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RISK ASSESSMENT AND COST BENEFIT ANALYSIS FOR PIPELINES BURIED IN SLOW-MOVING LANDSLIDES

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ABSTRACT

The annual risk of failure of a pipeline buried in a slow-moving landslide can be thought of as the product of the probability that landslide displacements within the next 12 months will exceed the capacity of the pipeline, and the associated consequence of pipeline failure. The current landslide displacement capacity of the pipeline will be subject to uncertainty, but can be estimated through interpretation of landslide morphology, inertial measurement unit (IMU) bending strain analysis, consideration of axial strain loading, and finite element analysis (FEA). A Markov Chain and Monte Carlo Simulation analysis can provide probability distributions of annual landslide displacements and estimates of the probability that displacements will exceed the pipeline capacity. Without intervention, the probability (and risk) of failure will increase with time as pipeline displacement capacity is used up and as uncertainties about future landslide movements grow. But with estimates of annualized time-dependent risk, the lifecycle cost of different management options such as monitoring and warning, landslide stabilization, and pipeline re-route, can be calculated to support risk-informed decision making. This paper outlines a procedure for estimating damage and failure probability and risk over the pipeline design life under a range of possible management options, and the analysis of the expected cost and benefit of each option.

Keywords: Landslide, Risk, Markov Chain, Monte Carlo Simulation, Cost benefit analysis, Lifecycle cost

1. INTRODUCTION

Consider, for example, two identical pipelines buried in two similar landslides, one of which is moving at 5 mm/yr and the other which is moving at 25 mm/yr. All else being equal, the faster-moving landslide will cause a more rapid reduction in the pipeline's remaining capacity for landslide displacement, has a greater probability of transitioning to even faster movement rates, and will pose a greater probability of service outage or failure than the slower-moving landslide. The differences in the uncertainties and risks can be quite significant when considering lifecycle costs over a long timeframe, such as a 25-year design life, for example.

In 2022, the authors (Porter, Van Hove and Barlow) outlined a methodology to quantify the probability of failure for pipelines crossing slow-moving landslides [1]. They described an approach to predict landslide velocity and displacement using Markov Chains that combined geomorphic evidence of long-term landslide behavior with current estimates or measurements of landslide velocity. A framework was proposed to combine time-dependent estimates of landslide displacement and the deterioration of pipeline strain capacity to estimate the changing probability of pipeline failure over time and in response to potential changes in landslide velocity. The approach involved the following components: establishing a landslide velocity classification system; establishing an approach to assign landslide velocity class probability distributions over a period of decades using Markov Chains; completing engineering assessments to establish remaining pipeline capacity to accommodate additional landslide displacement; and use of Monte Carlo Simulation to estimate the annual probabilities of the remaining pipeline capacity being exceeded using outputs from the Markov models. Similar models have been proposed to evaluate strain demand versus pipeline capacity [e.g., 2] but they focus more on the uncertainty associated with the capacity side of the equation than on rational approaches to predict landslide behavior and strain demand.

The approach presented in [1] is reviewed briefly here but the reader should consult the original reference for additional detail. This paper presents several important updates and advancements in the methodology and its applications. These include: updates to common landslide behavior types and characteristics; guidance on estimating current remaining landslide displacement capacity; definition of pipeline condition states associated with expected management actions and costs; improvements to the Monte Carlo Simulation process realized by transitioning from spreadsheet models to Python code; improved quantification of the benefits of inspection and monitoring; and improved procedures for using model outputs in cost benefit analysis and lifecycle cost modelling.

2. LANDSLIDE VELOCITY CLASSIFICATION

A landslide velocity classification system is presented in Table 1. It is modified from Cruden and Varnes [3] who proposed the qualitative descriptions and typical values presented in the second and third column of Table 1. Modifications include: assignment of velocity classes that can be treated as condition states in the Markov models that follow (the first column); subdivision of the Very Slow velocity class; assignment of total annual displacements associated with each velocity class (the fourth column); and, assignment of a left-triangular probability density function to each velocity class which yields the mean displacement values shown in the fifth column. For the purposes of Markov Chain modelling of velocity class distributions, all velocity classes Moderate and greater have been combined into Class 4+. The reasons for the proposed modifications are described in [1].

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

2.1 Intended Application of Models

The work presented here is heavily influenced by the authors' experience with normally slow-moving landslides in clay overburden and mudstones and shale that are encountered in many regions throughout the world. Common landslide mechanisms include deep-seated compound or translational slides along weak bedding planes in shale and glaciolacustrine clay, rotational slides in till and glaciolacustrine sediments, and earth flows of variable thickness in colluvium and residual soil. Most of these landslides normally move at rates ranging from Extremely Slow to Slow according to the velocity classification shown in the second and third columns in Table 1. Rapid to Extremely Rapid slides and flows are less common in these geological conditions but can initiate in till, normally and over-consolidated glaciolacustrine sediments and colluvium, and along over-steepened slopes where a cap of stronger rock overlies weaker shale [4]. First time slides, retrogression events and the formation of active wedges can result in Rapid to Very Rapid movements which may only persist for a few hours or days [5] [6] before these types of events transition back to Slow or Very Slow movement rates.

