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ADVANCING SEISMIC RESILIENCE: AN INNOVATIVE PERFORMANCE-BASED METHODOLOGY FOR EVALUATING BRIDGE SEISMIC PERFORMANCE WITH SOIL-STRUCTURE INTERACTION CONSIDERATIONS

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Abstract. *Seismic events pose a significant threat to the structural integrity of bridges, often exacerbated by inadequate consideration of nonlinear responses and soil-structure interaction (SSI) effects. Existing guidelines for assessing bridge collapse risks lack practical and comprehensive approaches, hindering effective design and retrofitting strategies. This paper introduces an innovative, performance-based seismic evaluation framework tailored to bridge structures, inspired by the FEMA P695 methodology. The proposed approach integrates advanced seismic hazard analysis, nonlinear structural modeling, and statistical evaluation of collapse risks, incorporating ground motion spectral shape effects and system uncertainties. The methodology was applied to the Meloland Road Overcrossing (MRO) in Southern California as a case study. Four discrete archetype models, each with varying levels of SSI representation, were developed and subjected to incremental dynamic analysis (IDA) using a suite of 22 ground motions. These models ranged from simplified SSI representations to a detailed model (D_4) explicitly accounting for abutment-soil and pile-soil interactions. Results reveal that the level of SSI representation significantly influences collapse behavior. The D_4 model, with detailed SSI features, exhibited higher collapse probabilities and lower collapse margin ratios than simplified models, underscoring the critical role of SSI in structural performance. Fragility curves demonstrated the interplay of ground motion characteristics and SSI modeling on failure sequences and global collapse predictions, highlighting the necessity of accurate SSI characterization in seismic evaluations. This methodology supports resilient bridge design and retrofit planning in seismic zones.*

1 INTRODUCTION

The inadequate consideration of nonlinear structural behavior and soil-structure interaction (SSI) effects has contributed to the unsafe seismic design of bridges, resulting in numerous collapses worldwide. Despite these recurring failures, current seismic design codes continue to lack practical, comprehensive guidance for engineers to conduct reliable collapse risk assessments of bridge structures.

To address this critical gap, this paper presents a streamlined methodology—adapted from the FEMA P695 framework [1]—for evaluating the seismic performance of bridges within a performance-based earthquake engineering (PBEE) context. The proposed approach incorporates key components including seismic hazard analysis, advanced nonlinear modeling, and detailed damage evaluation. It rigorously accounts for influential parameters such as ground motion spectral shape and system-level collapse uncertainty. Furthermore, both simulated and non-simulated failure modes are explicitly captured in the nonlinear response modeling to enhance predictive accuracy.

The methodology is applied to the Meloland Road Overcrossing (MRO) in Southern California as a case study, demonstrating its capability to deliver practical and technically robust insights for the seismic evaluation and resilient design of bridge infrastructure. By advancing the accuracy of seismic performance evaluations, the proposed methodology contributes to more resilient bridge design, retrofit prioritization, and seismic risk-informed infrastructure development.

2 FRAMEWORK FOR THE PROPOSED BRIDGE SEISMIC PERFORMANCE EVALUATION METHODOLOGY

This paper presents a comprehensive methodology for the seismic assessment of bridges, combining analytical and statistical approaches within a performance-based seismic design framework. The proposed approach is adaptable for both the design of new structures and the retrofit of existing bridges. It supports both discrete and continuum modeling techniques and incorporates the concept of an acceptable probability of collapse ($P_{acceptable}$). Ground motion characteristics are explicitly considered, and the methodology systematically addresses uncertainties in both data and modeling. Where applicable, soil-structure interaction (SSI) effects are also incorporated.

As illustrated in Fig. 1, the methodology consists of four key stages: (1) development of nonlinear models for collapse assessment, (2) nonlinear time history analyses, (3) seismic performance evaluation, and (4) detailed documentation with peer review [2].

