



SEISMIC FRAGILITY CURVES FOR HORIZONTAL AND VERTICAL GROUND MOTION OF BRIDGE PIERS WITH THE MACRO-ELEMENT SSI FOR SHALLOW FOOTINGS

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ABSTRACT

This study investigates the combined effects of vertical and horizontal seismic excitations on bridge piers. It explicitly accounts for Soil–Structure Interaction (SSI) using a macro-element modeling approach. The *sslink1* macro-element simulates the interaction between the pier and the underlying shallow foundation soil. To assess the influence of foundation size on seismic response, a range of variations in the width of rectangular foundations is introduced (2.5 m, 3.5 m, and 4.5 m). A suite of 21 ground motion records, incorporating both vertical and horizontal components, assesses the bridge piers' dynamic performance. The seismic response is analyzed through Incremental Dynamic Analysis (IDA) using *Seismostruct* software. This approach allows for the generation of IDA curves, which represent the evolution of structural demand with increasing seismic intensity. Based on the maximum drift ratio, fragility curves are subsequently developed. These curves quantify the probability of exceeding predefined damage states. Three distinct performance levels are considered: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Each level is defined by specific drift limit thresholds. The fragility functions are constructed using Peak Ground Acceleration (PGA) as the intensity measure, assuming a lognormal distribution. This enables a probabilistic assessment of seismic vulnerability across the different foundation widths.



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1. INTRODUCTION

Bridges are critical transportation lifelines that must remain operational after major earthquakes. Developing fragility curves for various bridge classes across countries is necessary. Earthquakes produce horizontal and vertical movements that stress and damage these structures [1], [2]. Seismic design of bridges taking into account seismic activity near faults is characterized by short duration impulses [3], [4]. There are major concerns when nearby faults and earthquakes cause horizontal and vertical ground displacement. When cracking and yielding of concrete are taken into account, the fragility curves of reinforced concrete bridges exhibit complex nonlinear behavior in seismically active regions. Earthquake near-faults pose significant risks because they cause horizontal and vertical ground vibrations. Rigorous analysis is necessary to ensure the safety of reinforced concrete continuous bridges, which are frequently used in seismic zones. RC bridges exhibit complex nonlinear behavior under seismic loads. To this end, fragility curves explain how concrete cracks and steel reinforcement yield under varying seismic forces. The Federal Emergency Management Agency uses the Multi-Hazard Loss Estimation methodology to assess earthquake intensity. RC bridges that suffer progressive damage, such as concrete cracking and reinforcement buckling, are subject to this method [5-7] have studied the effect of fragility on the structural brittleness of reinforced concrete bridges by looking at the effects of soil-structure interaction on the probability of failure of the system [8], [9] measured how the frequency dependence of the (linear) SSI (affected) on the fragility of RC bridges. By comparing the predicted vulnerability of a reference bridge using a conventional, frequency-independent kelvin-Voigt model and the lumped parameter formulation by the same authors, it was (discovered) uncovered that the simplified, frequency-independent approach can either overestimate or underestimate.

The actual fragility curves of a bridge. This could, of course lead to a behavior that is very different from that observed in reality. Current state-of-the-art in nonlinear foundation has refocused on macro-elements, concentrating primarily on shallow foundations e.g., [10-15] and more recently on piles and pile groups e.g., [16-23]. Hence, the system is modeled using macro-elements. They generally require in-depth analysis and have not yet implemented an element that would be influenced by the force and movement of the foundation soil, similar to the stress-strain-based dependency equations of elements. This study examines the coupled effects of vertical and horizontal seismic excitations on bridge piers, explicitly incorporating Soil-Structure Interaction (SSI) through a macro-element modeling approach. The interaction between the pier and the supporting shallow foundation soil is represented using the sslink1 macro-element. To evaluate the impact of foundation size on seismic behavior, rectangular foundation widths of 2.5 m, 3.5 m, and 4.5 m are considered. The dynamic performance of the bridge piers is assessed using a set of 21 ground motion records with both vertical and horizontal components. Seismic responses are evaluated through Incremental Dynamic Analysis (IDA) conducted using Seismostruct software.

