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# An Innovative Performance-based Methodology for Evaluation of Seismic Vulnerability and Collapse of Bridges

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## ABSTRACT

In a performance-based analysis and design framework, it is critical to evaluate the performance of the primary structural components and assess failure and collapse of the structure. Despite some strong earthquakes have resulted in collapse of numerous bridges worldwide, there is a lack of a thorough seismic collapse assessment methodology that is implemented in the design codes and provides a practical procedure for designers.

A procedure inspired by FEMA-P695 [1] is proposed for evaluation of seismic vulnerability and performance of bridges using the Adjusted Collapse Margin Ratio (ACMR) and the acceptable Adjusted Collapse Margin Ratio ($ACMR_{acceptable}$) as the collapse safety measures. The proposed procedure can be used for the seismic performance assessment of bridges both in the design stage and in the performance assessment and retrofitting of existing bridge structures. The methodology allows using either discrete or continuum approaches in defining the model. It can potentially consider soil-structure interaction effects, but including these effects is not essential in this approach. A case study simulating the California, Meloland Road Overcrossing (MRO) dynamic characteristics is provided to investigate failure modes and collapse capacity of the bridge using the proposed procedure. The MRO bridge has been selected for the utilization of past data and records, as it has been extensively instrumented and exposed to numerous strong earthquakes since the 1980s.

Strength and displacement capacities of bridge members are defined in the index archetype models as performance criteria using the guidelines provided in TRB's Seismic Retrofitting manual for the highway structures part 1-Bridges [2]. Incremental Dynamic Analysis is performed using a selected set of ground motions with probability of exceedence 2% in 50 years hazard level (return period of 2475 years) from the NGA-West2 ground motion database [3] to calculate and compare failure modes and fragility curves of the models.

Keywords: Seismic Performance-based Design, Bridge Seismic Performance Evaluation and Collapse Assessment, Simulated and non-simulated Failure Mode, Collapse Fragility Curve (CFC), Adjusted Collapse Margin Ratio (ACMR).

## INTRODUCTION

Lack of understanding of nonlinear response and consideration of the effect of Soil-Structure Interaction (SSI) has resulted in unsafe design which has led to the collapse of many bridges worldwide. Despite of the collapse of bridges in the past few decades, there is a lack of a practical and thorough procedure and guideline in code provisions that can assist engineers in performing collapse assessment of bridge structures.

The main goal of this paper is to propose a simplified procedure, similar to the FEMA P695 methodology, for performance evaluation of the bridge structures. To achieve this goal, a performance-based earthquake engineering approach in seismic hazard analysis, structural analysis, and damage assessment is adopted. In addition, the study takes into account ground motions' spectral shape effects and total system collapse uncertainty. Furthermore, simulated and non-simulated failure modes are considered in modelling of collapse in the developed nonlinear models. The collapse assessment of the Meloland Road Overcrossing (MRO) in Southern California is conducted as a case study.

## PROPOSED BRIDGE SEISMIC PERFORMANCE EVALUATION METHODOLOGY

### Background

A methodology is proposed for seismic assessment of bridges using analytical and statistical approaches within a performance-based seismic design framework. This proposed approach is applicable to both design or retrofit of existing bridge structures and can be used in discrete or continuum modelling. The methodology allows consideration of an acceptable probability of collapse ($P_{acceptable}$). It also accounts for ground motion characteristics and various aspects of data and modeling uncertainties. It can incorporate Soil-Structure Interactions (SSI) effects when needed [4].

As it can be seen from Figure 1, the proposed methodology consists of four main steps: Non-linear model development for collapse assessment, non-linear time history analyses, seismic performance evaluation, documentation, and peer review.