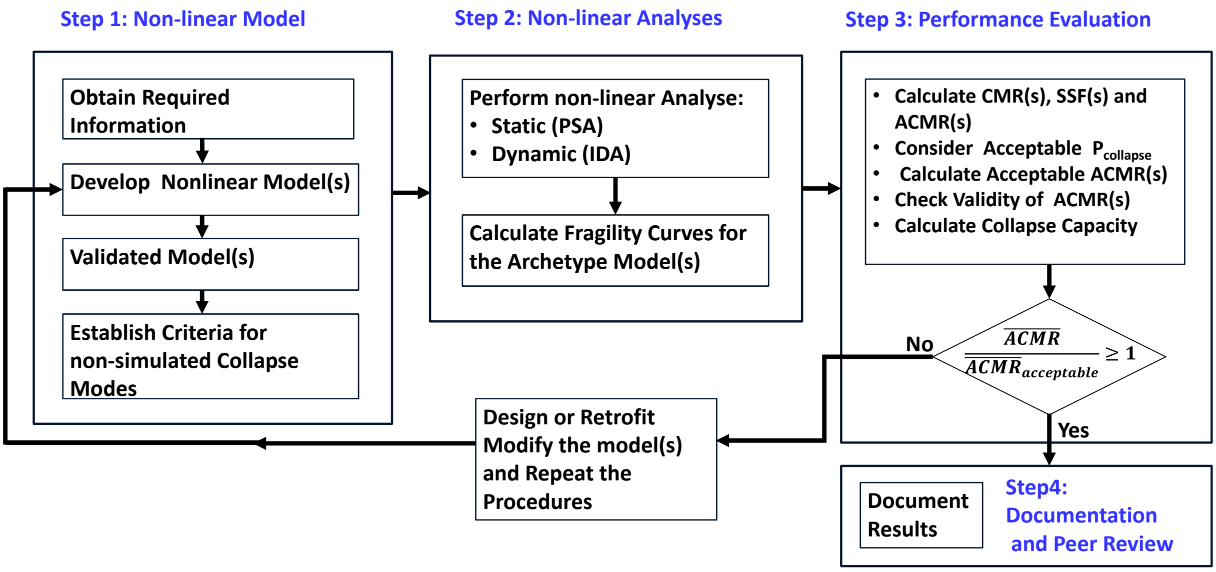


Figure 1: Workflow of the proposed seismic evaluation methodology [2].

3 NONLINEAR ARCHETYPE MODELS OF THE MRO BRIDGE

Four discrete archetype models of the bridge were developed and calibrated using data from ambient vibration testing [3]. The strength and displacement capacities of key structural elements were defined as performance benchmarks, following the guidelines outlined in the Seismic Retrofitting Manual for Highway Structures, Part 1: Bridges [4]. These models were subsequently utilized to conduct Incremental Dynamic Analysis (IDA).

Each model incorporates a unique level of soil-structure interaction (SSI) detail. Three of the models—D1, D2, and D3—were derived from earlier research efforts [5–7]. A schematic overview of the models, along with the corresponding Free Field Motion (FFM) input, is presented in Fig. 2.

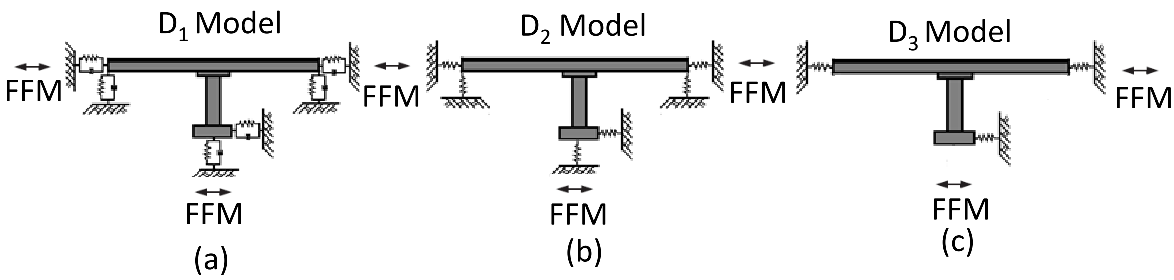
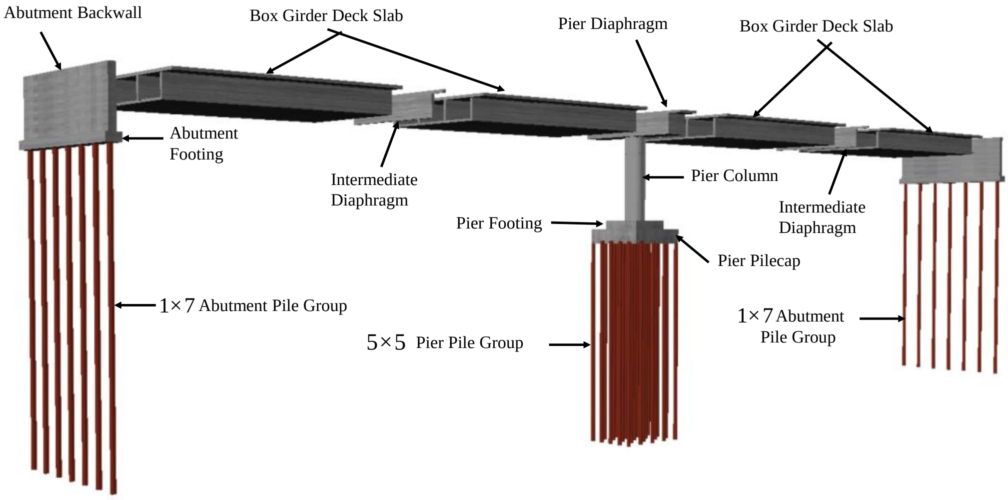