II. DESCRIPTION OF THE MODEL

II.1 DESCRIPTION OF THE BRIDGE

This study examines a bridge featuring a continuous box-type deck spanning four equal 20-meter sections. The structure is supported by three internal piers and two end abutments, which provide both stability and structural continuity. To maximize strength while minimizing material use, the piers employ hollow rectangular cross-sections. The pier heights 6.19 m, 3.13 m, and 9.21 m vary strategically to accommodate the site's topography and meet specific structural requirements. Incremental Dynamic Analysis (IDA) was performed on the structure using the three-dimensional finite element program, Seismostruct, for the nonlinear dynamic simulation. The constitutive behavior of the concrete components was simulated using the Mander et al. confined concrete model [24], which faithfully reproduces the nonlinear stress-strain curves under cyclic excitation. Furthermore, the Menegotto-Pinto model [25] was implemented for the steel reinforcement to account for both nonlinear hysteresis and the Bauschinger effect. Soil-structure interaction was modeled using a macro-element foundation model that integrates crucial geotechnical properties. The soil is defined by a shear wave velocity of 200 m/s, a Poisson's ratio of 0.40, a cohesion of 60 kPa, a density of 1850 kg/m³, and an initial shear modulus (Gmax) of 74 MPa. These defined parameters ensure that the simulation realistically captures the flexibility of the soil and its resulting influence on the bridge's seismic response.

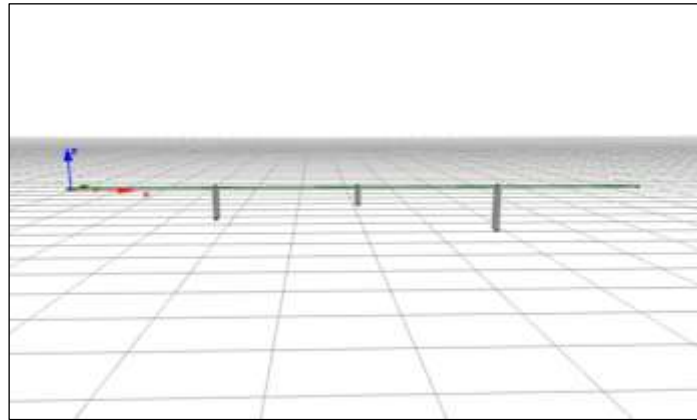


Figure 1: The Model design.
Source: Authors, (2026).

II.2 GROUND MOTION RECORDS USED IN THE ANALYSIS

The incremental dynamic examination required the selection of twenty-one ground motion records, sourced from the PEER strong motion database [26] (refer to Table 1). This group of records represents strong seismic events, evidenced by their high magnitudes, with Peak Ground Acceleration (PGA) values spanning from 5.2 to 7.14 MW.

Table 1: Earthquakes that were used in this study.

Num	Earthquake Name	Year	M
01	Imperial valle-06	1940	6
02	Imperial valley-03	1951	5.6
03	Northem calif	1967	5.20
04	Borrego mthn	1968	6.3
05	Hollister-02	1961	5.5
06	Whittier Narrows-01	1987	5.99
07	Whittier Narrows-02	1987	5.99
08	Chi-Chi,Taiwan-03	1999	6.20
09	Parkfield-02, CA	2004	6
10	Managua, Nicaragua-02	1972	5.20
11	Morgan Hill	1984	6.19
12	Mammoth Lakes-05	1980	5.7
13	N. Palm Springs	1986	6.06

14	Mammoth Lakes-10	1983	5.34
15	Duce, Turkey	1999	7.14
16	Tottori, Japan	2000	6.61
17	Coalinga-05	1983	5.77
18	Coyote Lake	1979	5.74
19	Imperial Valley-06	1979	6.53
20	Morgan Hill	1984	6.19
21	Parkfield-02, CA	2004	6.00

Source: Authors, (2026).

Figures 2, 3, 4 and 5 presents the results of the simulation of twenty-one acceleration records, illustrated through response spectrum curves alongside the target response spectrum. The Seismo-Match software [27] is employed to achieve compatibility between the selected ground motions and the target spectrum. This program modifies the acceleration records to ensure an adequate match with the specified response spectrum.