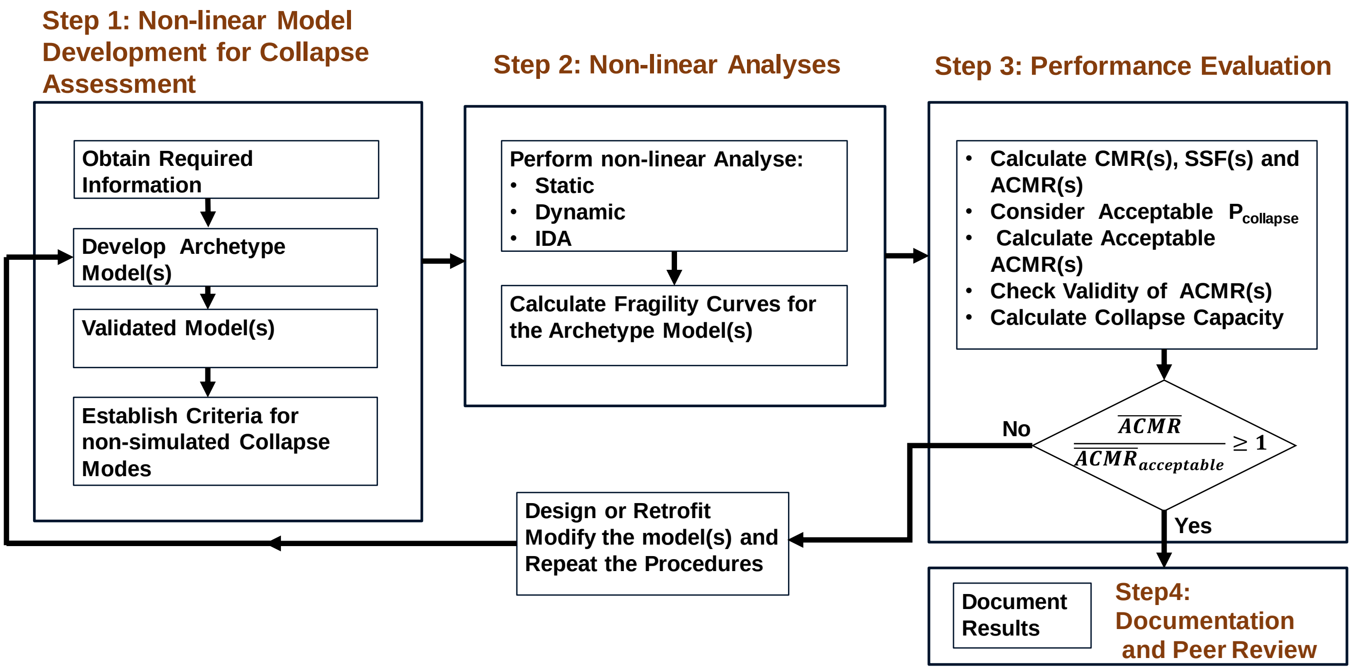



*Figure 1. Proposed bridge seismic Performance evaluation methodology [4]*

### MRO bridge nonlinear models

Four different discrete archetype models of bridge are constructed and verified using ambient vibration test result [5]. In these models, strength and displacement capacities of main structural components are defined as the performance criteria using the guidelines provided in TRB's Seismic Retrofitting manual for the highway structures part 1-Bridges [2]. The models are used to perform IDA analyses. Each of these archetype models include a different level of SSI representation. Three of these models namely $D_1$, $D_2$, and $D_3$ models are developed based on previous studies [6] [7] [8]. The schematic view of these models and applied Free Field Motion (FEM) are shown in Figure 2.