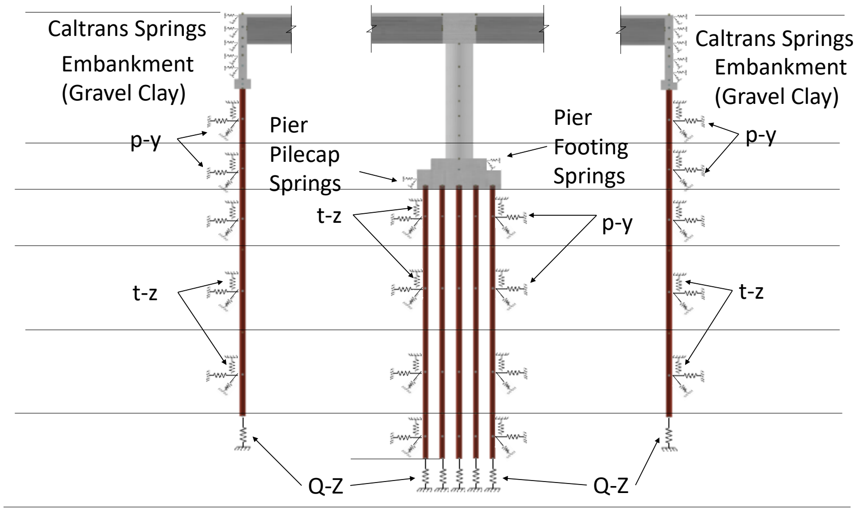
Figure 2: MRO models and applied Free Field Motion (FEM): (a) Viscoelastic embankments and center bent [5], (b) and (c) Elastic support at embankments and center bent [6,7].

The D_4 archetype model, developed specifically for this study, provides a detailed representation of soil-structure interaction (SSI) within a discrete modeling framework. This advanced model explicitly incorporates abutment and pier piles, as well as their interactions. It accounts for abutment wall–backfill interaction, pier foundation–soil interaction, and both lateral and vertical pile resistance, all of which were analytically estimated and integrated into the model [2].

All archetype models, including D_4, were subjected to a suite of 22 ground motions selected from the PEER NGA-West2 database [8]. These motions, chosen to reflect a broad range of dynamic characteristics, were intended to capture seismic hazard variability. Incremental Dynamic Analysis (IDA) was conducted on each model to evaluate seismic performance across varying intensity levels.



(a)



(b)

Figure 3: MRO models: (a) 3D view of the index archetype model D_4 constructed using SeismoStruct software, (b) Soil springs arrangement at pier and abutment piles and embankments in D_4 Model [2].

4 IDENTIFICATION AND COMPARISON OF STRUCTURAL FAILURE MODES IN ARCHETYPE MODELS

4.1 Mechanisms and Model Sensitivities

The structural integrity of a bridge is compromised when one or more primary components of its seismic force-resisting system (SFRS) fail. In this study, collapse is defined as the progressive failure of critical structural elements, culminating in numerical instability of the analytical model.

The sequence of failure modes observed in Incremental Dynamic Analysis (IDA) varies based on several factors, including ground motion characteristics and model configuration. For each archetype model, failure sequences at the point of collapse were extracted from the analysis results. Figure 4(a) presents the failure progression for models D_1 and D_4 under four selected ground motions, revealing a consistent pattern: failure typically initiates at the pier and subsequently propagates to the abutments.

As illustrated in Figure 4, both model-specific parameters and ground motion characteristics significantly influence the failure sequence and ultimate collapse mechanism. In some cases, features such as predominant period and peak ground acceleration (PGA) govern the structural response, producing similar collapse patterns across all models. In other instances, model-specific factors—particularly the degree of soil-structure interaction (SSI) representation—play a more dominant role in shaping the structural response and failure progression. This effect is especially evident under the Imperial Valley-06 ground motion, as shown in Figure 4(b).

Furthermore, certain earthquake records trigger multiple failure modes prior to final collapse, indicating the structure’s capacity to exploit its ductility and energy dissipation potential. This behavior delays complete collapse and enhances overall seismic resilience. These findings underscore the critical importance of jointly considering both ground motion properties and structural modeling details in the seismic evaluation of bridge systems.

