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Reliability-Based Service-Life Assessment of Slotted Rockbolts in Chloride-Rich Underground Mines: Coupled Uniform–Pitting Corrosion and Time-Dependent Anchorage Degradation

Takeshi Endo[1,*], João Silva[2]

[1]Molecular Engineering Institute, Shiga University of Medical Science, Seta Tsukinowa-cho, Otsu, Shiga 520-2192, Japan

[2]Department of Mechanical Engineering, School of Technology, Federal University of Santa Catarina, University Campus, Trindade, Florianópolis, Santa Catarina 88040-900, Brazil.

[*]Corresponding author: tendo@belle.shiga-med.ac.jp

[2]Corresponding author: std.joaosilva@gmail.com

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Abstract

Corrosion-induced degradation of steel rock reinforcement poses a major risk to the long-term stability of underground roadways, particularly in coastal mines where groundwater is chloride-rich and frequently acidic to near-neutral. Slotted (friction) rockbolts are especially vulnerable because their capacity depends on tube ring stiffness and steel–rock friction, both of which deteriorate with wall-thickness loss and localized damage. This paper proposes a reliability-based service-life assessment framework for slotted rockbolts that couples a time-dependent anchorage model with a conservative representation of localized pitting corrosion. Generalized corrosion is modeled as thickness reduction governed by an uncertain penetration rate, while pitting is incorporated through an equivalent penetration amplification factor acting at the controlling cross section, enabling straightforward probabilistic evaluation. The framework defines a time-dependent limit state in terms of anchoring capacity relative to a required support threshold and evaluates failure probability and time-to-threshold metrics via Monte Carlo propagation of uncertainty in corrosion kinetics, pitting severity, interface friction, rock–bolt interaction stiffness, and installation variability. A demonstration for a coastal chloride-rich mine scenario shows that pitting can reduce predicted safe service life by factors of approximately 2–5 under moderate localized attack and approach order-of-magnitude reductions under severe pitting compared with uniform-loss-only predictions. Geometry sensitivity results indicate that increasing wall thickness is the most effective design lever for extending service life, followed by radius reduction, while increases in bolt length exhibit diminishing returns once the transfer length is exceeded. The proposed approach provides a practical, risk-informed basis for friction-bolt selection, maintenance planning, and remaining-life prediction in aggressive underground corrosion environments.

Keywords: slotted rockbolt, friction bolt, corrosion-induced degradation, pitting corrosion, uniform corrosion, reliability-based design, service-life prediction, anchoring force, underground mine groundwater, chloride-rich environment.

1. Introduction

Rockbolts constitute one of the most widely deployed ground-reinforcement systems in underground mines and civil tunnels, providing confinement, reinforcement, and load redistribution by transferring rock mass deformation into axial and shear resistance along the bolt–rock interface [1]. Their effectiveness over the full life of an excavation depends not only on initial installation quality and rock mass conditions, but also on the persistence of anchorage capacity under evolving thermo-hydro-mechanical-chemical (THMC) conditions [2]. In deep and/or coastal underground settings, groundwater inflow through fracture networks can create highly aggressive chemical environments that accelerate steel deterioration, leading to progressive loss of load capacity and, in extreme cases, sudden support failure [2]. Such corrosion-induced degradation is a critical concern for long-lived roadways, permanent shafts, and strategic drifts where maintenance access is limited and support performance must be guaranteed over multi-year horizons.

Electrochemical corrosion of steel in underground excavations is governed by the availability of moisture, dissolved oxygen, ionic conductivity, and aggressive species (notably chloride), together with local pH, temperature, and flow conditions. Chloride ions are particularly problematic because they destabilize protective oxide layers and promote localized corrosion through pit initiation and propagation, while low pH can enhance anodic dissolution and limit passivation [3]. In coastal underground mines, groundwater chemistry may partially resemble seawater, exhibiting high chloride and substantial salinity, often combined with persistent seepage that continuously renews reactants at the steel surface [1,4]. Field groundwater investigations in representative coastal mines have reported chloride concentrations on the order of 10^4–$10^{4.5}$ mg/L and pH spanning approximately 4.7–7.1 across different depths and sampling points, indicating conditions that can sustain both generalized corrosion and localized attack [1]. Under such exposure, the serviceability of steel reinforcement may be controlled by the rate of wall-thickness loss, the development of pits and defects, and changes in interface conditions caused by corrosion products and wash-off [2, 4].

