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INTEGRATING MAINTENANCE INTO SEISMIC RISK ASSESSMENT: A COMPREHENSIVE APPROACH TO INFRASTRUCTURE RESILIENCE

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Abstract

A severe seismic event can cause significant damage to infrastructure systems, leading to both direct and indirect severe consequences. Thus, a comprehensive risk management approach is essential for developing earthquake-resilient infrastructure. This study introduces an innovative approach to seismic risk assessment that incorporates maintenance considerations with seismic fragility curves. Our methodology distinctively quantifies the impact of maintenance conditions on seismic risk, providing insights into the dynamic evolution of risk associated with loose maintenance and accelerated deterioration. It suggests that the condition of infrastructure maintenance and its level of deterioration significantly influence seismic resilience. By integrating the Building Performance Indicator (BPI) with deterioration over time, the proposed approach assesses their combined effect on fragility curves to calculate the total risk over the infrastructure's lifecycle (TRLC – Total Risk over Life Cycle). We demonstrate this methodology through a case study of a low-voltage substation in Bik'at HaYarden, Israel. A Monte Carlo simulation was carried out to examine the particular conditions of the substation thoroughly. Additionally, a sensitivity analysis was carried out to better understand how maintenance conditions influence the TRLC over time. Our findings reveal a statistically significant correlation between infrastructure performance and maintenance condition, and their subsequent impact on the TRLC. Notably, we found that loose maintenance conditions significantly increase the uncertainties in seismic risk. This research offers researchers, stakeholders, and decision-makers a novel and comprehensive view on the critical role of maintenance in managing and mitigating seismic risk.

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Keywords: Building Performance Indicator (BPI), Infrastructure, Lifecycle Risk Assessment, Maintenance, Seismic Fragility Curves, Seismic Risk

1. Introduction and Background

Infrastructure systems, including transportation, energy, water, wastewater, telecommunications, healthcare facilities, financial systems, educational institutions, and emergency services, are critical for daily operations and during extreme events in modern society and the economy [1], [2]. Comprising of structural and nonstructural components, these systems are highly interconnected, where damage to any single component can lead to widespread disruption. The severe damage observed during the 2023 Turkey-Syria earthquake [3] highlighted the devastating impact of seismic events, resulting in significant economic, structural, and human losses. Consequently, enhancing infrastructure resilience is imperative to maintain community safety and functionality following earthquakes. Therefore, a detailed assessment of the vulnerability of each component is essential for an accurate evaluation of a system's seismic performance [4].

Seismic fragility curves are widely used to evaluate potential damage to different types of infrastructure following seismic events. The fragility curve represents the probability that a component or system will reach or exceed a given damage state as a function of an earthquake's intensity-measure (IM) parameter [5]. Fragility curves can be implemented to evaluate the vulnerability of single components or entire systems [6], [7]. The typical formulation of a fragility function for a structure or system is represented as a lognormal cumulative distribution function (CDF), as detailed in Equations (1) and (2).

$$P\left[DS \geq ds|IM = x\right] = \Phi\left(\frac{ln(x/\theta_{ds})}{\beta_{ds}}\right); ds \in \{1,2, \dots N_{DS}\} \quad (1)$$

$$P(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 1 \leq i \leq n-1 \\ P(DS \geq ds_i|IM) & i = n \end{cases} \quad (2)$$

where P stands for a conditional probability of being at or exceeding a particular damage state (DS) for a given seismic intensity and x is defined by the earthquake-intensity measure (IM). Where,

DS The uncertain damage state of a particular component, {0, 1, ...$\mathrm{N_{DS}}$};

ds_i A particular value of the DS;

$\mathrm{N_{DS}}$ The number of possible damage states;

IM Uncertain excitation, the ground-motion-intensity measure (i.e., PGA, PGD, or PGV);

X A particular value of the IM;

Φ The standard cumulative normal distribution function;

θ_{ds} The median capacity of the component to resist a damage state ds measured in terms of the IM;

β_{ds} The logarithmic standard deviation of the uncertain capacity of the component to resist a damage state ds.

Many studies have examined the development and implementation of seismic fragility curves across various infrastructure types, including diverse building structures [8], [9], [10], unique structures such churches [11], bridges [12], different steel tanks [13], [14], [15], [16], power grids [17], water networks [18], transportation infrastructure [19], oil pumping station [7], [20], and concrete dams [21]. These fragility curves consider multiple factors, such as the geometry of the elements, the materials used, and the system's overall capacity. However, less attention has been paid to integrating maintenance into seismic fragility assessments, which ensures infrastructure durability, functionality, and effectiveness.