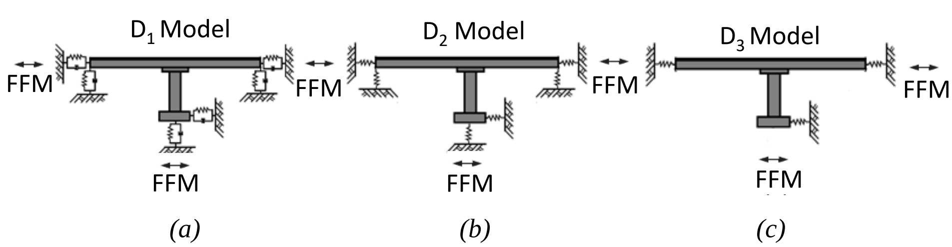
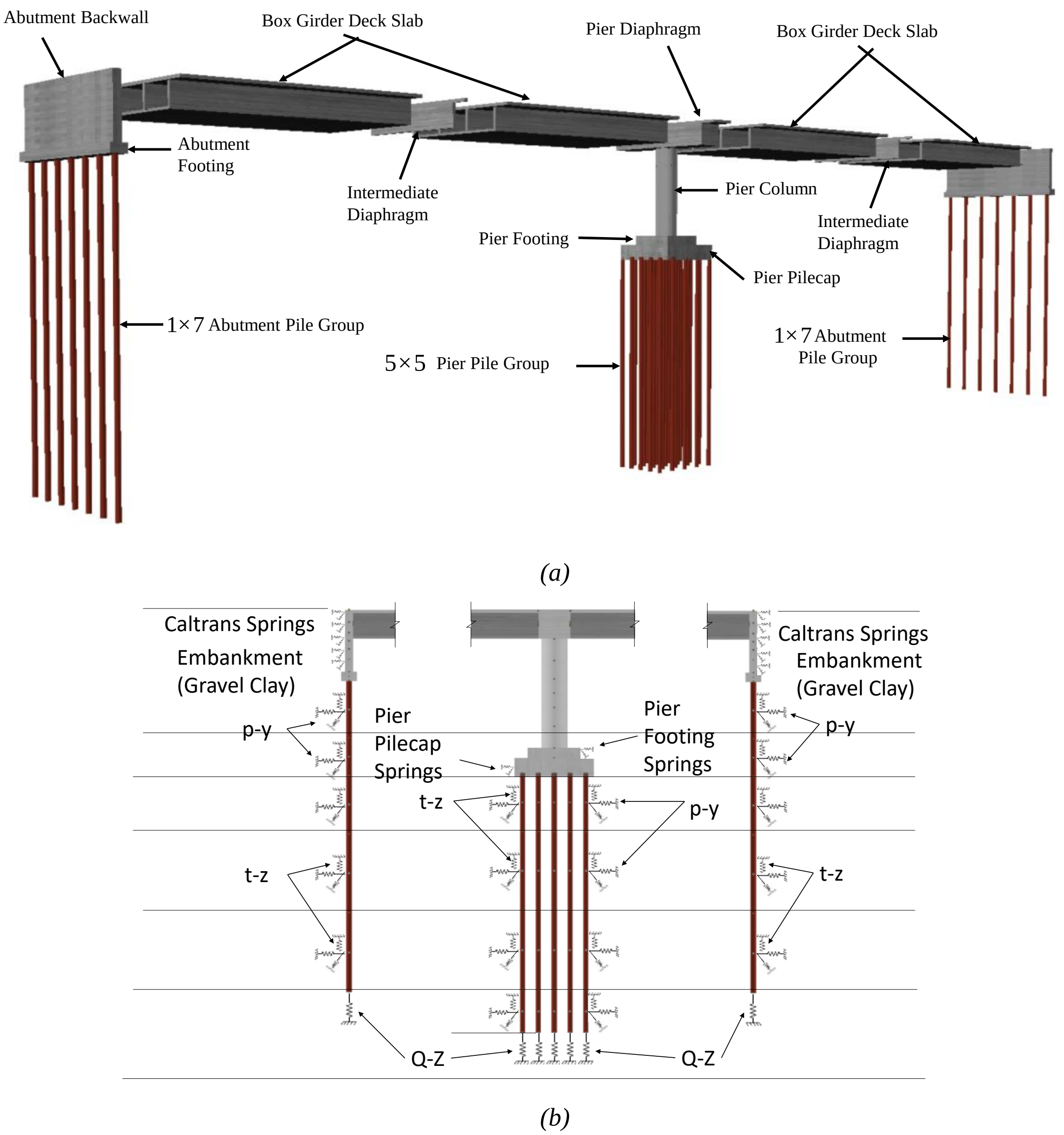



*Figure 2. MRO models and applied Free Field Motion (FEM): (a) Viscoelastic embankments and center bent [6], (b) and (c) Elastic support at embankments and center bent [7][8]*

The archetype model $D_4$ developed in this study includes a more detailed representation of SSI features in the discrete model. The $D_4$ archetype model includes explicit representation of abutment and pier piles. This model includes abutment wall-backfill soil interaction, pier foundations-surrounded backfill soil interactions and pile lateral and vertical resistance are calculated and considered in the model [4]. The models were subjected to a set of 22 ground motions selected from the PEER NGA-West 2 ground motion database [3], considering different dynamics characteristics to account for hazard uncertainty, to perform an Incremental Dynamic Analysis (IDA) for each model.




