Seismic Vulnerability of Bridges in Morocco Using Fragility Curves and Incremental Dynamic Analysis IDA: A Case Study of an Independent-Span Viaduct with Precast Reinforced Concrete Beams on the Selouane to Nador WESTMED Railway Link

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Abstract. Bridges represent critical yet vulnerable elements of Morocco's transportation infra-structure. This vulnerability is particularly concerning in seismically active regions such as the Nador area in northeast Morocco, where the convergence of the Eurasian and Nubian plates along the Alboran Sea generates significant seismic hazard. This study assesses the seismic vulnerability of a strategic viaduct on the Selouane-Nador WESTMED railway link, a vital connection to the Nador port, by developing analytical fragility curves. The methodology employs a probabilistic framework based on Incre-mental Dynamic Analysis (IDA), where a detailed finite element bridge model is sub-jected to 18 carefully selected seismic records.The results quantify the bridge's seismic performance, establishing median peak ground acceleration (PGA) thresholds of 0.25g, 0.55g, and 0.85g for the Immediate Occupancy (IO), Life Safety (LS), and Collapse Pre-vention (CP) damage states, respectively. Furthermore, the study translates these probabilistic results into practical decision-making tools by correlating the engineering damage states with the official bridge condition classification system used by the Mo-roccan Ministry of Equipment and Water. This integration provides infrastructure managers with a risk-based methodology to prioritize inspections, maintenance, and strengthening strategies, thereby enhancing the seismic resilience of essential bridge networks in Morocco.

Keywords: Seismic Vulnerability, Fragility Curves, Incremental Dynamic Analysis (IDA), Reinforced Concrete Bridges, Probabilistic Assessment, Moroccan Infrastructure.

1. Introduction

Earthquakes, with their destructive force and devastating impact on infrastructure, economy, and daily life, remain one of the most feared natural disasters. A single seismic event can reduce entire cities to rubble and cause thousands of deaths in seconds [1]. The social impact is often amplified by the destruction of critical communication links, such as bridges, which complicate rescue missions and supply chains for affected areas. Therefore, the effect of earthquakes on bridges cannot be neglected.

In Morocco, the road and railway networks are vital, connecting diverse regions and underpinning the national economy and citizen mobility. These networks have seen significant development in recent decades, necessitating substantial investment in both new construction and the maintenance of existing infrastructure [2]. Bridges, as the essential nodes of this network, are particularly vulnerable. Ensuring their operational continuity under seismic threats is paramount.

Recent advancements in seismic vulnerability assessment have moved toward the development of more efficient analytical tools and the integration of diverse structural typologies. For instance, (Rabi and Monti 2024) proposed closed-form equations for the fragility of hollow-core bridge piers to facilitate large-scale territorial risk studies, while (Rabi and Monti 2025) utilized machine learning techniques to derive fragility equations based on visible structural parameters, enhancing the predictability of analytical models. Furthermore, the importance of spectral consistency in seismic assessment has gained prominence; (Rabi and Monti 2025) explored seismic risk for code-noncompliant frames using spectrum-consistent fragility fuses, and (Monti, Rabi et al. 2024) introduced spectrum-consistent ag-based fragility curves to ensure a more robust correlation between ground motion intensity and structural demand. These developments underscore the necessity of refining fragility frameworks to align with modern engineering standards and specific regional hazards, such as those found in Northern Morocco.

This study focuses on a critical viaduct within this network, located in a region of high seismic significance. The city of Nador is situated in the northeast of Morocco, along the Alboran Sea. It is considered a seismically active area in North Africa due to the convergence of the Eurasian and Nubian plates[3-5]. This tectonic activity makes the region particularly vulnerable to earthquakes, underscoring the necessity for rigorous seismic assessment of its infrastructure. The bridge under investigation forms a vital link to the strategic Nador WESTMED port, highlighting the economic and logistical imperative of its resilience.

The objective of this work is to propose a methodology for assessing the seismic vulnerability of such structures. We employ a probabilistic framework that uses nonlinear dynamic analysis and Incremental Dynamic Analysis (IDA) to construct fragility curves. These curves predict the probability of reaching different damage levels as a function of seismic intensity, providing a powerful tool for performance-based assessment and informing maintenance, rehabilitation, and emergency planning strategies for bridge management in Morocco.

