

Deterioration-Aware Seismic Risk Analysis for Water Pipeline Networks

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ABSTRACT

Water distribution networks are increasingly threatened by the compound effects of ageing infrastructure and seismic hazards. While empirical fragility functions exist for pipelines subjected to ground shaking (PGV) and permanent ground deformation (PGD), these often fail to account for the cumulative effects of material deterioration, replacement strategies, and repeated seismic loading. This study presents a framework for deterioration-aware seismic risk assessment of buried pipelines that integrates component lifecycle degradation models, Markov chains for damage state transitions, and probabilistic seismic ground failure hazard analysis.

The proposed methodology builds on empirical repair rate functions (e.g., ALA, 2001) and fragility models for PGV. It introduces state and time-dependent fragility surfaces derived by integrating survival functions and a Markovian transition matrix to model cumulative seismic damage across discrete deterioration states.

Using real-world pipeline asset data from Latin American systems dominated by asbestos cement and polyvinyl chloride (PVC) pipes, deterioration pathways are simulated under varying maintenance and replacement strategies.

Results highlight that pipelines in advanced deterioration states can exhibit more than double the expected damage compared to newly replaced pipes under similar PGV demands.

This work bridges the gap between seismic fragility modeling and infrastructure lifecycle management, offering a time-evolving perspective for decision-making in water systems. The framework is extensible to other buried lifelines and contributes to the effort to enhance the resilience of critical infrastructure in the face of natural hazards and climate-driven stressors.

Keywords: water systems, deterioration, seismic risk

INTRODUCTION

Water distribution networks are exposed to multiple interacting stresses across their service life, including material aging, corrosion, operational loads, and extreme events. Seismic hazards affect buried pipelines through transient ground shaking and through ground deformation processes such as liquefaction induced lateral spreading, settlement, and cracking, which have repeatedly been identified as damaging mechanisms for buried lifelines (O'Rourke and Lane, 1989).

At the same time, pipelines commonly remain in service beyond their nominal design lives, and renewal decisions are often made under limited direct condition data. Break and repair records therefore become the operational signal for deterioration assessment and for prioritizing renewal. This has motivated a large body of work on deterioration and failure prediction that estimates time to next failure, break rate, or condition evolution using observable covariates such as age, material, diameter, soil proxies, pressure, and past breaks (Kleiner and Rajani, 2008). The need is reinforced by observed break rates across North American utilities, where break frequency varies strongly by material and pipe cohort (Barfuss et al., 2023).

In contrast, seismic risk assessments for pipelines are often executed as single event calculations that use empirical fragility or repair rate relations. A widely used reference is the American Lifelines Alliance guideline, which expresses expected repair rate as a function of an intensity measure such as peak ground velocity, with K factors that represent material, jointing, and other characteristics (American Lifelines Alliance, 2001). In many applications, these relations are applied under an implicit pristine assumption, meaning pipes are treated as if they start the event in a new or undamaged state. This can understate risk when components have accumulated damage from aging, corrosion, and prior shocks.

Recent research has begun to integrate deterioration into seismic damage estimation and resilience analysis. One direction is to modify seismic repair rate models to reflect corrosion deterioration and to connect seismic damage predictions to renewal planning and cost (Mazumder et al., 2020). A second direction is system level resilience and restoration analysis that explicitly considers time variant corrosion effects on pipeline vulnerability and post event functionality (Mazumder et al., 2020). Related work on multi age networks and corrosive environments shows that service age and corrosion conditions can shift seismic fragility and resilience outcomes (Long et al., 2024).

In parallel, deterioration literature continues to expand and consolidate evidence on time to failure modeling approaches and practical gaps in utility data (Bakhtawar et al., 2025).

This study adopts Markov chains because they provide a transparent way to represent cumulative damage as transitions among discrete condition states and to make fragility state dependent. A Markov formulation can propagate conditions through time under repeated earthquake loading and background deterioration and then evaluate risk conditional on the current state rather than assuming k1 for all segments. This yields a consistent bridge between seismic fragility modeling and lifecycle asset management, and it supports scenario comparisons that are difficult to express in single event assessments. (Iervolino et al., 2016).

This study is framed as representative of Latin American pipeline inventories because the region includes countries with high seismic hazard driven largely by active subduction along the western margin of South America, and many utilities face persistent performance and investment constraints in water services (Petersen et al., 2018). Using detailed statistics that can be assembled for typical material mixes and age cohorts, we demonstrate how results and priorities change when moving from the common pristine assumption to a deterioration aware, Markov based representation of prior damage, and how renewal and response policies further modify outcomes.

METHODOLOGY

This study used a synthetic water distribution network that is parametrized to represent Latin American systems with high shares of asbestos-cement (AC) and polyvinyl chloride (PVC) pipelines. The network is represented as an undirected graph with nodes and pipe segments.

The parametrization uses published systems statistics on pipe material and installation era as representative inputs. The statistics include the material composition of distribution pipes and installation periods, such as AC being installed until 2000 and PVC and high-density polyethylene (HDPE) being introduced from 1980.