Maintenance tasks such as inspections, repairs, and upgrades are vital for preserving structural integrity and performance [22]. Research has shown that maintenance levels significantly influence infrastructure

vulnerability to seismic events, highlighting a gap in how maintenance practices influence seismic risks [23], [24], [25], [26], [27], [28], [29]. Infrastructure functionality critically depends on each component's consistent performance, making maintenance crucial for mitigating seismic vulnerability. Proper maintenance enhances a system's condition and seismic resistance, whereas inadequate maintenance increases failure risk and does not typically address component vulnerability to seismic events, widening the gap between maintenance operations and seismic risk reduction strategies.

This study introduces a comprehensive approach to enhancing earthquake resilience by integrating maintenance data into the seismic risk analysis process, hypothesizing that incorporating maintenance-level data into seismic fragility curves will yield a more advanced, innovative, and reliable representation of system vulnerability. This integration allows infrastructure owners and managers to make informed decisions on maintenance strategies and investments, thereby boosting the resilience of their assets. Uniquely, this work pioneers the incorporation of maintenance considerations into seismic fragility curves, a notably absent feature in existing literature. This integration not only advances immediate seismic resistance understanding but also includes considerations for long-term sustainability through effective maintenance, aiming to bridge the gap between traditional seismic fragility models and the impact of ongoing maintenance activities on infrastructure resilience.

2. Methodology

The methodology of this study is structured into several critical steps that incorporate maintenance considerations into seismic risk analysis to enhance infrastructure resilience. Figure 1 presents a flowchart that outlines the main steps of the methodology.

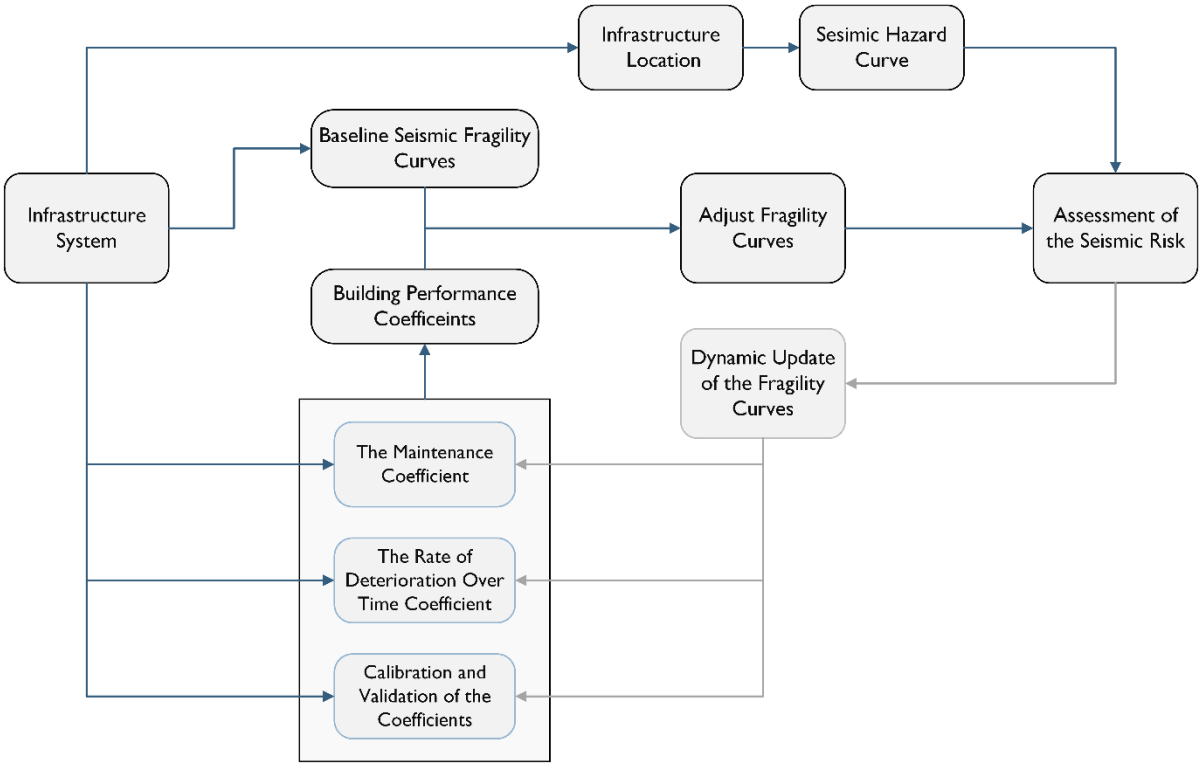

Figure 1 - Methodology Flowchart (the gray arrows represent the dynamic update of fragility curves based on routine inspection).