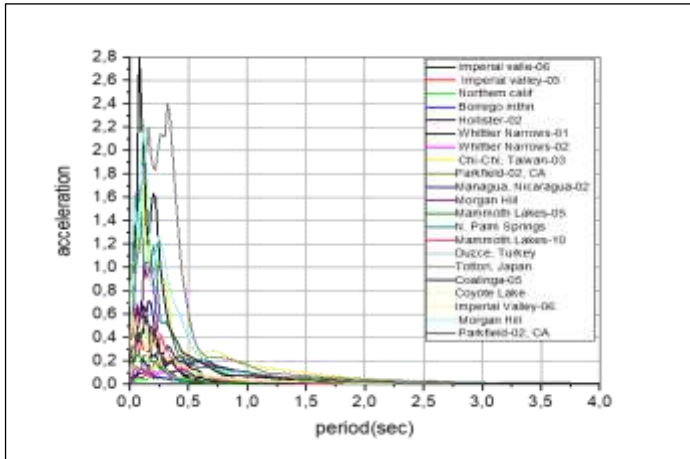


Figure 2: Horizontal acceleration response spectrum.
Source: Authors, (2026).

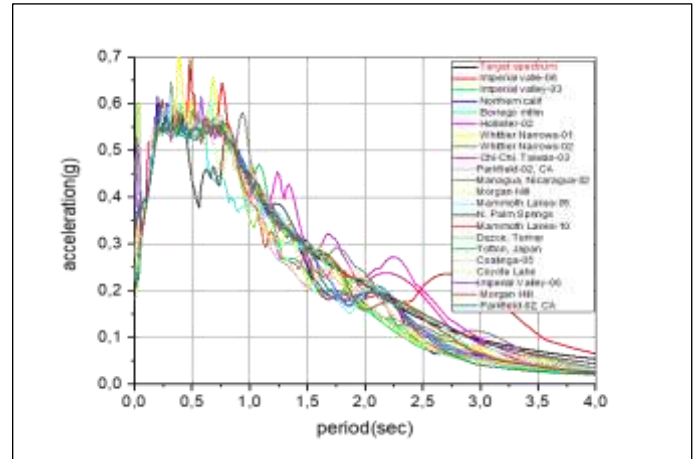


Figure 3: Ground motion spectra matched to the target using Seismo-Match (Horizontal).
Source: Authors, (2026).

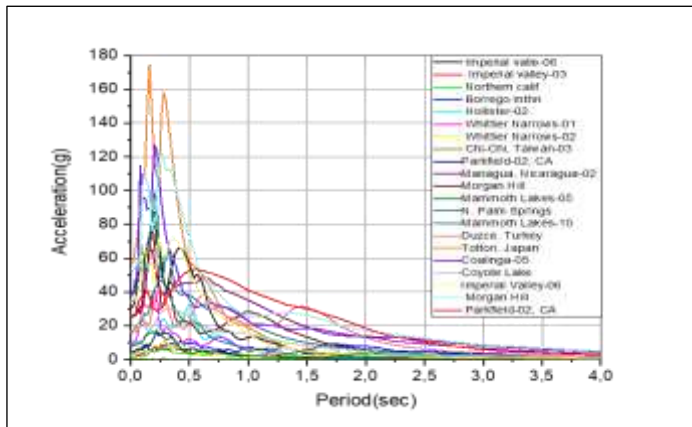


Figure 4: Vertical acceleration response spectrum.
Source: Authors, (2026).

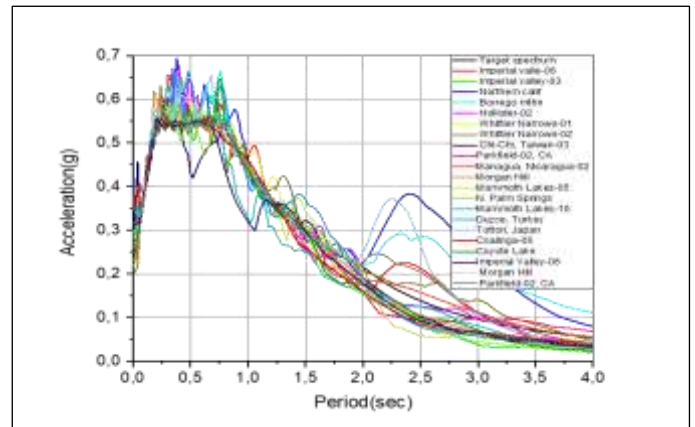


Figure 5: Ground motion spectra matched to the target using Seismo-Match (Vertical).
Source: Authors, (2026).

