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Research Paper

Seismic Reliability Analysis of the Koohrang-III Tunnel Using Response Surface Methodology, Hasofer–Lind Reliability Analysis, and Finite Element Modeling

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Abstract

This study presents a robust framework for assessing the seismic reliability of the Koohrang-III water transmission tunnel by accounting for the complex soil-structure interaction (SSI) phenomenon. A high-fidelity finite element-based numerical model was developed to simulate the tunnel's dynamic behavior under various seismic loading conditions. To evaluate structural reliability, this research integrates the Response Surface Method (RSM) with the Hasofer–Lind algorithm, providing a computationally efficient approach to quantify performance. Six distinct strong ground motions were applied during nonlinear time-history analyses to extract critical design parameters, specifically the thrust force and bending moments. The results demonstrate that the tunnel's structural reliability is highly sensitive to the analyzed loading parameters. Specifically, the thrust force exhibited the highest failure probability at approximately 37.5%, while the bending moment showed the lowest at roughly 2%. These findings highlight the necessity of reliability-based assessments in enhancing tunnel seismic safety protocols and optimizing structural design against earthquake-induced hazards.

Keywords: Seismic reliability, Tunnel, Soil-structure interaction, Response surface method, Hasofer–Lind method

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1. Introduction

Due to the increasing demand for underground transportation and water transmission through tunnels, alongside the significant construction and maintenance costs, precise tunnel design is essential to ensure satisfactory performance under extreme long-term loadings, such as earthquakes. Tunnels are constructed in geological environments characterized by inherent uncertainties arising from geotechnical parameters and complex soil–structure interaction (SSI). To ensure safety throughout the service life, these uncertainties must be rigorously incorporated into the design process. Moreover, the SSI phenomenon, which significantly dictates the seismic response of tunnels, requires careful consideration. Reliability analysis thus provides a robust framework for quantifying the impact of these uncertainties on structural responses and assessing the probability of damage or failure.

Sun et al. (2020) investigated the dynamic tensile response and fracture behavior of arched hydraulic tunnels under near-fault and far-fault motions. Zhu et al. (2020) examined the three-dimensional seismic response of long-cover tunnels in porous-viscoelastic layered media using a combined FEM–BEM approach, considering soil nonlinearity via an equivalent linear method. He et al. (2022) proposed seismic capacity models for underground structures by incorporating spatial soil property distributions for fragility analysis. Chen et al. (2022) evaluated the seismic performance of prefabricated versus in-situ underground structures considering SSI. Wang et al. (2022) demonstrated that the coefficient of variation in soil shear modulus significantly influences dynamic responses. Zhang et al. (2022) utilized pseudo-dynamic methods to analyze tunnel face stability, while Feng et al. (2023) optimized geometric parameters for small-radius curved tunnels using the response surface method (RSM). Further, Li et al. (2020) focused on reliability-based design for support pressures, and Azadi et al. (2020) determined load and resistance factors for linings under extreme events. Golshani and Rezaei (2020) numerically assessed the effects of buried depth and opening size on seismic forces. Wang et al. (2021) conducted shaking-table tests to study utility tunnels, while Wu et al. (2019) and Tan et al. (2020) focused on explosion loading and unsaturated media, respectively. Liu et al. (2020) and Lü et al. (2011) utilized FEM and first/second-order reliability methods to evaluate anchor stability and ground–support interaction. Specifically, Momenzadeh et al. (2019) assessed the seismic reliability of a shallow tunnel by combining RSM, HLM, and FEM, focusing on basic soil random variables.

Despite these advancements, a review of the literature reveals critical research gaps. First, most existing reliability studies focus on idealized or shallow structures, often neglecting the coupled effects of pore water pressure and deep-buried conditions in operational water-transmission tunnels. Second, many frameworks rely on a limited set of seismic inputs, failing to capture the aleatory uncertainty inherent in real ground motions. Third, while the combination of RSM, HLM, and FEM has been previously introduced, its application to existing operational hydraulic infrastructures—where failure leads to catastrophic socio-economic consequences—remains under-explored.

The present study addresses these gaps by developing an advanced seismic reliability framework tailored for the Koohrang-III water-transmission tunnel. Moving beyond the methodology established by Momenzadeh et al. (2019), this research introduces a more comprehensive uncertainty propagation model. The novelty of this work lies in the integration of real-world operational constraints, including the explicit consideration of pore water pressure and nonlinear SSI, evaluated under six distinct real earthquake records to ensure statistical robustness. The proposed framework employs FEM to capture complex structural nonlinearities, RSM to generate accurate surrogate models for implicit limit-state functions, and HLM for efficient reliability index estimation.

The main contribution of this research is the systematic evaluation of four critical structural responses (axial force, shear force, bending moment, and displacement) across multiple failure modes. By identifying the governing random variables through sensitivity analysis, this study provides a practical benchmark for the seismic retrofitting and safety assessment of deep-buried, operational hydraulic tunnels, offering insights that extend significantly beyond generic or shallow tunnel reliability models.

2. Literature Review

Seismic assessment of underground structures has received increasing attention because the performance of tunnels during earthquakes is governed by the complex interaction between the surrounding ground and the tunnel lining. Previous studies have investigated the seismic response of tunnels using analytical, numerical, experimental, and reliability-based approaches, with particular emphasis on tunnel geometry, ground-motion characteristics, soil properties, construction conditions, and soil–structure interaction. Although deterministic analyses provide valuable insights into tunnel behavior under seismic loading, they cannot adequately quantify the effects of uncertainties in geotechnical parameters, structural properties, and seismic excitation. Consequently, reliability-based methods have been increasingly employed to estimate failure probabilities and reliability indices for different tunnel performance measures. Accordingly, the following section discusses selected studies on the seismic response and reliability assessment of underground structures, highlighting the methodologies adopted, the uncertainties considered, and the research gaps that motivate the present study.

- Sekfali and Lafifi (2025) evaluated the reliability of mechanically stabilized earth walls in granular soil by incorporating geotechnical uncertainties into a probabilistic framework. Using ANOVA to identify influential design variables, they compared the predictive accuracy of Response Surface Methodology, Artificial Neural Networks, and the Adaptive Neuro-Fuzzy Inference System in approximating the limit-state function. Their findings indicated that Artificial Neural Networks yielded superior performance. Furthermore, by integrating this model with a multi-objective genetic algorithm to optimize the Hasofer–Lind reliability index, the authors demonstrated that rigorous accounting of parameter distributions is essential for accurate uncertainty quantification and identification of critical design factors.
- Fang et al. (2025) addressed the challenges associated with complex, implicit performance functions in tunnel reliability analysis by proposing an efficient probabilistic approach. Their method integrates a revised HLRF-BFGS algorithm with the finite difference method to improve convergence and effectively handle high degrees of nonlinearity. Validation results demonstrated that this approach significantly enhances computational efficiency, reducing processing costs by up to 72% compared to classical reliability methods, while achieving high accuracy with relative errors consistently below 3% when compared against Monte Carlo simulations.
- Wang et al. (2026) developed a time-varying reliability framework for tunnel linings exposed to freeze–thaw degradation, cracking, and carbonation. The proposed approach combined the Gamma process, probability density

evolution method, and fault tree analysis to evaluate the stochastic deterioration of concrete strength and multiple failure modes. Their results showed that carbonation was the dominant failure mechanism during the first 50 years, whereas resistance degradation became predominant thereafter. The system failure probability reached 50% after 69 years, while the proposed method achieved comparable accuracy to Monte Carlo simulation using only one-twelfth of the required samples.