2.1. Baseline Fragility Curves

Baseline fragility curves are developed using standard methodologies without maintenance considerations. These curves, which are essential for assessing the seismic vulnerability of various infrastructure components and systems, are based on data from sources like the FEMA P-58 component fragility function database (FEMA database [30]). For specialized infrastructure configurations, a

detailed methodology that utilizes fault-tree analysis can be applied [9]. These baseline curves provide a probabilistic measure of seismic vulnerability, serving as benchmarks for evaluating the impact of maintenance in further analysis steps.

2.2. Maintenance State of Critical Infrastructures

The maintenance state of the infrastructure is critically assessed through the evaluation of physical condition, material quality, age, wear and tear, and performed maintenance activities. Two key parameters are considered: the current maintenance condition and the level of deterioration over time, represented by the maintenance coefficient (M_c) and deterioration coefficient (D_c), respectively.

The maintenance coefficient (M_c) quantifies the maintenance status of an infrastructure component or system. It is derived from maintenance records, condition assessments, and expert evaluations and reflects factors such as maintenance frequency, quality, history, current condition, and performance metrics. This coefficient is calculated using the Building Performance Indicator (BPI) introduced by Shohet [31]. The BPI aggregates various maintenance aspects, including physical performance, failure frequency, and preventive maintenance, into a comprehensive score that reflects the overall maintenance state of the infrastructure, as detailed in Equations 3 and 4.

$$BPI = \sum_{n=1}^{N} P_n \cdot W_n \tag{3}$$

$$M_c = 0.01 \cdot BPI + 0.1 \tag{4}$$

Where,

BPI— Building Performance Indicator (0–100);

P_n— Performance level for system n (on a scale of 0 to 100)

W_n— Weight of system n in the BPI

The deterioration-over-time coefficient D_c (t) quantifies the progressive degradation of infrastructure components due to aging, environmental conditions, usage intensity, and material properties. This coefficient is modelled using an exponential decay function that reflects the natural aging and wear-and-tear processes, providing a time-dependent measure of infrastructure deterioration. The formulation of this coefficient is detailed in Equations 5 and 6.

$$P = a_0 + (99 - a_0) \cdot \left[\frac{S - (W_{SR} + W_{EC} + W_{MP})}{4 \cdot (W_{SR} + W_{EC} + W_{MP})}\right] \; ; \; S = SR \cdot W_{SR} + EC \cdot W_{EC} + MP \cdot W_{MP} \tag{5}$$

$$D_c(t) = P_0 \cdot e^{-P \cdot \frac{t}{LC} \cdot 100} \tag{6}$$

Where,

SR— Service-regime-intensity factor;

EC— Environmental-conditions factor;

MP— Material-properties factor;

W_{SR}, W_{EC}, W_{MP} — Weights associated with each factor;

a_0— Calibration coefficient for the performance score for perfect conditions;

P— Performance score of the infrastructure.

$D_c(t)$— Deterioration-over-time coefficient at time t;

t— Time. The number of years since the start of the evaluation period;

P_0— Initial performance (usually set at 1.0);

LC— Designed the lifecycle of the infrastructure.

2.3. Adjusted Fragility Curves

In this step, the baseline fragility curves are corrected to reflect infrastructure or components' current maintenance levels and deterioration rates. These adjustments are based on the maintenance-level indicator and the rate of the deterioration-over-time indicator. The adjustments are made to the fragility parameters for each damage state, using these indicators to ensure the curves dynamically represent the infrastructure's current state and resilience accurately. This process ensures that the seismic vulnerability assessments remain relevant and precise over time as conditions change.

2.4. Dynamic Update of the Fragility Curves

The seismic fragility curves are dynamically updated based on changes in the maintenance and deterioration states over time. This continuous update process allows for real-time adjustments to the seismic vulnerability assessments based on the latest maintenance data and deterioration analyses.

