.005 m)	19.0%	43.6%	57.7%	58.4%	49.8%
2a (0.064 m)	1.6%	3.8%	8.7%	19.6%	28%
2b (0.64 m)	0.2%	0.3%	0.8%	2.3%	7.9%
3 (6.4 m)	0.02%	0.06%	0.19%	0.47%	1.90%
4+ (64 m)	0.001%	0.006%	0.034%	0.13%	0.42%
Mean annual displacement	0.005 m	0.015 m	0.05 m	0.15 m	0.50 m

Landslide & Pipeline Condition States (3, 4)

Model Outputs – Velocity Class Probabilities

Markov Chain Velocity Class Probability Distributions						
Year	Class 0	Class 1	Class 2a	Class 2b	Class 3	Class 4+
0	0	0.67	0.33	0	0	0
1	0.00224	0.67272	0.32086	0.00356	0.00055	0.00006
2	0.00446	0.67535	0.31254	0.00644	0.00108	0.00014
3	0.00666	0.67788	0.30491	0.00877	0.00157	0.00021
4	0.00883	0.68032	0.29788	0.01067	0.00202	0.00029
5	0.01098	0.68266	0.29136	0.01221	0.00243	0.00036

FIGURE 2: EXAMPLE MARKOV CHAIN MODEL OUTPUTS FOR TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

Monte Carlo Simulation

- 100,000 trials for each year
- For each trial:
  - Randomly sample model output, estimate displacement for each trial
  - Subtract displacement from remaining pipe capacity
  - Determine pipe condition state
- Determine pipeline condition state probabilities based on outcomes for all trials

Pipeline Condition States (4)

From FEA: transition to State B after 100 mm; State C after 250 mm; State D after 750 mm; State F after 1,500 mm

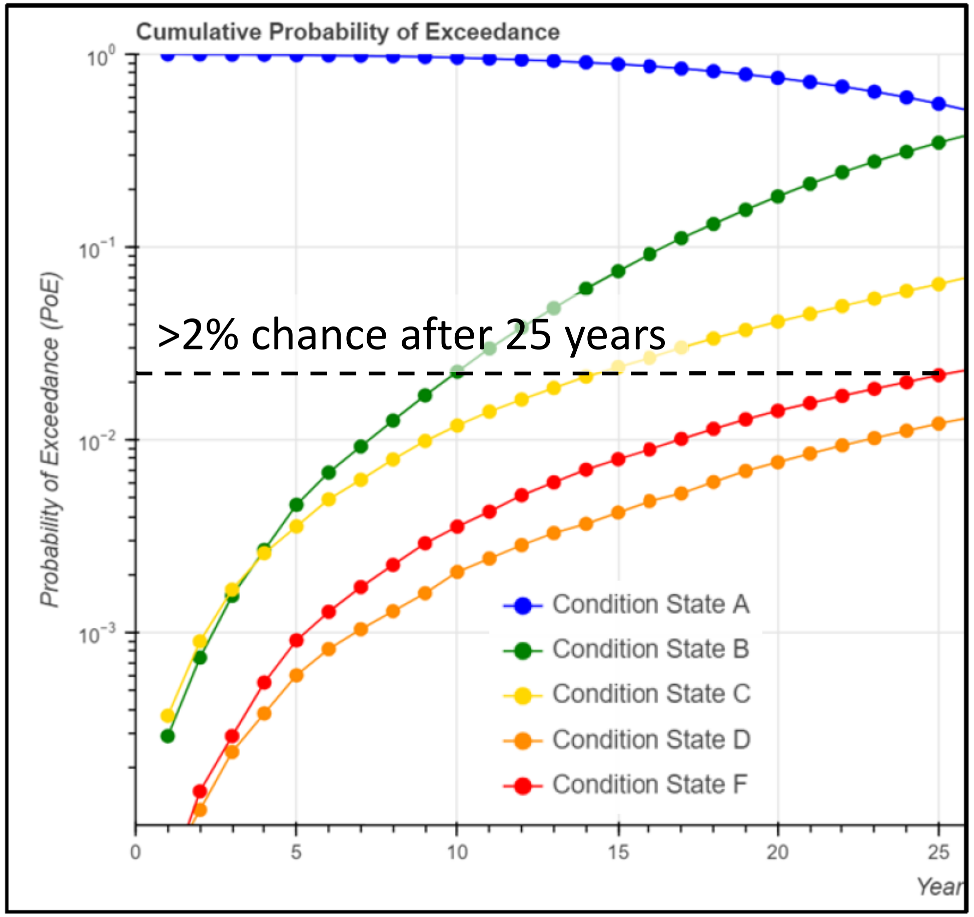


FIGURE 3: PIPELINE CONDITION STATE MODELLING OUTPUTS FOR TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 5 MM PER YEAR