III. INCREMENTAL DYNAMIC ANALYSES IDA

The structural performance under seismic events is estimated using an Incremental Dynamic Analysis (IDA) [28], [29], a nonlinear parametric method. This analysis, performed in Seismostruct, involved subjecting the structure to twenty-one sets of both vertical and horizontal ground motion records. The intensity metric, Peak Ground Acceleration (PGA), is progressively increased from 0.1g with increments of 0.1g. Maximum story drift displacement served as the response measure to track structural damage. The damage limit states IO (0.5% drift), LS (1.5% drift), and CP (2.0% drift) are presented graphically in Figures 6 through 11.

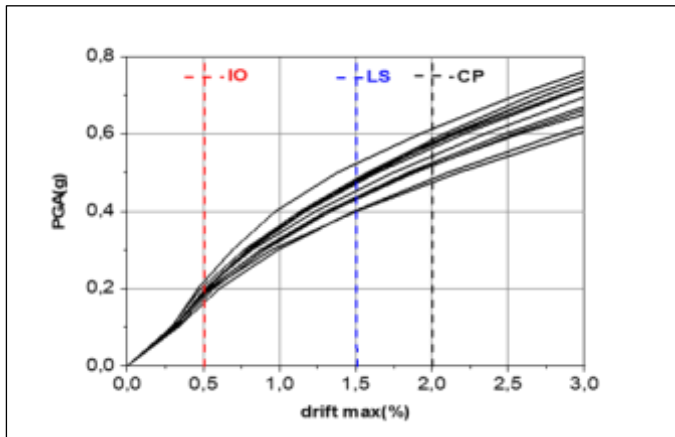


Figure 6: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (2.5×5 m) under vertical seismic excitation.
Source: Authors, (2026).

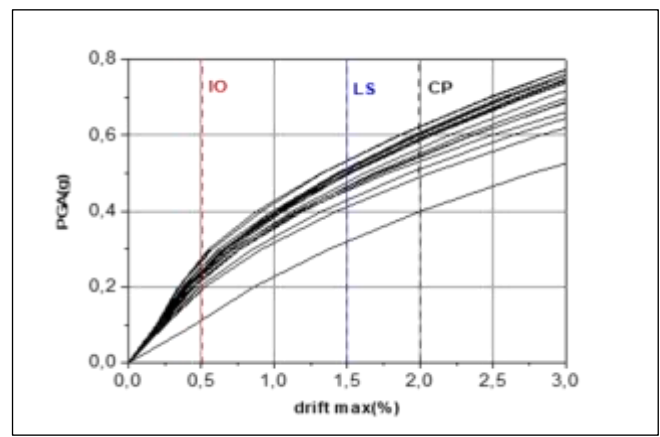


Figure 7: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (3.5×5 m) under vertical seismic excitation.
Source: Authors, (2026).

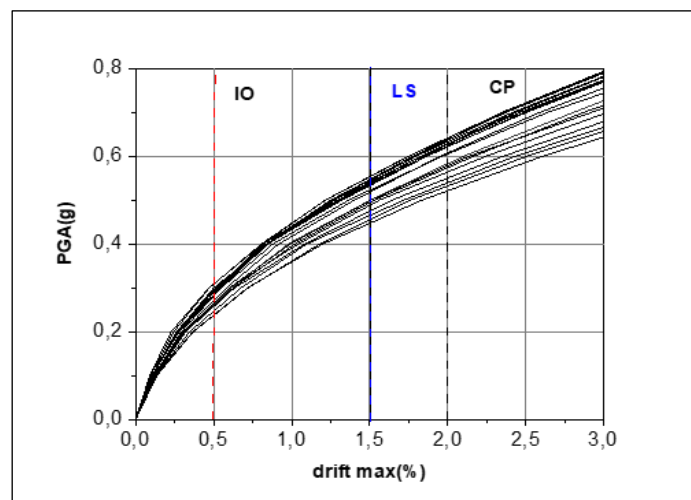


Figure 8: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (4.5×5 m) under vertical seismic excitation.
Source: Authors, (2026).

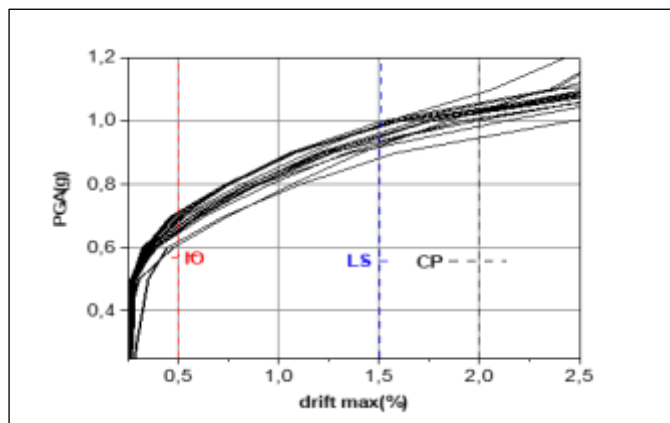


Figure 9: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (2.5×5 m) under horizontal seismic excitation.
Source: Authors, (2026).