2.5. Assessment of the Seismic Risk

In this step, the seismic risk expectancy for the infrastructure over its designated lifespan (T years) is assessed using maintenance indicators. Equations (7) and (8) calculates the Total Risk Life Cycle (TRLC), which estimates the cumulative risk from potential earthquake events during the system's lifecycle.

$$\mathrm{TRCL} = \left[\sum_{t=1}^{T}\sum_{m=1}^{IM}\left(\sum_{i=1}^{N} P(ds_i|IM)\cdot DR_{ds_i}\right)\cdot PE_A(IM)\right]\cdot R_U \quad (7)$$

$$R_U = (\sum C_R + \sum C_D)\cdot C_I \quad (8)$$

where,

$TRLC$—Total risk for the infrastructure design lifecycle;

DR_{ds_i}—Damage rate of damage state i;

$P(ds_i\,|IM)$—Conditional probability of being in a certain damage state i for a given IM;

T—Design lifecycle;

$PE_A(IM)$—Annual rate of exceedance of a given IM;

C_R—Cost of repair (US$);

C_D—Direct loss (US$);

C_I—Indirect loss coefficient;

R_U—Overall consequences (US$).

3. Case-Study

In this case study, we explore the application of our methodology through the analysis of a low-voltage substation within a hi-tech industrial complex used for distributing electrical power from the main grid to end-users. Due to security reasons, specific details about the location and layout are substituted with an alternative scenario. The substation, embedded in a one-story, shear-moment reinforced-concrete

structure, includes critical components such as transformers, switchgear, and an uninterruptible power supply (UPS), complete with advanced HVAC and fire-detection systems. Positioned in the Bik'at HaYarden region of Israel, its seismic vulnerability is initially assessed using baseline fragility curves derived from the HAZUS methodology [6], as shown in Figure 2. A hazard curve specific to the Bik'at HaYarden region further supports the seismic risk analysis, which is illustrated in Figure 3.

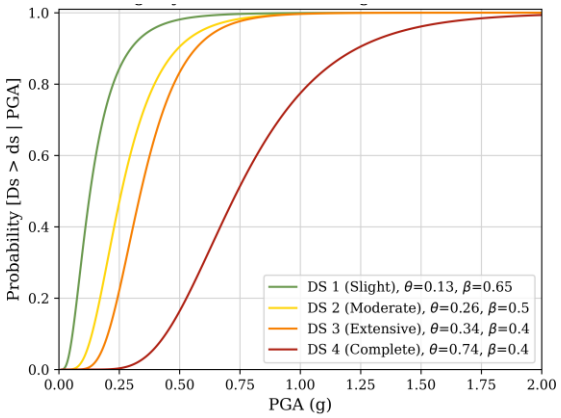

Figure 2 - Fragility curve of a low-voltage substation

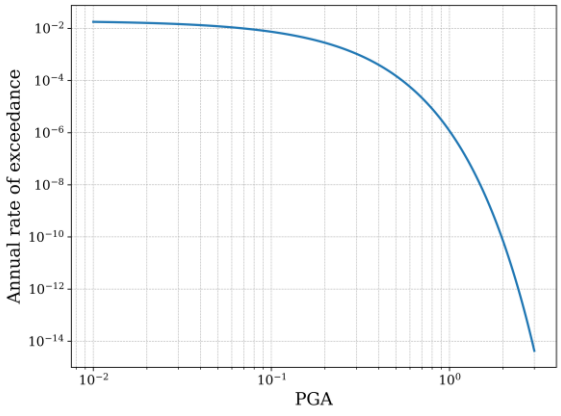

Figure 3 - Hazard curve for Bik'at HaYarden region

The BPI represents maintenance conditions, with surveys recording scores across various infrastructure systems over multiple years, reflecting the substation's upkeep and guiding maintenance strategy. The deterioration rate, influenced by service intensity, environmental conditions, and material durability, is evaluated and incorporated into risk calculations. A Monte Carlo simulation was used to project the annual risk across the substation's lifecycle, with potential repair costs quantified and the need for comprehensive risk assessments, considering both direct and indirect impacts, emphasized. A total of 1,000 simulations were performed (n = 1,000) for the described case study. The variation of the annual risk across these simulations over the lifecycle of the substation is presented in Figure 4. Each simulation is represented in gray, with the mean risk across all simulations highlighted in dark blue. The risk for Year 0 (beginning of Year 1) represents the scenario without considering maintenance and deterioration. Random BPI and P values were generated in the simulation based on the defined mean and standard deviation. This detailed examination underscores the importance of dynamic risk assessment in infrastructure management, particularly in seismically active areas.