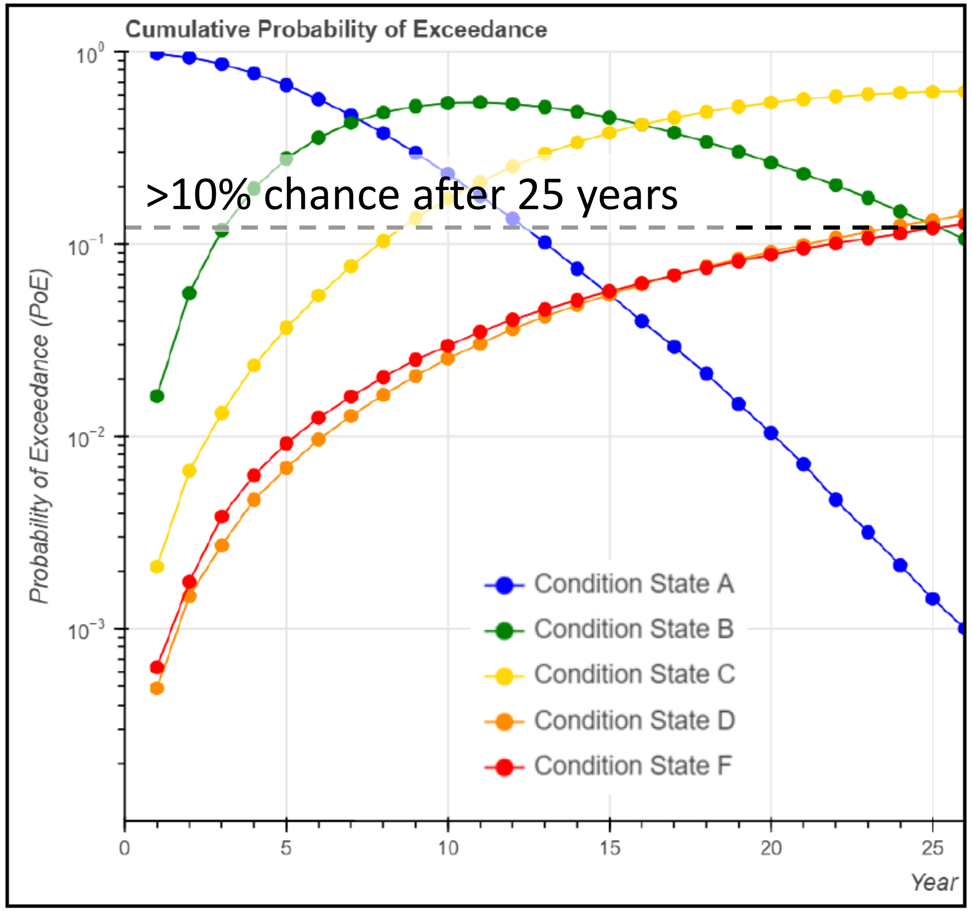


FIGURE 4: PIPELINE CONDITION STATE MODELLING OUTPUTS FOR TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

Lifecycle Cost Models (5) – Purely Reactive

TABLE 3. PIPELINE CONDITION STATES AND TYPICAL ACTIONS AND COSTS FOR LIFECYCLE COST MODELLING

	Condition State	Description	Typical Actions if Condition State is Known	Typical Annual or Event Cost
	A	No definitive evidence of pipe strain	Infrequent visual inspection or aerial patrol	
100 mm	B	Strain well below plastic limit	Visual inspection and IMU	
250 mm	C	Strain approaching plastic limit	Frequent inspections and IMU; detailed investigation; planned strain relief	
750 mm	D	Strain exceeding plastic limit	Pipe shut-in; slope stabilization; emergency strain relief; re-route	
1,500 mm	F	Loss of containment	Service outage; cleanup and repair; emergency strain relief; slope stabilization; re-route	$50M

TABLE 4. LIFECYCLE COST MODELLING ASSUMPTIONS

Item	Assumptions
Pipeline Design Life	25 years
Discount Rate	3%
Initial Pipeline Condition State Displacement Thresholds (mm)	A/B=100 mm; B/C=250 mm; C/D=750 mm; D/F=1,500 mm
Un-planned Outage and Strain Relief/Repair Cost	$5M
Cost of Pipeline Rupture While Operating	$50M
Do Nothing (No Inspection or Monitoring)	No cost realized unless pipe fails (State F)

Lifecycle Cost Models (5) – Purely Reactive

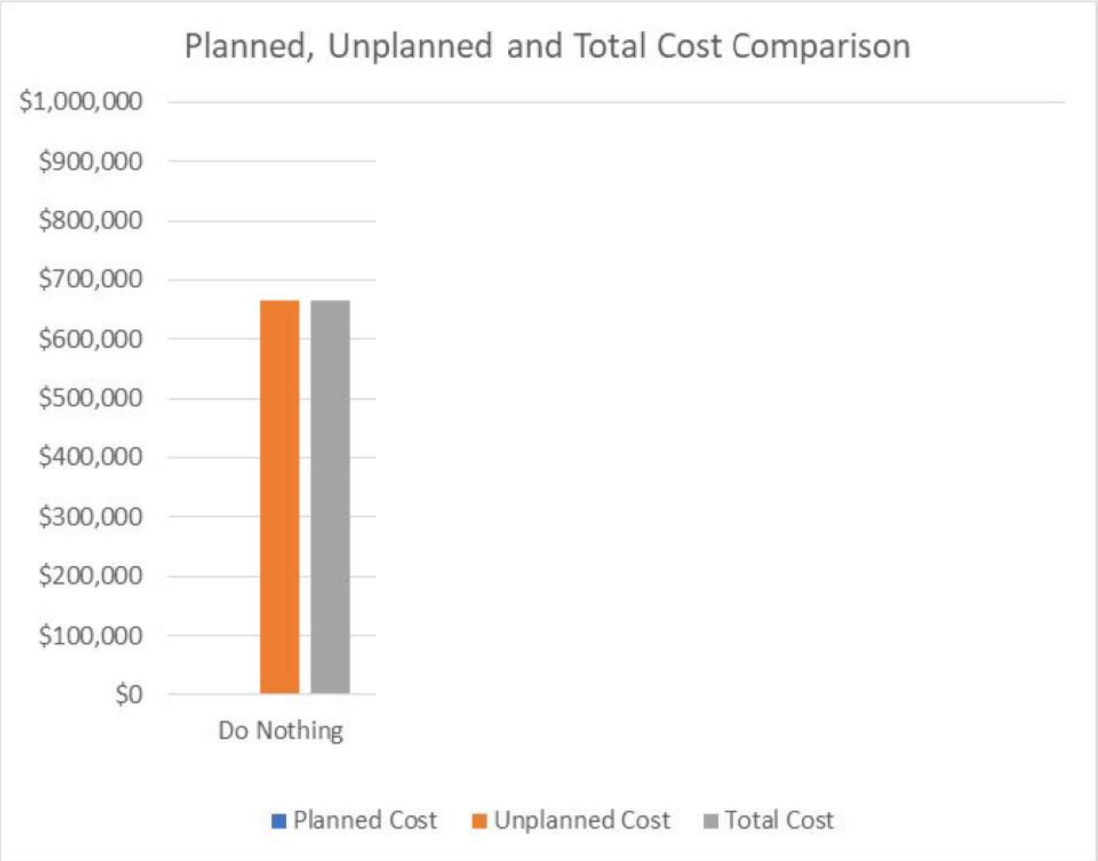


FIGURE 5: ESTIMATED LIFECYCLE COSTS FOR PIPELINE CROSSING TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 5 MM PER YEAR