*(b)*

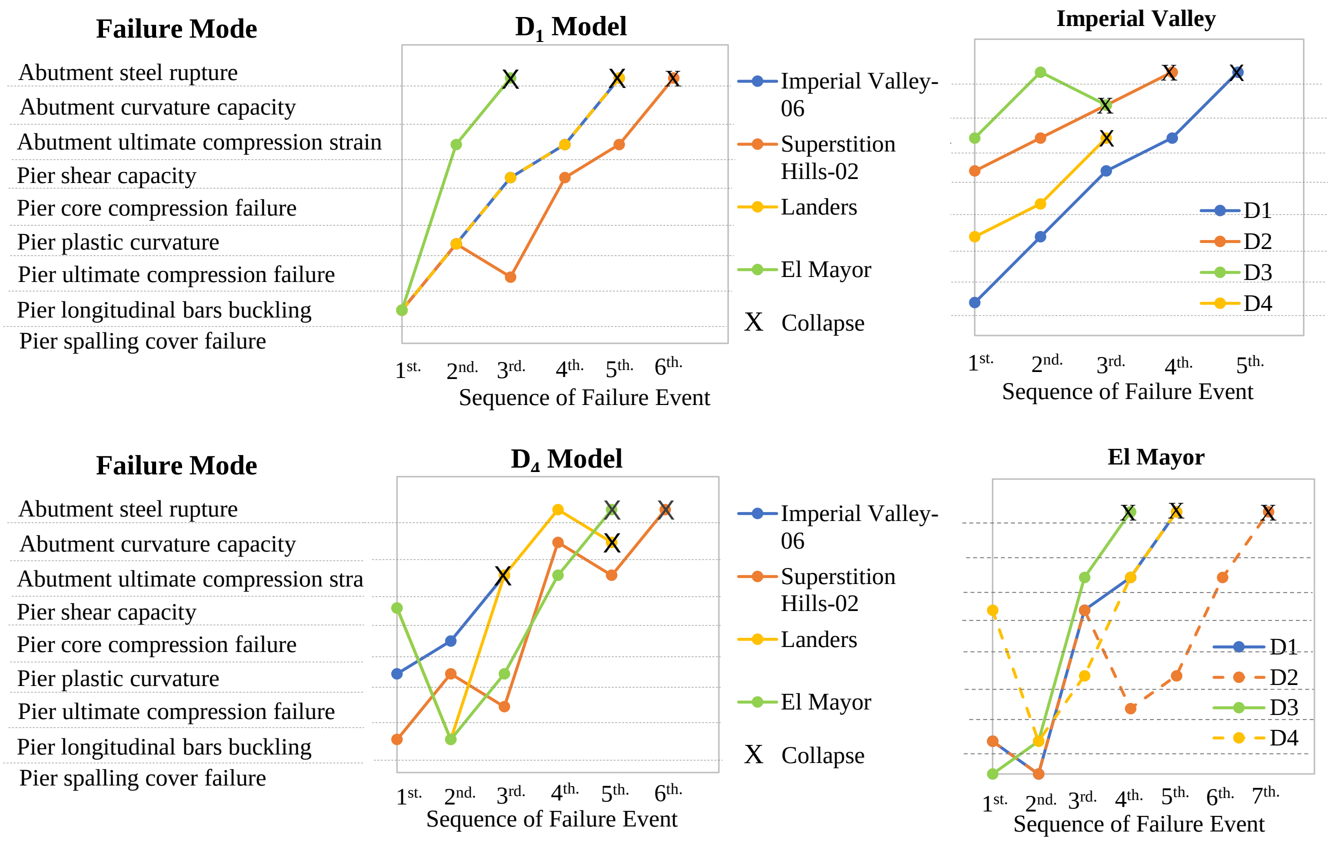
*Figure 3. MRO models: (a) 3D view of the index archetype model $D_4$ constructed using SeismoStruct software, (b) Soil springs arrangement at pier and abutment piles and embankments in $D_4$ Model[4]*

## Identification and comparison of Structural Failure Modes in the archetype models

Structural integrity cannot be maintained when one or more main structural components belonging to the shear force resisting system of a bridge structure fail. Thus, in this study, collapse of the models is defined as sequence of failure of the main structural members, which lead to the model instability.

The sequence of failure modes predicted in the IDAs depend on many factors, including ground motion characteristics and model details. The sequence of failure modes at the collapse level for all the archetype models subjected to all ground motions were extracted from the analyses results. Figure 4(a) shows the failure sequence for models $D_1$ and $D_4$ for four of the ground motions. As shown in this figure, an overall similarity in the sequence of failure modes is observed, generally starting with failure of the pier and propagating into the abutment.