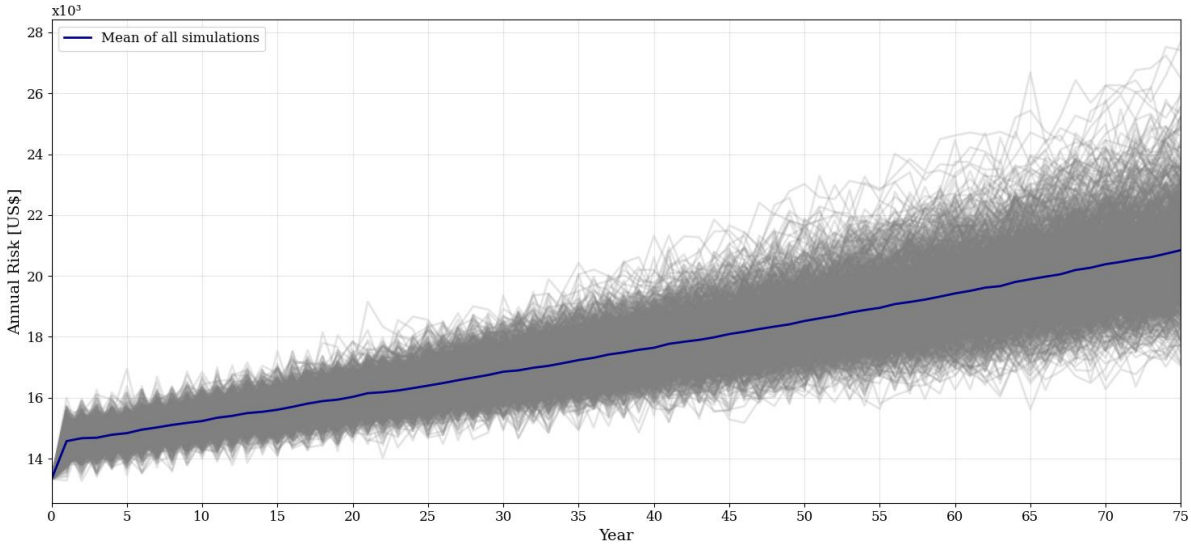

Figure 4 - The annual risk over the design lifecycle of the substation. Each simulation is represented in gray. The mean risk is highlighted in dark blue. The risk for Year 0 represents the scenario without considering maintenance and deterioration.

4. Results and Discussion

The results from the Monte Carlo simulation provide a detailed analysis of risk patterns over a 75-year lifecycle of an infrastructure project, highlighting the significant correlations between the Building Performance Indicator (BPI) and P scores and their combined impact on the Total Risk Life Cycle (TRLC), as illustrated in Figures 5 and 6. It was observed that an increase in BPI, which indicates improved infrastructure performance, leads to reduced associated risks, confirming the balance between performance levels and potential risks; higher BPI scores suggest lower risks due to better infrastructure conditions. Additionally, sensitivity analyses of the BPI and P scores revealed that higher P values, which indicate deteriorating conditions, correlate with increased seismic risk variance and greater unpredictability in potential outcomes. This emphasizes the need for robust risk mitigation strategies, particularly in scenarios with high P values, to effectively manage the wider spectrum of potential risks, providing crucial insights for stakeholders and decision-makers in making informed choices to enhance infrastructure resilience.

This study used Monte Carlo simulation to analyze the risk patterns and validate the impact of maintenance on seismic resilience. However, future studies can integrate ML capabilities to improve the adjustment and validation of the fragility functions. ML algorithms can analyze large datasets [32], [33], identify complex patterns, and dynamically update fragility curves based on real-time maintenance data. Furthermore, in cases of limited data, ML can leverage transfer learning techniques to improve model accuracy [34]. By incorporating ML, future research can enhance the accuracy of seismic risk assessments and optimize maintenance strategies, leading to more resilient infrastructure systems.