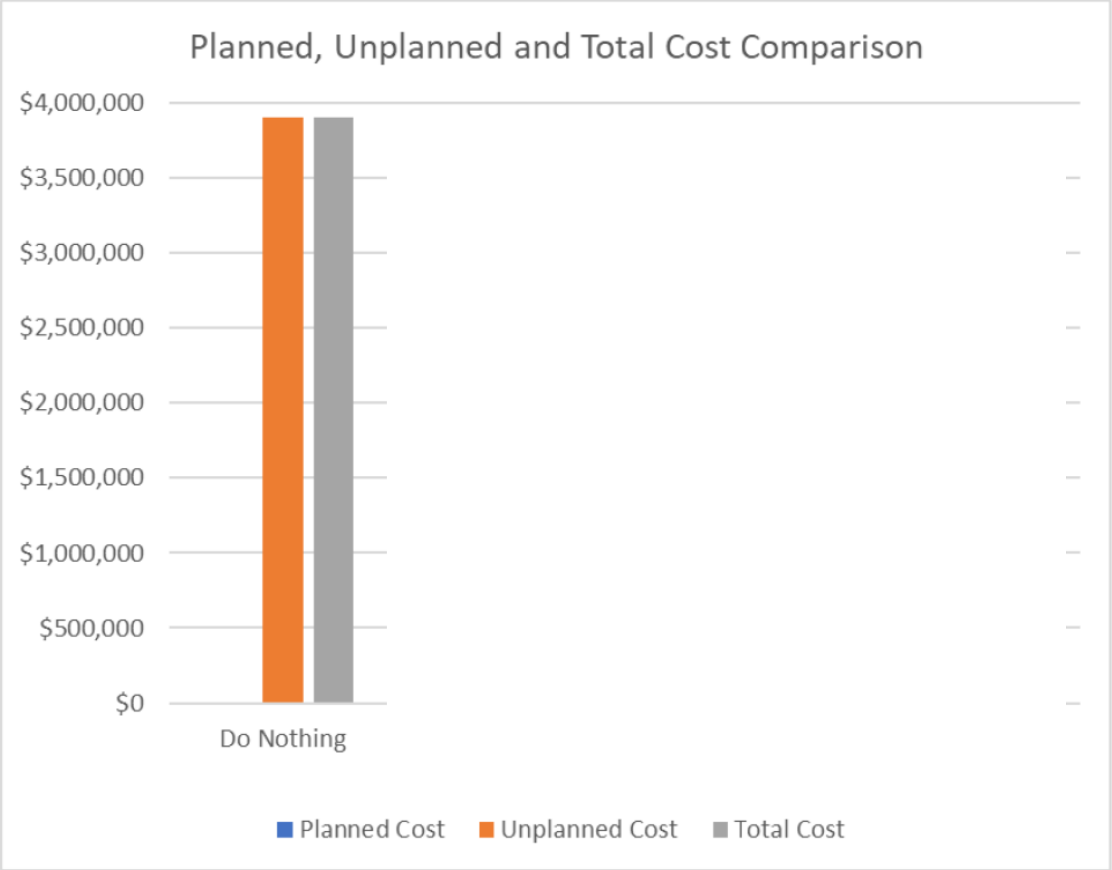


FIGURE 6: ESTIMATED LIFECYCLE COSTS FOR PIPELINE CROSSING TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

Modelling Benefits of Management Approaches

- Management actions will provide opportunity for early detection of change (landslide velocity or pipeline condition state)
  - Some actions will have a higher probability of successful detection than others (e.g. visual inspection v. slope inclinometer)
  - Some actions will lead to earlier or more frequent detection (e.g. slope inclinometer v. real-time SAA)
- Early detection will allow for intervention
  - Slope stabilization (reduce landslide movement rate)
  - Planned or un-planned strain relief (re-set condition state)
  - Shut-in pipeline (reduce rupture impact and cost)
  - Re-locate pipeline (avoid hazard)
- Detection and intervention will take time
  - The shorter the time interval, the lower the likelihood that a deterioration to pipeline condition state D or F will occur
- Simplified modelling approach:
  - increase remaining pipeline displacement capacity as a function of the probability and timing of successful detection and intervention
  - re-set pipeline condition state at regular intervals if known through IMU analysis

Costs and Benefits of Annual Visual Inspections

Inspection Costs

- ~$1,500/yr if part of a larger inspection program
- $5M for un-planned strain relief (State D)
- $50M if rupture occurs (State F)