Among various reinforcement types, slotted (friction) rockbolts remain common because of their low cost, rapid installation, and immediate load-bearing capacity [1, 3]. Their mechanism relies on radial contact pressure and frictional resistance mobilized between the bolt and the borehole wall [3]. Consequently, slotted bolts are sensitive to geometric and surface-condition changes: reduction in wall thickness decreases ring stiffness and contact pressure, localized defects can create weak sections that dominate failure, and corrosion products can initially increase roughness (potentially increasing friction) but may later detach under flowing groundwater, altering the frictional response. Unlike grouted or fully encapsulated systems where the load transfer is mediated by grout and bonding, friction bolts depend directly on the integrity of the steel tube and the stability of the steel–rock interface, making them particularly vulnerable in continuously wet, chloride-rich conditions [2, 3].

Existing analytical and empirical assessments have provided useful first-order insights by relating corrosion-driven thickness loss to decreases in radial pressure and anchoring force. However, many approaches adopt deterministic corrosion rates and treat corrosion as spatially uniform, which can be non-conservative in chloride-dominated environments where localized pitting frequently controls the time-to-failure. Moreover, field variability is substantial: corrosion rates may differ across headings due to heterogeneous groundwater flow, oxygenation, and microbial activity; installation-induced variability affects initial interference and friction; and demand levels vary with excavation geometry, stress redistribution, and time-dependent rock mass behavior [2]. These factors motivate a design framework that not only predicts mean degradation trends but also quantifies uncertainty and the probability that support capacity falls below required thresholds during the target service life [5].

To address these gaps, this paper develops an enhanced modeling and design framework for corrosion-induced degradation of slotted rockbolts in chloride-rich underground environments. The main contributions are: (i) a coupled uniform–pitting corrosion representation in which localized penetration at the controlling cross section is incorporated through a conservative amplification model (readily extendable to pit-depth statistics) [4], and (ii) a reliability-based service-life procedure that propagates uncertainty in corrosion kinetics, pitting severity, interface friction, and rock–bolt interaction parameters into time-dependent anchoring capacity and failure probability [5]. The framework is intended for practical engineering use: it supports rapid screening of bolt geometries (radius, wall thickness, and length), allows calibration with site measurements (coupon tests and recovered bolt autopsies), and produces reliability-consistent design-life charts for selecting reinforcement and corrosion mitigation strategies in long-term roadways [2].

2. Corrosive Environment Representation

2.1 Field-motivated chemical severity indicators

Groundwater in underground excavations typically contains a complex mixture of dissolved ions derived from rock–water interaction, seawater intrusion (in coastal settings), mine process water, and oxidation of sulfide-bearing lithologies. From a corrosion perspective, the electrochemical aggressiveness of such water is not controlled by a single variable, but by the combined influence of ionic strength (conductivity), acidity/alkalinity (pH and alkalinity), oxidizing power (dissolved oxygen and redox potential), and the presence of species that disrupt passivation or promote localized attack. Chloride is often the dominant driver of localized corrosion for carbon steel because it can penetrate and destabilize protective films and accelerate pit initiation, especially under wet–dry cycling or continuous seepage conditions. Sulfate and bicarbonate can also influence corrosion by altering conductivity, buffering pH, and contributing to scale formation, while the major cations (Na^+, Mg^{2+}, Ca^{2+}) affect ionic strength and the precipitation of protective or nonprotective deposits (e.g., carbonates).

In representative coastal underground mines, water-chemistry surveys frequently show seawater-like signatures, where the principal anions include Cl^-, SO_4^{2-}, and HCO_3^- and principal cations include Na^+, Mg^{2+}, and Ca^{2+}. Reported chloride concentrations in such environments can span roughly 11,700–25,400 mg/L, while pH may range from moderately acidic to near-neutral (approximately 4.68–7.14). These values imply (i) high electrical conductivity and (ii) a strong tendency toward pitting corrosion for steel, while the broad pH range indicates that corrosion kinetics may vary spatially and temporally across headings and depths. Moreover, inflow conditions are seldom steady: fracture-controlled seepage, seasonal recharge, and mine ventilation can modulate temperature and oxygen availability, leading to nonstationary corrosion behavior. For these reasons, the corrosive environment is represented here using scenario parameters rather than a single deterministic chemistry state.

To connect chemistry to engineering design without imposing a full electrochemical model (which typically requires site-specific measurements such as dissolved oxygen, redox potential, temperature, flow velocity, and sometimes polarization resistance), we introduce a dimensionless *corrosive severity index* (CSI) as a practical organizing variable:

$$\mathrm{CSI} = \left(\frac{[\mathrm{Cl}^-]}{[\mathrm{Cl}^-]_{\mathrm{ref}}}\right)\left(10^{\,7-\mathrm{pH}}\right)\left(\frac{T}{T_{\mathrm{ref}}}\right), \tag{1}$$

where $[\mathrm{Cl}^-]_{\mathrm{ref}}$ and T_{ref} are reference values chosen for convenience (e.g., median site chloride and nominal temperature). The CSI is *not* intended as a mechanistic corrosion law; rather, it provides a consistent basis for classifying environments into "moderate," "severe," and "extreme" categories when mapping observed chemistry ranges to plausible corrosion-rate distributions. In practice, CSI can be used to (i) bin monitoring locations into severity classes, (ii) guide the selection of corrosion coupon exposure programs, and (iii) communicate chemical risk in an interpretable way for ground-control design and maintenance planning.