3. A MARKOV CHAIN APPROACH TO ESTIMATING ANNUAL LANDSLIDE VELOCITY CLASS PROBABILITIES

3.1 Condition States and State Transition Probabilities

The Markov process is a probabilistic model useful in analyzing complex systems [7]. In these models, the condition of a physical system can be described by a number of state variables. For the physical system comprising a landslide, velocity (or annual displacement) can be treated as a state variable and the velocity classes listed in Table 1 treated as condition states.

In the course of time a system passes from state to state and thus exhibits dynamic behavior. For a landslide, factors such as changes in shear strength, porewater pressure or landslide geometry can cause a change in velocity. Velocity is a continuous variable that can change at any time, but in a simplified Markov model changes in velocity can be treated as transitions occurring at discrete timesteps (years) and between a finite number of velocity classes defined in terms of expected annual landslide displacement (Table 1).

The probabilities of transitioning between velocity classes (or remaining in the current class) are described by transition probabilities encapsulated in a transition matrix. The Year 1 velocity class probability distribution for a landslide can be estimated by multiplying the initial (Year 0) landslide velocity class state vector (i.e., the probabilities of being in the different landslide velocity classes at Year 0, ($\pi(0)$), by the transition matrix (P) for the applicable landslide behavior type.

The initial state vector can be thought of as either a probabilistic estimate of the current landslide velocity (when that velocity is uncertain) or as a means of specifying a precise current velocity when it is known. For example, with reference to the mean annual displacements shown in the fifth column of Table 1, the initial state vector [0, 0.67, 0.33, 0, 0, 0] yields an initial velocity of 25 mm/yr.

The state probability vector for any year can be calculated by post-multiplying the state probability vector at the preceding timestep by the transition matrix, or alternatively, the nth state probability vector can be calculated by post-multiplying the initial state vector by the transition matrix raised to the nth power [7]:

$$\pi(n+1) = \pi(n)P \quad (1)$$

$$\pi(n) = \pi(0)P^n \quad (2)$$

The changing values of the state vector (the distribution of condition state probabilities) calculated for various timesteps following an observation of the process reflect a changing state of knowledge in the absence of observation [7]. A characteristic of these types of Markov models is that after many timesteps without observation, knowledge of the state of the system diminishes to a constant value referred to as the limiting state probability vector, irrespective of the value of the initial state vector. In the case of landslide velocity, the limiting state probability vector can be thought of as the distribution of velocity classes that might be realized over a very long period of observation (i.e., thousands of years). Alternatively, if one was able to observe the distribution of velocity classes from a large inventory of landslides of a certain type and within a certain geography over a period of a few decades, for example, that distribution also ought to resemble the limiting state probability vector for that type of landslide operating in that type of environment. The authors made use of this limiting state behavior to develop conceptual Markov models for a range of landslide behavior types.

3.2 Landslide Behavior Types

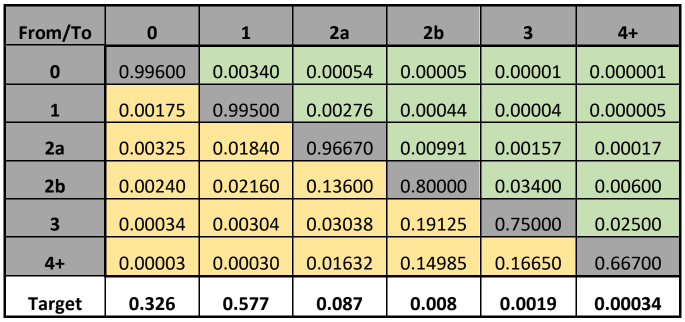
Markov models (transition matrices) have been developed for five landslide behavior types to help estimate velocity class transition probabilities for a range of normally slow-moving landslide types often encountered in practice. The five proposed landslide behavior types and their typical characteristics are shown in Table 2.

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

The Markov models for each landslide behavior type have been 'tuned' to yield specified long-term average outputs including velocity class distributions and mean annual displacements which can be used by a landslide practitioner to help guide the assignment of an appropriate behavior type to each landslide of interest. The underlying premise is that if the models yield appropriate long-term average velocity class distributions and displacements, they might also generate useful insight to potential near-term conditions (over periods of years to decades) which will tend to be of interest to pipe integrity managers and other decision makers. Transition matrices have been developed for each behavior type, and an example of the matrix developed for Type C landslides is shown in Figure 1.