As it can be seen in Figure 4, model details and ground motion characteristics contribute to the sequence of failures and final collapse mode. In some ground motion cases, the ground motion characteristics such as predominant period and peak ground acceleration appear to be the dominant factor in response of the archetype models. As a result, similar failure sequence and collapse modes are observed in all models. In some other cases, details of the model, including the SSI representation, appear to dominate the response and failure modes. As an example, this effect is clearly observed in the case of the Imperial Valley-06 shown in Figure 4(b). In some earthquake events, models experience multiple modes of failure before collapse. As a result, the structure has been able to utilize its ductility and energy absorption.




*(a)* *(b)*

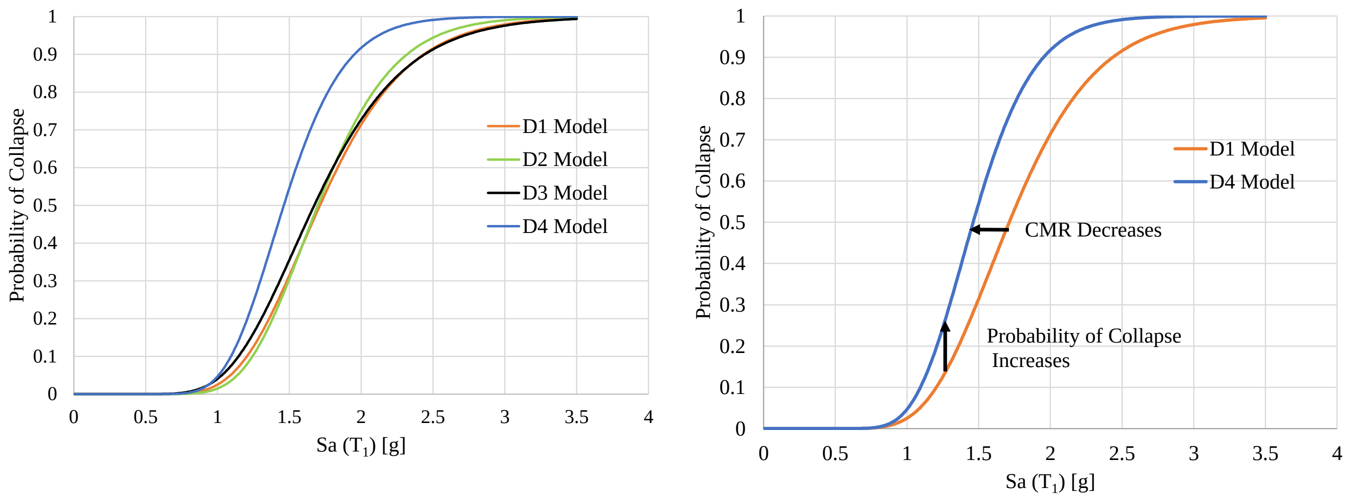
*Figure 4. (a) Failure mode and their sequence of occurrence for the models when subjected to the four earthquake ground motions at the collapse levels corresponding to each model, (b) Failure mode sequence of the models $D_1$, $D_2$ , $D_3$ , and $D_4$ due to the collapse level ground motions Imperial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

Based on the variation of the sequence of failure modes, a statistical approach needs to be employed to analyze the data. It is important to define the details of the structural models, including SSI representation, and perform the analysis on a wide range of ground motions. This will enable a meaningful statistical analysis of results.

## Collapse Fragility Curves (CFCs)

Fragility curves are useful statistical tools to study the probability of reaching or exceeding a given failure state. In this study, fragility curves represent the estimated probability of collapse. Using this fragility fitting approach and a MATLAB code developed by Baker [9], fragility curves for all archetype models were calculated as a function of spectral acceleration (Sa), as shown in Figure 5(a). The figure shows that the models $D_1$, $D_2$ and $D_3$ resulted in very similar fragility curves. However, model $D_4$ which includes a comprehensive SSI representation shows a significantly different global collapse fragility curve.

Among the simplified SSI models of MRO used in this study, $D_1$ which was originally developed by Zhang and Makris [6] is the most feature-rich model that includes representation of the soil effect on embankment and foundations using springs and dashpots. To demonstrate the effect of archetype model on the fragility curves and probability of collapse, $D_1$ and $D_4$ models are compared in Figure 5 (b).