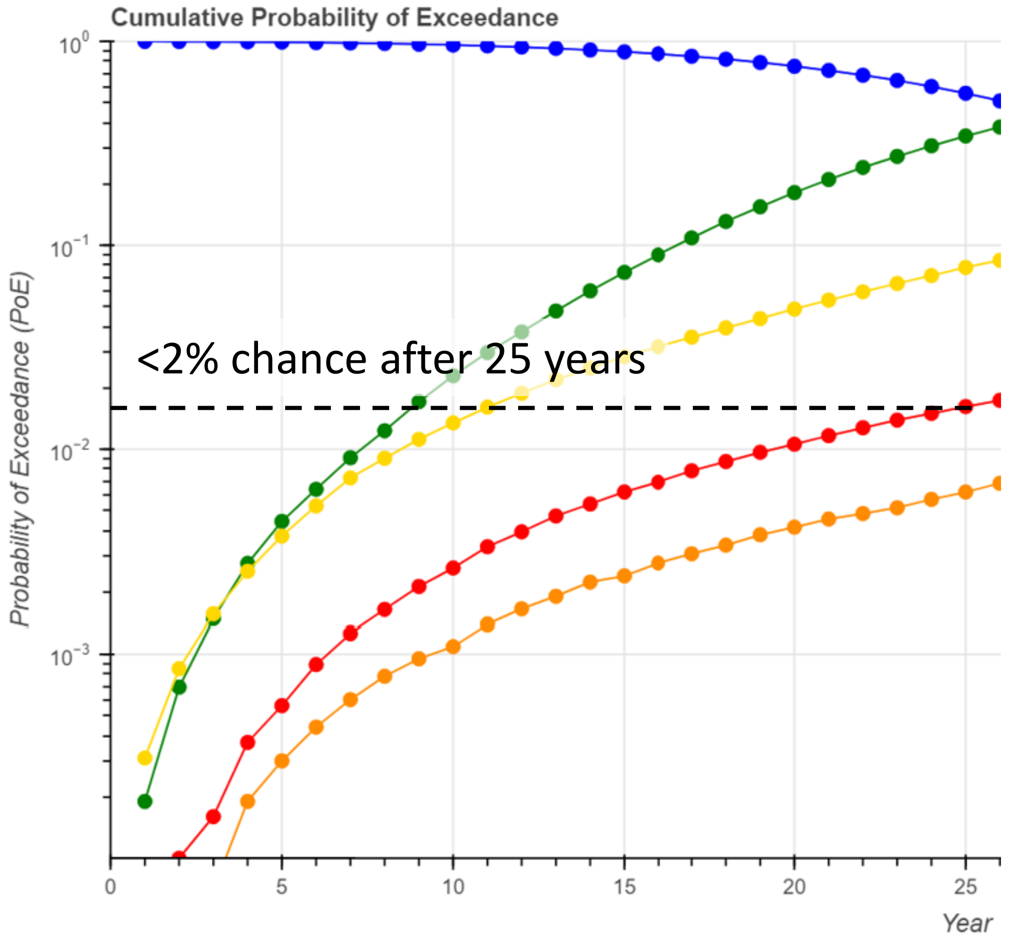
Benefits

- From experience, good success of detecting landslide displacement >50 mm/yr from visual inspection
- Landslide displacement was detected from visual inspection in about 50% of critical strain hits identified from IMU
- Increase landslide displacement required to transition to State D or F by ~50%

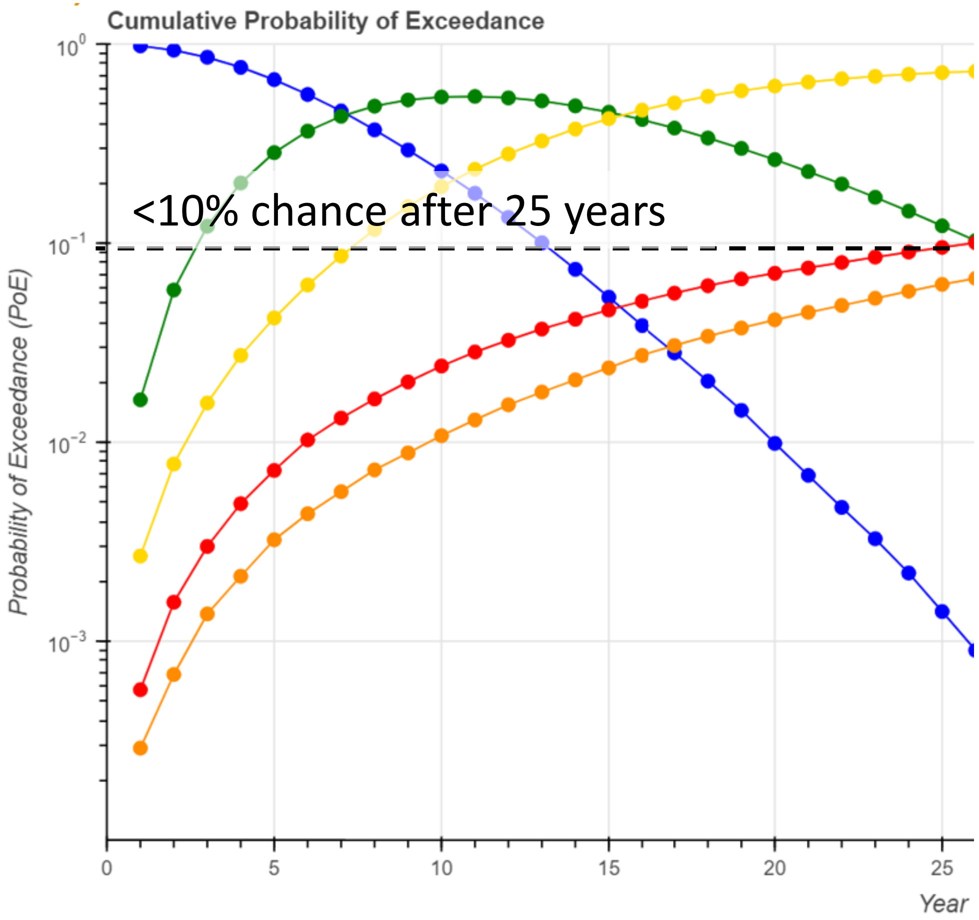
Example: Annual Visual Inspections

From FEA: transition to State B after 100 mm; State C after 250 mm; State D after 1,125 mm; State F after 2,250 mm