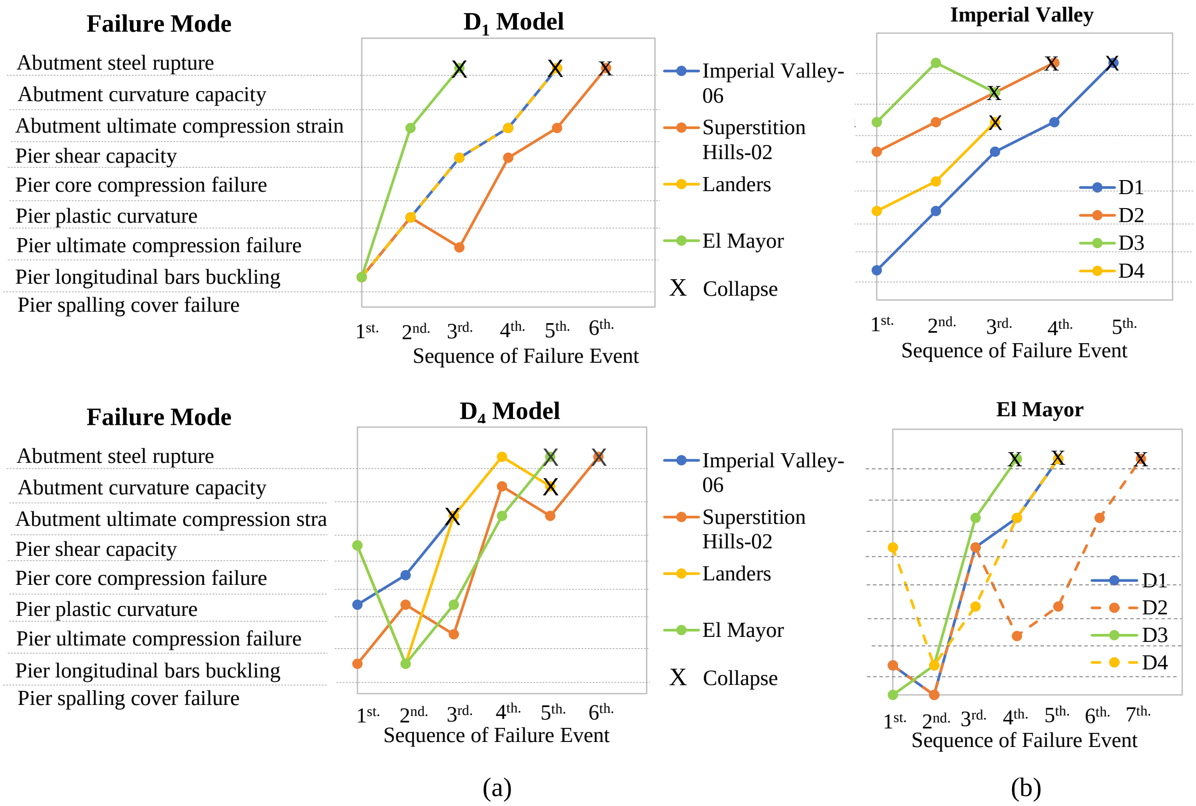


Figure 4: (a) Failure mode and their sequence of occurrence for the models when subjected to the four earthquake ground motions at the collapse levels corresponding to each model, (b) Failure mode sequence of the models D_1, D_2, D_3, and D_4 due to the collapse level ground motions Imperial Valley and El Mayor [2].

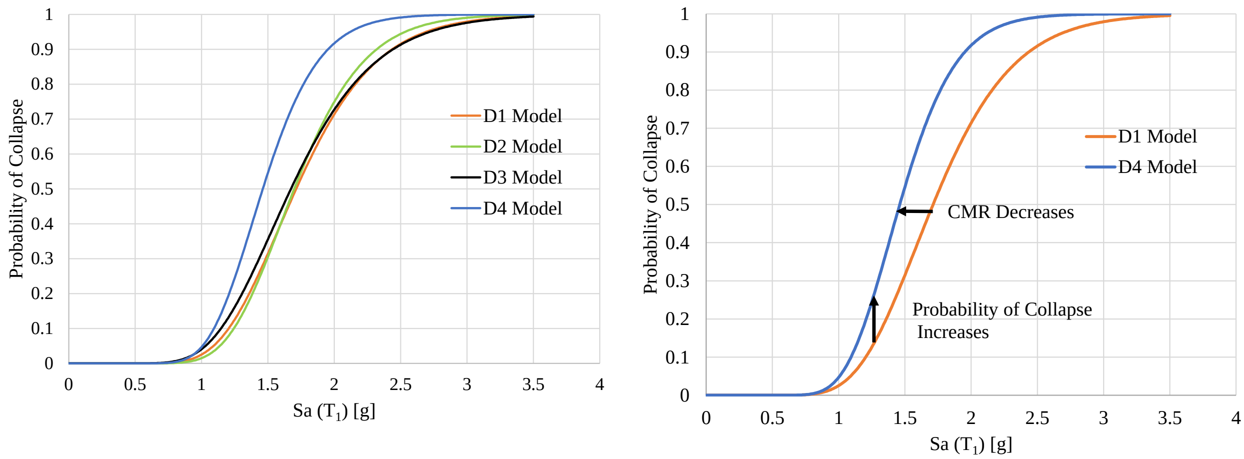
To capture the variability in failure mode sequences, a statistical framework is essential for data analysis. This necessitates precise structural modeling that explicitly incorporates Soil-Structure Interaction (SSI). Additionally, the analysis should include a wide spectrum of ground motion records with varying properties to enable a comprehensive and statistically sound evaluation. Such an approach helps reveal key patterns and interdependencies, thereby improving the accuracy and reliability of seismic performance assessments.

4.2 Fragility Curves and Collapse Risk Assessment

Fragility curves are essential probabilistic tools for evaluating the likelihood of a structure reaching or exceeding a defined limit state, particularly collapse. In this study, the fragility curves quantify the estimated probability of collapse for each archetype model. These curves were developed using a fragility fitting methodology implemented through MATLAB code by Baker [9], with spectral acceleration (Sa) as the intensity measure, as depicted in Fig. 5(a). The analysis reveals that models D_1, D_2, and D_3—each employing simplified representations of soil-structure interaction (SSI)—produce similar fragility profiles. In contrast, model D_4, which integrates a more rigorous and detailed SSI formulation, exhibits a distinct and notably different global collapse fragility curve.

Among the simplified models, D_1—originally introduced by Zhang and Makris [5]—

features the most advanced characterization of SSI effects, incorporating springs and dashpots to simulate soil behavior at embankments and foundations. To highlight the implications of model fidelity on collapse probability, Fig. 5(b) presents a comparative analysis of D_1 and D_4. The results underscore the substantial influence of SSI modeling detail on the shape and shift of fragility curves, affirming the necessity of high-fidelity SSI representation for reliable seismic risk assessment and collapse prediction.