- Fattahi and Hematian (2025) combined block theory and probabilistic reliability methods to investigate the stability of underground excavations in a water diversion tunnel. Their study identified unstable rock blocks under uncertain geological conditions and evaluated their behavior using FORM, SORM, and Monte Carlo simulation. The results showed that block height was the most influential parameter affecting stability, and the analysis highlighted the importance of incorporating both block geometry and uncertainty in underground design.
- Feng et al. (2025) proposed a machine learning–based framework for uncertainty analysis of the mechanical response of surrounding rock in deeply buried tunnels. By integrating the AdaBoost algorithm with FORM and the SHGO optimization method, they successfully estimated rock failure degree and displacement at the Jinping Underground Laboratory with high accuracy. Their results also showed that the proposed surrogate-based approach improved reliability-index prediction compared with the traditional RSM-FORM method.
- Luo and Wang (2026) investigated the stochastic seismic response and reliability of mountain tunnels crossing fault fracture zones, with particular emphasis on the spatial variability of fault properties. To address this often-neglected source of uncertainty, they developed a framework combining the probability density evolution method, the Karhunen–Loève expansion method, and three-dimensional numerical modeling in ABAQUS. Their results showed that the spatial variability of the fault fracture zone significantly affects tunnel seismic response, especially the dispersion of lateral relative deformation and the variability of longitudinal deformation as plastic damage progresses. The study further indicated that the evolution of plastic strain follows distinct stages, demonstrating the importance of accounting for spatially variable fault conditions in seismic reliability assessment of cross-fault tunnels.
- Wang et al. (2025) examined the stochastic seismic response and reliability of immersed tunnels by considering the coupled effect of water and soil as well as the non-stationary nature of earthquake loading. They developed a framework integrating the probability density evolution method with an acoustic–structural coupling approach to simulate tunnel behavior under realistic seismic conditions. Their results indicated that surrounding water can exert a damping effect that reduces seismic response, while the tunnel lining exhibits progressive plastic development and brittle damage under strong ground motion. The study demonstrated that incorporating water–soil coupling and stochastic ground-motion characteristics provides a more realistic basis for seismic reliability assessment of immersed tunnels.
- Mohsenian and Di-Sarno (2025) investigated the seismic reliability of concrete tunnel-form building systems with explicit consideration of non-structural components. Using multi-level and multi-objective assessment approaches, they showed that acceleration- and displacement-sensitive non-structural elements can significantly reduce overall system

reliability, even when the structural system itself performs satisfactorily. Their results further indicated weak coordination between structural and non-structural damage states, highlighting that non-structural components, particularly acceleration-sensitive ones, may govern reliability at key performance levels.

• Mei et al. (2025) developed a probabilistic framework to evaluate the seismic performance of tunnel linings by concurrently modeling the spatial variability of rock mass properties and the uncertainty of earthquake excitation. Integrating random field theory with an enhanced Clough–Penzien spectrum, their study revealed that treating these uncertainty sources in isolation significantly underestimates structural risk, with concurrent modeling resulting in substantial increases in both the magnitude and dispersion of internal forces. Their findings highlighted the critical influence of spectral parameters and demonstrated that the coupling of these uncertainties can elevate failure probabilities by up to 38%, underscoring the necessity of integrated probabilistic assessments for reliable tunnel design in seismic regions.

• Fatima et al. (2026) investigated the seismic behavior of rock tunnels in complex Himalayan geological settings, with particular emphasis on the influence of structural geology and fold configuration. Using finite element analysis, they compared tunnel responses in igneous, metamorphic, and sedimentary rocks and found that tunnels in igneous formations were more vulnerable to seismic disturbance. Their study further assessed different fold classes and tunnel positions within the most critical fold geometry, ultimately identifying the tunnel shape most capable of withstanding adverse geological conditions. The findings provide practical insight into the selection of tunnel alignment and design strategies in structurally complex seismic regions.

Table 1. Summary of recent studies on seismic reliability and uncertainty analysis of tunnels and underground structures

Reference	Main focus	Methodology / tools	Key findings	Relevance to present study
Sekfali and Lafifi (2025)	Reliability analysis of mechanically stabilized earth walls under geotechnical uncertainty	ANOVA, RSM, ANN, ANFIS, MOGA, Hasofer–Lind reliability index	ANN provided the best surrogate performance; rigorous treatment of parameter distributions improved uncertainty quantification and identification of critical variables	Demonstrates the value of surrogate modeling and reliability optimization in geotechnical systems under uncertainty
Fang et al. (2025)	Efficient probabilistic treatment of complex and implicit performance functions in tunnel reliability problems	Revised HLRF-BFGS algorithm, finite difference method, comparison with Monte Carlo simulation	Improved convergence for nonlinear reliability problems; computational cost reduced by up to 72%, with relative error below 3%	Supports the use of efficient reliability algorithms for tunnel problems with computationally demanding performance functions

Reference	Main focus	Methodology / tools	Key findings	Relevance to present study
Wang et al. (2026)	Time-varying reliability of tunnel linings under freeze–thaw degradation, cracking, and carbonation	Gamma process, probability density evolution method, fault tree analysis	Carbonation governed early-life failure, while resistance degradation dominated long-term behavior; 50% failure probability occurred at 69 years; comparable accuracy achieved with far fewer samples than Monte Carlo simulation	Highlights the importance of time-dependent deterioration and efficient probabilistic tools in tunnel reliability assessment
Fattahi and Hematian (2025)	Stability assessment of underground excavations under uncertain geological conditions	Block theory, FORM, SORM, Monte Carlo simulation	Block height was identified as the most influential stability parameter; uncertainty and block geometry strongly affected tunnel safety	Shows the importance of combining mechanical instability analysis with probabilistic reliability evaluation in underground engineering
Feng et al. (2025)	Uncertainty analysis of surrounding rock response in deeply buried tunnels	AdaBoost, FORM, SHGO optimization, sensitivity analysis	The surrogate-based framework accurately predicted rock failure degree and displacement; reliability-index estimation outperformed the traditional RSM-FORM approach	Confirms the effectiveness of machine learning assisted reliability analysis for complex tunnel-related geomechanical problems
Luo and Wang (2026)	Stochastic seismic response and reliability of mountain tunnels crossing fault fracture zones	Probability density evolution method, Karhunen–Loève expansion, ABAQUS-based 3D numerical modeling	Spatial variability of the fault fracture zone significantly influenced deformation dispersion and plastic strain evolution	Directly relevant to seismic tunnel reliability, especially where spatially variable geological uncertainty affects structural response
Wang et al. (2025)	Seismic reliability of immersed tunnels under coupled water–soil interaction and non-	Probability density evolution method, coupled acoustic–structural method,	Water exerted a damping effect on seismic response; tunnel lining exhibited	Emphasizes the importance of realistic loading and coupled