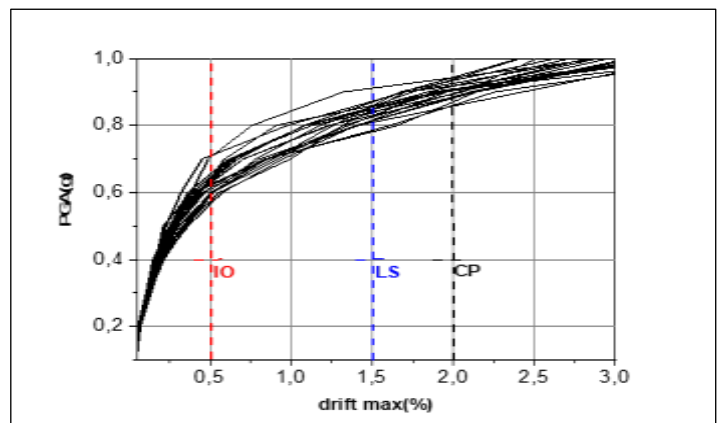


Figure 10: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (3.5×5 m) under horizontal seismic excitation.
Source: Authors, (2026).

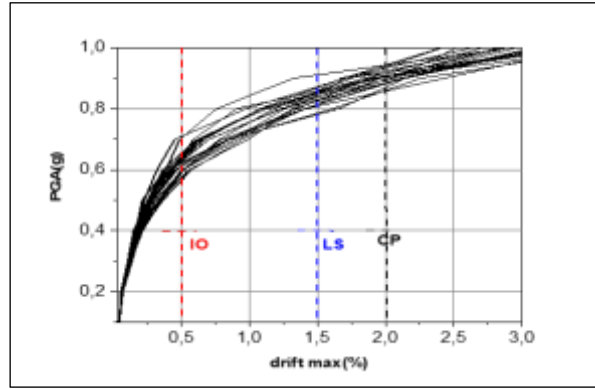


Figure 11: Incremental Dynamic Analysis (IDA) curves of the bridge pier with macro-element foundation (4.5×5 m) under horizontal seismic excitation.

Source: Authors, (2026).

IV. FRAGILITY CURVE

Fragility curves play a central role in seismic risk analysis. They are typically represented through a probability (PR) function, and are derived as lognormal distributions. These curves are built by calculating the likelihood that a structure will reach or surpass a defined level of damage under certain seismic conditions.

$$P_f(x) = \varphi\left(\frac{\ln\left(\frac{x}{A_m}\right)}{\beta}\right) \quad (1)$$

The standard normal cumulative distribution function is denoted by the symbol φ . The fragility curve is most effectively characterized by two parameters: the logarithmic standard deviation β and the median capacity A_m [30]. This probability is modeled using the log-normal distribution function (as described by Tavares et al., 2012). The study also considers an internal, randomly distributed (rectangular) cavity that varies in both size and depth. Figures 12 through 17 illustrate the fragility curves for stone bridges, along with the changes in the width B of the macro-element foundation.

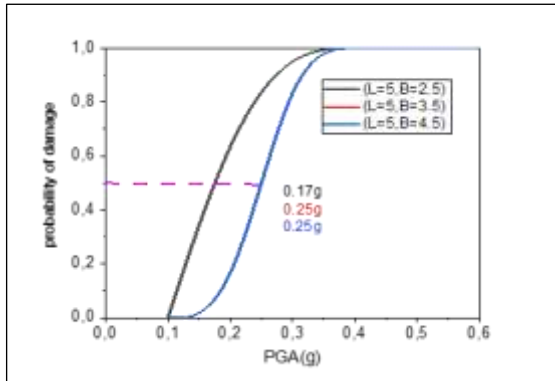


Figure 12: Fragility curves for the (IO) limit state under vertical seismic loading.

Source: Authors, (2026).