(a) (b)

Figure 5: (a) Collapse fragility curves for archetype models D_1–D4 of the MRO Bridge. (b) Comparison of models D_1 and D_4, highlighting SSI effects and Collapse Margin Ratio (CMR) differences [2].

The analysis presented in Fig. 5(b) yields two key conclusions:

1) For any given level of spectral acceleration (Sa), model D_4 exhibits a higher probability of collapse than model D_1.
2) At a specified collapse probability, model D_4 corresponds to a lower Sa, resulting in a reduced Collapse Margin Ratio (CMR).

These findings demonstrate that model D_4, which incorporates a more detailed characterization of the supporting soil layers, is more susceptible to collapse and thus reflects lower seismic resilience. This highlights the sensitivity of structural response to the level of soil-structure interaction (SSI) modeling detail, influencing both localized failures and global collapse mechanisms. Moreover, the results underscore the inherent modeling uncertainties in seismic performance evaluation and reinforce the critical importance of considering multiple model configurations—particularly when SSI effects are significant.

4.3 Integration of Fragility and Failure Sequences

To examine the influence of model characteristics and ground motion properties on collapse fragility curves and global collapse predictions, the failure mode sequences for selected earthquake records used in the IDA are summarized in Table 1. These records are also incorporated into the fragility curves for the D_1 and D_4 models, as shown in Fig. 5.

Table 1: Sequence of failure modes of the index archetype models D_1 and D_4 at onset of collapse [2].

Event No.	Event	D_1 Model		D_4 Model	
		$Sa(T_1)$	SFMs	$Sa(T_1)$	SFMs
1	Imperial Valley-06	1.23	b→d→f→g→i	1.57	d→e→g→i
2	Superstition Hills-02	1.85	b→d→c→f→g→i	1.16	b→d→c→e→h→g→i
3	Hector Mine	1.71	b→f→g→i	1.38	d→b→g→i
4	Landers	1.90	b→d→f→g→i	1.28	f→b→g→i→h
5	El Mayor -5836	1.96	b→a→f→g→i	2.01	f→b→d→g→i
6	San Fernando	2.11	b →g→i	1.88	b→d→f→g→i
7	Northridge-01	1.62	b→d→c→f→g→i	1.76	f→b→c→d→g→i
8	Cape Mendocino	2.19	d→a→f→g→i	1.31	d→c→e→g→i
9	Loma Prieta	1.88	b→d→c→g→i→h →f	1.59	f→a→d→b→g→i
10	El Centro	2.01	b→d→f	1.43	a→g→i
11	Parkfield	1.47	b→f→c→d→i	1.54	a→b→c→d→i

Key:
SFMs: Sequence of Failure Modes
CSF: Collapse Scale Factor
T_1: Fundamental period in second
$Sa(T_1)$: Spectral acceleration at CSF in g

a: Pier spalling cover failure
b: Pier longitudinal bars buckling
c: Pier ultimate compression strain
d: Pier plastic curvature
e: Pier core compression failure

f: Pier shear capacity
g: Abutment ultimate compression strain
h: Abutment curvature capacity
i: Abutment steel rupture

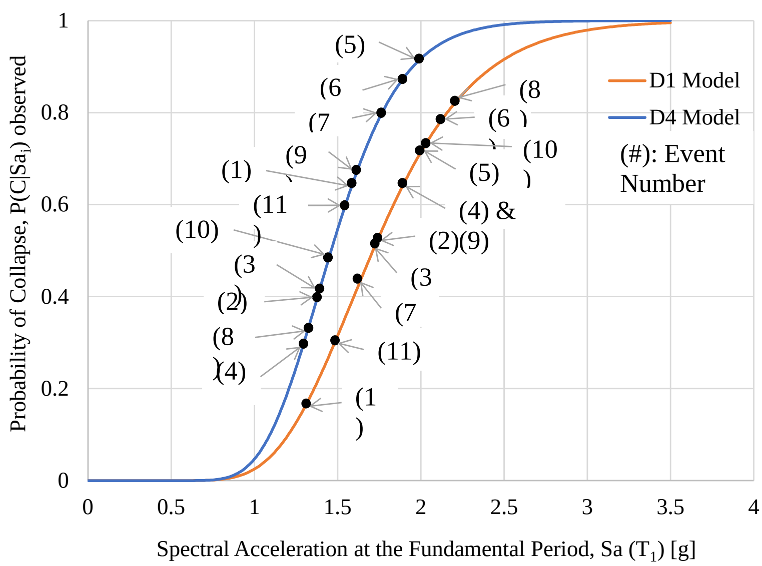


Figure 6: Collapse fragility curves for the index archetype models D_1 and D_4 of the Meloland Road Overcrossing (MRO) Bridge [2].

Based on Table 1 and Figure 6, the following observations can be made [2]:

1) The models exhibit multiple failure modes prior to collapse, with differences in both the sequence and number of these modes, reflecting variations in energy dissipation

mechanisms.