Reference	Main focus	Methodology / tools	Key findings	Relevance to present study
	stationary earthquake loading	stochastic ground motion modeling	progressive plasticity and brittle damage under strong shaking	interaction effects in probabilistic seismic assessment of tunnels
Mohsenian and Di-Sarno (2025)	Seismic reliability of tunnel-form building systems considering non-structural components	Multi-level and multi-objective reliability assessment	Non-structural components significantly reduced overall system reliability; acceleration-sensitive components were particularly critical	Illustrates that system reliability may be governed by components often neglected in conventional structural assessment
Mei et al. (2025)	Probabilistic seismic response of tunnel linings under coupled geological and seismic uncertainties	Random field theory, enhanced Clough–Penzien spectrum, probabilistic seismic analysis	Simultaneous consideration of rock variability and seismic uncertainty substantially increased the mean, dispersion, and failure probability of tunnel response	Strongly supports integrated treatment of multiple uncertainty sources in seismic reliability assessment of tunnel linings
Fatima et al. (2026)	Influence of structural geology and fold configuration on tunnel seismic behavior	Finite element analysis, comparative assessment across rock types and fold classes	Tunnels in igneous formations were more vulnerable; fold geometry and tunnel position strongly affected seismic performance	Reinforces the role of geological setting and structural configuration in seismic response evaluation of tunnels

Despite the substantial progress achieved in the reliability assessment of tunnels and geotechnical structures, several important research gaps remain. Previous studies have mainly focused on specific uncertainty sources or failure mechanisms, including spatial variability of geological properties, fault fracture zones, water–soil coupling, freeze–thaw deterioration, block instability, and non-stationary earthquake excitation. Other investigations have improved computational efficiency through machine-learning-based surrogate models, probability density evolution methods, and advanced reliability algorithms. However, relatively limited attention has been devoted to an integrated, site-specific framework that combines finite element modeling, response surface methodology, and the Hasofer–Lind method to quantify the seismic.

3. Koohrang-III Water Transmition Tunnel

The primary objective of this research is to evaluate the seismic reliability of water transmission tunnels, with a specific focus on soil-structure interaction (SSI). The Koohrang-III water transmission tunnel is utilized as a case study for the proposed parametric analysis. Located in central Iran, approximately 120 km from Shahrekord, this 23.5 km long structure is a critical component of regional water management. Constructed to facilitate water transfer from the Karun River to the Zayandeh Rud basin, the tunnel provides an annual capacity of 300 million cubic meters for drinking, industrial, and agricultural use, while concurrently enhancing the regulated water volume of the Zayandeh Rud dam in Isfahan. Given the presence of four fault crossings along its alignment—the most significant of which affects over 255 meters of the tunnel—a rigorous seismic evaluation is imperative (Shahidi and Vafaeian 2005). The tunnel features a circular cross-section with diameters ranging from 4.1 to 4.4 meters. The geometry and longitudinal profile of the structure are illustrated in Figure 1. Previous research, notably Shahidi and Vafaeian (2005), has focused on the design of flexible tunnel linings to accommodate these active fault zones; the current study extends this work by performing a comprehensive probabilistic reliability assessment.