*(a)* *(b)*

*Figure 5. (a) Fragility curves for the index archetype models $D_1$ to $D_4$ for the MRO Bridge, (b) Fragility curves for the index archetype models $D_1$ and $D_4$ for the MRO Bridge and CMR comparison [4].*

The following can be concluded from Figure 5(b):

1) For a given spectral acceleration (Sa), the probability of collapse is higher for model $D_4$.
2) For a given probability of collapse, the spectral acceleration associated with model $D_4$ is smaller compared to $D_1$, resulting in a lower CMR value for $D_4$.

As a result, model $D_4$ shows an increase in probability of collapse and, consequently, a poor performance when soil supporting layers are included in the analyses. This example demonstrates the sensitivity of model response on the choice of SSI features in the model. This is not only in terms of component failure, but also on the global collapse predictions. It also highlights the uncertainty around the model features and the essential need to include various models when studying collapse assessment of bridge structures considering SSI effects.

**Collapse Margin Ratio (CMR)**

The CMR offers an objective measure of assessment of structural collapse [1]. To calculate CMR, the following tasks are performed:

1) Selecting a sufficient number of ground motions
2) Performing IDA analyses and calculating the IDA curves for each model
3) Calculating the Collapse Fragility Curve (CFC)
4) Determining the Maximum Considered Earthquake (MCE) based on the relevant soil site class and Calculating Collapse Margin Ratio (CMR)

The required tasks and their sequence for calculating Collapse Margin Ratio (CMR) are shown in Figure 6.