2. Seismic DATA

In this study, time domain analyses were conducted using a curated set of 18 seismic records applied to a reinforced concrete girder bridge model. The selection process rig-orously prioritized three critical dimensions to ensure both scientific validity and re-gional relevance. First, strict adherence to EUROCODE 8 spectral shape requirements [6] guaranteed that all ground motions accurately represented site-specific seismic hazards, with particular attention to spectral acceleration characteristics across periods relevant to medium-span bridge dynamics (0.2–2.0 seconds). Second, recognizing Morocco's com-plex seismotectonic environment—characterized by moderate-to-high magnitude events along the Azores-Gibraltar Fault Zone—the records were deliberately chosen to mirror regional hazard profiles. This involved targeting earthquakes within magnitude ranges (M5.0–6.95) and source-to-site distances (R_{rup} = 2.92–222.42 km) documented in Morocco's seismic history, including near-field pulse-dominated motions and far-field attenuated waves to capture diverse structural excitation mechanisms. Third, to maintain data integrity, all accelerograms—formatted as acceleration-time histories [7] for precise reproduction of displacement/velocity components—were sourced exclusively from the Pacific Earthquake Engineering Research (PEER) Center database [8], leveraging its standardized processing protocols and global recognition as a benchmark repository for peer-reviewed ground motion records. The resulting du-al-intensity suite (Tables 1–2) enables robust assessment of vulnerability curves across operational to collapse limit states while addressing epistemic uncertainties inherent in nonlinear dynamic analysis of transportation infrastructure.

Table 1. Low-to-Medium Magnitude Earthquake Records (M5.0–6.0) for Seismic Analysis.

Record	Earthquake	Year	Magnitude	R_rup (km)
1	Imperial Valley-04	1953	5.5	15.64
2	Central Calif-01	1954	5.3	25.81
3	San Francisco	1941	5.28	11.02
4	Northern Calif-05	1976	5.6	28.73
5	Lytle Creek	1970	5.33	12.14
6	Central Calif-02	1960	5.00	9.02
7	Managua_ Nicaragua-02	1972	5.2	4.98
8	Hollister-03	1974	5.14	10.46
9	Northern Calif-07	1975	5.2	62.75

Table 2. Medium-to-Strong Magnitude Earthquake Records (M6.0–7.0) for Seismic Analysis.

Record	Earthquake	Year	Magnitude	R_rup (km)
1	Managua_ Nicaragua-01	1972	6.24	4.06
2	Borrego Mtn	1968	6.63	222.42
3	San Fernando	1971	6.61	22.77
4	Parkfield	1966	6.19	9.58
5	Borrego	1942	6.5	56.88
6	Northwest Calif-02	1941	6.6	91.22
7	Imperial Valley-02	1940	6.95	6.09
8	Helena_ Montana-01	1935	6.0	10.27
9	Helena_ Montana-02	1935	6.0	2.92

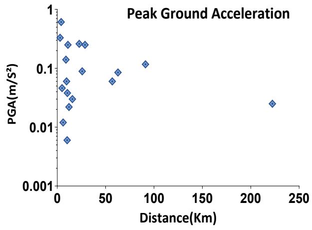
Using the collected seismic data and converting this data into spectral acceleration values corresponding to 5% damping, the results obtained are shown in Figure 1.

The selected seismic records encompass magnitude ranges comparable to historical earthquakes in Morocco, while capturing diverse parameters such as focal distance and peak ground acceleration, for example the focal distance and the maximum acceleration recorded with each earthquake.

The recordings will be used to produce an energy similar to that which could be generated by an earthquake on the pier of a reinforced concrete beam bridge as pre-sented on a simulation dissected in the next paragraph.

In Figure 1 we obtain the Variation of PGA (peak ground acceleration) of the earthquakes chosen for this project as well as the Variation of PGD (peak ground dis-placement); the Displacement Spectrum is calculated for a damping of 5%. At the end we can conclude the Spectral Displacement for the two recording ranges.

A)



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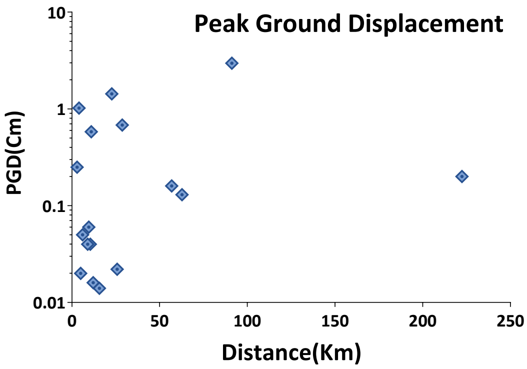
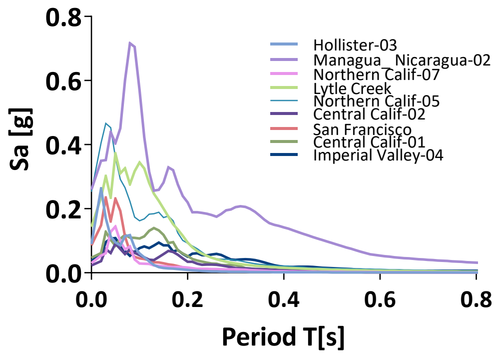


Figure 1. A) Variation of PGA of the earthquakes chosen for the project. B) Variation of PGD of the earthquakes chosen for the project.