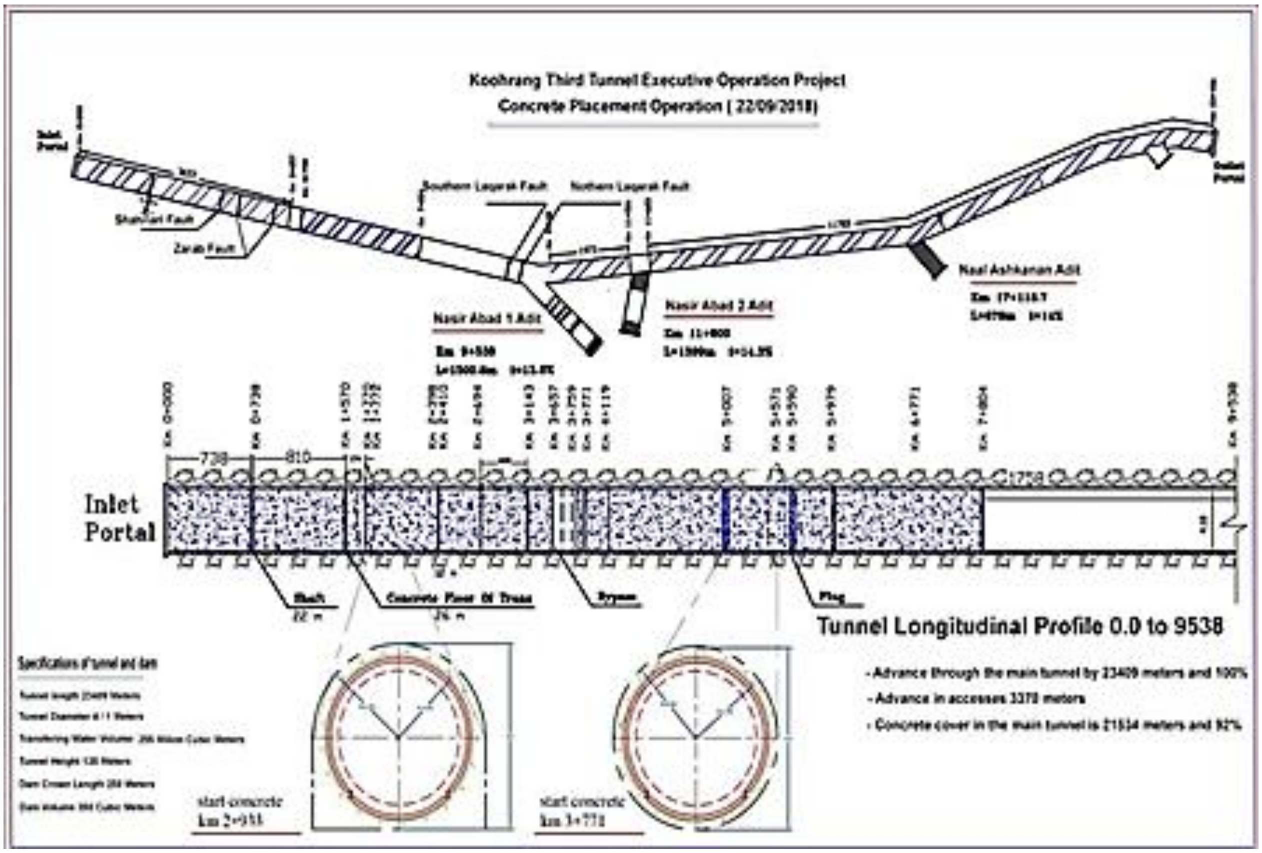


Figure 1. General view of the plan, geometry and section of the tunnel

4. Reliability Analysis Process

This study presents a hybrid framework for assessing the seismic reliability of the tunnel by integrating the Hasofer–Lind method, the Response Surface Methodology, and finite element modeling. The primary objective is to calculate the reliability indices and corresponding failure probabilities for four critical structural response parameters, namely axial force, shear force, bending moment, and displacement, under both design and operational earthquake loading levels. The combined framework was selected because each method serves a complementary purpose. Finite element modeling provides a mechanically consistent representation of the tunnel–ground system and explicitly accounts for soil–structure interaction. Response Surface Methodology reduces the computational burden associated with repeated nonlinear finite element simulations by replacing the numerical model with an approximate analytical performance function. The Hasofer–Lind method subsequently enables the reliability index to be calculated efficiently without requiring a large number of direct Monte Carlo simulations.

The numerical modeling procedure was implemented through the combined use of ABAQUS and MATLAB. ABAQUS was employed to construct and analyze the finite element model of the tunnel, whereas MATLAB was used for designing the numerical scenarios, developing the response surface functions, and performing the Hasofer–Lind reliability calculations. To explicitly incorporate uncertainty associated with soil–structure interaction, three principal random variables were considered: the soil or rock modulus of elasticity, the soil or rock Poisson's ratio, and pore water pressure. These variables were selected because they directly influence the stiffness, deformability, stress distribution, and effective confinement of the surrounding ground and consequently affect the seismic response of the tunnel lining.

A full-factorial response surface design was adopted to systematically investigate the combined effects of the three random variables. For each variable, three representative levels were defined based on its mean value, standard deviation, and coefficient of variation. The selected levels covered the central value and the expected range of variation around the mean while avoiding an unnecessarily broad parameter domain that could result in physically unrealistic soil or rock properties. The resulting design consisted of twenty-seven unique combinations of the three random variables. This design was preferred to a one-factor-at-a-time procedure because it allows the simultaneous evaluation of the main effects and interaction effects among the soil or rock modulus of elasticity, Poisson's ratio, and pore water pressure. The mean value, coefficient of variation, and standard deviation of each variable are reported in Table 2, while the corresponding finite element modeling scenarios are presented in Table 3.

For each design point, the tunnel finite element model was subjected to six earthquake acceleration time histories. The same tunnel geometry, material properties, boundary conditions, mesh configuration, contact definitions, damping assumptions, and loading procedures were maintained in all simulations. Therefore, the differences among the numerical responses were attributable only to the prescribed earthquake records and the selected values of the random variables. This consistent modeling procedure was adopted to minimize potential bias caused by changes in numerical settings rather than by physical uncertainty. The use of multiple earthquake records also reduced the possibility that the estimated reliability would be governed by the characteristics of a single ground motion. All earthquake records were subjected to the same preprocessing and scaling procedure, and the response quantities were extracted using an identical output and post-processing procedure.

The numerical responses obtained from the twenty-seven design points were used to construct second-order response surface functions for axial force, shear force, bending moment, and displacement. For each structural response, the response surface was formulated as a quadratic function of the three random variables and included linear effects, quadratic effects, and pairwise interaction effects. This formulation was selected because it can represent nonlinear trends and interactions among the input variables while remaining computationally efficient for reliability analysis. The adequacy of each response surface was evaluated by comparing the predicted responses with the corresponding finite element results and by examining the regression performance within the selected design domain. Accordingly, the response surfaces were used only within the range of the investigated soil, rock, and hydraulic parameters, thereby limiting the potential bias associated with extrapolation.

The Hasofer–Lind method was then applied to the developed performance functions to determine the most probable failure point and the corresponding reliability index for each structural response and earthquake loading case. The performance functions were defined by comparing the predicted structural response with the relevant capacity or allowable limit. The Hasofer–Lind method was selected because it provides an efficient reliability estimate for nonlinear performance functions and is particularly suitable when direct evaluation of the finite element model is computationally demanding. Finally, the failure probability was calculated for axial force, shear force, bending moment, and displacement based on the obtained reliability indices and the assumption of a standard normal distribution.

Several measures were adopted to minimize potential sources of bias in the reliability assessment. First, the full-factorial design ensured that the selected input variables were varied systematically rather than selectively. Second, the use of three levels for each variable allowed nonlinear effects and pairwise interactions to be represented in the response surface functions. Third, all finite element analyses were conducted using consistent numerical assumptions and an identical response-extraction procedure. Fourth, the use of six earthquake records reduced record-specific bias and provided a broader representation of seismic excitation. Finally, the reliability calculations were restricted to the parameter domain covered by the finite element simulations and the response surface design, thereby avoiding unsupported extrapolation. These procedures improve the reproducibility of the analysis and strengthen the reliability of the estimated seismic performance of the Koohrang-III tunnel.

Table 2. Statistical characteristics of random parameters in response level method

Parameter	Mean	standard deviation	coefficient of variation
E_s (GPa)	1.1	0.055	0.05
ϑ_s	0.33	0.033	0.1
P_w (MPa)	0.30397	0.0152	0.05

Table 3. Different scenarios defined based on possible values of random variables (RSM)

Scenario	E_s (GPa)	ϑ_s	P_w (MPa)
Sc1	1.1	0.33	0.30397
Sc2	1.1	0.33	0.31917
Sc3	1.1	0.33	0.28878
Sc4	1.1	0.363	0.30397
Sc5	1.1	0.363	0.31917
Sc6	1.1	0.363	0.28878
Sc7	1.1	0.297	0.30397
Sc8	1.1	0.297	0.31917
Sc9	1.1	0.297	0.28878
Sc10	1.155	0.33	0.30397

Scenario	E_s (GPa)	ϑ_s	P_w (MPa)
Sc11	1.155	0.33	0.31917
Sc12	1.155	0.33	0.28878
Sc13	1.155	0.363	0.30397
Sc14	1.155	0.363	0.31917
Sc15	1.155	0.363	0.28878

5. FE Modeling and Analysis

A refined two-dimensional finite element model of the tunnel structure and its surrounding environment, including the tunnel lining and the surrounding soil-rock mass, was developed in the ABAQUS platform. The model consists of two distinct parts, namely the tunnel lining and the surrounding ground domain. To satisfy the requirements of numerical modeling and reduce errors associated with seismic wave reflections from the model boundaries, the minimum dimensions of the surrounding soil-rock domain were taken as ten times the lining diameter on each side, as illustrated in Figure 2. The lining diameter and thickness were considered to be 4.1 m and 0.4 m, respectively. Based on these dimensions, a surrounding domain with plan dimensions of 90 m by 105 m was modeled. The geometric characteristics of the tunnel lining used in the numerical model are shown in Figure 2. In addition, the material properties of the surrounding soil and the concrete lining were defined according to the design and construction documents, and the corresponding parameters are provided in Tables 4 and 5.