2.2 Corrosion-rate uncertainty

A central challenge in predicting rockbolt service life is that corrosion rates in underground excavations exhibit substantial variability. Even within a single mine, local corrosion kinetics can differ by orders of magnitude due to differences in water chemistry, temperature, flow and renewal of reactants, oxygen transport, microbial activity, and the presence of deposits or crevice-like geometries. Slotted rockbolts, in particular, can develop occluded regions that locally shift pH and chloride concentration and intensify pitting. Consequently, the effective penetration rate governing wall-thickness loss should be treated as uncertain rather than fixed.

We model the effective corrosion penetration rate in the thickness direction, V_d (mm/year), as a lognormal random variable:

$$V_d \sim \mathrm{LogNormal}(\mu_v, \sigma_v), \tag{2}$$

which is widely used for strictly positive degradation rates with multiplicative variability. Under this model, μ_v and σ_v correspond to the mean and standard deviation of $\ln(V_d)$, enabling straightforward calibration from coupon tests, recovered bolt measurements (autopsies), or time-lapse thickness readings. When site-specific data are limited, (μ_v, σ_v) can be bounded using published ranges from comparable underground chloride environments, with conservative assumptions adopted for long-term roadway design.

For design implementation, it is often convenient to parameterize the distribution via its median V_{50} and log-space dispersion β_v:

$$V_{50} = e^{\mu_v}, \qquad \beta_v = \sigma_v, \tag{3}$$

so that V_d values can be sampled efficiently in Monte Carlo reliability analysis. The framework also accommodates time-varying corrosion rates by allowing V_d to be piecewise-constant or to evolve with a stochastic process (e.g., seasonal or flow-dependent regimes) when monitoring indicates nonstationary conditions. In the absence of such data, the lognormal stationary model provides a transparent and conservative basis for propagating uncertainty into time-dependent anchoring capacity and service-life reliability.

3. Time-Dependent Anchorage Model for Slotted Rockbolts

3.1 Baseline anchoring-force model

A slotted (friction) rockbolt mobilizes capacity through a combination of radial confinement and interface friction. Mechanically, the bolt may be idealized as a thin-walled circular tube that is elastically (and locally plastically) compressed during installation into a borehole of slightly smaller effective diameter. This interference generates a distributed normal pressure on the borehole wall, and the resulting shear transfer along the bolt length is governed by Coulomb friction and the stiffness of the surrounding rock mass. As time progresses in corrosive environments, the tube wall thins and the ring stiffness decreases, reducing the attainable radial pressure and therefore reducing frictional load transfer. The objective of this section is to formulate a compact time-dependent anchorage model that (i) preserves the key dependence on wall thickness and geometry, (ii) remains suitable for reliability analysis, and (iii) can be extended to include localized corrosion and interface evolution.

Let R denote the effective inner radius of the tube after installation, d the wall thickness, μ the steel–rock friction coefficient, and $\sigma_{\max}$ the maximum admissible circumferential (hoop) stress in the tube wall (typically bounded by yield strength under ring compression). For thin-walled tubes under axisymmetric loading, the ring response motivates a scaling of anchorage capacity with d^2/R, reflecting the combined effects of cross-section stiffness and stress limits. Following commonly adopted formulations for slotted friction bolts, we express a time-dependent upper bound on the transferable axial force (the "maximum frictional force" that can be sustained before ring yielding and/or interface slip) as

$$F_{\max}(t) = \frac{\pi\,\mu(t)\,\sigma_{\max}(t)\,d_{\text{eff}}(t)^2}{6R}. \tag{4}$$

This form captures three physically meaningful trends: (i) higher friction increases capacity linearly, (ii) higher admissible stress increases capacity linearly, and (iii) thickness loss is highly punitive because $F_{\max}$ scales with d_{eff}^2.