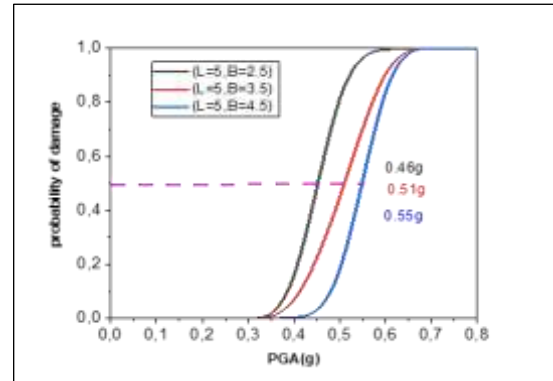


Figure 13: Fragility curves for the (LS) limit state under vertical seismic loading.

Source: Authors, (2026).

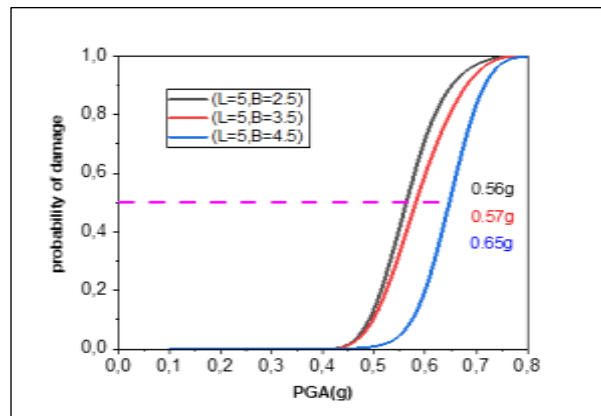


Figure 14: Fragility curves for the (CP) limit state under vertical seismic loading.

Source: Authors, (2026).

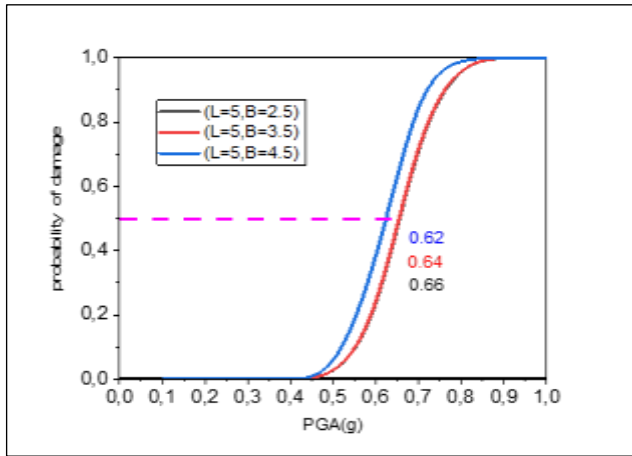


Figure 15: Fragility curves for the (IO) limit state under horizontal seismic loading.
Source: Authors, (2026).

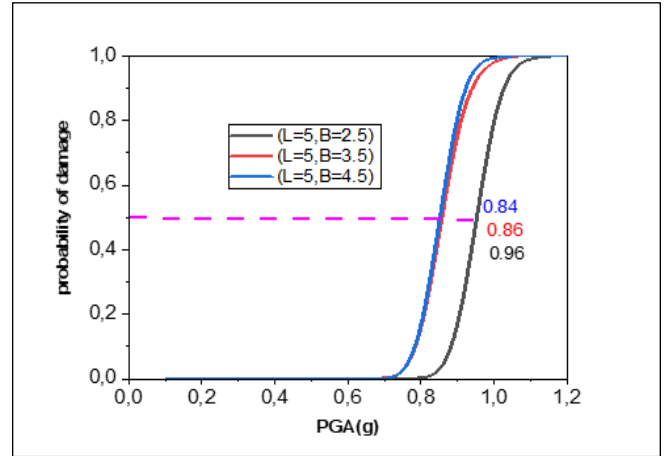


Figure 16: Fragility curves for the (LS) limit state under horizontal seismic loading.
Source: Authors, (2026).