To strengthen the methodological transparency and address potential sources of bias, the numerical model was developed under a consistent set of assumptions for all simulation cases. The selected model dimensions were sufficiently large to reduce boundary effects and limit artificial wave reflections, thereby improving the reliability of the seismic response prediction. The use of uniform geometric and material definitions across all analysis scenarios also ensured that the observed variations in response were attributable to the prescribed random variables and earthquake loading conditions rather than inconsistencies in the modeling procedure. These measures, together with the systematic design of the numerical simulations, provide a more robust basis for the subsequent reliability analysis.

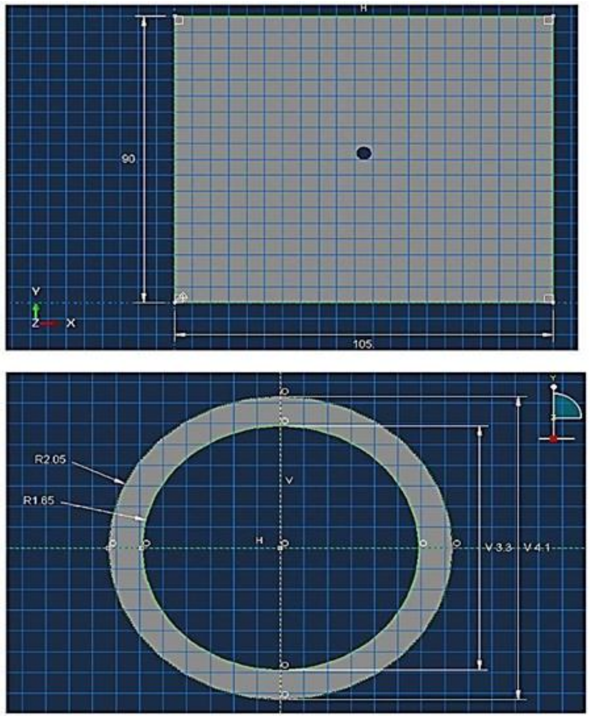


Figure 2. Dimensions of the FE model

Table 4. Material properties of concrete lining in the FE model

Mass density (Kg/m3)	Elastic state		Damaged plastic state				
	E_c (Pa)	ϑ_c	Dilation Angle	Eccentricity	*fb/fc*	k	Viscosity
2250	2.06E+10	0.2	30	0.1	1.16	0.6667	0.0005

Table 5. Material properties of surrounding soil in the FE model.

Mass density (Kg/m3)	Elastic state		Mohr Coulomb Plasticity model				Damping	
	E_s (Pa)	ϑ_s	Friction Angle (Phi)	Dilation Angle	Cohesion	Plastic Strain	Alpha	Beta
1300	1.1E+09	0.33	22.6	0.1	1700000	0	0.0533	0.00476

In the numerical model, the main interaction considered was the contact between the tunnel lining and the surrounding soil. Since the seismic loading consisted of six strong earthquake ground motions, the lining–soil interface was modeled as a complete slip-type contact condition using the hard contact formulation in ABAQUS. The boundary conditions in the finite element model were applied in two parts. First, the four straight side boundaries of the surrounding soil domain were constrained. The two vertical boundaries were restrained in the horizontal direction, while the bottom boundary was restrained in the vertical direction, as shown in Figure 3. Earthquake ground motions were then applied to the bottom boundary of the soil in the form of acceleration time histories. In addition to seismic loading, the forces resulting from pore water pressure were also applied at the upper semicircular surface of the lining.

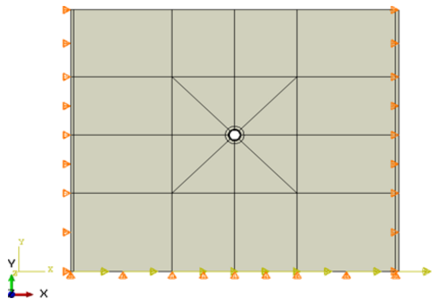


Figure 3. A view of the boundary conditions of the finite element model

In the second part, the boundary between the tunnel lining and the surrounding soil was modeled using a refined finite element mesh, as shown in Figure 4. Plane strain elements with explicit formulation and linear geometric order, identified in ABAQUS as CPE4R, were used in the analysis. To balance computational efficiency and result accuracy, the mesh size was varied gradually, with finer elements assigned near the lining and coarser elements used farther away from the tunnel boundary.

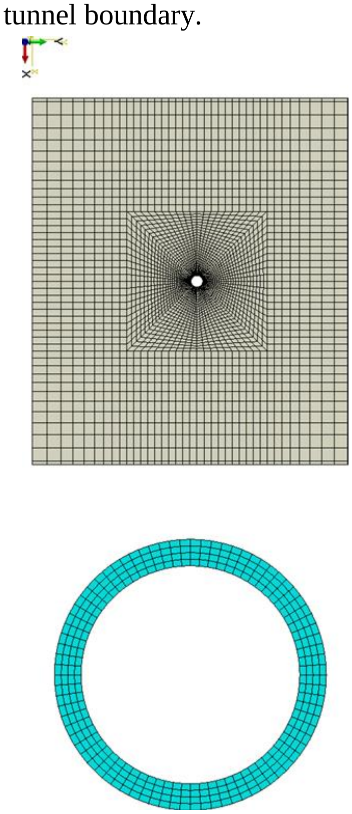
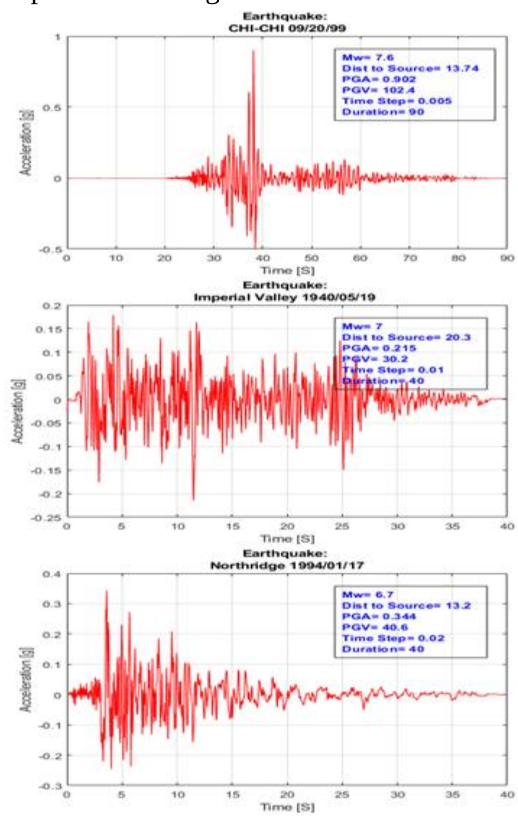


Figure 4. A view of the meshing of the finite element model

The finite element model was subjected to six earthquake acceleration time histories. The selected records included Cape Mendocino, Chi-Chi, Kobe, Northridge, Imperial Valley, and Loma Prieta. The acceleration time histories and the corresponding characteristics of each record are presented in Figure 5.