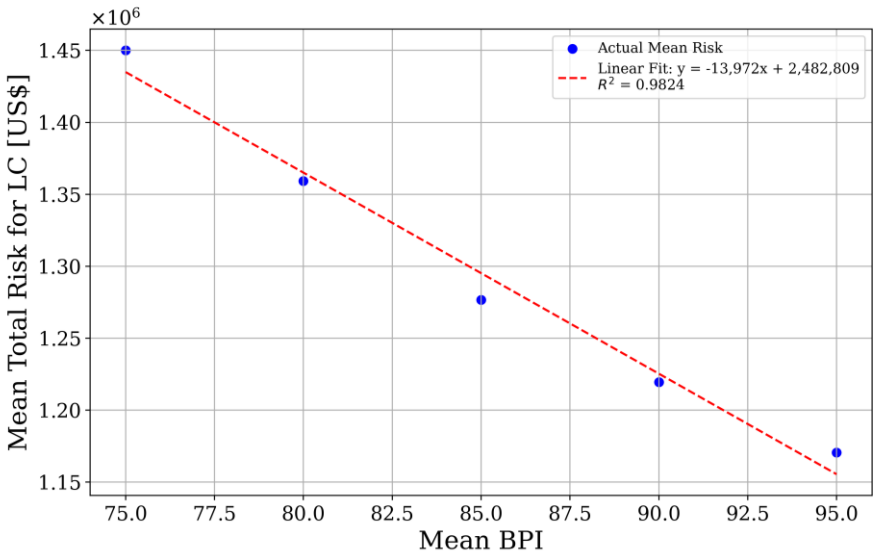

Figure 5 - A linear regression model for the relationship between the BPI and the Mean Total Risk for Lifecycle

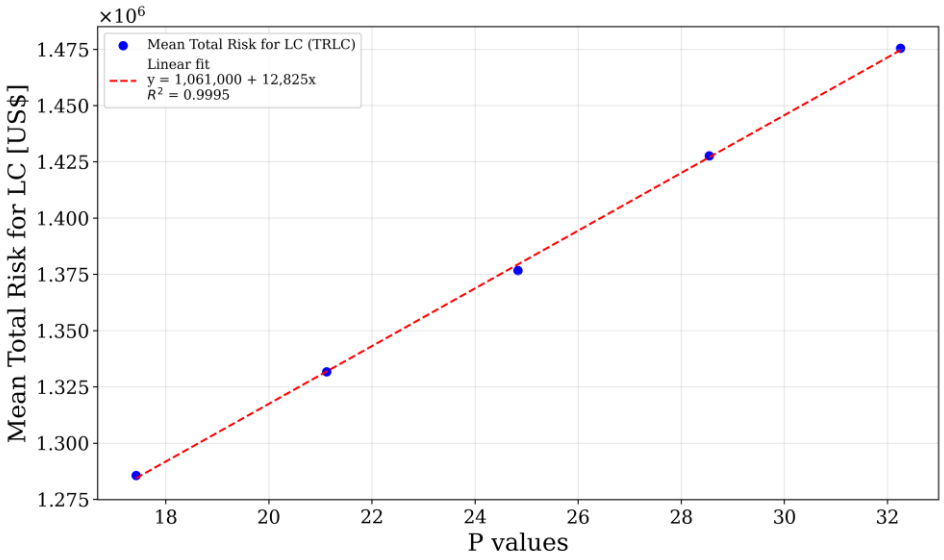

Figure 6 - A linear regression model for the relationship between P and the Mean Total Risk for Lifecycle

5. Conclusion

The conclusion of this paper underscores the significant contribution of integrating maintenance considerations into seismic risk management for infrastructures. By introducing a methodology that accounts for the current condition of infrastructure components and evaluates how maintenance influences seismic vulnerability, this research offers a practical and innovative approach to enhancing earthquake resilience. The practical applicability of this framework extends across various domains, including informed decision-making for infrastructure maintenance, dynamic seismic risk assessment, comprehensive policies and regulations, and economic efficiency through resource allocation.

Validated through a case study on a low-voltage substation in Bik'at HaYarden using Monte Carlo simulation and sensitivity analysis, the findings demonstrate a crucial correlation between maintenance practices and seismic risks, where loose or poor maintenance increases uncertainties in risk assessments. This emphasizes the necessity of thorough maintenance regimes to mitigate seismic risks effectively. The study presents a paradigm where proactive maintenance is pivotal, offering stakeholders a deeper, holistic understanding of infrastructure resilience amid earthquakes. This adaptable framework can be further refined with new data and extended across different infrastructure typologies, paving the way for creating earthquake-resilient environments by bridging the gap between maintenance and seismic considerations.

References

[1] A. Urlainis, D. Ornai, R. Levy, O. Vilnay, and I. M. Shohet, "Loss and damage assessment in critical infrastructures due to extreme events," *Saf Sci*, vol. 147, p. 105587, Mar. 2022, https://doi.org/10.1016/J.SSCI.2021.105587.