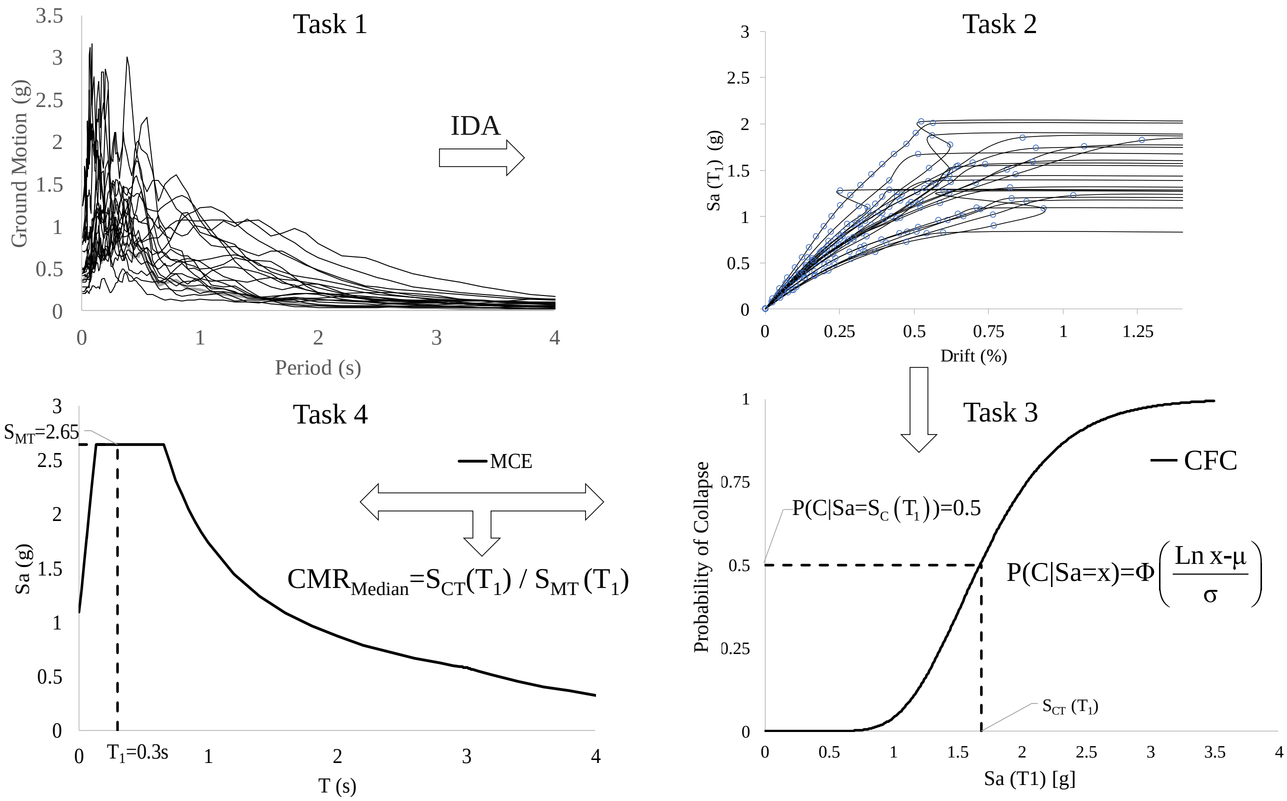



*Figure 6. Procedure for calculating Collapse Margin Ratio (CMR) [4]*

**Adjusted Collapse Margin Ratio (ACMR)**

The Spectral Shape Factor (SSF) is a parameter to account for spectral shape effects. The Adjusted Collapse Margin Ratio (ACMR) is defined as the product of SSF parameter and the CMR as shown in Equation (1) [1].

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

Epsilon ( $\varepsilon$ ) 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 Equation (2)[10].

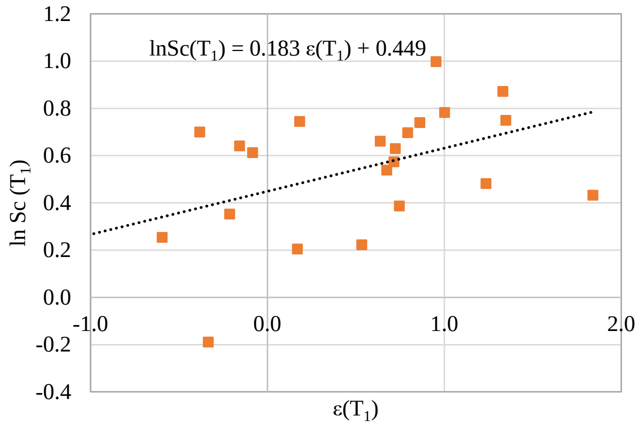
$$\varepsilon(\mathrm{T}) = \frac{\ln(\mathrm{Sa}) - \mu_{\ln \mathrm{Sa}}(\mathrm{M,R,T})}{\sigma_{\ln \mathrm{Sa}}} \tag{2}$$

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

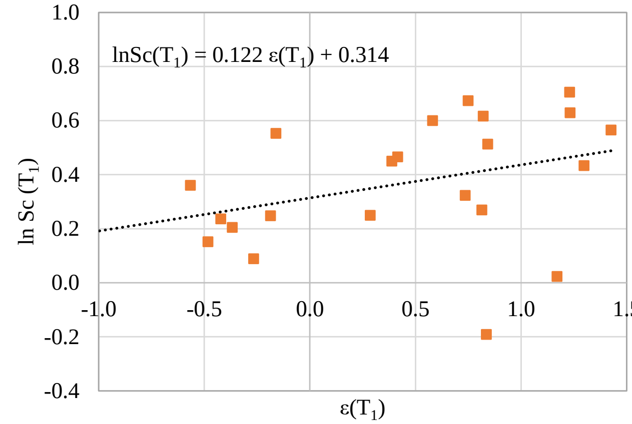
In an IDA analysis, the selected ground motions leading to failure are inherently different from the Maximum Considerable Earthquake (MCE). Thus, the response spectrum of the motions has a different epsilon parameter compared to MCE. To take this difference into account, the SSF parameter shown in Equation (3) is calculated as suggested in FEMA P695 [1].

$$\mathrm{SSF} = \exp\left[\beta_1\left(\bar{\varepsilon}_0(\mathrm{T}_1) - \bar{\varepsilon}(\mathrm{T}_1)_{\mathrm{records}}\right)\right] \tag{3}$$

where, $\bar{\varepsilon}_0(\mathrm{T}_1)$ 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. $\bar{\varepsilon}(\mathrm{T}_1)_{\mathrm{records}}$ is the mean epsilon value of the ground motion set, evaluated at period, $T_1$. The $\beta_1$ parameter is the sensitivity of collapse-level spectral acceleration to variation of epsilon of ground motions as shown in Figure 7.