A toy network is introduced with N nodes and E pipe segments. Each segment connects two nodes and has a length. The topology was chosen to include loops and branching so that prioritization outputs are non-trivial. Each segment (e) is assigned the following attributes, sampled from a normal distribution:

- Material (m). Four material classes are considered AC, PVC, HDPE, and steel.
- Installation year (y). Sampled from an installation era distribution consistent with the representative statistics and narrative that AC was installed mainly between 1950 and 2000, PVC from 1980 onward, HDPE from 1990, and steel across older installation periods.
- Age (a). Defined as the period between the simulated year (t) and the installation year.

- Condition state (k). Discrete values defined as k1= good, k2= moderate, k3= poor, and k4= near failure
- Repair history (r). Discrete values defined as r0= no prior events of break or leak, r1= at least one prior leak or break, and r2= repeated events of break or leak. This is latent at t0 and evolves via simulated damage and repairs.

The initial material proportions are set to match representative shares. For distribution networks, PVC and asbestos cement are dominant. The distribution considered is AC: 40%, PVC: 40%, HDPE: 15%, and steel: 5%.

Initial state (k at t0) is assigned using a material- and age-dependent probability rule. Older AC and steel pipes have higher probability of being assigned to k3 and k4, while newer PVC and HDPE have higher probability of being assigned to k1 and k2.

The condition state evolves in discrete annual steps. For each segment, background deterioration is modeled as a Markov transition on k, conditional on material (m) and age (a) bin. Only transitions k to k and k to k+1 are allowed under background deterioration.

The annual background transition, $p_w(m, a)$ can be written as:

$$p_w(m, a) = P(k(t+1) = k(t) + 1 | m, a)$$

With k(t+1) capped at k4. This represents gradual deterioration due to ageing, corrosion, and operational effects without requiring detailed physical deterioration data.

Earthquake occurrence and induced damage

Earthquake occurrence is modeled as a homogeneous Poisson process in time with annual rate ν . The number of events in year t is sampled as $N_{\text{events}}(t)$ from a Poisson distribution with mean ν .

Each event generates a network wide shaking intensity described by PGV. Each segment receives a segment level PGV that is sampled from a lognormal distribution around the event level PGV, representing spatial variability.

For each segment and each earthquake event, repair rate (RR) in repairs per kilometer is calculated using the vulnerability function for wave propagation proposed by ALA (2001):

$$RR = 0.00187 \cdot K_1 \cdot PGV \quad (1)$$

where PGV is expressed in cm/s and the coefficient K_1 is selected by material. The K_1 values used in this study are AC=1.0, PVC=0.5, HDPE=0.5, and steel=0.9.

For a segment of length L in kilometers, the expected number of repairs for an event, μ , is:

$$\mu = RR \cdot L \quad (2)$$

It is assumed the number of repairs on each segment follows a Poisson distribution, the probability of at least one repair on a segment is therefore:

$$P(\text{damage}) = 1 - e^{-\mu} \quad (3)$$

If damage occurs, the model classifies the outcome as leak or break. The assumption is that for a wave propagation dominated damage, 20% of repairs are breaks and 80% are leaks. This ratio is reported as a commonly used assumption based on Ballantyne et al. (1990) in water system damage. A leak increments the condition state by one level, k goes to min(k+1,4). A break increments the condition state by two levels, k goes to min(k+2,4). This provides an event-driven Markovian state update that represents damage accumulation without invoking hydraulic simulation or detailed component failure mechanics.

To represent the effect of prior deterioration on seismic vulnerability, the baseline repair rate is modified using a condition-state multiplier g(k). The state dependent repair rate is

$$RR = RR(0) \cdot g(k) \quad (3)$$

Where:

- g(1)= 1.0
- g(2)= 1.5
- g(3)= 2.0

- $g(4) = 3.0$

The multiplier is used as a sensitivity representation of reduced residual capacity in deteriorated pipes and is not calibrated. It allows the analysis to test how seismic damage estimates and prioritization outputs change when pipes are not assumed to be in a pristine k1 condition at the time of the earthquake.

Simulation

Two analysis modes are compared. The conventional pristine analysis assumes that all pipe segments are in condition state k1 at the time of the earthquake scenario. This represents a common single event seismic assessment in which pre-existing deterioration is not explicitly modeled. And the deterioration-aware analysis, that starts from the synthetic initial condition distribution and evolves the network over a horizon of T years under background deterioration and earthquake damage. In this mode, segments undergo annual background deterioration. In each year, each segment has a material and age dependent probability of worsening by one state, k goes to k+1, capped at k4. This background transition is applied once per year.

The comparison is performed using the same network topology, material inventory, segment lengths, and PGV scenario in both analysis modes. This isolates the effect of deterioration and prior damage on expected repairs, expected breaks, and risk ranking.