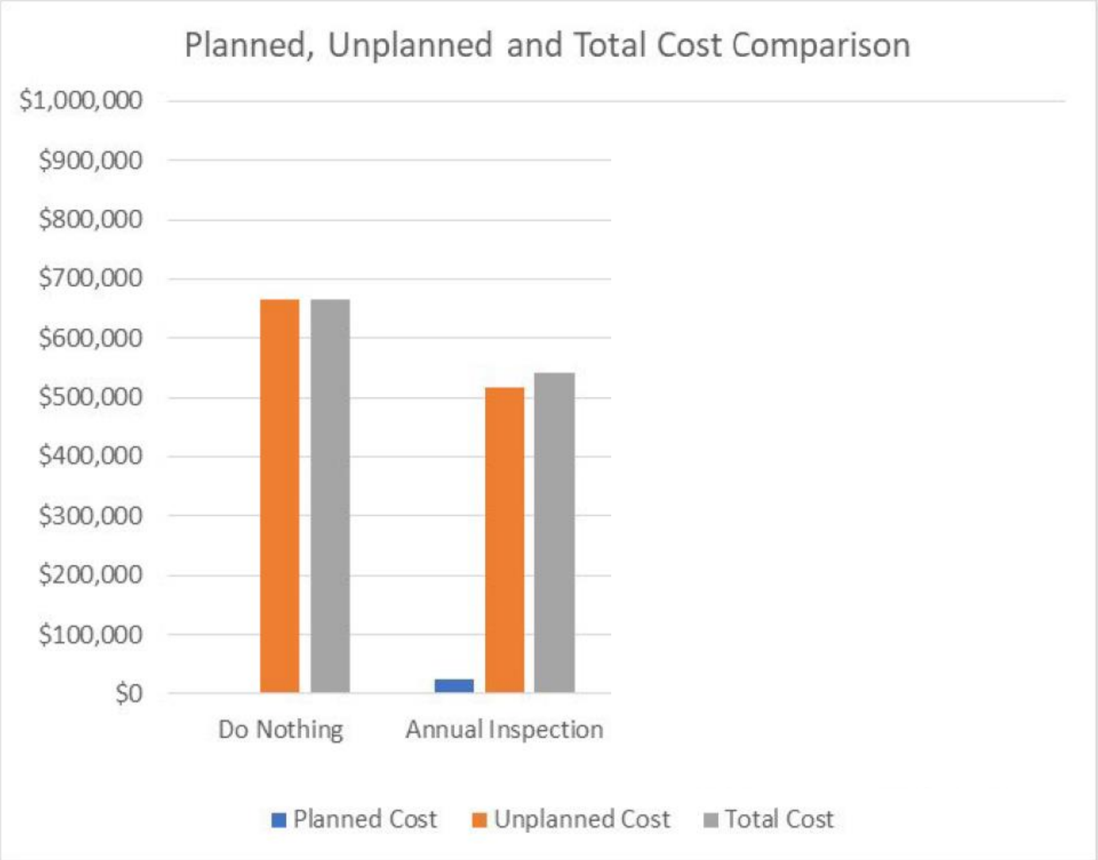
Initial Velocity = 5 mm/yr



Initial Velocity = 25 mm/yr



Lifecycle Cost Models – Annual Inspections



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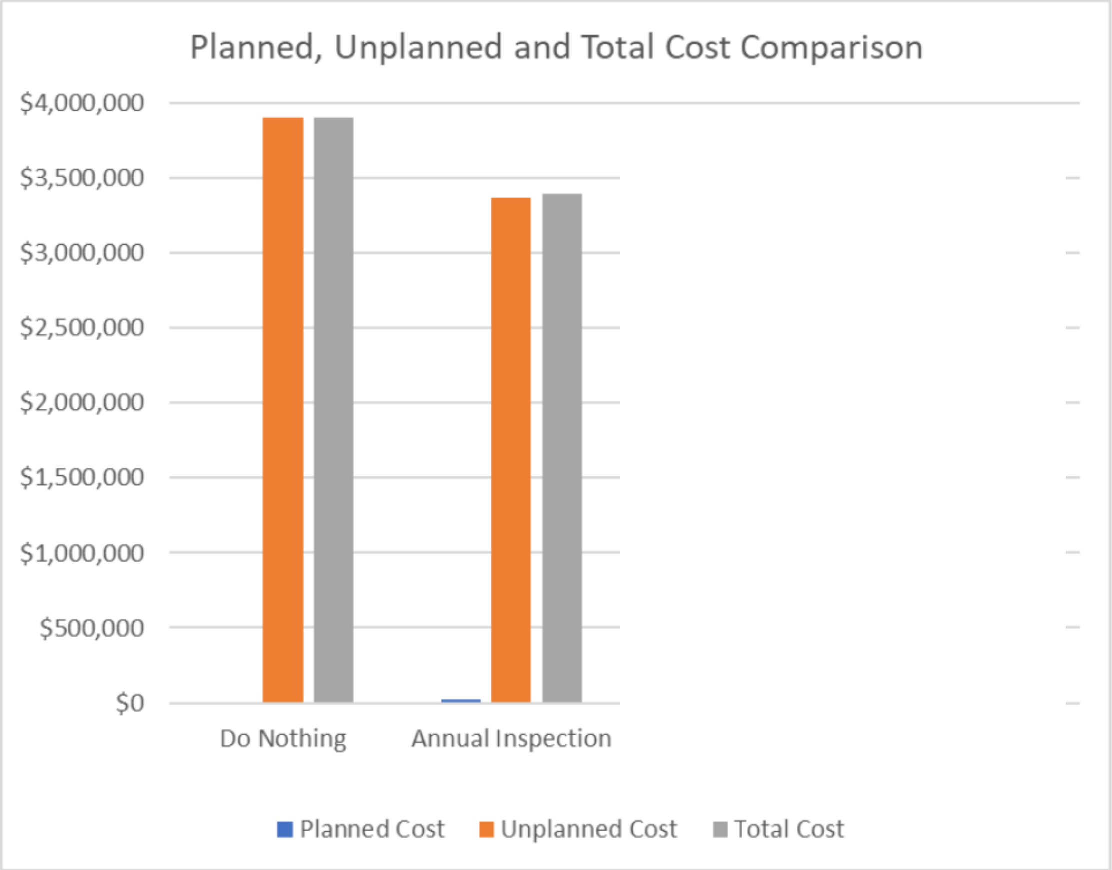


FIGURE 6: ESTIMATED LIFECYCLE COSTS FOR PIPELINE CROSSING TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

Costs and Benefits of Inspections + IMU

IMU Costs

- Assume IMU is already being collected ~every 5 years as part of integrity program
- Cost of detailed geotechnical assessment of IMU ~$10k (~$2k/yr)
- No additional cost if pipe is found to be in State A or B
- Planned strain relief (~$1.5M) in State C