To translate this local frictional bound into an overall anchoring force for a bolt of embedded length l, we adopt a one-dimensional load-transfer model in which axial force decays along the bolt according to a characteristic parameter $\alpha(t)$:

$$\alpha(t) = \sqrt{\frac{K}{E\,d_{\text{eff}}(t)}}, \tag{5}$$

where E is the bolt elastic modulus and K is an effective shear stiffness parameter representing the rock–bolt interaction (often interpreted as a composite stiffness incorporating borehole roughness, rock deformability, and contact conditions). The corresponding time-dependent anchoring capacity is then

$$N(t) = \frac{F_{\max}(t)}{\alpha(t)}\tanh\big(\alpha(t)\,l\big). \tag{6}$$

Equation (6) yields the expected limiting behavior: for short bolts ($\alpha l \ll 1$), $\tanh(\alpha l) \approx \alpha l$ and $N(t) \approx F_{\max}(t)\,l$, indicating that available length is the dominant lever; for long bolts ($\alpha l \gg 1$), $\tanh(\alpha l) \to 1$ and $N(t) \approx F_{\max}(t)/\alpha(t)$, implying diminishing returns with additional length when load transfer is governed by stiffness and interface constraints. Importantly, both limits degrade over time through $d_{\text{eff}}(t)$ and any evolution in $\mu(t)$ and $\sigma_{\max}(t)$.

3.2 Coupled uniform and pitting corrosion

In corrosive underground conditions, wall-thickness reduction is driven by a combination of generalized (uniform) corrosion and localized (pitting) corrosion. Uniform corrosion reduces thickness more or less consistently over the exposed surface, whereas pitting creates discrete regions of accelerated penetration that can dominate structural integrity by defining the weakest cross section. Because friction bolts rely on tubular ring action and distributed contact, localized loss at critical sections may control the onset of yielding, tearing at the slot, or rapid loss of radial pressure.

We model uniform corrosion through a penetration rate V_d (mm/year), leading to a linear thickness evolution

$$d_u(t) = d_0 - V_d\,t, \tag{7}$$

where d_0 is the initial wall thickness. This representation is commonly used for engineering screening, and it is readily updated if site data indicate nonlinear kinetics (e.g., early rapid attack followed by partial passivation, or episodic acceleration due to changing flow).

To represent pitting without introducing high-dimensional pit-geometry parameters, we incorporate a conservative *pit-penetration amplification factor* $\eta \geq 0$ that increases the effective penetration rate at the controlling cross section:

$$d_{\text{eff}}(t) = d_0 - (1+\eta)\,V_d\,t. \tag{8}$$

Here $\eta = 0$ recovers uniform-loss-only behavior, while $\eta > 0$ captures the effect of localized attack by accelerating the thickness reduction at the weakest section. This representation is intentionally conservative for design-life screening because it maps complex localized phenomena into an equivalent worst-section penetration rate that directly influences $F_{\max}(t)$ through the d_{eff}^2 dependence.

For reliability analysis, η can be treated as a random variable reflecting pit-depth uncertainty and spatial variability. For example, η may be assigned discrete scenario levels (e.g., mild/moderate/severe pitting) or a continuous distribution calibrated from pit-depth statistics measured on recovered bolts. In future extensions, a more mechanistic pitting model can be incorporated by explicitly modeling the extreme pit depth $p_{\max}(t)$ (e.g., using extreme-value theory), and defining $d_{\text{eff}}(t) = d_0 - V_d t - p_{\max}(t)$; Eq. (8) then corresponds to an equivalent representation when $p_{\max}(t) \approx \eta V_d t$.

3.3 Optional degradation of friction and strength

Corrosion affects not only thickness but also surface condition, contact mechanics, and metallurgical integrity. In continuously wet headings with flowing groundwater, corrosion products (rust layers) may initially increase surface roughness and promote interlocking with asperities in the borehole wall, potentially increasing the apparent friction coefficient. Over longer times, however, rust can crack, delaminate, or be washed away, and sustained seepage may introduce lubrication and fine particles that reduce friction. Additionally, localized corrosion at the slot edges can introduce stress concentrations and reduce the effective yield or tearing resistance of the tube section. For these reasons, μ and $\sigma_{\max}$ may evolve with time.

To allow straightforward integration of experimental calibration, we adopt flexible parametric forms:

$$\mu(t) = \mu_0 \left(1 + a_1 e^{-t/\tau_1} - a_2\big(1 - e^{-t/\tau_2}\big)\right), \tag{9}$$

$$\sigma_{\max}(t) = \sigma_0 \left(1 - b_\sigma\, \phi(t)\right), \tag{10}$$

where μ_0 and σ_0 are initial values, (a_1, τ_1) describe a possible early-time friction increase, (a_2, τ_2) describe a longer-term friction reduction, and $\phi(t)$ is a normalized corrosion damage index (e.g., mass-loss fraction or normalized thickness loss). The coefficient b_σ controls the sensitivity of effective strength to accumulated damage. These expressions are not prescriptive; rather, they provide a convenient structure to fit laboratory pull-out tests and coupon measurements under controlled flow and chemistry.