To evaluate how the importance of deterioration changes with seismic demand level, the comparison is repeated for multiple return period PGV scenarios. Three reference shaking levels are considered: a frequent or service-level event, a design-level event, and a rare event. These are represented by PGV values associated with selected return periods: 50 years, 475 years, and 2475 years. The prescribed PGV for each return period is treated as the median shaking intensity in the network. PGV values per segment are sampled from a lognormal distribution around this network value to represent spatial variability in ground motion across the network.

For each return period, the same deterioration-aware pre-event condition states are used, and expected damage is recalculated under the corresponding PGV level. This allows the analysis to quantify whether deterioration has limited influence under low intensity shaking but becomes more important under higher seismic demands.

A Monte Carlo (MC) simulation is used to propagate uncertainty in initial condition state, background deterioration, earthquake occurrence, event PGV, segment level PGV variability, and leak vs break outcome. For each MC trial, the network topology is initiated with its segment attributes, for each year t from 1 to T.

In each year, segment age is updated, background deterioration is applied, earthquake occurrence is sampled, event damage is computed, and condition states are updated. For policy cases, planned replacement is applied before earthquake occurrence, while post-earthquake repair or replacement is applied after event damage. The simulation is repeated over multiple trials and expected values, percentile ranges, and decision metrics are then computed for the conventional and deterioration-aware analyses.

Mitigation policy actions

Two mitigation policy sets are evaluated. These policies modify the condition state and age of selected segments. Replacement resets k to k1 and r to r0, repair resets r to r1 and sets k to k2, unless k is k4, in which case, it becomes k3. These simplified rules are intended to represent policy effects on condition state, not detailed repair design.

Policy Set 1 includes:

- Replace 20% of pipelines length in k4 every 5 years
- After earthquake
 - AC segments. Replace the segment after any detected damage outcome, including a leak.
 - PVC, HDPE, and steel segments. Repair after damage outcomes, unless the segment is already in k3 or worse, in which case, replace.

Policy Set 2 includes:

- Replace 20% of pipelines length in k4 every 5 years and 5% AC every year, prioritizing the worst condition states.

- After earthquake
 - AC segments. Replace the segment after any detected damage outcome, including a leak.
 - PVC, HDPE, and steel segments. Repair after damage outcomes.

These policies are used to assess how deterioration-aware modeling interacts with renewal and post-event response decisions. Because it can trigger earlier replacement, amplification values below 1 are possible and this means that this approach can produce lower subsequent damage than the conventional approach because it prompts earlier intervention.

Decision metrics

To quantify the practical consequence of neglecting deterioration, four decision metrics were computed.

First, the damage underestimation ratio (DUR), defined as:

$$DUR = DDA/DC \quad (4)$$

Where DDA is the total damage or expected breaks from the deterioration-aware analysis and DC is the corresponding value from the conventional pristine analysis. Values greater than 1 indicate that the conventional analysis underestimates damage.

Second, the missed high-risk segment rate (MHR), computed by ranking segments according to expected breaks under both approaches. The top 10% of segments under the deterioration-aware analysis is treated as the reference high-risk set. MHR is defined as the fraction of those segments that are not included in the top 10% under the conventional analysis.

Third, the additional expected breaks are computed as the sum of positive differences between deterioration-aware and conventional expected breaks across all segments. This metric quantifies the expected damage that is hidden by the pristine assumption.

Fourth, condition-state contribution metrics are computed by grouping segments according to their deterioration-aware condition state before the earthquake scenario. For each state, the number of segments, total pipe length, mean expected breaks per segment, and total expected breaks are calculated. The total expected-break contribution is used for policy comparison because policies change the number, length, and composition of segments in each condition-state group. Mean expected breaks per segment are reported only as mechanism diagnostic.

RESULTS

Figure 1 shows the synthetic water distribution network used in the analysis. The network includes loops and branching segments to produce non-trivial ranking and prioritization outcomes.

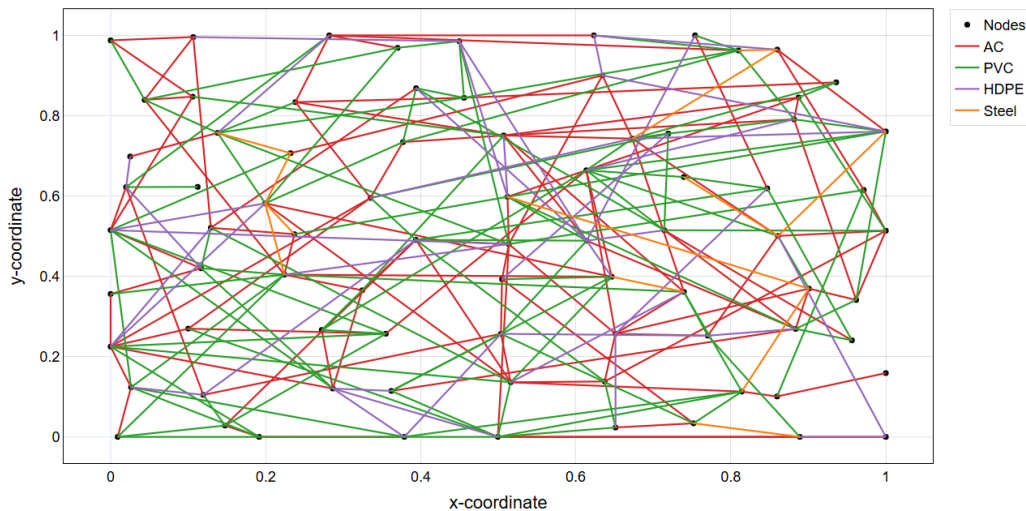


Figure 1. Toy network and material composition (AC=40%, PVC=40%, HDPE=15%, and Steel=5%)