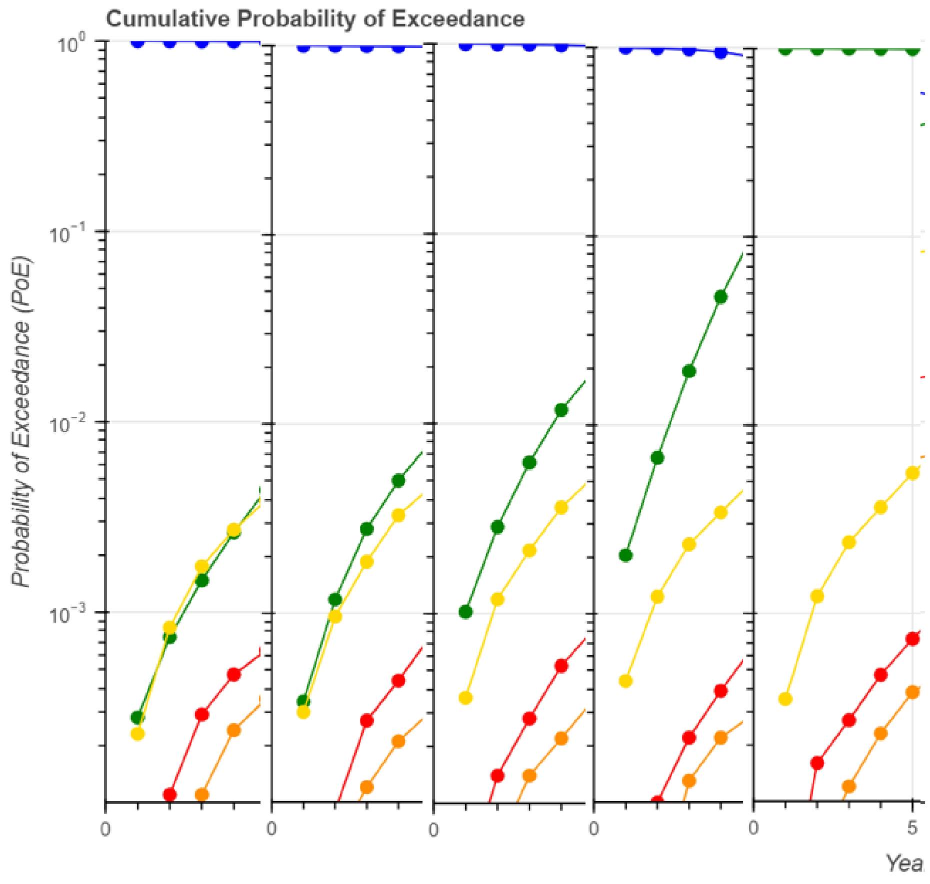
IMU Benefits

- Re-set worst pipeline condition state to State C every 5 years

Inspections + IMU

From FEA: transition to State B after 100 mm; State C after 250 mm; State D after 1,125 mm; State F after 2,250 mm

Initial Velocity = 5 mm/yr



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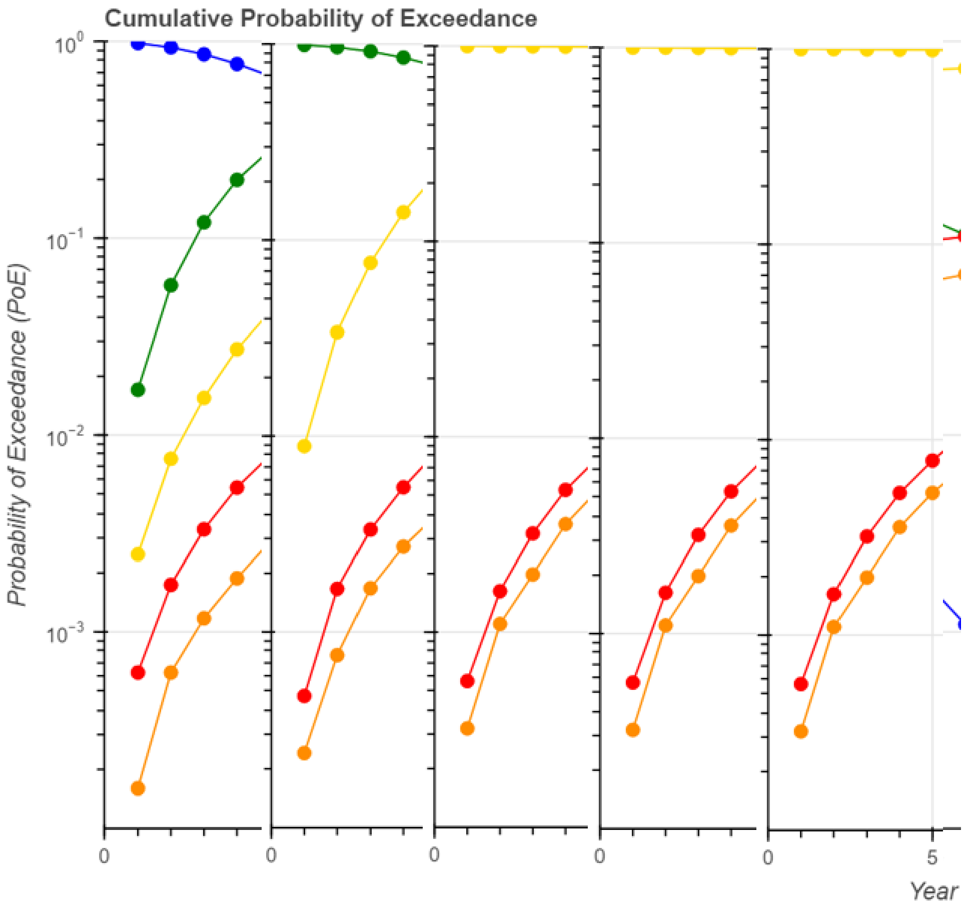
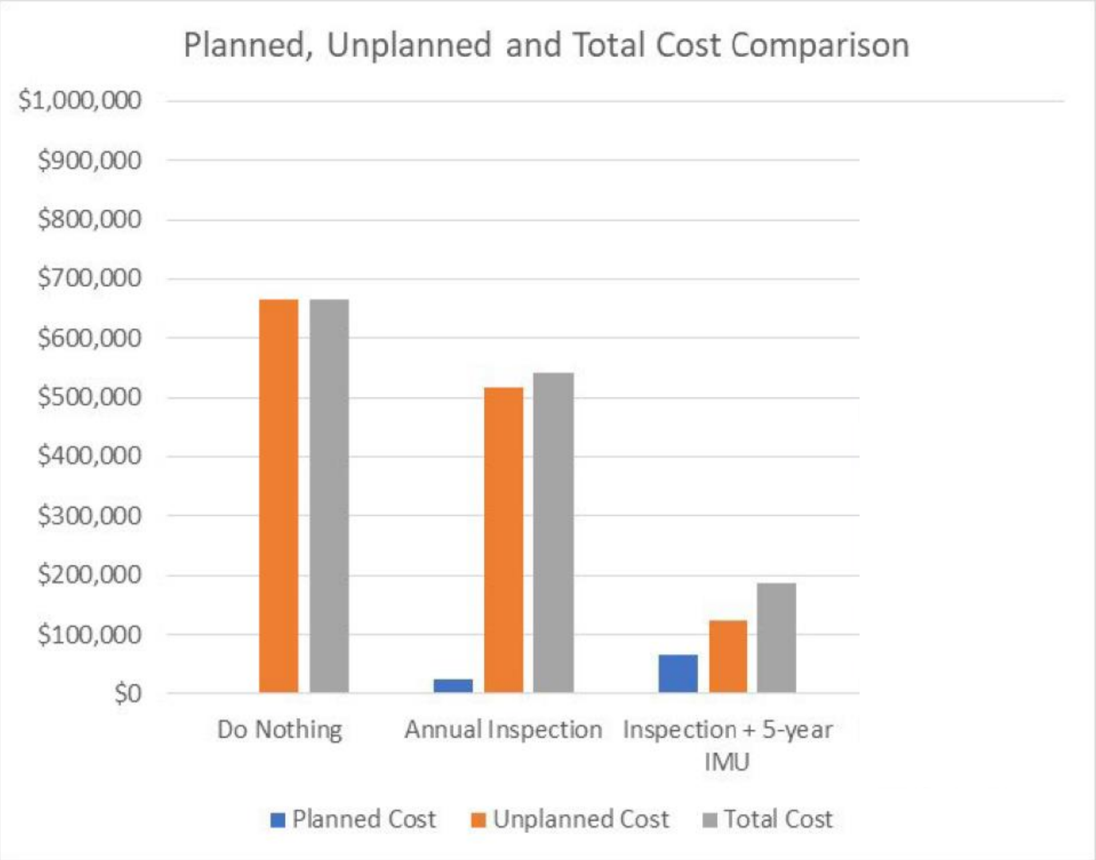