The models developed for each proposed landslide behavior type incorporate several important assumptions that have tentatively been assigned based on literature review (e.g., [8]), our experience and judgment, and supported by trial and error. They continue to be tested and will be improved upon as more data for model calibration become available. New models will be added if different behavior types are encountered.



From/To	0	1	2a	2b	3	4+
0	0.99600	0.00340	0.00054	0.00005	0.00001	0.000001
1	0.00175	0.99500	0.00276	0.00044	0.00004	0.000005
2a	0.00325	0.01840	0.96670	0.00991	0.00157	0.00017
2b	0.00240	0.02160	0.13600	0.80000	0.03400	0.00600
3	0.00034	0.00304	0.03038	0.19125	0.75000	0.02500
4+	0.00003	0.00030	0.01632	0.14985	0.16650	0.66700
Target	**0.326**	**0.577**	**0.087**	**0.008**	**0.0019**	**0.00034**

FIGURE 1: VELOCITY CLASS TRANSITION MATRIX FOR LANDSLIDE BEHAVIOUR TYPE C AND TARGET LIMITING STATE VECTOR.

3.3 Annual Landslide Velocity Class Probabilities

Landslide velocity class probability distributions can be calculated for any model timestep using Eq. 1 or 2. For example, the first five years of model outputs using the transition matrix for Type C Landslides (Figure 1) and an initial state vector equivalent to 25 mm/yr (as per above) yields the landslide velocity class probability distributions shown in Figure 2.

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

The Markov model state vectors at each timestep can be used to estimate a mean annual displacement each year by multiplying the velocity class probability distribution by the mean displacement associated with each velocity class show in the fifth column of Table 1. However, what is usually of greater interest is the probability of exceeding specific landslide displacement criteria, such as the assessed remaining pipeline capacity determined from a multi-disciplinary engineering assessment.

4. PIPELINE CONDITION STATES AND REMAINING LANDSLIDE DISPLACEMENT CAPACITY

4.1 Pipeline Condition States

A pipeline buried in a slow-moving landslide can exist in several possible condition states which can be related to expected management actions and costs (e.g., Table 3).

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 critical strain threshold	Visual inspection and infrequent IMU survey and bending strain review	$1k to $10k/yr
C	Strain approaching critical strain threshold	Frequent inspections and IMU; detailed investigations; planned strain relief	$10k to $1M/yr
D	Strain exceeding critical strain threshold	Pipe shut-in; slope stabilization; emergency strain relief or cutout/repair; 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)

The typical condition state actions and costs reported in Table 3 are based on the authors' experience with geohazard management on approximately 450,000 km of pipeline across North and South America over the past decade.

If the pipeline and landslide are not being monitored, the operator might not realize any cost associated with any of the condition states until a failure occurs (State F). Failure will result in an event-based cost that we assume, for practical considerations, will be realized no more than once over the pipeline design life. If the pipeline and landslide are being monitored, annualized costs will be realized at the earlier condition states, and activities such as strain relief are likely to be planned in advance and executed at lower cost. Additionally, the likelihood of more expensive event-based costs such as for an unplanned outage and strain relief (that we assume would be triggered at State D) or failure (State F) will be reduced. A program of proactive monitoring and response will improve safety and, in most instances, result in lower lifecycle costs.

4.2 Remaining Pipeline Displacement Capacity

To establish the condition state for a pipeline and the remaining displacement capacity before transitioning into the other more adverse condition states, it is necessary to first estimate the current strain state of the pipeline and then to estimate the additional slope displacement that would be required to exceed critical tensile or compressive strain limits. The inertial measurement unit (IMU) tool provides an accurate measure of the bending strains along the pipeline, but the longitudinal strains generated by a combination of factors, including the component of ground movement parallel to the pipeline axis are not measured by the tool. For the large, slowly moving landslides that are the subject of this paper, it is often necessary to conduct a Finite Element Analysis (FEA) [9] to estimate the longitudinal component of strain to evaluate both the current total axial strain in the pipeline and the tolerance for further movement. The soil tractions that the moving ground exert on the pipeline as the slide moves are modelled in an FEA to produce a relationship between ground movement and pipeline strain (bending, longitudinal and total axial strain) that progressively grows with continued landslide displacement.