Segment materials were assigned according to the representative inventory proportions used in the model: AC = 39.7%, PVC = 40.2%, HDPE = 15.1%, and steel = 5.0%. These proportions are consistent with the intended synthetic representation of systems where AC and PVC dominate the pipe inventory.

Figure 2 compares the Damage Underestimation Ratio (DUR) for the conventional pristine-state analysis and the deterioration-aware analysis across return-period PGV scenarios. DUR is defined as the ratio between expected breaks computed with deterioration-aware condition states and expected breaks computed assuming all pipes are in condition state k1. Each line is itself a comparison between the deterioration-aware analysis and the conventional pristine-state analysis under the same policy assumptions. For example, the no-policy line represents the ratio between deterioration-aware expected breaks and conventional expected breaks when no renewal policy is applied. Similarly, the Policy Set 1 and Policy Set 2 lines represent the same ratio after applying their respective renewal and post-earthquake response rules.

The no-policy case produces the largest underestimation. DUR is approximately 2.7 to 2.8 across the 50-year, 475-year, and 2475-year PGV scenarios. This means that, in the absence of intervention, the conventional pristine-state analysis captures only about 35% to 40% of the expected breaks estimated by the deterioration-aware model. In other words, neglecting prior deterioration underestimates expected breaks by approximately 60% to 65%. Policy Set 1 reduces the DUR to approximately 1.8, while Policy Set 2 reduces it further to approximately 1.4. This indicates that condition-based renewal reduces the gap between conventional and deterioration-aware estimates. The relative underestimation ratio remains nearly constant across return periods because both conventional and deterioration-aware expected breaks scale approximately linearly with PGV over the range analyzed. However, the absolute effect of ignoring deterioration increases with return period.

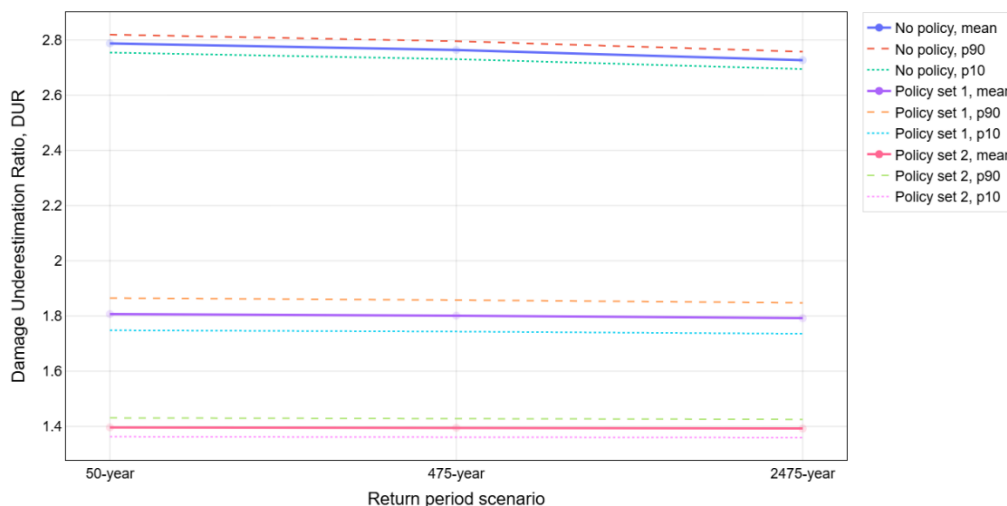


Figure 2. Damage Underestimation Ratio (DUR) per return period

Figure 3 shows the total expected breaks for the conventional and deterioration-aware analyses. This figure makes the comparison underlying DUR explicit. For all policy cases and return-period scenarios, the deterioration-aware curves are above the conventional curves. The difference is largest for the no-policy case and decreases from Policy Set 1 to Policy Set 2. Under the 2475-year scenario, the no-policy deterioration-aware estimate is approximately 2.2 expected breaks, compared with approximately 0.8 expected breaks under the conventional assumption. Policy Set 1 reduces the deterioration-aware expected breaks to approximately 1.45, while Policy Set 2 reduces them to approximately 1.1. This shows that the policies reduce total expected damage, with Policy Set 2 providing the largest reduction.