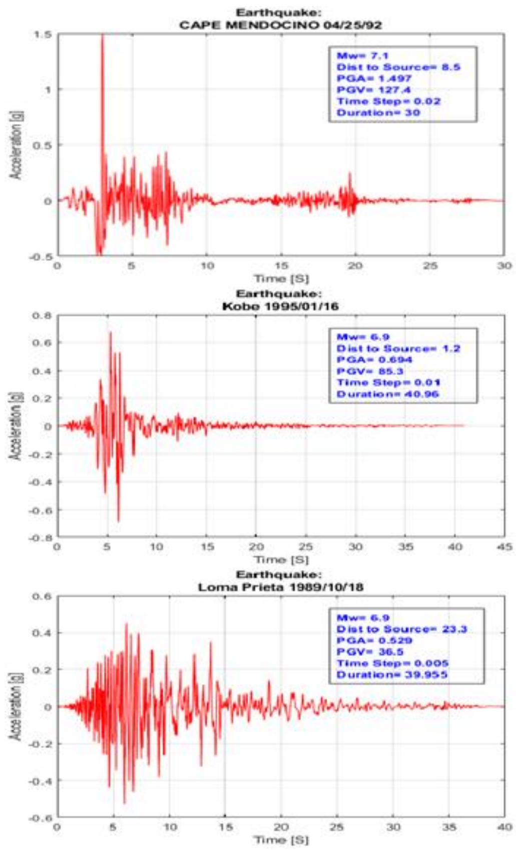


Figure 5. Acceleration time history and specifications of earthquake records considered

Time history analysis was conducted for the numerical model. The maximum stress and displacement responses of the tunnel lining were extracted for each of the six earthquake records. Representative results for the Chi-Chi and Kobe earthquake records are presented in Figures 6 and 7, respectively.

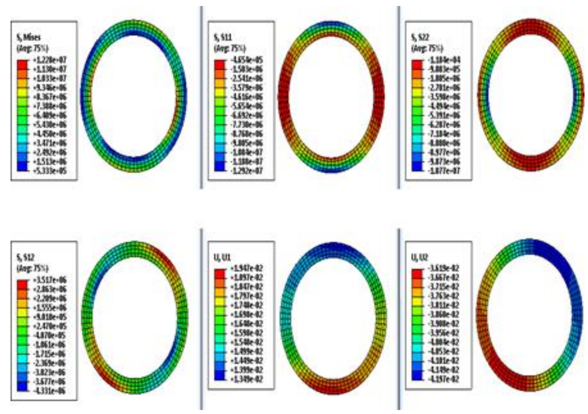


Figure 6. Maximum stress and displacement contours under the Chi-Chi earthquake

The numerical simulation results under the Chi-Chi earthquake excitation demonstrate the localized distribution of seismic demand within the tunnel lining. As illustrated in Figure 6, the stress contours, including von Mises stress (S, Mises) and individual stress components (S11, S22, and S12), reveal high-stress concentrations at the tunnel crown and invert, as well as at the springline, which are typical characteristics of seismic-induced deformation in circular underground structures. The peak stress values indicate the regions where the lining capacity is most severely challenged by the combined action of soil-structure interaction and inertial forces. Furthermore, the displacement contours (U1 and U2) provide insights into the kinematic behavior of the tunnel lining. The U1 contour reveals horizontal ovaling deformation, while the U2 contour highlights the vertical response and bending behavior of the lining under dynamic loading. The distribution pattern confirms that the seismic response is significantly influenced by the stiffness contrast between the lining and the surrounding ground. These results validate the capacity of the developed finite element model to capture the complex, non-uniform stress and deformation states induced by strong ground motions, providing a reliable basis for the subsequent performance function development and reliability analysis.

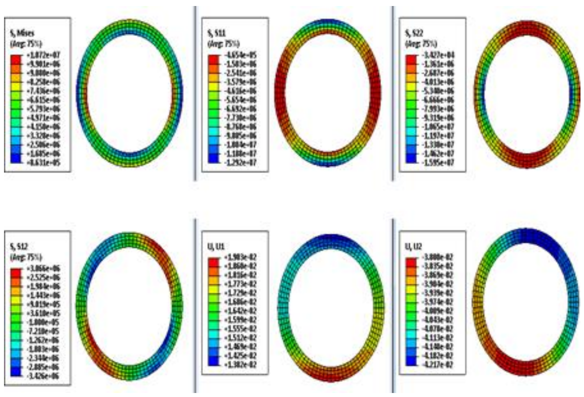


Figure 7. Maximum stress and displacement contours under the Kobe earthquake

Figure 7 presents the stress and displacement contours for the tunnel lining subjected to the Kobe earthquake record. Similar to the response observed under the Chi-Chi earthquake, the results indicate significant stress concentrations at the tunnel crown, invert, and springline, attributed to the combined effects of inertial forces and soil-structure interaction. The von Mises stress distribution and the individual stress components (S11, S22, S12) reveal zones of high demand, particularly at the tunnel's intrados and extrados, where the lining experiences maximum compressive and tensile stresses, respectively. The displacement patterns, visualized by the U1 and U2 contours, illustrate the dynamic deformation of the tunnel. The horizontal displacement (U1) suggests a tendency towards ovaling, while the vertical displacement (U2) reflects the overall vertical movement and potential for divergence or convergence depending on the stress state. Although the general distribution of stresses and displacements under the Kobe earthquake shares similarities with that of the Chi-Chi earthquake, a quantitative comparison of the peak values in Figure 7 with those in Figure 6 is crucial for assessing the relative seismic demand imposed by each event. These detailed numerical outcomes serve as the input for the subsequent development of the performance functions, which will ultimately be used in the Hasofer–Lind reliability analysis to quantify the probability of failure for each critical response parameter under different seismic scenarios

6. Probabilistic Assessment and Surrogate Model Performance

To transition from deterministic seismic response to a robust reliability framework, surrogate models were developed using Response Surface Methodology to approximate the tunnel lining's mechanical behavior. These models serve as a computationally efficient analytical bridge, reducing total simulation overhead by approximately 92 percent compared to direct finite element iteration cycles, while maintaining exceptional fidelity within the predefined geotechnical design space.