5. PIPELINE CONDITION STATE MODELLING

5.1 Probability of Displacement Criteria Exceedances

The probabilities of exceeding specific landslide displacement criteria can be determined through Monte Carlo Simulation. Monte Carlo Simulation involves completing thousands of trials that sample the velocity class probability distribution from each Markov Chain model timestep. In each trial, a random number is used to select a velocity class from the probability distribution for that timestep, and an additional random number is used to select a specific displacement from the selected velocity class range using the left-triangular probability density function. For each trial the cumulative displacement is calculated to estimate the total amount of landslide displacement that may be impacting the pipeline. In this way the calculated cumulative landslide displacements for each timestep account for any reduction in pipeline capacity from displacement in prior years.

The final step in this process is to count the number of trials for which the simulated cumulative landslide displacement exceeds the different condition state thresholds. The total number of exceedances is then divided by the total number of trials to obtain estimates of the probabilities of being in each of the different condition states at the end of each year.

5.2 Condition State Modelling Examples

To illustrate the pipeline condition state modelling approach and outputs a hypothetical scenario is used involving a new NPS12 transmission line that obliquely crosses two similar Behavior Type C landslides for a length of 300 m. The first landslide is assumed to be currently moving at 5 mm/yr at the depth of the pipeline, while the second is moving at 25 mm/yr. At both landslides, subsurface investigations, FEA and experience and judgment have determined that up to 10 cm of landslide displacement might be accommodated before evidence of pipe strain is observed (the transition from Condition State A to B). The transition from Condition State B to C is expected to occur if the landslide moves 25 cm, the transition from Condition State C to D is expected to occur if the landslide moves 75 cm, and pipeline failure (Condition State F) is expected to occur if the landside moves 1.5 m. The Markov Chain and Monte Carlo Simulation results for these scenarios are illustrated in Figure 3 and 4.

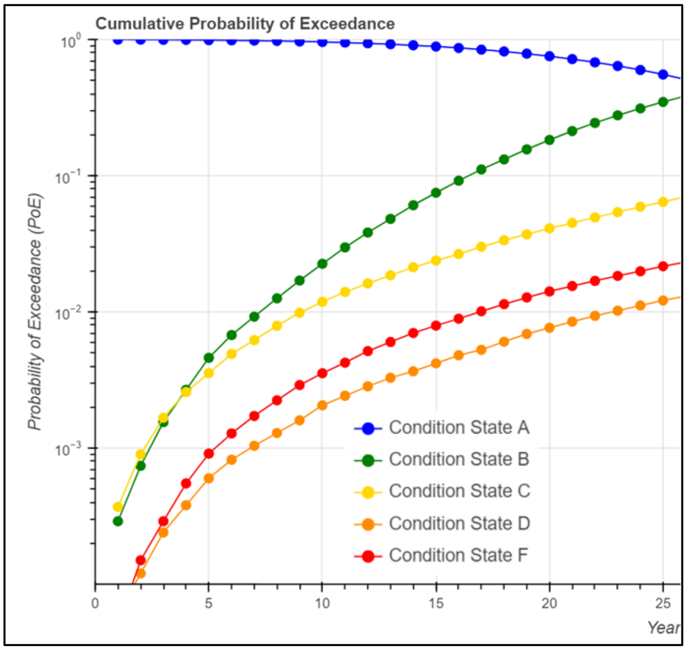


FIGURE 3: PIPELINE CONDITION STATE MODELLING OUTPUTS FOR TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 5 MM PER YEAR