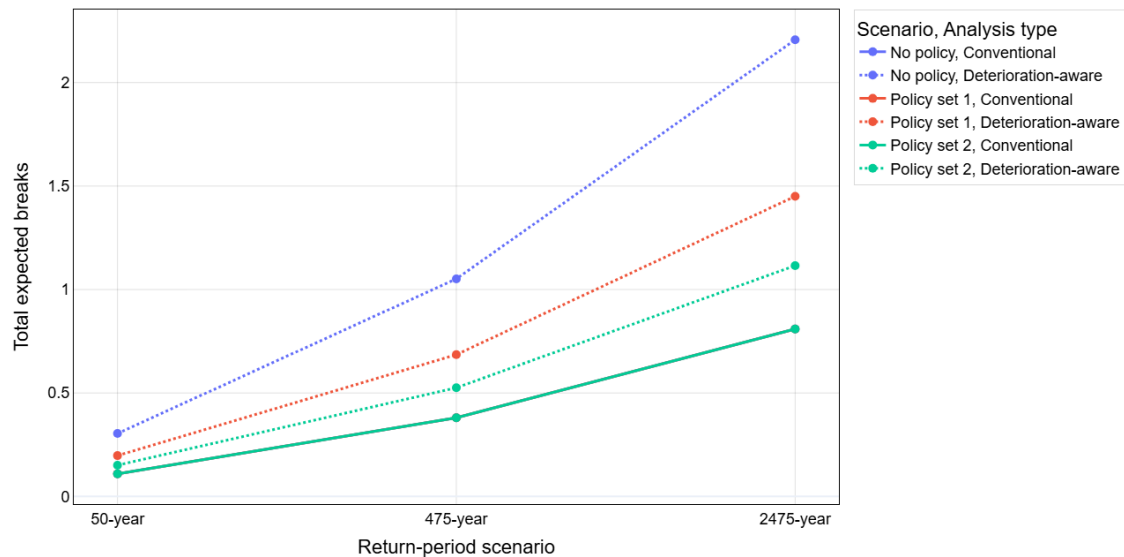


Figure 3. Total expected breaks

Figure 4 presents the additional expected breaks associated with prior deterioration. This metric is computed as the sum of the positive differences between deterioration-aware and conventional expected breaks across all segments. The additional expected breaks increase with return period in all scenarios, indicating that the absolute consequence of neglecting deterioration becomes more important as seismic demand increases. Under the 2475-year scenario, the no-policy case produces approximately 1.4 additional expected breaks. Policy Set 1 reduces this value to approximately 0.65, and Policy Set 2 reduces it to approximately 0.30. Relative to the no-policy case, this corresponds to an approximate 50% reduction for Policy Set 1 and an approximate 75% reduction for Policy Set 2.

The DUR curves are relatively flat across return periods, while the additional expected breaks increase strongly with return period. This behavior is expected because, over the analyzed PGV range, expected breaks in both the conventional and deterioration-aware analyses scale approximately with shaking intensity. As a result, the ratio between the two analyses remains relatively stable. However, the absolute difference grows as PGV increases. Therefore, DUR is useful for showing relative bias, while additional expected breaks are more useful for showing the practical consequence of neglecting deterioration.

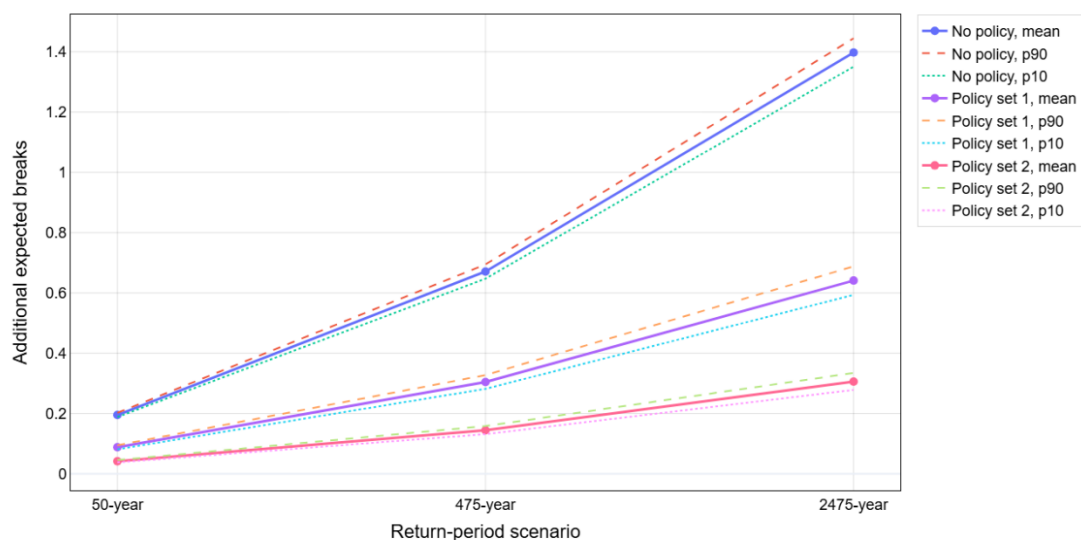


Figure 4. Additional expected breaks

Figure 5 shows the condition-state length inventory after the deterioration horizon for the 2475-year scenario. In the no-policy case, most pipe length accumulates in k4, indicating severe deterioration by the end of the simulation horizon. Policy Set 1 shifts part of the inventory out of k4, but a substantial length remains in k3 and k4. Policy Set 2 produces the strongest shift toward improved condition states, with the largest length in k1 and the smallest k4 length among the three cases. This confirms that the proactive annual AC replacement rule in Policy Set 2 produces earlier intervention and a healthier post-horizon inventory.