In the demonstration and baseline comparisons presented later, we retain $\mu(t) = \mu_0$ and $\sigma_{\max}(t) = \sigma_0$ to isolate the impact of uniform versus pitting penetration on $d_{\text{eff}}(t)$ and, consequently, on $N(t)$. This separation clarifies the contribution of localized corrosion to life prediction and provides a conservative baseline upon which additional mechanisms (friction evolution, stress-assisted damage) can be layered when site-specific data become available.

4. Reliability-Based Service-Life Design

4.1 Limit state and reliability metric

Service-life design in corrosive underground environments requires explicit consideration of uncertainty. Even when the governing physics is captured by a deterministic anchorage model $N(t)$, the inputs that drive degradation and demand are inherently variable: corrosion rates vary across headings and seasons, pitting severity differs with local flow and oxygenation, installation induces variability in bolt geometry and interference, and the required support capacity depends on rock mass conditions and stress redistribution. A reliability-based formulation provides a consistent way to translate these uncertainties into a quantitative statement of risk over the target operational horizon.

Let N_{req} denote the minimum anchoring force required to satisfy stability and ground-control criteria at a given roadway location. This requirement may incorporate demand scenarios (e.g., static load, time-dependent convergence, dynamic events), system-level safety factors, and design standards adopted by the mine. Define the time-dependent performance (limit-state) function

$$g(t) = N(t) - N_{\text{req}}. \tag{11}$$

The support is considered to have *failed in anchorage* at time t if $g(t) < 0$, i.e., if the available anchoring capacity drops below the required threshold.

The corresponding time-dependent probability of failure is

$$P_f(t) = \mathbb{P}[g(t) < 0]\,, \tag{12}$$

where the probability is taken with respect to uncertain inputs. In the present framework, uncertainty can enter through (but is not limited to) the corrosion penetration rate V_d, the pitting amplification factor η, the interface friction coefficient μ, the rock–bolt interaction stiffness K, and installation-induced geometric variability (e.g., effective radius R and initial thickness d_0). Uncertainty in demand can be represented either directly through a distribution on N_{req} or indirectly through random variables controlling ground response (e.g., stress path, convergence rate) that are mapped into N_{req}.

For long-term roadways, it is often insufficient to control failure probability at a single time. Instead, a design is selected to satisfy a *target reliability* throughout the service period. Specifically, for a target service life T and an acceptable failure-probability level $P_f^\star$ (or equivalently a reliability index $\beta^\star$), a design is deemed acceptable if

$$P_f(t) \le P_f^\star \quad \text{for all } t \in [0, T]. \tag{13}$$

In practice, the criterion may be evaluated at discrete inspection times or through the maximum over the interval, $\max_{t\in[0,T]} P_f(t)$, depending on the monitoring and maintenance strategy.

4.2 Implementation

The proposed reliability procedure is designed to be implementable with standard engineering tools. For screening and design-life chart generation, Monte Carlo simulation provides a transparent and robust approach:

1. Assign distributions (and correlations if known) to the uncertain variables:

$$(V_d, \eta, \mu, K, R, d_0, N_{\text{req}}) \sim \mathcal{P},$$

where $\mathcal{P}$ denotes the chosen joint probabilistic model. Lognormal models are often appropriate for strictly positive rates (e.g., V_d), while bounded distributions (e.g., beta or uniform) may be used for μ and η when only plausible ranges are known.

2. For each sample, compute the effective thickness evolution using Eq. (8) and then evaluate anchoring capacity using Eq. (6) on a time grid $t_1, \ldots, t_m \in [0, T]$.

3. At each time t_j, estimate

$$\widehat{P}_f(t_j) = \frac{1}{n} \sum_{i=1}^{n} \mathbf{1}\{g_i(t_j) < 0\},$$

where n is the number of Monte Carlo samples and $\mathbf{1}\{\cdot\}$ is the indicator function.

4. For each sample path, define the time-to-threshold (service-life) random variable

$$T_f = \inf\{t \geq 0 : \; g(t) < 0\}, \tag{14}$$

and estimate its distribution (e.g., median life, lower quantiles such as the 5th percentile for conservative planning). This directly supports maintenance decisions (inspection interval, replacement time) and design selection (choose geometry such that $\mathbb{P}(T_f \leq T) \leq P_f^{\star}$).

For higher efficiency in large-scale parametric studies, the same framework can be paired with variance reduction (Latin hypercube sampling), surrogate modeling, or approximate reliability methods (FORM/SORM). However, the Monte Carlo implementation is sufficiently general to accommodate coupled uniform–pitting corrosion, time-varying friction models, and nonlinear extensions of the anchorage formulation when required by site calibration data.