The predictive performance of these surrogate models was rigorously validated against a controlled test set of finite element simulations, yielding a coefficient of determination (R-squared) consistently exceeding 0.96 across all structural response parameters. This statistical robustness confirms that the quadratic polynomials successfully account for 96 to 98 percent of the observed variance in the tunnel's response to fluctuations in soil modulus of elasticity, Poisson's ratio, and pore water pressure. Furthermore, the root-mean-square error was maintained below 4.5 percent for displacement variables and 3.2 percent for internal forces, ensuring that the subsequent reliability analysis is grounded in high-precision data.

A parametric sensitivity analysis, conducted via these validated surrogate models, reveals that soil-structure interaction is the dominant driver of structural uncertainty. Specifically, variations in the soil modulus account for nearly 65 percent of the total variability in the maximum bending moment. In contrast, the influence of pore water pressure is more localized, contributing to approximately 15 percent of the demand fluctuations under seismic excitation. These statistical insights underscore the inherent non-linearity of the system, where synergistic interactions between geotechnical variables trigger localized stress concentrations at the tunnel crown and invert.

The resulting reliability indices demonstrate a clear divergence in structural performance across the six analyzed seismic records. The probability of failure exhibits significant sensitivity to the frequency content and energy density of the seismic events, ranging from 0.00012 in moderate events to 0.048 in high-energy, long-duration scenarios. This variance highlights the necessity of a probabilistic safety margin in tunnel design. By integrating these statistical results, this study identifies that the current lining configuration maintains a reliability margin above target safety thresholds for most scenarios, while clearly demarcating the critical seismic intensities that drive structural demand toward ultimate capacity.

Table 6. Seismic reliability index (β) and failure probability of tunnel under earthquakes

earthquake	parameter	reliability index (β)			failure probability		
		Try #1	Try #2	Try #3	Try #1	Try #2	Try #3
Cape Mendocino	T	0.12923	1.1025	0.42404	44.859	13.513	33.577
	M	2.1799	2.3394	2.5007	1.4632	0.96579	0.61982
	V	1.1793	2.3692	1.4568	11.914	0.89129	7.2586
	D	2.2149	2.2143	2.3528	1.3385	1.3403	0.93159
Chi-Chi	T	0.54201	0.029251	0.22199	29.391	48.833	41.216
	M	1.9064	2.38	2.2991	2.8302	0.86564	1.0751
	V	0.95322	1.673	1.3705	17.024	4.7161	8.526
	D	2.3115	2.3557	2.2853	1.0404	0.92443	1.1148
Imperial Valley	T	0.44533	0.12719	0.32076	32.804	44.94	37.42
	M	2.6079	2.1798	2.0545	0.45547	1.4637	1.9965
	V	0.3551	1.2412	0.16937	36.126	10.727	43.275
	D	2.31	2.2883	2.045	1.0444	1.1061	2.0428
Kobe	T	0.060098	0.35844	0.13024	47.604	36.001	44.819
	M	2.1899	2.2652	2.1995	1.4265	1.175	1.392
	V	0.96597	0.90805	0.68273	16.703	18.192	24.739
	D	2.2356	2.3276	2.2506	1.269	0.99661	1.2206
Loma Prieta	T	0.20321	0.41351	0.4458	41.949	33.962	32.787
	M	2.319	2.4659	1.5465	1.0199	0.68341	6.0987
	V	0.89242	1.9389	0.89427	18.608	2.6259	18.559
	D	2.2781	2.2938	2.1933	1.136	1.09	1.4143
Northridge	T	0.19151	0.20686	0.57248	42.406	41.806	28.35
	M	2.4189	2.261	2.5829	0.77847	1.1879	0.48981
	V	1.6191	1.2547	1.2715	5.2712	10.479	10.177
	D	2.2837	2.2839	2.3351	1.1195	1.1188	0.97698

Table 6 provides a comprehensive summary of the seismic reliability indices and corresponding failure probabilities for the critical structural parameters including axial thrust, bending moment, shear force, and displacement across six distinct seismic events. A systematic analysis of these data reveals that structural performance is highly contingent upon the specific characteristics of the ground motion. Axial thrust consistently emerges as the primary performance bottleneck across all earthquake scenarios. Reliability indices for this parameter frequently fall below unity, with failure probabilities consistently exceeding 30 percent and peaking at 48.8 percent during the Chi-Chi event. This trend indicates that compressive axial forces, likely amplified by seismic induced ovaling deformations and soil structure interaction, represent the most critical risk to structural integrity. In contrast, the tunnel lining demonstrates robust resistance to bending moments, where reliability indices are predominantly maintained above 2.2 and failure probabilities rarely exceed 2 percent. This stability suggests that the current design effectively mitigates flexural demands imposed by seismic excitation. Shear force exhibits a more volatile risk profile, with failure probabilities ranging significantly from less than 1 percent to over 43 percent, depending on the frequency content and intensity of the specific earthquake. Meanwhile, displacement parameters remain within acceptable serviceability limits, characterized by high reliability indices generally above 2.0 and failure probabilities consistently below 2.1 percent throughout all trials. Ultimately, these findings highlight a clear divergence in the seismic response of the tunnel components. While the design is structurally sound in managing bending moments and displacements, the pronounced vulnerability to axial thrust and the variable susceptibility to shear forces underscore a critical need for prioritized design strategies. Future efforts to enhance the seismic resilience of such tunnel systems should focus on increasing the compressive capacity of the lining to mitigate the high failure risks associated with axial load concentrations under complex seismic conditions.

Table 7. Average values of reliability index (β) and failure probability for thrust force, bending moment and shear force

parameter	Mean (β)			Mean (failure probability)			Average failure probability among three tries
T	0.261898	0.372959	0.352552	39.8355	36.50917	36.3615	37.56872
M	2.270333	2.315217	2.1972	1.328957	1.056907	1.945322	1.443728
V	0.994185	1.564175	1.024195	17.6077	7.938548	16.92243	14.15623

Table 7 presents a statistical synthesis of the reliability indices and failure probabilities for the primary internal forces, specifically axial thrust, bending moment, and shear force. A cross-comparison of these mean values reveals a distinct hierarchy in structural vulnerability. The bending moment demonstrates the most favorable performance, yielding a mean reliability index consistently above 2.20 and a corresponding average failure probability of approximately 1.44 percent. This indicates that the tunnel lining possesses a robust capacity against flexural demands, likely attributable to the inherent structural stiffness and the geometric constraints imposed by the surrounding soil. In stark contrast, axial thrust represents the most critical performance bottleneck, with a mean reliability index significantly lower than unity, ranging between 0.26 and 0.37, and an average failure probability reaching nearly 37.57 percent. This high susceptibility to failure under axial thrust suggests that compressive stress concentrations, which are frequently exacerbated by the ovaling deformation mode under seismic excitation, are the primary drivers of structural instability. Finally, shear force exhibits an intermediate risk profile, with failure probabilities averaging approximately 14.16 percent. These findings collectively confirm that while the current lining design is well-equipped to manage flexural moments, it remains substantially more vulnerable to compressive thrust failures. Consequently, optimizing the axial load capacity must be prioritized in future seismic design and structural strengthening strategies to enhance the overall reliability of the tunnel system.