2) The models collapse at different intensity measures and probabilities for a given ground motion. For instance, under the Imperial Valley event, the D_1 model collapses at a spectral acceleration of 1.23g with an 18% probability of collapse, whereas the D_4 model collapses at 1.57g with a 65% probability.
3) For a given model, the failure sequence and collapse mechanism vary depending on the input excitation. For example, when subjected to the Landers earthquake, the D_4 model's collapse initiates with pier shear failure and concludes with abutment curvature capacity failure. In contrast, under the Imperial Valley earthquake, the collapse initiates with pier plastic curvature and ends with abutment steel rupture.
4) Both model characteristics and ground motion properties significantly influence structural response and failure mechanisms. Therefore, careful consideration must be given to model development—including representation of soil-structure interaction (SSI)—and to the selection of ground motions for seismic collapse assessment.

5 COLLAPSE SAFETY MEASURES FOR SEISMIC PERFORMANCE ASSESSMENT

Assessing a structure's ability to withstand collapse during strong ground shaking is a fundamental aspect of seismic performance evaluation. Accordingly, the Collapse Margin Ratio (CMR) and Adjusted Collapse Margin Ratio (ACMR) are used as key safety indicators to quantify collapse capacity relative to established thresholds under Maximum Considered Earthquake (MCE) conditions [1,2].

5.1 Collapse Margin Ratio (CMR)

The Collapse Margin Ratio (CMR) offers an objective measure for evaluating structural collapse capacity [1]. The CMR is computed through the following key steps:

1) Select a sufficient number of ground motions to ensure statistical robustness.
2) Perform Incremental Dynamic Analysis (IDA) and generate IDA curves for each model.
3) Develop the Collapse Fragility Curve (CFC) based on the IDA results.
4) Determine the Maximum Considered Earthquake (MCE) for the relevant site class and compute the CMR.

These steps, along with their sequence, are depicted in Fig. 7, outlining a clear workflow for calculating the Collapse Margin Ratio.

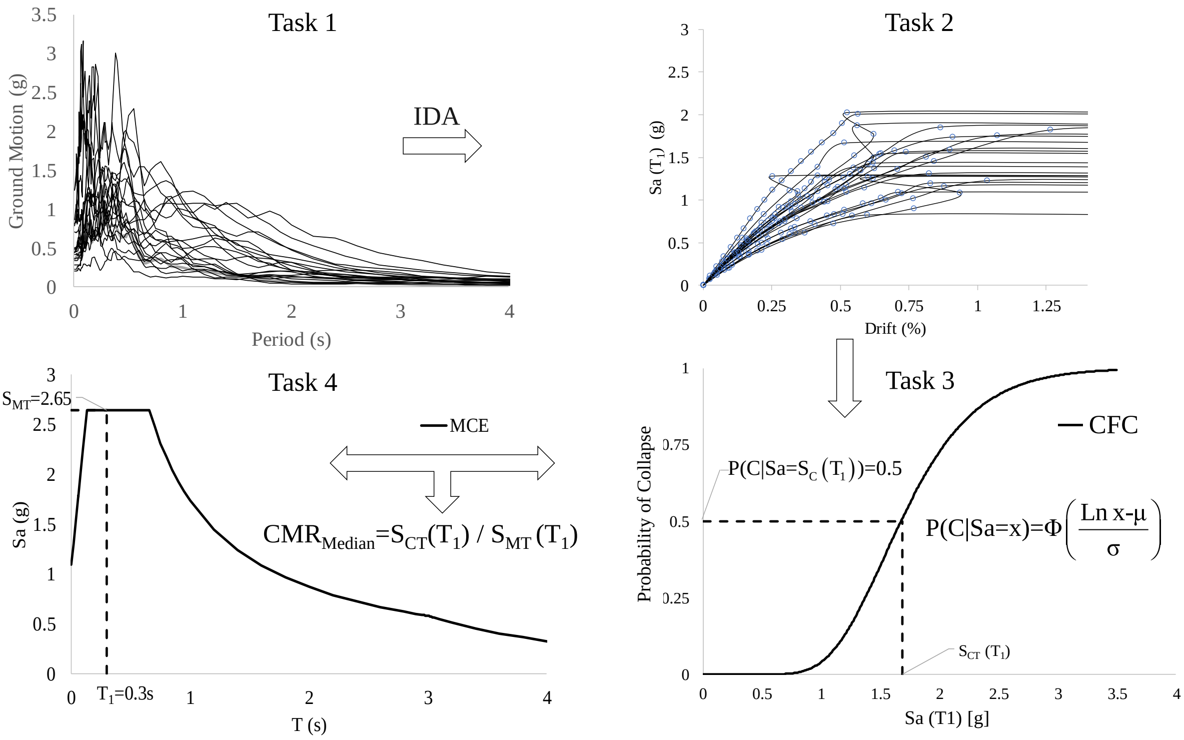


Figure 7: Procedure for calculating the Collapse Margin Ratio (CMR) [1,2].

5.2 Adjusted Collapse Margin Ratio (ACMR)

The Spectral Shape Factor (SSF) is used to account for spectral shape effects in seismic evaluations. The Adjusted Collapse Margin Ratio (ACMR) is obtained by multiplying the SSF by the Collapse Margin Ratio (CMR), as defined in Eq. (1) [1].

$$\mathrm{ACMR}=\mathrm{SSF}\times\mathrm{CMR} \tag{1}$$

Epsilon (ε) is a measure of the spectral shape of the records. It is defined as the number of standard deviations by which a given ln(Sa) value differs from the mean predicted ln(Sa) value for a given magnitude and distance. This difference is expressed in terms of the number of standard deviations in a logarithmic space as shown in Eq. (2) [10].