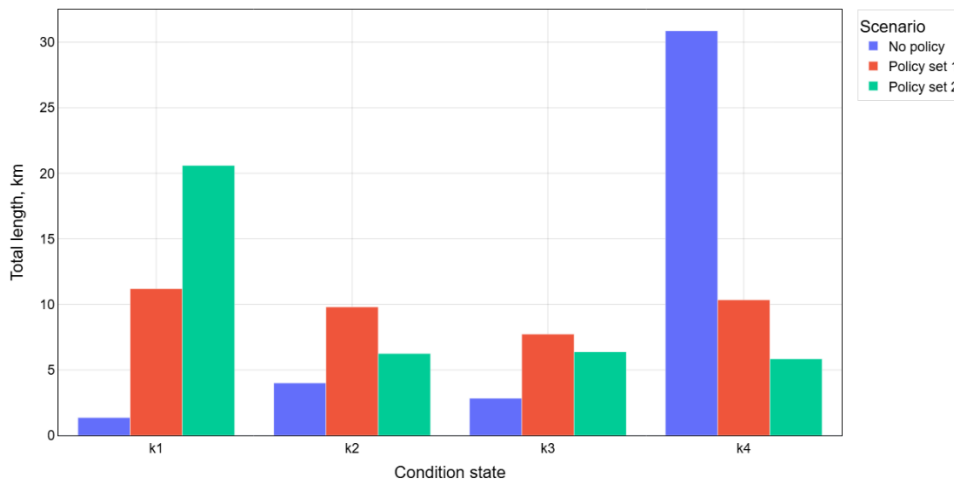


Figure 5. Conditional-state length inventory

Figure 6 shows the deterioration-aware expected-break contribution by condition state and policy for the 2475-year scenario. In the no-policy case, expected breaks are dominated by k4 segments. This confirms that the effect of deterioration is concentrated in segments that reach poor or near-failure condition states before the earthquake scenario. Under Policy Set 1, the k4 contribution is substantially reduced, although k2, k3, and k4 still contribute to total expected breaks. Under Policy Set 2, expected breaks are redistributed toward k1 and reduced in the higher deterioration states. This confirms that policy action reduces risk not only by lowering total expected breaks, but also by shifting the inventory away from the most vulnerable condition states.

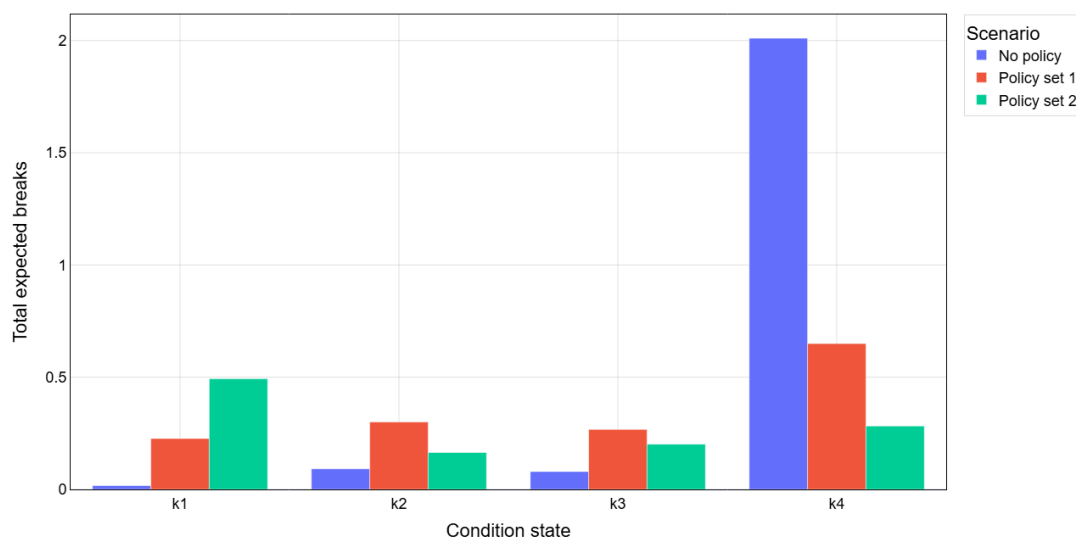


Figure 6. Deterioration-aware expected-break contribution

Figure 7 compares conventional and deterioration-aware expected breaks by condition state for each policy case. In the no-policy case, the k4 deterioration-aware contribution is much larger than the conventional contribution. This shows that assuming all pipes are pristine substantially underestimates the damage contribution from severely deteriorated pipes. In the policy cases, the difference between conventional and deterioration-aware estimates is smaller than in the no-policy case, but it remains visible for k2, k3, and k4. This result supports the use of deterioration-aware modeling even when renewal policies are implemented, because remaining deteriorated segments continue to contribute more damage than would be estimated under a pristine-state assumption.