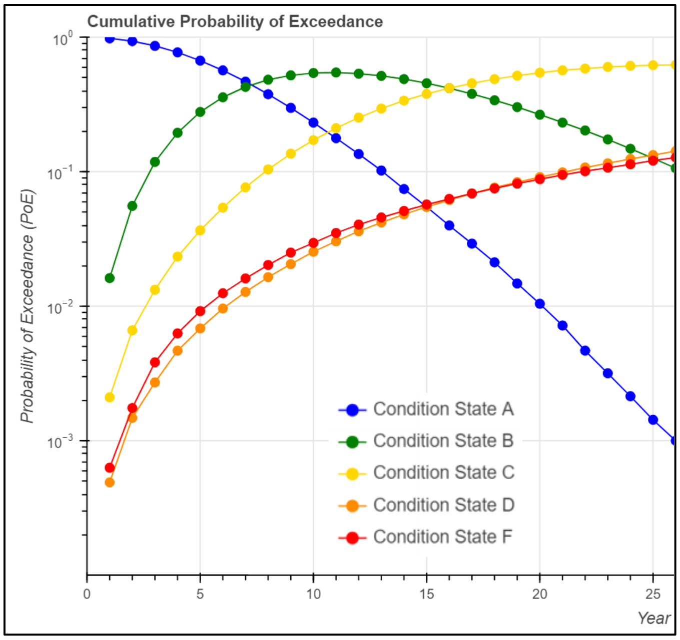


FIGURE 4: PIPELINE CONDITION STATE MODELLING OUTPUTS FOR TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

In the examples above, the pipeline is expected to remain in Condition State A over a period of 25 years where it crosses the landslide moving at 5 mm/yr (Figure 3), while Condition State B becomes the most likely condition state at Year 7 where it crosses the landslide moving at 25 mm/yr (Figure 4). At Year 25, the probabilities of the pipeline having transitioned to Condition State F (failure) are approximately 0.02 for the landslide moving at 5 mm/yr and slightly greater than 0.1 for the landslide moving at 25 mm/yr. In either case, the assumption is that the operator has no monitoring and response plan in place, and no effort is undertaken to prevent pipeline failure. While this is an unrealistic assumption, it provides a base case that other risk management options can be compared against. The potential costs and benefits of different risk management options are compared in the section that follows.

6. LIFECYCLE COST MODELLING OF MANAGEMENT OPTIONS

The landslide displacement and pipeline condition state modelling approach outlined above creates opportunities to inform risk management decisions where the dynamic nature of landslide risk is an important consideration.

Landslide risk and risk management costs come in different forms. Proactive management costs include visual ground inspection, regular review of lidar change detection, interferometric synthetic aperture radar (InSAR), inertial measurement unit (IMU) in-line inspection tool data and geotechnical instrumentation, near-real time instrumentation and weather monitoring, or combinations of the above activities. These provide opportunities for early intervention to maintain or improve the pipeline condition state through landslide stabilization or planned pipeline strain relief. In some instances, a decision might be made to avoid the landslide hazard by re-routing the pipeline or installing it beneath the landslide using horizontal directional drilling (HDD) or other trenchless methods. Other costs tend to be unplanned and reactive, including the costs of emergency pipeline shut-ins, unplanned strain relief activities, cut-outs, or pipeline ruptures. All scenarios involve the trade-off of accepting higher planned, proactive management costs in order to reduce expected but unplanned, reactive costs.

Once a slow-moving landslide can be characterized in terms of its behavior type (Table 2) and initial velocity (Section 3.1), probabilities can be assigned to landslide displacements in future years. If an assessment of pipeline fragility to landslide displacement has been completed (Section 4.2), the probability of experiencing different condition states (Table 3, Section 5) can also be estimated (Figures 3 and 4). This is useful for lifecycle cost planning and cost-benefit analysis of different management options because it allows the operator to estimate the likelihood and timing of incurring different costs.

The optimal risk management strategy will depend on the cost of the available management options, the impact each option has on the probability of transitioning to the more adverse pipeline condition states, and the costs associated with being in each pipeline condition state. Once costs and probabilities of experiencing those costs can be estimated they can be forecast over the life of the pipeline and compared in terms of present value (PV).

6.1 Lifecycle Cost Modelling Examples

To help illustrate the process, Table 4 presents lifecycle cost modelling assumptions for different risk management scenarios for the hypothetical landslide crossings introduced in Section 5.

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)
Annual Visual Inspection	\$1,500 per year for inspections; increase C/D and D/F landslide displacement capacity by 50%
Annual Visual Inspection + 5-yr IMU	Additional \$2,000/yr (\$10,000 every 5 years) for bending strain analysis + pro-rated cost for planned strain relief; model re-set every 5 years
Annual Visual Inspection + 5-yr IMU + Real-time Monitoring	Additional \$25,000/yr for real-time monitoring program; increase C/D and D/F landslide displacement capacity by 400% (assume detection and response possible within 3 months)

The assumptions presented in Table 4 were used to model pipeline condition states and generate annual cash flows for each management scenario. Cash flows included planned (proactive) management and maintenance costs that would likely be incurred while the pipeline is in Condition State A, B or C, and unplanned (reactive) event-based costs that would likely be incurred if the pipeline transitioned into Condition State D (unplanned outage and strain relief) or State F (rupture).

Results of the lifecycle cost modelling using the assumptions presented in Table 4 for the pipeline crossings of landslides moving at 5 and 25 mm/yr are shown in Table 5, and in Figure 5 and 6, respectively. The modelling approaches and insights that can be gleaned from the results are elaborated on in the sections that follow.