A)



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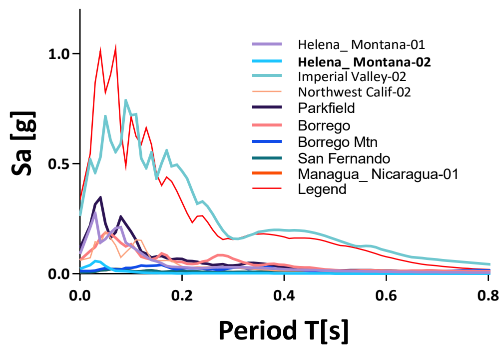
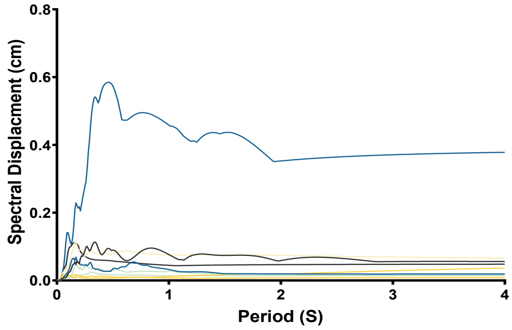


Figure 2. A) Displacement spectrum of 5% damping for the first range of records. B) Displace-ment spectrum of 5% damping for the second range of records.

A)



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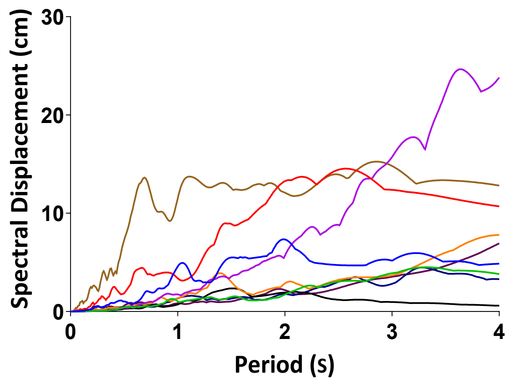

Figure 3. A) Spectral displacement for the first range of records; b) Spectral displacement for the second range of records.

3. Modelling and analysis of the bridge structure

The subject structure of this study forms part of the development of the railway network. The structure is located at the new Nador Port (Morocco), at Lambert coordinates X = 704393.96, Y = 505259.13, connecting the Nador WESTMED port to Selouane.

The structure is an independent-span viaduct composed of precast reinforced concrete beams. It has a total length of 73.10 m, divided into three 23.10 m isostatic spans. The deck width is 10.35 m. The superstructure is supported on two piers and two abutments at the extremities via steel-reinforced elastomeric bearings, as presented in figure 4.

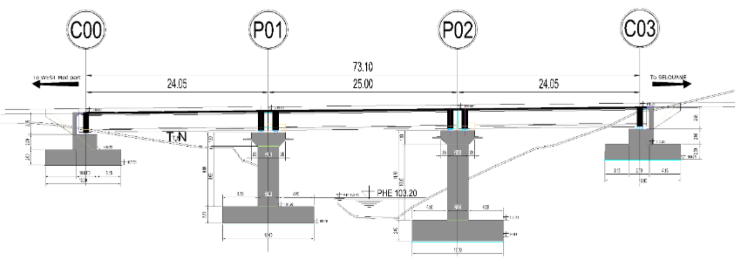

Figure 4. Longitudinal Profile of the bridge**.**

The superstructure is composed of three independents, simply supported spans, each with a length of 23.10 m and a total deck width of 10.35 m.

Longitudinal expansion joints are provided between each span. In the transverse direction, the deck utilizes five reinforced concrete girders with a hollow block slab infill, giving a total structural depth of 2.60 m, as detailed in Figure 5.

Substructure elements consist of single circular piers (diameter D = 2.80 m) topped with a rectangular pier cap. The foundations consist of rectangular shallow spread footings, illustrated in Figure 6.