Epsilon (ε) is a parameter that quantifies the spectral shape of ground motion records. It is defined as the number of standard deviations by which a given ln(Sa) value differs from the mean predicted ln(Sa) value for a given magnitude and distance. This deviation is measured in logarithmic space and expressed in terms of standard deviations, as shown in Eq. (2) [10].

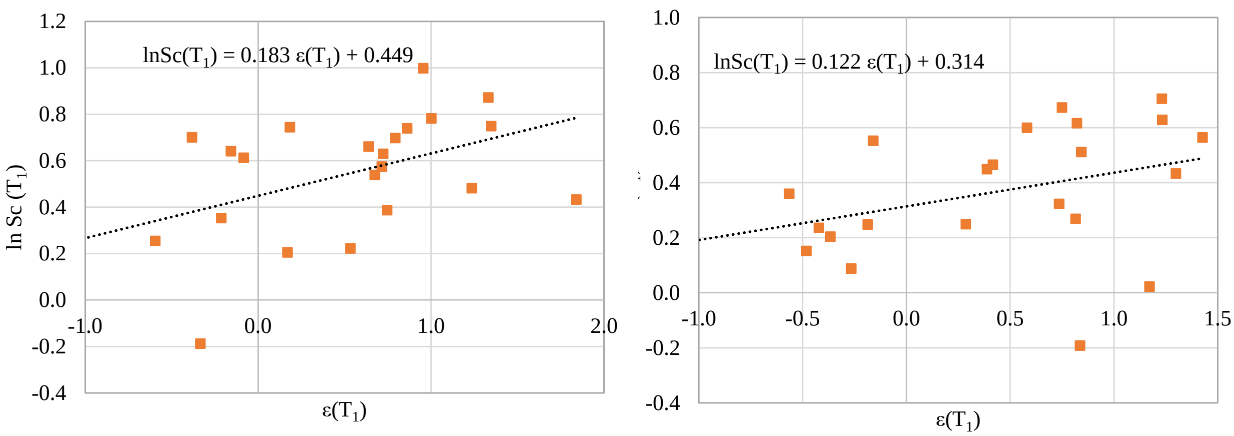
$$\varepsilon(\mathrm{T})=\frac{\ln(\mathrm{Sa})-\mu_{\ln \mathrm{Sa}}(\mathrm{M},\mathrm{R},\mathrm{T})}{\sigma_{\ln \mathrm{Sa}}} \tag{2}$$

where, $\mu_{\ln\mathrm{Sa}}$ and $\sigma_{\ln\mathrm{Sa}}$ are mean and standard deviation of ln(Sa) and are calculated using one or more ground motion attenuation equations.

In an IDA analysis, the selected ground motions leading to failure are inherently different from the Maximum Considerable Earthquake (MCE). As a result, the response spectrum of these motions has a different ε parameter compared to the MCE. To account for this discrepancy, the Spectral Shape Factor (SSF) parameter, as defined in Eq. (3), is calculated following the recommendations in FEMA P695. To take this difference into account, the SSF parameter shown in Eq. (3) is calculated as suggested in FEMA P695 [1].

$$SSF = \exp\left[\beta_1\left(\bar{\varepsilon}_0\left(T_1\right) - \bar{\varepsilon}\left(T_1\right)_{records}\right)\right] \tag{3}$$

where, $\bar{\varepsilon}_0\left(T_1\right)$ is the expected or target epsilon value for the site and hazard-level of interest obtained from the deaggregation of the seismic hazard of the site. is the mean epsilon value of the ground motion set, evaluated at period, T_1. The β_1 parameter is the sensitivity of collapse-level spectral acceleration to variation of epsilon of ground motions as shown in Fig. 8 [1,2].



(a) (b)

Figure 8: β_1 shown as the slope of the fitted line (a) for the model D_1 ,(b) for the model D_4 [2].

5.3 Acceptable Collapse Margin Ratio ($ACMR_{acceptable}$)

To assess the seismic performance of the archetype models, the Adjusted Collapse Margin Ratio (ACMR) is compared against an acceptable threshold, denoted as $ACMR_{acceptable}$. This threshold is defined based on a specified probability of collapse under Maximum Considered Earthquake (MCE)-level ground motions. The value of $ACMR_{acceptable}$ is computed using the procedure described in Eq. (4) [2, 11, 12].

$$ACMR_{acceptable} = \frac{SSF}{\exp\left(\beta_{TOT} \times \Phi^{-1}\left(P^{C}_{acceptable}\right)\right)} \tag{4}$$

where, Φ^{-1} is the inverse cumulative normal distribution function, is the acceptable probability of collapse, SSF is given by Eq. (3), and β_{TOT} represents system uncertainty in predicting the collapse capacity of the structure. Based on FEMA P695, the total system collapse uncertainty can be calculated as per Eq. (5) [1].

$$\beta_{TOT} = \sqrt{\beta_{RTR}^{\ 2} + \beta_{DR}^{\ 2} + \beta_{TD}^{\ 2} + \beta_{MDL}^{\ 2}} \tag{5}$$

where, β_{RTR} is the record-to-record collapse uncertainty (0.20 – 0.40), β_{DR} is the design requirements-related collapse uncertainty (0.10 – 0.50), β_{TD} is the test data-related collapse uncertainty (0.10 – 0.50), and β_{MDL} is the modelling-related collapse uncertainty (0.10 – 0.50).