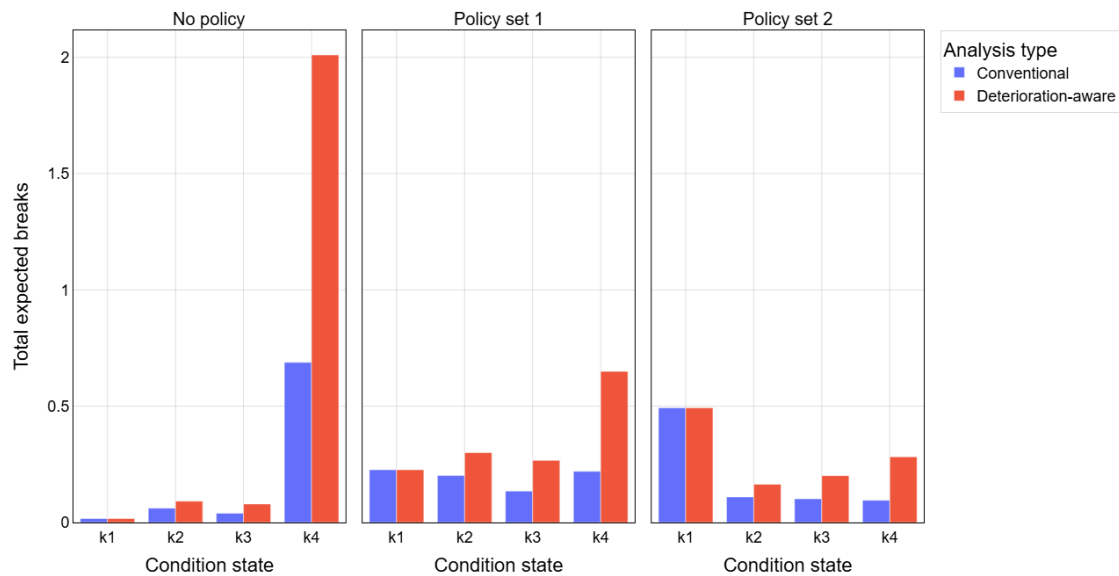


Figure 7. Conventional and deterioration-aware expected breaks by condition state

Figure 8 presents deterioration-aware expected breaks by material and policy under the 2475-year scenario. AC contributes the largest expected damage in all scenarios, followed by PVC, with smaller contributions from HDPE and steel. In the no-policy case, AC expected breaks are approximately 1.25. Policy Set 1 reduces the AC contribution to approximately 0.75, and Policy Set 2 reduces it further to approximately 0.45. This confirms that the policy benefits are strongly linked to reducing the contribution of AC pipes, which are both highly represented in the inventory and assigned a relatively high seismic repair-rate coefficient.

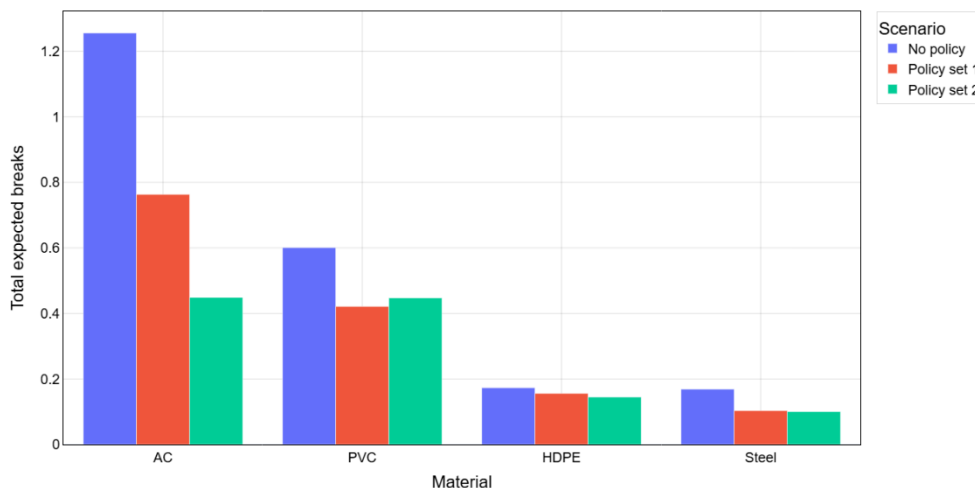


Figure 8. Deterioration-aware expected breaks by material and policy for the 2475-yr scenario