TABLE 5. PRESENT VALUE (PV) LIFECYCLE COST ESTIMATES

Scenario	5 mm/yr	25 mm/yr
Do Nothing	Total PV = \$670k Planned Maintenance PV = \$0k 2% chance of State F by Year 25	Total PV = \$3.91M Planned Maintenance PV = \$0k >10% chance of State F by Year 25
Annual Visual Inspection	Total PV = \$540k Planned Maintenance PV = \$25k <2% chance of State F by Year 25	Total PV = \$3.39M Planned Maintenance PV = \$25k <10% chance of State F by Year 25
Annual Visual Inspection + 5-yr IMU	Total PV = \$190k Planned Maintenance PV = \$65k <0.1% chance of State F by Year 25	Total PV = \$2.34M Planned Maintenance PV = \$990k <1% chance of State F by Year 25
Annual Visual Inspection + 5-yr IMU + Real-time Monitoring	Total PV = \$550k Planned Maintenance PV = \$500k <0.03% chance of State F by Year 25	Total PV = \$1.83M Planned Maintenance PV = \$1.43M <0.3% chance of State F by Year 25

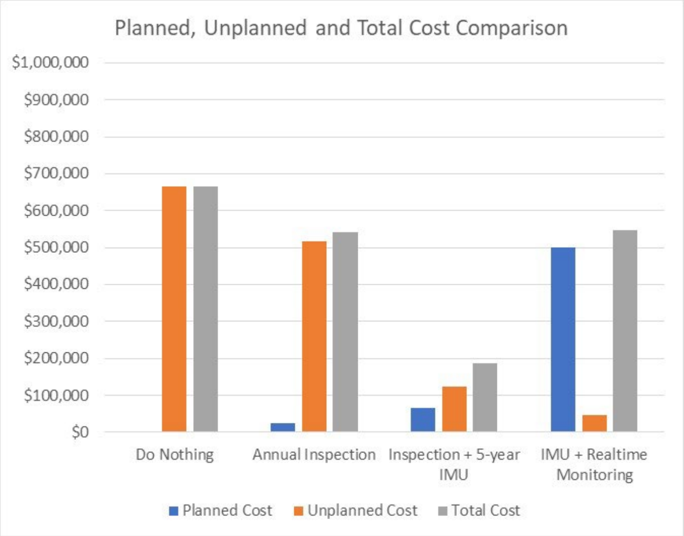


FIGURE 5: ESTIMATED LIFECYCLE COSTS FOR PIPELINE CROSSING TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 5 MM PER YEAR

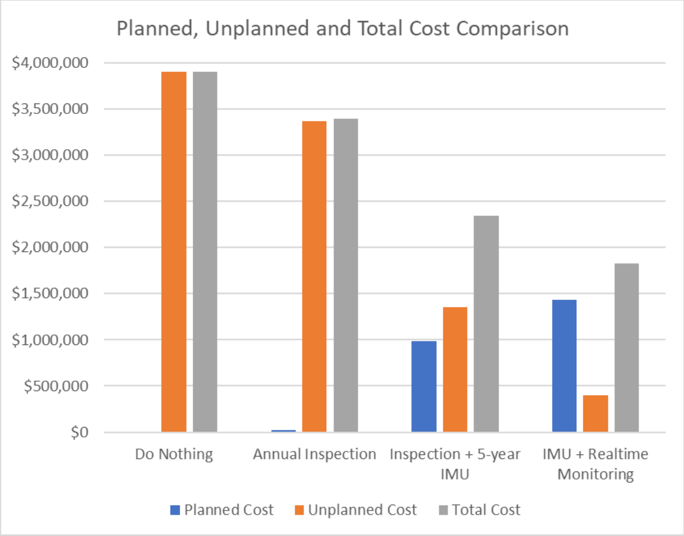


FIGURE 6: ESTIMATED LIFECYCLE COSTS FOR PIPELINE CROSSING TYPE C LANDSLIDE WITH AN INITIAL VELOCITY OF 25 MM PER YEAR

6.2 Do Nothing Option

Present Values of lifecycle costs for the Do Nothing management option range from approximately $670k to $3.9M for crossings of the landslides initially moving at 5 mm/yr and 25 mm/yr, respectively. In this scenario, it is assumed that because no observation of pipeline condition state is available, the pipeline operator will incur no planned or unplanned costs unless the pipeline ruptures. The cash flow model is based on the annual probability of transitioning into pipeline Condition State F, extracted from the modelling results presented in Figures 3 and 4, and assuming the cost of a rupture is approximately $50M. It is also assumed that no more than 1 pipeline rupture would be allowed to occur over the 25-year pipeline operating life.

While the Do Nothing management option is an unrealistic option that few operators would intentionally choose to adopt, it provides a basis to compare the costs and benefits of other options.

6.3 Annual Visual Inspection Option

Visual ground inspections can often detect changes in landslide activity and movement rate, creating the opportunity to trigger more detailed investigation or intervention. Possible early detection and intervention reduce (but do not eliminate) the probability of transitioning to pipeline Condition States D and F compared to a Do Nothing option. The approach taken to simulate these benefits is to increase the expected amount of landslide displacement at which transitions to Condition State D and F might occur in proportion with the expected likelihood of detecting deteriorating conditions leading to a successful planned intervention, and with consideration of the amount of time required to conduct this intervention. While the actual pipeline capacity to accommodate landslide displacement does not change in response to visual inspection, the likelihood of critical displacements occurring without detection and intervention does.