FEMA P695 provides a simplified method for estimating the total uncertainty (β_{TOT}) in predicting collapse capacity. Table 2 lists β_{TOT} values for superior model quality and index archetype models with a period-based ductility (μ_T) of $\mu_T \geq 3$. However, the selection of β_{TOT} introduces an additional layer of uncertainty, as it involves judgmental decisions.

The accuracy of a performance evaluation using the proposed method is highly sensitive to the assumed β_{TOT} value. Therefore, careful consideration is required when selecting this parameter during the evaluation process. This can be achieved by investigating uncertainties related to record-to-record variability, test data, and modeling requirements. Additionally, conducting a sensitivity analysis before the performance evaluation is crucial to ensure robust and reliable outcomes [1].

Table 2: Proposed total system collapse uncertainty (β_{TOT}) based on quality of model and design for the period-based ductility, $\mu_T \geq 3$ [1].

Quality of Test Data	Quality of Design Requirements			
	(A) Superior	(B) Good	(C) Fair	(D) Poor
(A) Superior	0.425	0.475	0.550	0.650
(B) Good	**0.475**	0.500	0.575	0.675
(C) Fair	0.550	0.575	0.650	0.725
(D) Poor	0.650	0.675	0.725	0.825

In this study, a total system collapse uncertainty of 0.475 is adopted for calculating $ACMR_{acceptable}$ [2].

6 EVALUATING THE SEISMIC RESILIENCE OF MRO BRIDGE

To achieve an acceptable performance, the following two criteria need to be satisfied [1,2]:

1) The average value of adjusted collapse margin ratio for each performance group exceeds $\overline{ACMR}_{10\%}$ ($\overline{ACMR} \geq \overline{ACMR}_{10\%}$)

2) Individual values of adjusted collapse margin ratio for each index archetype model (ACMRj) within a performance group exceeds $ACMR_{20\%}$ ($ACMRj \geq ACMR_{20\%}$)

Table 3: ACMR, $ACMR_{aceptable}$ and their ratio ($ACMR/ ACMR_{aceptable}$) corresponding to MCE level (2% in 50 years), Sa(T1) MCE=2.65g [4].

Index Archetype Model	SSF	ACMR	Acceptable Probability of Collapse			
			$P^{C}_{acceptable} = 10\%$		$P^{C}_{acceptable} = 20\%$	
			$ACMR_{acceptable}$	Ratio	$ACMR_{acceptable}$	Ratio
D_1	1.33	1.04	0.95	1.10	0.86	**1.21(Y)**
D_2	1.35	1.04	0.96	1.08	0.87	**1.19(Y)**
D_3	1.38	1.04	1.00	1.04	0.90	**1.16(Y)**
D_4	1.22	0.81	0.98	0.83	0.89	**0.92(N)**
Average	1.32	0.98	0.97	**1.01(Y)**	0.88	**1.12(Y)**
Note	**(Y)** : Methodology requirement is fulfilled **(N)** : Methodology requirement is NOT fulfilled					

As shown in Table 3, the average Adjusted Collapse Margin Ratio (ACMR) for the performance group exceeds the $ACMR_{acceptable}$ threshold by more than 10%. However, the ACMR for the D_4 model falls below its corresponding $ACMR_{acceptable}$ value. Consequently, the D_4 model exhibits inadequate collapse resistance, clearly indicating its increased vulnerability under seismic loading conditions.

7 CONCLUSIONS

A FEMA-based methodology has been developed to assess the seismic performance of bridges within a performance-based seismic design framework. This approach evaluates collapse potential by comparing the Adjusted Collapse Margin Ratio (ACMR) of each model to its corresponding threshold value, $ACMR_{acceptable}$.

The methodology is applicable to both the design of new bridges and the retrofit of existing structures. It accommodates both discrete and continuum modeling strategies, incorporates an acceptable probability of collapse ($P_{acceptable}$), accounts for spectral shape effects in ground motions, and integrates system-level collapse uncertainty—collectively enhancing infrastructure resilience against future seismic hazards.

To address modeling uncertainties, the use of multiple archetype models is encouraged. However, a single, well-calibrated model may be sufficient if it accurately captures the essential characteristics of the structure–soil system and primary failure mechanisms.

The methodology was applied to the Meloland Road Overcrossing (MRO) as a case study. Findings underscore the critical role of Soil-Structure Interaction (SSI) in influencing both component-level and global collapse behavior, as well as the importance of model fidelity in SSI representation. The results reveal that the D_4 model, which includes a more comprehensive SSI characterization, did not meet performance criteria, indicating the need for retrofit measures to improve the bridge's seismic resilience.

Practicing engineers can use this methodology for seismic design and retrofit planning, especially for critical structures in high-risk zones. Future studies may apply it to other structural types or validate it with experimental data. To better capture spectral shape effects, alternative parameters to epsilon (ε) could also be explored.

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