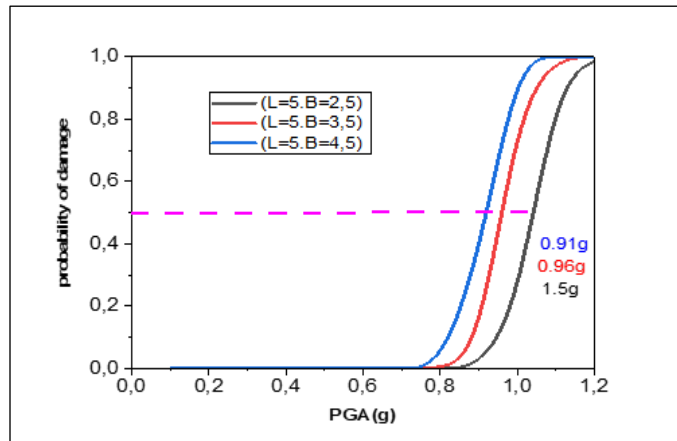


Figure 17: Fragility curves for the (CP) limit state under horizontal seismic loading.
Source: Authors, (2026).

V. RESULTS AND DISCUSSIONS

In this research, Incremental Dynamic Analysis (IDA) is conducted on a seismic structural model using 21 vertical and horizontal ground motion records. Fragility curves for the bridge are established according to specified limit states to evaluate its seismic behavior. Figures 12, 13, and 14 show the resulting fragility curves for the performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The findings reveal that, for bridges with macro-element foundation dimensions of $L=5$ m and $B=2.5$ m, 3.5 m, or 4.5 m, the fragility probabilities are 100% for IO, 96% for LS, and 16% for CP, indicating a higher vulnerability to the effects of vertical ground motion. Figure 12 illustrates that as the foundation width B increases, the Peak Ground Acceleration (PGA) required to reach a 50% probability of damage under vertical ground motion also increases. Specifically, for the Immediate Occupancy (IO) limit state, the PGA values rise from $0.17g$ to $0.25g$ and then to $0.25g$ as B grows. Similarly, Figure 13 shows that for the Life Safety (LS) limit state, the PGA values needed for a 50% damage probability increase from $0.46g$ to $0.51g$ and finally to $0.55g$ with increasing B . In Figure 14, for the Collapse Prevention (CP) limit state, the PGA values corresponding to a 50% probability of damage also increase from $0.17g$ to $0.25g$ and then remain at $0.25g$, following the same trend as B increases. The findings presented in Figures 15–17 demonstrate the impact of horizontal ground motion. As the foundation width (B) increases, the Peak Ground Acceleration (PGA) values associated with a 50% probability of damage decrease, signifying improved structural resistance. Specifically, for the Immediate Occupancy (IO) limit state (Figure 15), PGA values fall from $0.66g$ to $0.64g$ and $0.62g$. For the Life Safety (LS) limit state (Figure 16), PGA values reduce from $0.96g$ to $0.86g$ and $0.84g$. Lastly, in the Collapse Prevention (CP) limit state (Figure 17), PGA values drop from $1.50g$ to $0.96g$ and $0.91g$. In summary, a wider foundation improves a structure's seismic performance when subjected to horizontal ground motion. However, for vertical ground motion, larger foundation widths result in higher PGA values for the same damage probability, suggesting an increased demand under vertical excitation.

VI. CONCLUSIONS

This study investigate the seismic performance of a bridge structure supported by macro-element foundations, specifically examining the influence of varying foundation widths ($B = 2.5$ m, 3.5 m, and 4.5 m) while maintaining a constant length of $L = 5$ m. Utilizing the Incremental Dynamic Analysis (IDA) method, the bridge is subjected to 21 vertical and horizontal ground motions. Fragility curves, derived from maximum drift values, are employed to assess the probability of exceeding defined performance limit states. The analysis revealed that a decrease in the macro-element foundation width (B) leads to an increased Probability of Exceedance (POE) in the fragility curves, particularly under vertical ground motions, indicating heightened vulnerability for narrower foundations.

This trend is further supported by the observation that reduced foundation width correlates with a decrease in spectral acceleration, signifying lower overall stiffness and diminished resistance to seismic loads. Consequently, the macro-element foundation pier bridge with a width of $B = 4.5$ m demonstrated superior seismic performance in the vertical direction compared to those with $B = 3.5$ m and $B = 2.5$ m, aligning with previous research [31]. Furthermore, the findings confirmed that the wider macro-element foundation ($B = 4.5$ m) also exhibited enhanced horizontal seismic performance. These results collectively underscore the critical role of foundation width in significantly improving the overall dynamic stability and seismic resilience of bridge structures.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Methodology: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Investigation: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Discussion of results: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Writing – Original Draft: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid.

Writing – Review and Editing: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Resources: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Supervision: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

Approval of the final text: Azza Gueliane, Mohamed Saadi and Tayeb Bouzid

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