Based on the authors' experience with supporting operators with landslide risk management on approximately 450,000 km of pipeline, we have observed that displacements can usually be detected from visual ground inspection if they exceed about 50 mm/yr. By comparing IMU bending strain data and ground inspection observations, approximately 50% of landslide impacts causing observable pipeline bending strain can be detected by visual ground inspection, creating the opportunity for early intervention. When a pipeline crosses a known or suspected active landslide, visual ground inspections are often conducted on an annual basis. The cost for a visual ground inspection varies depending on site access, site complexity and other factors, but is typically in the range of $1,500 per site when conducted as part of a larger program.

Based on this experience, the potential benefits of an Annual Inspection management option were simulated by increasing the landslide displacement required to cause a transition from pipeline Condition State C to D and D to F (Table 4) by 50%. Event-based costs associated with a detected transition to Condition State D were accounted for by assuming they would trigger an unplanned shut-in and strain relief with a cost of $5M.

Condition state modelling using these assumptions yielded a new set of condition state probabilities that were converted to annual cash flows. Present Values of lifecycle costs for the Annual Inspection management option range from approximately $540k to $3.4M for crossings of the landslides initially moving at 5 mm/yr and 25 mm/yr, respectively.

Present Value of the inspection cost over a period of 25 years is approximately $25,000. The modelling results suggest that these planned, proactive management costs yield a very large benefit-cost ratio. However, unplanned costs associated with potential transitions to Condition State D and F are still relatively high and remain the dominant contributor to the lifecycle costs.

6.4 Annual Inspection + 5-yr IMU Option

Many pipeline operators now run IMU tools at least once every five years as part of their in-line inspection programs. IMU offers the opportunity to detect much more subtle landslide impacts that result in pipeline bending strain if the IMU data are carefully reviewed in conjunction with lidar and other imagery and monitoring data. Early detection of these landslide impacts can dramatically increase the odds that planned intervention such a strain relief can be carried out in a way that minimizes business interruption costs. Assuming IMU data are already being collected, the incremental additional cost for incorporating bending strain profiles with other monitoring data to assess landslide impact varies but is typically on the order of $10,000. These analyses might be conducted once every 5 years, on average, with an average annualized cost of about $2,000/yr.

The potential benefits of a management option comprising annual visual inspections and review of IMU were simulated by re-setting the pipeline condition state to the State B/C transition every five years for the Monte Carlo Simulation Trials where that state had been exceeded. The underlying assumption is that every five years the condition state of the pipeline and recent landslide movement rates will be known with a high degree of confidence, and either the condition will be deemed acceptable (i.e., it is still in State A or B) or a planned strain relief will be undertaken to return the pipe to the beginning of Condition State C. An additional cost of $2,000 per year was included for Condition States A, B and C to allow for bending strain analysis every 5 years. For the typically small number of trials landing in Condition State C, an additional cost of $100,000 per year was added to accumulate budget to cover the potential cost of a planned strain relief that would be conducted before a transition to Condition State D occurred. Event-based costs assumed for those transitions to Condition State D and F that still do occur were the same as those for the Annual Inspection management option.

Present Values of lifecycle costs for the Annual Inspection + 5-yr IMU management option range from approximately $190k to $2.3M for crossings of the landslides initially moving at 5 mm/yr and 25 mm/yr, respectively. Present Value of the costs for visual inspections, bending strain reviews, and potential planned strain relief activities account for about $65k and $1M of the total lifecycle costs for the slower and faster landslide scenarios, respectively, or about one-third to one-half of the total costs. For both landslide velocity scenarios, this management option offers significant expected cost savings over an approach that only relies on visual inspection.

6.5 Realtime Monitoring + 5-yr IMU Option

Cash flows for a fourth management option that incorporates the potential costs and benefits of near real-time monitoring were also analyzed. Real-time monitoring options include use of strain gauges, vibrating wire piezometers, Shape Accel Arrays or In-place Inclinometers, global navigation satellite system (GNSS or GPS) monitoring hubs, and weather monitoring. The incremental costs for these types of monitoring systems include the cost for instrument purchase, installation and maintenance, data management costs, and data interpretation costs. We've assumed an incremental cost of $25,000 per year for Condition States A, B and C, over and above those assumed for the Annual Inspection and 5-yr IMU management option.

The potential benefits of a management option that incorporates real-time monitoring were simulated by increasing the displacement required to cause transitions to Condition State D and F by a factor of four. Similar to the approach taken to simulating the benefits of annual visual inspections, the underlying assumption is that real-time monitoring should enable an operator to identify and implement a planned response to a change in landslide movement rate within a 3-month period (a quarter of a year), making transitions to Condition State D or F much less likely.