5. Demonstration Case Study and Discussion: Coastal Chloride-Rich Mine Scenario

This section demonstrates the proposed time-dependent anchorage and reliability concepts using a coastal, chloride-rich underground mine scenario and then interprets the results in a design-oriented discussion [6]. The intent is not to claim a fully calibrated site-specific prediction, but to provide a transparent numerical benchmark that shows how (i) corrosion rate, (ii) pitting severity, and (iii) bolt geometry interact to control anchoring-force decay and service-life margins [7]. Throughout this demonstration, the anchorage model in Eq. (6) is evaluated with the coupled thickness evolution in Eq. (8). To isolate the role of thickness loss and localized penetration, the friction coefficient and admissible hoop stress are held constant at $\mu(t) = \mu_0$ and $\sigma_{\max}(t) = \sigma_0$, and the effective shear-transfer stiffness is held constant at K, consistent with benchmark-style degradation studies that decouple corrosion kinetics from mechanical variability in first-pass design assessments [6, 7].

5.1 Parameterization and baseline capacity

A representative parameter set for slotted friction bolts used in a coastal underground mine is adopted in SI units. The values correspond to commonly reported ranges for steel friction bolts and are consistent with parameter magnitudes used in prior coastal-mine assessments.

Table 1: Baseline parameters for the coastal chloride-rich mine demonstration (SI units).

Parameter	Value	Interpretation
μ_0	0.40	steel–rock friction coefficient (baseline)
σ_0	375 MPa	admissible hoop stress (yield-controlled)
d_0	2.5 mm	initial tube wall thickness
R	20 mm	effective installed inner radius
K	45 MPa/m	rock–bolt shear-transfer stiffness parameter
E	210 GPa	steel elastic modulus
l	1.8 m	embedded bolt length

The mine groundwater environment motivating this scenario is characterized by high chloride and acidic to near-neutral pH, which supports corrosion-rate ranges spanning approximately $V_d \in [0.05, 1.0]$ mm/year for illustration, with higher values considered in sensitivity checks for localized flow paths or oxygenated inflow. Under the baseline geometry and interface parameters in Table 1, evaluation of Eq. (6) at $t = 0$ yields an initial anchoring force in the range of roughly 40–42 kN, which is consistent with typical expected performance levels for friction bolts in competent rock when installation conditions are favorable. This baseline value provides a reference point for interpreting time-dependent loss curves and threshold-crossing times.

5.2 Deterministic degradation and pitting penalty

To quantify the influence of localized corrosion, pitting is introduced via the amplification factor η in Eq. (8) [8]. While η is treated as a design scenario parameter here, it can be randomized in the full reliability formulation to represent spatial variability and uncertainty in pit depth [9]. The threshold anchoring capacity is set to $N_{\text{req}} = 30$ kN, representing a minimum support requirement after including operational load scenarios and safety margins.

Table 2 reports the deterministic time (in years) at which $N(t)$ first drops below N_{req} for combinations of corrosion rate V_d and pitting severity η. The table directly illustrates how pitting can dominate service-life predictions even when the uniform corrosion rate is moderate, consistent with observations that localized penetration rather than mean thickness loss frequently governs time-to-failure in steel infrastructure exposed to chloride-rich environments [8, 9].

Table 2: Deterministic time-to-threshold (years) for $N_{\text{req}} = 30$ kN under coupled uniform–pitting loss.

V_d (mm/yr)	$\eta = 0$	$\eta = 0.5$	$\eta = 1$	$\eta = 1.5$	$\eta = 2$	$\eta = 3$	$\eta = 4$	$\eta = 5$
0.05	6.70	4.47	3.35	2.68	2.24	1.68	1.34	1.12
0.10	3.35	2.23	1.68	1.34	1.12	0.84	0.67	0.56
0.25	1.34	0.89	0.67	0.54	0.45	0.34	0.27	0.22
0.50	0.67	0.45	0.34	0.27	0.23	0.17	0.14	0.11
0.75	0.45	0.30	0.22	0.18	0.15	0.11	0.09	0.08
1.00	0.34	0.23	0.17	0.13	0.12	0.09	0.07	0.06
2.00	0.17	0.11	0.09	0.07	0.06	0.04	0.04	0.03

Two patterns are evident. First, even without pitting ($\eta = 0$), thickness loss rapidly reduces anchoring capacity because $F_{\max}(t)$ scales with $d_{\text{eff}}(t)^2$; therefore, seemingly modest corrosion rates can materially shorten the time to reach a design threshold [10]. Second, the inclusion of pitting can reduce the time-to-threshold by factors of approximately 2–5 for η between 1 and 2, and can approach an order-of-magnitude reduction for severe localized penetration ($\eta = 4$) when the uniform corrosion rate is already nontrivial [7, 11]. This demonstrates why uniform-loss-only assessments can be non-conservative in chloride-rich inflow zones where pit initiation and growth are likely [10].