[2] A. Urlainis, I. M. Shohet, R. Levy, D. Ornai, and O. Vilnay, "Damage in critical infrastructures due to natural and man-made extreme events - A critical review," *Procedia Eng*, vol. 85, pp. 529–535, 2014, https://doi.org/10.1016/j.proeng.2014.10.580.

[3] E. N. Cinar, A. Abbara, and E. Yilmaz, "Earthquakes in Turkey and Syria-collaboration is needed to mitigate longer terms risks to health," *BMJ (Clinical research ed.)*, vol. 380. 2023. https://doi.org/10.1136/bmj.p559.

[4] G. Lifshitz Sherzer, A. Urlainis, S. Moyal, and I. M. Shohet, "Seismic Resilience in Critical Infrastructures: A Power Station Preparedness Case Study," *Applied Sciences*, vol. 14, no. 9, p. 3835, Apr. 2024, https://doi.org/10.3390/app14093835.

[5] K. Porter, "Beginner's guide to fragility, vulnerability, and risk," *Encyclopedia of earthquake engineering*, pp. 235–260, 2015.

[6] NIBS, “Hazus Earthquake Model Technical Manual Hazus 4.2 SP3,” 2020.

[7] A. Urlainis and I. M. Shohet, “Development of exclusive seismic fragility curves for critical infrastructure: an oil pumping station case study,” *Buildings* , vol. 12, no. 842, Jun. 2022, https://doi.org/10.3390/buildings12060842.

[8] A. Sandoli, B. Calderoni, G. P. Lignola, and A. Prota, “Seismic vulnerability assessment of minor Italian urban centres: development of urban fragility curves,” *Bulletin of Earthquake Engineering*, vol. 20, no. 10, 2022, https://doi.org/10.1007/s10518-022-01385-0.

[9] A. Rosti, M. Rota, and A. Penna, “Empirical fragility curves for Italian URM buildings,” *Bulletin of Earthquake Engineering*, vol. 19, no. 8, 2021, https://doi.org/10.1007/s10518-020-00845-9.

[10] A. Rosti *et al.*, “Empirical fragility curves for Italian residential RC buildings,” *Bulletin of Earthquake Engineering*, vol. 19, no. 8, 2021, https://doi.org/10.1007/s10518-020-00971-4.

[11] S. Ruggieri, C. Tosto, G. Rosati, G. Uva, and G. A. Ferro, “Seismic Vulnerability Analysis of Masonry Churches in Piemonte after 2003 Valle Scrivia Earthquake: Post-event Screening and Situation 17 Years Later,” *International Journal of Architectural Heritage*, 2020, https://doi.org/10.1080/15583058.2020.1841366.

[12] N. Rojas-Mercedes, K. Erazo, and L. Di Sarno, “Seismic fragility curves for a concrete bridge using structural health monitoring and digital twins,” *Earthquake and Structures*, vol. 22, no. 5, 2022, https://doi.org/10.12989/eas.2022.22.5.503.

[13] N. Buratti and M. Tavano, “Dynamic buckling and seismic fragility of anchored steel tanks by the added mass method,” *Earthq Eng Struct Dyn*, 2014, https://doi.org/10.1002/eqe.2326.

[14] M. J. O’Rourke and P. So, “Seismic fragility curves for on-grade steel tanks,” *Earthquake Spectra*, 2000, https://doi.org/10.1193/1.1586140.

[15] M. S. Razzaghi and S. Eshghi, “Development of Analytical Fragility Curves for Cylindrical Steel Oil Tanks,” *Proccedings of The 14 th World Conference on Earthquake Engineering*, no. March, p. 8, 2008, [Online]. Available: https://www.iitk.ac.in/nicee/wcee/article/14_06-0017.PDF

[16] M. S. Razzaghi and S. Eshghi, “Probabilistic Seismic Safety Evaluation of Precode Cylindrical Oil Tanks,” *Journal of Performance of Constructed Facilities*, vol. 29, no. 6, p. 4014170, 2014.

[17] C. Y. Tseng, C. H. Wang, X. Y. Zheng, H. C. Chiu, and J. A. Jiang, “Design of a seismic hazard risk assessment model for EHV transmission grid,” in *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, LNICST*, 2017. https://doi.org/10.1007/978-3-319-61813-5_9.

[18] A. Nariman, M. H. Fattahi, N. Talebbeydokhti, and M. S. Sadeghian, “Assessment of Seismic Resilience in Urban Water Distribution Network Considering Hydraulic Indices,” *Iranian Journal of Science and Technology - Transactions of Civil Engineering*, 2022, https://doi.org/10.1007/s40996-022-00941-7.