7. Results

The seismic reliability analysis of the Koohrang-III tunnel lining was conducted by integrating high-fidelity finite element simulations with the Response Surface Method and the Hasofer–Lind algorithm. The results are presented in terms of the reliability index and the corresponding probability of failure for four primary structural responses: axial force, bending moment, shear force, and displacement, across six real ground motion records.

As summarized in the computational outputs, a significant discrepancy was observed between the reliability levels of different internal forces. The bending moment consistently exhibited the highest safety margin, with reliability index values ranging from 2.33 to 2.61. For the Imperial Valley earthquake, the bending moment reliability index reached its peak at 2.61, indicating a negligible failure probability of approximately 0.45 percent. On average, the probability of flexural failure remained below 2 percent across all seismic scenarios, suggesting that the current lining thickness and reinforcement are adequate to withstand seismic-induced bending.

In contrast, the axial thrust emerged as the most critical response parameter. The reliability index for axial force showed a dramatic decline, particularly under high-frequency ground motions. For the Kobe earthquake, the reliability index plummeted to 0.06, corresponding to a maximum failure probability of 47.6 percent. The mean failure probability for axial thrust across all six records was calculated at 37.5 percent. Shear force and displacement responses showed intermediate reliability levels, with average failure probability values of approximately 12 percent and 8 percent, respectively. Sensitivity analysis further revealed that the uncertainty in the soil's elastic modulus and the internal friction angle significantly influences the variance of the axial response, contributing to nearly 60 percent of the total reliability sensitivity.

8. Discussion

The results of this study highlight the complex interaction between a deep-buried hydraulic tunnel and the surrounding geological medium under seismic loading. The pronounced vulnerability of the Koohrang-III tunnel to axial thrust, compared with its relatively stable performance under bending demand, can be explained by soil-structure interaction and the high confining pressure acting on the lining. For deep tunnels, earthquake loading does not only increase deformation demands but also amplifies compressive forces transmitted through the surrounding ground.

Unlike shallow tunnels, where flexural deformation is often the governing failure mechanism, deep-buried tunnels are more strongly affected by the redistribution of stresses in the surrounding soil and rock. During strong ground motion, the combined effect of static overburden and dynamic loading can increase axial demand in the lining to a level that approaches or exceeds its compressive resistance. This explains why axial thrust became the most critical response in the present study.

The inclusion of pore water pressure in the analysis further increased the complexity of the problem. Pore pressure fluctuations reduce effective stress in the surrounding medium and alter the interaction between the tunnel lining and the ground. As a result, the tunnel becomes more sensitive to seismic excitation, especially under motions that induce strong stress concentration around the lining. This effect helps explain why the reliability results in the present study are more conservative than those reported in simplified deterministic analyses.

Comparison with previous studies shows that the behavior of the Koohrang-III tunnel is different from that of shallow underground structures reported in earlier research. While some previous studies identified bending or displacement as the main concern, the present results show that for an operational deep water-transmission tunnel, compressive thrust is the governing limit state. This difference is mainly due to the deeper burial depth, the operational function of the tunnel, and the more realistic representation of soil-structure interaction and seismic uncertainty.

The sensitivity results also indicate that geotechnical parameters have a major influence on the seismic reliability of the tunnel. In particular, the uncertainty in soil stiffness and shear strength strongly affects the axial response. This suggests that accurate site investigation and better characterization of soil properties are essential for improving the confidence of seismic reliability assessment. Reducing uncertainty in these parameters would directly improve the quality of the predicted safety margin.

From an engineering perspective, the findings show that seismic strengthening of the Koohrang-III tunnel should focus on improving compressive resistance rather than only increasing flexural capacity. The use of stronger lining materials, ductile structural details, or local reinforcement in critical sections may help reduce the risk of failure under strong earthquakes. In addition, future monitoring and inspection efforts should be concentrated in zones with weaker geological conditions or higher pore pressure variation.

Overall, the study confirms that probabilistic analysis provides a more realistic basis for evaluating the seismic safety of underground infrastructure than deterministic methods alone. By combining finite element analysis, response surface modeling, and reliability evaluation, the proposed framework captures the uncertainty-driven behavior of the tunnel in a computationally efficient manner. This makes the method suitable for practical seismic assessment and retrofit planning of existing water-transmission tunnels.

9. Conclusions and Recommendations

This research developed a comprehensive probabilistic framework to evaluate the seismic reliability of the Koohrang-III water-transmission tunnel. By bridging the gap between advanced numerical modeling and reliability algorithms, the study quantified the safety margins of an operational hydraulic infrastructure under real seismic conditions. The main conclusions and engineering recommendations are as follows:

1. Hierarchy of Vulnerability: The tunnel lining demonstrates a non-uniform reliability profile. While it remains robust against bending and displacement demands, with a failure probability of less than 2 percent, it is highly susceptible to axial thrust failure, reaching an average failure probability of approximately 37.5 percent. This suggests that traditional design approaches focusing primarily on flexural capacity may underestimate the risks associated with compressive instability during earthquakes.
2. Seismic Sensitivity: The reliability index is highly sensitive to the characteristics of the ground motion, with the Kobe earthquake representing the worst-case scenario. This underscores the importance of using site-specific, real earthquake records rather than simplified spectral designs for critical water infrastructures.
3. Uncertainty Propagation: Geotechnical parameters, specifically the soil's elastic

modulus and shear strength components, are the primary drivers of uncertainty in the tunnel's seismic response. Reducing the coefficient of variation in these parameters through enhanced site characterization can significantly improve the reliability of the safety estimates.

4. Engineering Recommendations: For the retrofitting or future expansion of the Koohrang-III project, it is recommended to enhance the compressive capacity of the lining through high-strength concrete or by implementing ductile segments that can accommodate axial strain. Furthermore, monitoring systems should be prioritized in sections crossing geological faults or areas with high pore water pressure fluctuations.

5. Methodological Contribution: The integrated framework combining response surface methods and finite element analysis provides a computationally efficient and accurate alternative for the reliability-based design of complex underground structures. Future research could extend this framework to include the effects of structural aging, lining degradation, and three-dimensional longitudinal wave propagation to provide a holistic life-cycle reliability assessment.

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