Inspections + IMU



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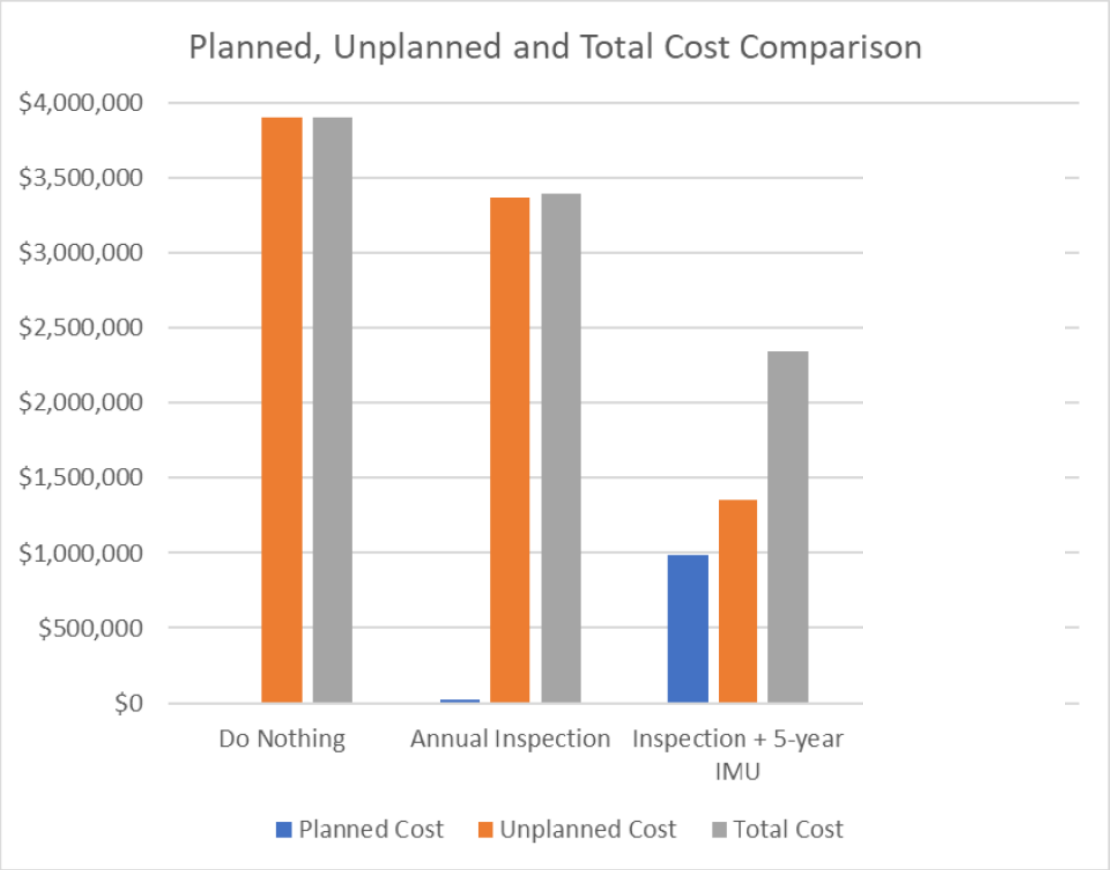

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Costs and Benefits of Inspections + IMU + Real-time Monitoring