Overall, the results show that deterioration-aware seismic analysis provides three decision-relevant benefits. First, it quantifies hidden expected damage. In the no-policy case, deterioration-aware expected breaks are approximately 2.7 to 2.8 times larger than the conventional pristine-state estimate. Second, it allows policy effectiveness to be quantified. Policy Set 1 reduces the additional deterioration-driven expected breaks by about 50%, while Policy Set 2 reduces them by about 75% relative to no policy under the 2475-year scenario. Third, it improves prioritization after intervention. While conventional analysis may identify similar top-risk segments in the no-policy case, it misses nearly half of the deterioration-aware high-risk segments in the policy cases. These results support the use of deterioration-aware seismic analysis as a practical decision tool for renewal planning, seismic screening, and emergency response prioritization in ageing water distribution networks.

CONCLUSIONS

This study presented a deterioration-aware framework for seismic risk assessment of buried water pipelines. The framework combines a PGV-based repair-rate formulation with a Markov condition-state model that represents background deterioration, earthquake-induced damage accumulation, and renewal policies. The objective was to evaluate how much conventional pristine-state seismic analysis can underestimate expected damage and how deterioration-aware modeling can support renewal and emergency-response prioritization.

The results show that neglecting deterioration can substantially underestimate expected breaks. In the no-policy case, the Damage Underestimation Ratio (DUR) is approximately 2.7 to 2.8 across the 50-year, 475-year, and 2475-year PGV scenarios. This means that the conventional pristine-state analysis captures only about 35% to 40% of the expected breaks estimated by the deterioration-aware model. The relative underestimation remains nearly constant across return periods, but the absolute number of additional expected breaks increases as PGV increases. Therefore, the practical consequence of neglecting deterioration becomes more important for rarer and stronger earthquake scenarios.

The policy simulations show that condition-based renewal reduces the hidden damage associated with prior deterioration. Under the 2475-year PGV scenario, the no-policy case produces approximately 1.4 additional expected breaks relative to the conventional analysis. Policy Set 1 reduces this value to approximately 0.65, while Policy Set 2 reduces it to approximately 0.30. Relative to no policy, this corresponds to an approximate 50% reduction for Policy Set 1 and an approximate 75% reduction for Policy Set 2. These results indicate that deterioration-aware policies can reduce total expected damage and also reduce the bias introduced by assuming pristine pipe conditions.

The condition-state inventory and expected-break contribution results show that the effect of deterioration is concentrated in pipes that reach poor or near-failure condition states. In the no-policy case, most pipe length evolves into k4, and k4 segments dominate the deterioration-aware expected-break contribution. Policy Set 1 reduces the k4 contribution but leaves a substantial amount of pipe length in degraded states. Policy Set 2 produces the strongest improvement by shifting more pipe length into k1 and reducing the k4 inventory. This confirms that proactive renewal can reduce seismic risk by changing the condition-state distribution before the earthquake occurs.

The material-specific diagnostics indicate that the improvement under Policy Set 2 is mainly associated with the proactive renewal of AC pipes. AC represents a large fraction of the synthetic inventory and has a relatively high repair-rate coefficient in the adopted seismic damage model. Under no policy, AC expected damage is dominated by k4 segments. Policy Set 2 shifts most AC length into k1 and substantially reduces the k4 AC contribution. This supports the use of material-specific renewal strategies when ageing and seismic vulnerability are correlated.

The results also show that deterioration-aware analysis affects prioritization after policies are introduced. In the no-policy case, the conventional and deterioration-aware top-risk lists largely overlap, meaning that the conventional analysis may identify similar priority segments but underestimates their damage magnitude. In the policy cases, however, the conventional analysis misses nearly half of the deterioration-aware top-risk segments. This indicates that once renewal and post-earthquake response actions change the condition-state distribution, conventional pristine-state analysis could miss which segments remain critical.

Overall, the framework provides three decision-relevant outputs that are not available from a conventional pristine-state seismic analysis: the magnitude of hidden expected damage, the reduction in hidden damage achieved by renewal policies, and the change in high-risk segment prioritization after deterioration and interventions are considered. These outputs are directly relevant to utilities because renewal planning and emergency response decisions depend on expected damage totals, but also on which pipe segments are likely to control post-earthquake losses.

The present implementation should be interpreted as a methodological and sensitivity study rather than a site-calibrated prediction. The synthetic network, deterioration transition probabilities, condition-state vulnerability multipliers, and return-period PGV values are scenario inputs. Future work should calibrate the deterioration model using observed break and repair histories, replace the synthetic PGV scenarios with site-specific probabilistic seismic hazard outputs, include permanent ground deformation, and evaluate system-level hydraulic consequences. Even with these limitations, the results demonstrate that incorporating deterioration into seismic pipeline analysis can materially change expected damage estimates, policy evaluation, and renewal prioritization for ageing water distribution networks. The key contribution of this deterioration-aware approach is that it exposes hidden damage magnitude, quantifies the benefit of renewal, and changes priority selection once policies are introduced.

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