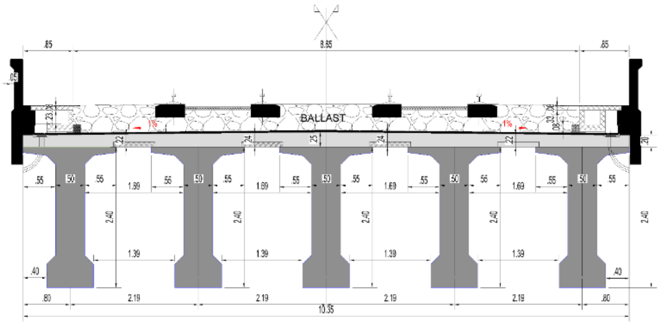

Figure 5. Bridge Deck Cross-Section.

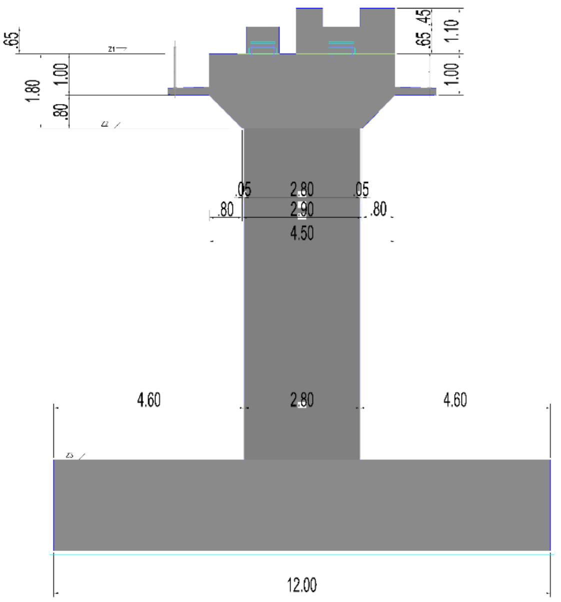

Figure 6. Cross Section at the Piers.

The longitudinal reinforcement for Pile 1 comprises two layers of 56 No. 32 mm diameter bars each. Transverse reinforcement consists of 40 No. 20 mm diameter circular ties spaced at 200 mm centers. For Pile 2, the longitudinal reinforcement is similarly arranged in two layers, but with 77 No. 32 mm diameter bars per layer. The transverse reinforcement for Pile 2 utilizes 50 No. 20 mm diameter circular ties, also spaced at 200 mm centers. These reinforcement details are illustrated in Figure 7.

A) B)

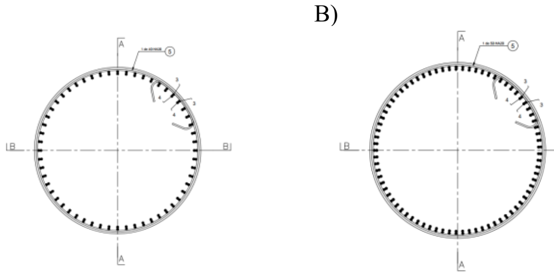

Figure 7. Pier renforcement sections **: a) Pier 1 ; b) Pier 2.**

3.1 Numerical Modeling Assumptions

To ensure the accuracy and reproducibility of the seismic assessment, the bridge piers were modeled using detailed nonlinear finite element approaches in MIDAS Civil. The following key assumptions and modeling choices were adopted:

A) Element Type and Discretization

The piers were modeled using nonlinear force-based beam-column elements. This formulation allows the spread of inelasticity along the member length and through the cross-section, which is more accurate than lumped plasticity models for capturing the distributed damage expected in reinforced concrete piers under seismic loading.

B) Fiber Section Modeling

The cross-sections of the piers were discretized into fiber sections. Each fiber is as-signed a uniaxial material constitutive law, enabling a detailed tracking of the neutral axis migration and the moment-curvature response. The section was divided into three regions: unconfined cover concrete fibers, confined core concrete fibers, and reinforcing steel fibers placed at their exact geometric locations based on the reinforcement draw-ings provided in Figure 7.

C) Constitutive Material Models

Concrete: The Mander et al. (Mander, Priestley et al. 1988) model was adopted for both confined and unconfined concrete. This model accurately simulates the increase in compressive strength and ductility of the core concrete due to confinement from transverse reinforcement. The compressive strength (f'c) was taken as 35 Mpa, based on the design specifications. The tensile strength of concrete was neglected.

Reinforcing Steel: A Menegotto-Pinto model was used for the longitudinal and transverse reinforcement. This model accounts for the Bauschinger effect and post-yield behavior with isotropic strain hardening. The yield strength (fy) was taken as 500 Mpa, the ultimate strength (fu) as 550 Mpa, and the modulus of elasticity (Es) as 200 Gpa.