[19] S. Argyroudis, S. Mitoulis, A. M. Kaynia, and M. G. Winter, “Fragility Assessment of Transportation Infrastructure Systems Subjected to Earthquakes,” 2018, https://doi.org/10.1061/9780784481479.018.

[20] A. Urlainis and I. M. Shohet, “Seismic Risk Mitigation and Management for Critical Infrastructures Using an RMIR Indicator,” *Buildings*, vol. 12, no. 10, Oct. 2022, https://doi.org/10.3390/buildings12101748.

[21] G. Sevieri, A. De Falco, and G. Marmo, “Shedding light on the effect of uncertainties in the seismic fragility analysis of existing concrete dams,” *Infrastructures (Basel)*, vol. 5, no. 3, 2020, https://doi.org/10.3390/infrastructures5030022.

[22] A. Urlainis, M. Paciuk, and I. M. Shohet, “Service Life Prediction and Life Cycle Costs of Light Weight Partitions,” *Applied Sciences*, vol. 14, no. 3, p. 1233, Feb. 2024, https://doi.org/10.3390/app14031233.

[23] A. Urlainis and I. M. Shohet, “A Comprehensive Approach to Earthquake-Resilient Infrastructure: Integrating Maintenance with Seismic Fragility Curves,” *Buildings*, vol. 13, no. 9, p. 2265, Sep. 2023, https://doi.org/10.3390/buildings13092265.

[24] X. Lei, L. Sun, and Y. Xia, “Seismic fragility assessment and maintenance management on regional bridges using bayesian multi-parameter estimation,” *Bulletin of Earthquake Engineering*, vol. 19, no. 15, 2021, https://doi.org/10.1007/s10518-021-01072-6.

[25] M. A. Zanini, F. Faleschini, and C. Pellegrino, “Cost analysis for maintenance and seismic retrofit of existing bridges,” *Structure and Infrastructure Engineering*, vol. 12, no. 11, 2016, https://doi.org/10.1080/15732479.2015.1133661.

[26] G. C. Manos, N. Simos, and E. Kozikopoulos, “The Structural Performance of Stone-Masonry Bridges,” *Structural Bridge Engineering*, 2016, https://doi.org/10.5772/64752.

[27] P. Crespi, M. Zucca, M. Valente, and N. Longarini, “Influence of corrosion effects on the seismic capacity of existing RC bridges,” *Eng Fail Anal*, vol. 140, p. 106546, Oct. 2022, https://doi.org/10.1016/J.ENGFAILANAL.2022.106546.

[28] G. Tecchio, M. Donà, E. Saler, and F. da Porto, “Fragility of single-span masonry arch bridges accounting for deterioration and damage effects,” *European Journal of Environmental and Civil Engineering*, 2022, https://doi.org/10.1080/19648189.2022.2108504.

[29] M. Soltani, M. Raissi Dehkordi, M. Eghbali, D. Samadian, and H. Salmanmohajer, “Influence of Infill Walls on Resilience Index of RC Schools Using the BIM Analysis and FEMA P-58 Methodology,” *International Journal of Civil Engineering*, 2022, https://doi.org/10.1007/s40999-022-00777-2.

[30] FEMA, “Seismic Performance Assessment of Buildings - FEMA P-58,” 2012.

[31] I. M. Shohet, “Building evaluation methodology for setting maintenance priorities in hospital buildings,” *Construction Management and Economics*, vol. 21, no. 7, pp. 681–692, Oct. 2003, https://doi.org/10.1080/0144619032000115562.

[32] A. Mitelman, B. Yang, A. Urlainis, and D. Elmo, “Coupling Geotechnical Numerical Analysis with Machine Learning for Observational Method Projects,” *Geosciences (Basel)*, vol. 13, no. 7, p. 196, Jun. 2023, https://doi.org/10.3390/geosciences13070196.

[33] A. McQuillan, A. Mitelman, and D. Elmo, “Back-Analysis of Structurally Controlled Failure in an Open-Pit Mine with Machine Learning Tools,” *Geotechnics*, vol. 3, no. 4, pp. 1207–1218, Nov. 2023, https://doi.org/10.3390/geotechnics3040066.

[34] A. Mitelman and A. Urlainis, “Investigation of Transfer Learning for Tunnel Support Design,” *Mathematics*, vol. 11, no. 7, p. 1623, Mar. 2023, https://doi.org/10.3390/math11071623.