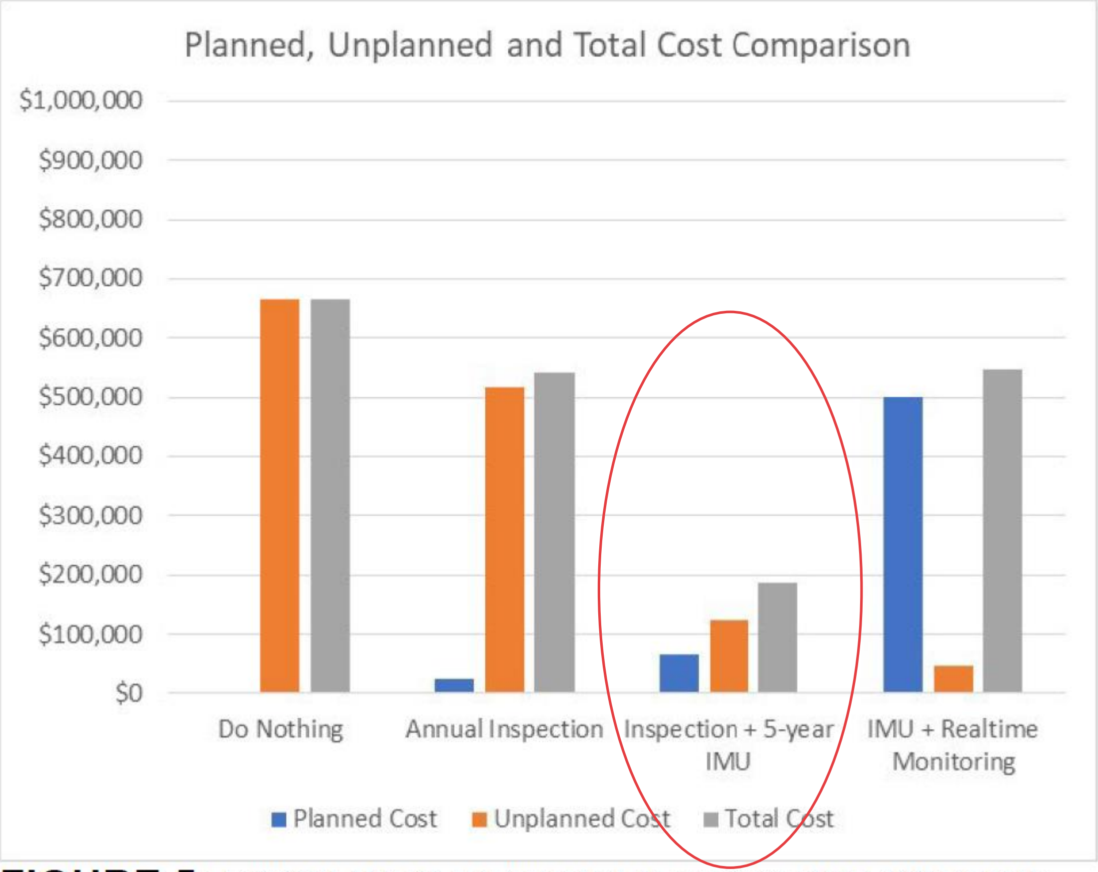
Real-time Monitoring Costs

- ~$25,000/yr

Real-time Monitoring Benefits

- High likelihood of successful detection and response within a 3-month period (1/4 year)
- Increase landslide displacement required to transition to State D or F by a factor of 4

Inspections + IMU + Real-time Monitoring



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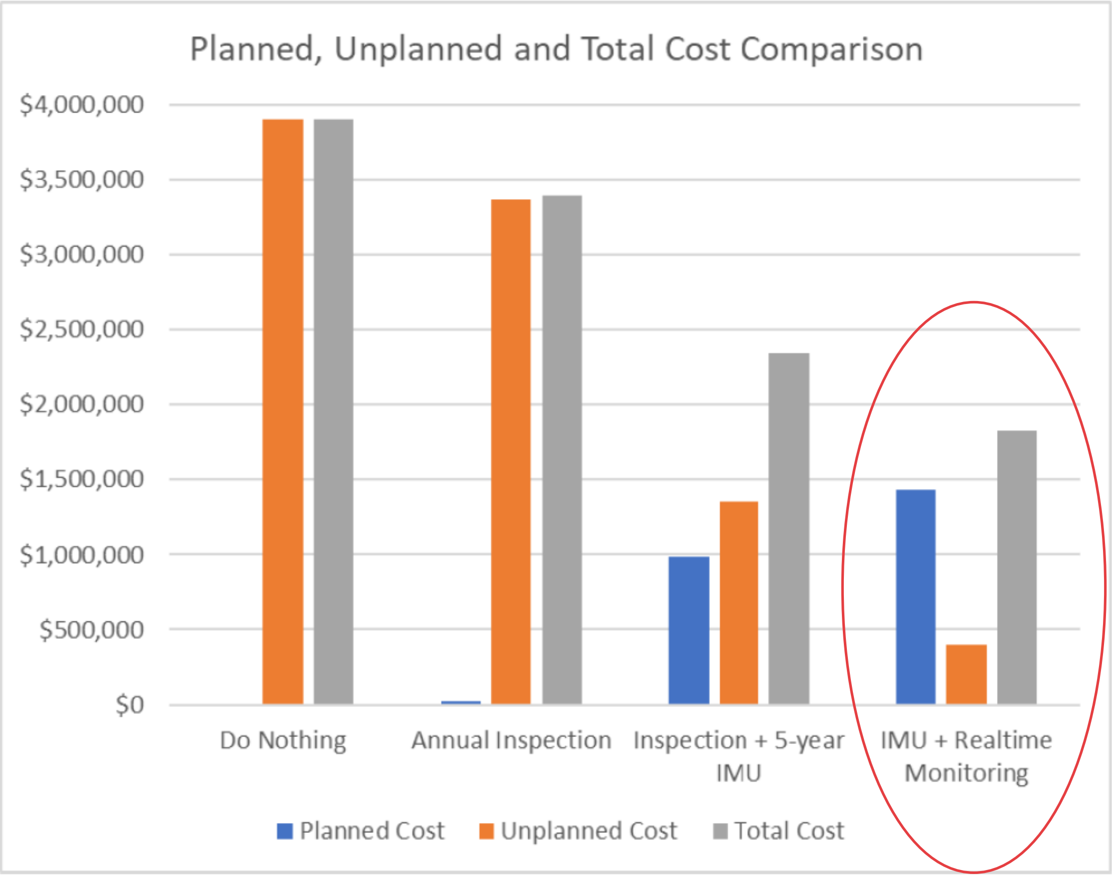

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Thank You!