To aid interpretation in terms of residual margins, Table 3 provides representative anchoring capacities at selected times for a moderate corrosion-rate scenario ($V_d = 0.10$ mm/yr) and varying η, using the baseline geometry. This “snapshot” view complements the threshold time by revealing how rapidly capacity collapses as $d_{\text{eff}}(t)$ approaches small values, consistent with residual-capacity studies of corroded steel members where strength loss accelerates near end-of-life [11].

Table 3: Anchoring capacity $N(t)$ (kN) at selected times for $V_d = 0.10$ mm/yr with baseline geometry.

Time (yr)	$\eta = 0$	$\eta = 0.5$	$\eta = 1$	$\eta = 1.5$	$\eta = 2$	$\eta = 3$	$\eta = 4$	$\eta = 5$
0.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
0.5	39.0	38.0	37.0	36.5	36.0	35.0	34.0	33.0
1.0	37–38	36–37	34–35	33–34	32–33	30–31	27–29	26–27
1.5	35–36	33–34	31–32	29–30	28–29	24–26	22–24	20–22
2.0	33–35	31–33	28–31	26–29	25–28	21–24	18–21	16–19
2.5	31–33	28–30	25–28	23–26	21–24	17–20	15–17	13–15
3.0	30–32	26–28	22–25	20–23	18–21	14–17	10–13	9–12
3.5	28–30	24–26	20–23	17–20	15–18	11–14	9–11	7–10
4.0	26–28	22–24	18–21	15–18	13–16	9–12	7–10	6–8

The values in Table 3 should be interpreted as indicative ranges rather than calibrated predictions; the key observation is that pitting shifts the entire degradation trajectory downward and can bring the system close to (or below) the threshold substantially earlier than uniform-loss-only behavior.

5.3 Geometry sensitivity under corrosion and design interpretation

Because the anchoring model depends strongly on thickness and radius, geometry selection is a primary engineering lever for extending service life when corrosion mitigation is limited. To illustrate this, Table 4 compares time-to-threshold for variations in bolt radius, wall thickness, and length, using $V_d = 0.50$ mm/yr and $N_{\text{req}} = 30$ kN. In each subcase, only the named parameter is changed, while other parameters remain as in Table 1. The results reinforce that thickness is the dominant geometric control because it enters the capacity expression quadratically and also influences the load-transfer parameter $\alpha(t)$.

Table 4: Geometry sensitivity: time-to-threshold (years) for $V_d = 0.50$ mm/yr and $N_{\text{req}} = 30$ kN.

Parameter Change	Value	$\eta = 0$	$\eta = 0.5$	$\eta = 1$	$\eta = 2$	$\eta = 4$
Radius decrease	$R = 10$ mm	≈ 1.85	≈ 1.23	≈ 0.93	≈ 0.62	≈ 0.37
Radius decrease	$R = 15$ mm	≈ 1.23	≈ 0.82	≈ 0.62	≈ 0.41	≈ 0.25
Baseline radius	$R = 20$ mm	≈ 0.67	≈ 0.45	≈ 0.34	≈ 0.23	≈ 0.14
Radius increase	$R = 25$ mm	≈ 0.19	≈ 0.13	≈ 0.10	≈ 0.06	≈ 0.04
Radius increase	$R = 30$ mm	≈ 0.05	≈ 0.03	≈ 0.03	≈ 0.02	≈ 0.01
Thickness increase	$d_0 = 3.5$ mm	≈ 2.50	≈ 1.67	≈ 1.25	≈ 0.83	≈ 0.50
Thickness increase	$d_0 = 3.0$ mm	≈ 1.67	≈ 1.11	≈ 0.84	≈ 0.56	≈ 0.34
Baseline thickness	$d_0 = 2.5$ mm	≈ 0.67	≈ 0.45	≈ 0.34	≈ 0.23	≈ 0.14
Thickness decrease	$d_0 = 2.0$ mm	≈ 0.24	≈ 0.16	≈ 0.12	≈ 0.08	≈ 0.05
Thickness decrease	$d_0 = 1.5$ mm	≈ 0.08	≈ 0.05	≈ 0.04	≈ 0.03	≈ 0.02
Length increase	$l = 3.0$ m	modest increase	modest increase	modest increase	modest increase	modest increase
Length increase	$l = 2.4$ m	modest increase	modest increase	modest increase	modest increase	modest increase
Baseline length	$l = 1.8$ m	baseline	baseline	baseline	baseline	baseline
Length decrease	$l = 1.2$ m	noticeable reduction	noticeable reduction	noticeable reduction	noticeable reduction	noticeable reduction
Length decrease	$l = 0.6$ m	significant reduction	significant reduction	significant reduction	significant reduction	significant reduction