D) Explicit Modeling of Confinement

Confinement was explicitly modeled by assigning distinct material properties to the core and cover concrete fibers. For the core fibers, the confined concrete parameters were calculated using the Mander model, considering the volumetric ratio and yield strength of the circular ties (spaced at 200 mm). The cover fibers were modeled as unconfined concrete, with a steep post-peak descending branch to represent spalling.

E) Geometric Nonlinearity (P-Delta Effects)

Given that the assessment extends to the Collapse Prevention limit state where large displacements are expected, P-Delta (Δ) effects were activated in all nonlinear time-history analyses. This accounts for the additional second-order moments generated by gravity loads (self-weight of the superstructure and the pier) acting on the laterally displaced structure. This is essential for capturing the dynamic instability and the flattening of the IDA curves near the collapse threshold.

F) Boundary Conditions and Interactions

Foundations: The shallow spread footings were modeled as fixed at their base. Soil-structure interaction was not considered in this study, which is a common and conservative simplification for this type of vulnerability assessment.

Bearings: The steel-reinforced elastomeric bearings were modeled using nonlinear link elements. The horizontal behavior (longitudinal and transverse) was simulated using an elastic-perfectly plastic hysteresis rule to account for potential shear defor-mation, while the vertical stiffness was modeled as linear elastic.

The methodology for assessing the seismic vulnerability of the bridge structure is grounded in a well-established analytical framework that integrates advanced numeri-cal modeling with probabilistic seismic analysis (Wang and Meng 2017). This approach involves developing a high-fidelity model of the bridge pier using the spe-cialized engineering software MIDAS Civil (Jacob 2022) as illustrated in Figure 8. To ensure the reliability of the numerical simulation, the model's response was verified against a simplified model implemented in opensees (McKenna 2011), a practice that enhances the credibility of complex nonlinear analyses (Priestley, Seible et al. 1996).

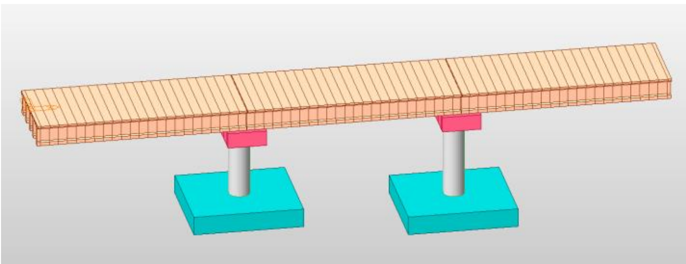

Figure 8. Global finite element model of the bridge structure developed in MIDAS Civil.

The global finite element model developed in MIDAS Civil is shown in Figure 8. The detailed modeling assumptions for the piers and bearings are described in the following subsections.

The core of the assessment employs Incremental Dynamic Analysis (IDA), a standard method for evaluating structural performance under seismic loading (Vamvatsikos and Cornell 2002). The process begins with a series of Nonlinear Time History Analyses (THA) using the curated set of seismic records. The key engineering demand parameter (EDP) the maximum displacement at the pier head—is extracted from each analysis. Subsequently, these results are processed through the IDA, where each ground motion is scaled to multiple intensity levels to construct curves plotting spectral acceleration (Sa) against the maximum pier displacement. This methodology has been successfully applied to the seismic vulnerability assessment of bridge structures in numerous studies (Mackie and Stojadinović 2007). The dispersion of the resulting IDA curves provides a probabilistic view of structural performance, identifying the intensity levels at which the structure transitions through different damage limit states. This data is fundamental for developing the analytical fragility curves that form the basis of this vulnerability assessment.

4. Probabilistic Framework for Seismic Performance and Bridge Management in Morocco

A probabilistic methodology was employed to assess the seismic vulnerability of the structure. This approach quantifies the probability of reaching or exceeding specific damage states as a function of seismic intensity. The probability of reaching a damage limit state (Damage State, DS) is given by equation (1), where the seismic demand (Q) and the structural capacity (R) are considered random variables (Calvi, Pinho et al. 2006).

$$P_{LS} = \sum_x P[DS|Q = x].P[Q = x] \quad (1)$$

Where P[DS|Q=x] represents the seismic fragility of the structure and P[Q=x] represents the seismic hazard.

Equation (1) represents the complete theoretical formulation for seismic risk assessment, which requires the convolution of fragility curves with a site-specific seismic hazard model. The scope of the present study is limited to the development of the fragility component P[DS|Q=x]. The convolution with a hazard curve for the Nador site, which would necessitate a dedicated probabilistic seismic hazard analysis (PSHA), is beyond the scope of this paper and is identified as a necessary step for future work.