Present Values of lifecycle costs for the Annual Inspection + 5-yr IMU management option range from approximately $550k to $1.8M for crossings of the landslides initially moving at 5 mm/yr and 25 mm/yr, respectively. Present Value of the real-time monitoring costs plus costs for visual inspections, bending strain reviews, and potential planned strain relief activities account for about $500k and $1.4M of the total lifecycle costs, while the residual risk-based event costs account for $50k and $400k of the remaining total. In alignment with our intuition, the lifecycle cost modelling suggests that for the faster-moving landslide the addition of real-time monitoring has a positive benefit-cost ratio and results in the lowest lifecycle costs of all the options considered. But for the slower-moving landslide, the additional benefits of the real-time monitoring system do not outweigh the costs.

6.6 Partial Landslide Stabilization

An operator may also consider the cost-benefit of implementing measures, such as drainage improvements, aimed at reducing the landslide velocity. The potential benefit of partial landslide stabilization can be evaluated by estimating a range of values for the expected reduction in landslide movement rate. In the above example with a Do Nothing management option, drainage improvements which are expected to reduce the landslide velocity from 25 mm/yr to 5mm/yr might reduce lifecycle costs from $3.9M to $670k, a difference of about $3.2M. This suggests that if drainage improvements and landslide velocity reduction could be achieved for less than $3.2M, such an approach might be warranted.

In these types of option analyses, however, the lifecycle costs for the best available options are usually compared. For the landslide initially moving at 25 mm/yr, the two best options appear to be implementation of real-time monitoring in conjunction with annual inspections and IMU review at five-year intervals, or the option of improving drainage to slow landslide movements in conjunction with annual inspections and IMU review. The first option has a Present Value lifecycle cost of $1.8M, while the second has a Present Value lifecycle cost of $190k, a difference of about $1.6M. In this case, if there is high confidence that landslide movement rates can be reduced through drainage improvements or other slope stabilization measures for a cost of less than $1.6M, this would likely be the preferred management option.

6.7 Landslide Avoidance via Re-route or Horizontal Directional Drill

There are situations where an operator will contemplate hazard avoidance through re-routes or horizontal directional drills. For the scenarios modelled above, the combined lowest lifecycle cost options are $190k for the 5 mm/yr landslide and $1.8M for the 25 mm/yr landslide, or a total of about $2M. If hazard avoidance of both landslides could be implemented for less than $2M, that would likely be the preferred management option.

6.8 Other Lifecycle Cost Modelling Considerations

The hypothetical scenarios outlined above provide some insight to the expected cost and benefit of different management options when a pipeline with a certain amount of landslide displacement capacity is buried in landslides moving at 5 and 25 mm/yr. As expected, more aggressive management effort is warranted for faster-moving landslides, all else being equal, and it appears that the benefit of efforts to complete visual inspections and regular review of IMU bending strain data will usually outweigh the costs.

Every pipeline system and landslide crossing will have different characteristics that will likely warrant site-specific analysis. For example, some pipelines will be able to accommodate much less (or potentially much more) landslide displacement than considered in the scenarios above. Because of pipe diameter, product type, access constraints, proximity to high consequence areas, or commercial commitments, the costs of pipeline shut-ins, unplanned strain reliefs, or ruptures could vary significantly from the $5M and $50M that have been modelled. Some landslide behavior types are more (or less) susceptible to sudden changes in activity and movement rate in response to precipitation and other factors, which would result in differences in the probabilities of pipeline condition state transitions. All these factors are easily accounted for in the modelling approach that has been presented.

7. CONCLUSION

In this paper we reviewed a conceptual approach to predict landslide velocity and displacement using Markov chains that combine geomorphic evidence of long-term landslide behavior with current estimates of landslide velocity. We proposed a framework to combine time-dependent estimates of landslide displacement and the deterioration of pipeline strain capacity to estimate the probability of changing pipeline condition states and management and risk cost over time. The results can better inform decisions about pipeline integrity and risk management option selection, particularly where pipelines cross and are currently being impacted by slow landslide movements.

The model inputs and outputs presented in this paper are for hypothetical scenarios but are representative of the authors' experience with numerous examples of pipeline damage and failure over the past decade. The processes for modelling the probabilities of landslide velocity transitions will benefit from large databases of landslide displacements over time that are being assembled to improve landslide early warning systems. These databases are leveraging instrumentation, visual inspection, lidar change detection and InSAR data from multiple pipeline operators across North America. The approaches to modelling pipeline damage, and management actions, costs and benefits, will continue to be refined as they are applied during detailed geotechnical investigations for priority landslide crossings as part of operators' geohazard management programs.

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