*(a)*




*(b)*

*Figure 7. $\beta_1$ shown as the slope of the fitted line (a) for the model $D_1$ ,(b) for the model $D_4$ [1],[4]*

**Acceptable Collapse Margin Ratio (ACMR)**

To evaluate the performance of the archetype models, the adjusted collapse margin ratio (ACMR) is compared with an acceptable threshold of adjusted collapse margin ratio ($ACMR_{acceptable}$). The $ACMR_{acceptable}$ is calculated considering a given probability of collapse when the model is subjected to MCE-level ground motions. $ACMR_{acceptable}$ is calculated using Equation (4) [4][11][12].

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

where, $\Phi^{-1}$ is the inverse cumulative normal distribution function, $P^{c}_{acceptable}$ is the acceptable probability of collapse, SSF is given by Equation (3), and $\beta_{TOT}$ 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 Equation (5) [1].

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

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

FEMA P695 provides a simplified assessment method to estimate the total uncertainty in the prediction of the collapse capacity. Values of total collapse system uncertainty, $\beta_{TOT}$, for superior model quality and index archetype models with a period-based ductility $\mu_T \geq 3$, are provided in Table 1. The selection of the total collapse system uncertainty ($\beta_{TOT}$) itself is a source of uncertainty since it includes a judgmental decision. A performance evaluation using the proposed method highly depends on the assumed value of $\beta_{TOT}$ and special attention needs to be placed in selecting this parameter in the evaluation process. This can be achieved by performing an investigation on record-to-record, test data, and modeling requirement uncertainties and performing a sensitivity analysis prior to performance evaluation.

*Table 1. Proposed total system collapse uncertainty ($\beta_{TOT}$) 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 | $\boxed{0.475}$ | 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 collapse system uncertainty 0.475 is adopted to calculate $ACMR_{acceptable}$ [4].

**Seismic Performance of the MRO**

To achieve an acceptable performance, the following two criteria need to be satisfied [1] [4]:

1) The average value of adjusted collapse margin ratio for each performance group exceeds $\overline{\text{ACMR}}_{10\%}$ ($\overline{\text{ACMR}} \geq \overline{\text{ACMR}}_{10\%}$)
2) Individual values of adjusted collapse margin ratio for each index archetype model ($ACMR_i$) within a performance group exceeds $ACMR_{20\%}$ ($ACMR_i \geq ACMR_{20\%}$)

*Table 2. ACMR, $ACMR_{aceptable}$ and their ratio ($ACMR/ ACMR_{aceptable}$) corresponding to MCE level (2% in 50 years), $Sa(T_1)$ 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(Y) | 0.86 | 1.21(Y) |
| $D_2$ | 1.35 | 1.04 | 0.96 | 1.08(Y) | 0.87 | 1.19(Y) |
| $D_3$ | 1.38 | 1.04 | 1.00 | 1.04(Y) | 0.90 | 1.16(Y) |
| $D_4$ | 1.22 | 0.81 | 0.98 | 0.83(N) | 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<br>(N) : Methodology requirement is NOT fulfilled | | | | | |

As shown in Table 2, the average value of the adjusted collapse margin ratio for the performance group ($\overline{\text{ACMR}}$) exceeds $\overline{\text{ACMR}}_{10\%}$ by 1%. However, ACMR for $D_4$ model was greater than its corresponding $ACMR_{20\%}$ acceptable value. As a result, model $D_4$ does not have enough collapse resistance.

## CONCLUSION

A FEMA-based methodology has been proposed for seismic assessment of bridges using a performance-based seismic design approach. The methodology was based on the comparison of the calculated value of the ACMR for each model with its corresponding acceptable value.

The proposed evaluation methodology is applicable to both design or retrofit of existing bridge structures and can be used in discrete or continuum approaches. The methodology allows for consideration of an acceptable probability of collapse ($P_{acceptable}$). The methodology also accounts for the ground motion spectral shape effects and total collapse system uncertainty

To achieve a better understanding of the structure's performance, it's best to choose a set of models to cover the modelling uncertainty. However, employing a single model is possible if the model provides a good representation of the key features of the structure/soil system and the potential failure modes.

The MRO was used as a case study to demonstrate the workflow of the proposed methodology. The cases studied here showed how SSI plays a significant role in both component-level and global structural collapse predictions. It also highlights the uncertainty around the SSI features representation and the need to consider various archetypes in collapse assessment of bridges.

The results indicate that $D_4$ model does not satisfy the performance requirements of the proposed methodology and retrofit for the bridge needs to be considered.

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