Fema 356 (FEMA 2000) provides three levels of structural performance:

- Collapse Prevention (CP), Life Safety (LS), and Immediate Occupancy (IO). Corresponding maximum allowable displacement ratios of 5%, 2.5% and 0.7%.
- We also consider other damage limit states as 0.2% for Slight Damage, 0.5% for Moderate Damage, 1.0% for Extensive Damage, and 2.5% for Complete Damage.

Fragility F (x) is estimated as a lognormal distribution indicating the probability of exceeding the different levels of damage Equation 2 (Calvi, Pinho et al. 2006).

$$F_R(X) = \Phi[(\text{Ln}\,X - \text{Ln}\,\widehat{S_A})/B_R] \quad (2)$$

Where $\hat{S}_a$ The mean of the fragility values of the S_a Unit structure, β_R Is the lognormal standard deviation of the frailty system. The dispersion parameter β_R, which reflects the uncertainties, is associated with the seismic demand.

To contextualize these probabilistic results within the operational framework of managing Morocco's infrastructure heritage, a comparison is established with the condition rating system of the Ministry of Equipment and Water. This system classifies the condition of structures to prioritize maintenance interventions. The following table proposes a correlation between probabilistic seismic damage states and the Moroccan condition classes(KINGDOM OF MOROCCO MINISTRY OF EQUIPMENT AND WATER 2021):

Table 3. Correlation between Seismic Damage States and Moroccan Bridge Condition Classes.

Seismic Damage State	Moroccan Condition Class	Description and Management Implications
Slight Damage / IO	1P: Good apparent condition	The structure is safe and operational. No significant structural damage. Interventions fall under routine maintenance and minor post-seismic checks.
Moderate Damage / LS	2P: Defects requiring specialized maintenance	The structure exhibits distress (cracking, moderate deformations) that does not immediately affect global stability but require specialized, non-urgent maintenance. Further investigations are required.
Extensive Damage / CP	3P: Defects requiring urgent specialized maintenance	The structure has sustained severe damage, with reduced residual load-bearing capacity. It presents a risk of short-term deterioration. Urgent and specialized intervention (repair, strengthening, load restriction) is imperative to guard against partial or total collapse.
Complete Damage	Beyond Class 3P	The structure is out of service, with an imminent risk of collapse. Interventions are no longer maintenance but demolition and reconstruction.

This correlation translates the abstract results of probabilistic analysis, particularly fragility curves, into concrete management actions. By establishing a direct link between damage occurrence probabilities and regulatory condition classes, this integrated approach provides infrastructure managers with a powerful decision-making tool. It enables them to prioritize investments in seismic strengthening and proactively plan maintenance strategies and emergency response plans, based on a quantitative seismic risk assessment aligned with national classification criteria.

5. Results and Discussion

This section focuses on analyzing the results obtained using the incremental dynamic analysis (IDA) method and developing analytical fragility curves. The purpose of examining these results is to assess the seismic resistance and vulnerability of bridge piers. This data provides essential quantitative information for risk analysis and decision-making.

The resulting IDA curves for Pile 1 and Pile 2 are presented in Figures 9 and 10, respectively. These curves plot $Sa(T_1)$ against Δ_max, effectively creating a "seismic footprint" of the structure's behavior. The analysis reveals several critical performance thresholds :

Initial Stiffness and Elastic Range: For low intensity shaking ($Sa(T_1) < \sim 0.3g$), the IDA curves for all records cluster closely, exhibiting a steep, linear slope. This indicates a consistent, predominantly elastic response from the reinforced concrete piers, with minimal stiffness degradation.

Onset of Nonlinearity and Yielding: Beyond approximately 0.3g, the curves begin to fan out, demonstrating significant record-to-record variability. More importantly, the slope of the curves decreases, signaling the initiation of nonlinear behavior. This corresponds to the yielding of the longitudinal reinforcement in the plastic hinge region at the pier base, a conclusion validated by the moment-curvature analysis integrated into the model.

Global Instability (Collapse Limit State): At high intensity levels ($Sa(T_1) > \sim 1.0g$ for most records), the curves approach a near-horizontal plateau. This flattening indicates that small increments in seismic intensity cause very large increases in displacement demand, a classic signature of dynamic instability and the approach of the structural collapse limit state. The dispersion of these collapse points highlights the profound influence of the specific frequency content and duration of different ground motions on the ultimate capacity.

A comparative observation between Pile 1 and Pile 2 figure 9 shows that Pile 2, with its denser longitudinal reinforcement (77 bars vs. 56 bars of 32 mm diameter), generally exhibits a slightly higher capacity for a given displacement demand, particularly in the high-intensity range. This underscores the role of detailing in enhancing ductility and postponing collapse.