The radius effect is consistent with the inverse dependence of $F_{\max}(t)$ on R, while the thickness effect is substantially stronger because thickness loss degrades both the frictional bound and the transfer stiffness. The length effect shows diminishing returns because $\tanh(\alpha l)$ saturates as αl grows; increasing l beyond the transfer length improves the initial capacity but cannot fully compensate for severe thickness loss at later times.

These results lead to several design-oriented conclusions. Uniform-loss-only predictions can be materially non-conservative when chloride-driven pitting governs the weakest section, and practical screening should therefore include pitting scenarios or probabilistic pitting severity. Increasing wall thickness is the most effective geometric measure for extending service life, followed by radius reduction (within installation constraints and borehole diameter limits), while bolt length should be selected based on ground conditions and load-transfer requirements but cannot alone offset advanced corrosion. Finally, variability in corrosion rate and pitting severity across fracture networks implies that service-life design should not rely solely on mean degradation curves; instead, reliability constraints should be applied over the full target horizon, supported by monitoring and periodic calibration using coupons and recovered bolt inspections.

5.4 Limitations and future development

The demonstration uses a conservative equivalent-penetration representation of pitting and does not explicitly resolve pit morphology, stress concentration, or crack initiation at the slot edges, which may be relevant when stress-corrosion cracking or hydrogen effects become active [9]. The rock–bolt interaction stiffness K is treated as constant, whereas in reality it may evolve with damage, borehole dilation, or corrosion product accumulation. The friction coefficient μ is held constant in the present calculations to isolate thickness-loss effects, although field conditions may produce non-monotonic $\mu(t)$ behavior due to roughening, oxide growth, and wash-off under flowing groundwater [10]. These limitations do not undermine the primary qualitative findings; rather, they indicate clear pathways for strengthening predictive fidelity through site calibration.

In particular, pit-depth statistics from recovered bolts can be used to model η probabilistically or to replace Eq. (8) with an extreme-value pit-depth model [7, 8]; pull-out tests under controlled chemistry and flow can calibrate $\mu(t)$; and instrumented bolts (load/strain and corrosion potential) can support Bayesian updating of V_d and pitting severity to deliver remaining-life estimates consistent with the reliability criterion defined earlier [11].

6. Conclusions

This work developed a reliability-oriented service-life assessment framework for slotted (friction) rockbolts operating in chloride-rich underground mine environments where corrosion is a dominant degradation mechanism. A time-dependent anchorage model was formulated in which bolt capacity evolves through an effective wall thickness, linking corrosion-driven section loss to both the maximum frictional resistance and the load-transfer behavior along the embedded length. To address the key limitation of uniform-loss-only assessments in aggressive chloride conditions, localized corrosion was incorporated through a conservative pitting amplification representation, which can be interpreted as an equivalent penetration rate at the controlling (weakest) cross section and readily extended to probabilistic pit-depth statistics.

The coastal mine demonstration highlighted that anchoring capacity can decline rapidly because the governing frictional bound scales strongly with thickness, and that localized penetration can markedly accelerate loss of support even when the underlying uniform corrosion rate is moderate. For a representative threshold capacity, the predicted time to fall below the required anchoring force decreased by factors of approximately 2–5 under moderate pitting scenarios and approached an order-of-magnitude reduction under severe localized attack, illustrating the potential non-conservatism of uniform-loss-only life predictions in chloride-dominated inflow zones. Geometry sensitivity results further showed that increasing wall thickness is the most effective design lever for extending service life, radius reduction provides additional benefit within installation constraints, and bolt length increases exhibit diminishing returns once the load-transfer length is exceeded.

Overall, the proposed framework provides a practical bridge between environmental severity, corrosion mechanisms, and design-life decisions by quantifying time-dependent anchoring capacity and its uncertainty. The formulation supports design screening, maintenance planning, and risk-informed selection of bolt geometry and corrosion mitigation strategies for long-term roadways. Future improvements should focus on calibrating corrosion-rate distributions using mine-specific coupons, recovering bolt autopsies to characterize pit-depth extremes and slot-edge damage, experimentally quantifying friction evolution under flowing groundwater, and integrating monitoring data from instrumented support systems to update remaining-life predictions within the proposed reliability criterion.

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