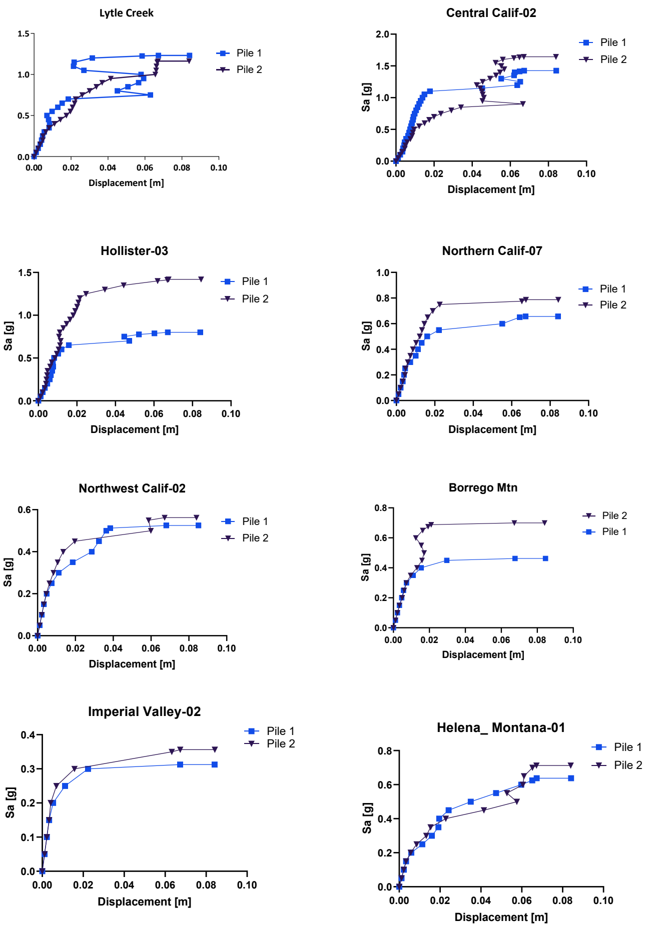

Figure 9. IDA curves for Pile 1 and Pile 2 under selected earthquake records.

The data from the IDA formed the basis for constructing analytical fragility curves using a probabilistic framework. These curves express the probability of exceeding predefined damage limit states as a function of the Peak Ground Acceleration (PGA), a widely used intensity measure in engineering practice. A lognormal cumulative distribution function was fitted to the data.

The resulting fragility curves for the FEMA 356(FEMA 2000) damage limit states(Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)),are presented in Figures 10 and 11 for Pile 1 and Pile 2, respectively. The curves exhibit the characteristic "S" shape of a lognormal distribution, effectively capturing the increasing probability of damage with rising seismic intensity.

Based on the fitted curves, the median PGA thresholds ($\hat{\theta}$) for the piers can be estimated:

- The Immediate Occupancy (IO) limit state, corresponding to a drift ratio of 0.7% and representing minor, repairable damage, is reached at a median PGA of approximately 0.25g.
- The Life Safety (LS) limit state, defined by a drift ratio of 2.5% and indicating significant damage with reduced margin of safety, has a median PGA of approximately 0.55g.
- The Collapse Prevention (CP) limit state, associated with a drift ratio of 5.0% and representing severe damage with imminent collapse, is reached at a median PGA of approximately 0.85g.

The progression of these curves clearly illustrates the structure's vulnerability. For instance, at a PGA of 0.4g, the bridge has a high probability of having exceeded the IO state but a low probability of being in the CP state. This granular probabilistic information is crucial for performance-based assessment.

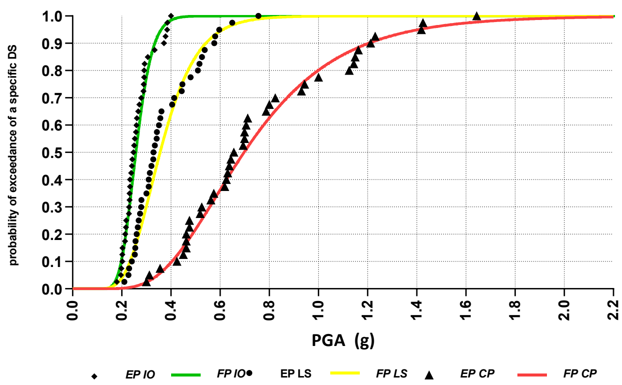

Figure 10. Fragility curves for pile 1, classification (IO ; LS ; CP) Empirical and fitted Probability.

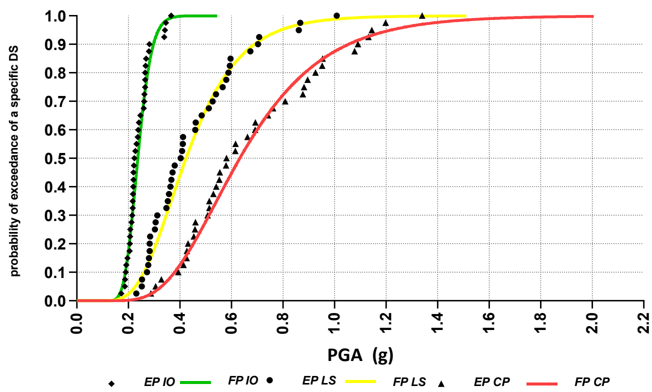

Figure 11. Fragility curves for pile 1, classification (IO; LS; CP) Empirical and fitted Probability.

Fragility curves serve as a vital translational tool, converting complex engineering analysis into actionable intelligence for infrastructure management. By integrating the probabilistic damage states with the Moroccan Ministry of Equipment and Water's bridge condition classification system (Table 3), a direct link is established between analysis and practice.

This integration enables a proactive, risk-based management strategy:

- At PGA = 0.25g (IO Threshold): The probability of exceeding the IO state becomes significant. This correlates with a transition from Condition Class 1P (Good) to 2P (Defects requiring specialized maintenance). This level of shaking would likely necessitate a system-wide post-earthquake inspection program to identify and schedule non-urgent repairs.
- At PGA = 0.55g (LS Threshold): The probability of the structure reaching the LS state is approximately 50%. This aligns with Condition Class 2P/3P, indicating distress that compromises safety and requires urgent, specialized intervention. At this intensity, bridge closures, detailed assessments, and significant repairs or strengthening would be imperative for a large portion of the network.
- At PGA > 0.85g (CP Threshold): The high probability of exceeding the CP state corresponds to a condition Beyond Class 3P. The structure is at imminent risk of collapse, shifting the management focus entirely from maintenance to demolition and reconstruction.

5. Conclusions

This study successfully demonstrated a comprehensive methodology for assessing the seismic vulnerability of bridges in Morocco using Incremental Dynamic Analysis (IDA) and analytical fragility curves. Application to a viaduct case study on the Selouane-Nador railway line provided critical and quantifiable information on the structure's performance under seismic loading. The developed fragility curves constitute a powerful probabilistic tool, translating complex technical data into clear probabilities of exceeding key damage limit states—Immediate Occupancy (IO), Safety of Persons (LS), and Prevention of Collapse (CP)—as a function of maximum ground acceleration. The analysis established median PGA thresholds of approximately 0.25g for IO, 0.55g for LS, and 0.85g for CP, thus providing a clear seismic performance benchmark for the studied bridge typology. Furthermore, the comparative analysis of the two piers confirmed that increased longitudinal reinforcement improves ductility and slightly raises the collapse threshold, highlighting the importance of structural detail.

Crucially, this research bridges the gap between theoretical analysis and practical infrastructure management. By correlating probabilistic damage states with the Moroccan Ministry of Equipment and Water's bridge condition classification system, the study provides a direct decision-making framework for authorities. This enables a proactive, risk-based strategy, progressing from routine maintenance triggered by minor tremors to emergency interventions and, potentially, reconstruction planning for severe earthquakes.

It should be noted that the present study focuses exclusively on the development of analytical fragility curves. Equation (1) was presented to illustrate the complete theoretical framework for seismic risk assessment, of which fragility curves are an essential component. The convolution with a site-specific seismic hazard curve for Nador, which would require a dedicated probabilistic seismic hazard analysis (PSHA), was not performed. This convolution remains a necessary and logical extension of the current work to compute annual failure probabilities and to support fully risk-informed decisions for infrastructure management. Integrating the developed fragility curves with a local hazard model is therefore identified as a priority for future research.

In conclusion, the integration of the IDA and fragility curves proves to be a reliable and operational methodology for assessing the seismic vulnerability of Moroccan bridges. While this study focuses on record-to-record variability, future extensions of this work should incorporate epistemic uncertainties, such as material property variations and modeling errors, to provide a fully coupled probabilistic assessment of bridge seismic risk. Looking ahead, applying this same framework to other common bridge types within the national network would be a logical and valuable extension, paving the way for a comprehensive and risk-informed strategy for the protection of Morocco's critical transport infrastructure heritage.

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