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Selection of optimal intensity measure for probabilistic seismic demand analysis of highway bridges under long duration ground motions

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ABSTRACT

Numerous earthquakes of large magnitude have occurred in the recent past where the recorded ground motions have long durations. As a result of a significant number of load reversals, the cumulative damage to structural components becomes critical under such motions. Therefore, the development of probabilistic seismic demand models (PSDMs) for bridges under long duration (LD) earthquakes is necessary to predict the vulnerability of structures under LD ground motions. However, there exist several intensity measures (IMs), including peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), spectral acceleration at different periods (Sa(T)), and arias intensity (I_a). Selecting the most effective and optimal ground motion IM is essential for the seismic fragility study of bridges and the development of trustworthy PSDMs, relating the input seismic hazard and structural response. Using an ideal IM decreases uncertainty in PSDMs, hence boosting the PSDMs' reliability in performance-based seismic evaluations. Although, many past studies investigated the suitability of various IMs for PSDM of bridges, an optimal IM for LD motions has not been reported in the literature. This research seeks to determine the ideal IM for a bridge subjected to LD ground motions in order to develop reliable PSDMs. Using a suit of LD ground motions from Chile and New Zealand earthquakes, nonlinear time-history analysis was undertaken to observe the seismic responses of the bridge. The optimality of IMs for LD ground motions is investigated by first determining the relationship between various intensity measures (IMs) and bridge seismic responses. Various evaluation metrics is considered for identifying the optimal IM. The outcome of this study shows that $Sa(T1)$ and $Sa(1.0)$ parameters are the most optimal IMs for LD ground motions and suggest using these IMs in the development of PSDMs for assessing the fragility of bridges subject to LD ground motions.

Keywords: Optimal intensity measure, PSDM, Performance-based earthquake engineering, Bridge, Long-duration motion.

INTRODUCTION

The development of probabilistic seismic demand models (PSDMs) provides the correlation between structural demand response (for example, component deformation, internal forces, etc.) and the ground motion intensity measures (IMs) (for example, peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration at different periods ($Sa(T)$). The likelihood that the structural demand (D) reaches or exceeds a specified value (d), given the ground motion IM ($P(D \geq d|IM)$) is calculated using PSDMs. Since there exists several intensity measures, including peak ground acceleration (*PGA*), peak ground velocity (*PGV*), peak ground displacement (*PGD*), spectral acceleration at different periods (*Sa*(*T*)), and arias intensity (I_a), selecting an optimal ground motion intensity measure (*IM*) is important in the seismic fragility analysis of bridges and development of reliable PSDMs, relating the input seismic hazard and structural response. An appropriate selection of IM reduces uncertainty and allows to predict the performance of a structure in a reliable way [1]. Therefore, some metrics to assess the optimality of IMs have been proposed by past researchers. These metrics are efficiency, practicality, and proficiency, which will be described in the following sections.

Several studies have been conducted to investigate an optimum IM for different structures [1]–[4]. Mackie and Stojadinovic [2] investigated the optimum IM for highway bridges in California. The employed fifteen different IMs and concluded that spectral displacement and acceleration at the natural period are the most optimal IMs. Padgett et al. [3] conducted research to identify optimal IMs for U.S. bridges considering 10 different IMs. They concluded that PGA was the optimal IM. Harriri-Ardebili and Saouma [4] studied the optimality of seventy IMs for a concrete gravity dam and concluded that PGV is an appropriate IM for the concrete gravity dam. Khosravikia and Clayton [1] proposed an updated framework for evaluating the optimality of IMs and the proposed framework was applied to the Texas steel bridges. They found that the velocity related IM is an appropriate IM and estimates the response of the bridges accurately.

Numerous earthquakes of large magnitude have occurred in the recent past where the recorded ground motions have long durations. Long duration (LD) ground motions usually occur at subduction zones. As a result of a significant number of load reversals under LD motions the cumulative damage to structural components becomes critical. Therefore, this issue has become a serious challenge for structural engineers and researchers [5]. Due to the distinctive nature of LD ground motions, it is necessary to predict the vulnerability of highway bridges under LD ground motions. Although many studies have investigated the seismic performance and vulnerability of bridges under LD motions [6]–[9], no study investigated the optimal IM for the development of reliable PSDMs of bridges under LD motions.

The objective of this study is to determine the most optimal IM for a highway bridge when subjected to LD ground motions. Using a suit of LD ground motions obtained from recorded events, nonlinear time-history analysis has been undertaken to observe the seismic responses of the various bridge components such as pier, bearing, and abutment. The optimality of IMs for LD ground motions is investigated by first determining the relationship between various IMs and bridge seismic responses. Various evaluation metrics are considered for identifying the optimal IM. The results of this research determine the most optimal IM for developing reliable PSDMs that can be used to assess bridge fragility under LD ground motions.

PROBABILISTIC SEISMIC DEMAND MODELS (PSDMS)

A Probabilistic Seismic Demand Model (PSDM) is produced by combining Probabilistic Seismic Hazard Analysis (PSHA) with nonlinear structural analysis in a technique called Probabilistic Seismic Demand Analysis (PSDA). The demand and the ground motion IM are related in PSDMs. Eq. (1) demonstrates that PSDMs follow a log-normal distribution [10].

$$\boldsymbol{P[D \geq d \,|IM] = 1 - \Phi\left(\frac{\ln(d) - \ln(S_D)}{\beta}\right)} \tag{1}$$

In which, Φ is the standard normal cumulative distribution function, S_D is the median value of the engineering demand parameter, and β is the logarithmic standard deviation or dispersion of the demand conditioned on IM. According to Cornell et al. [10], the median of seismic demands follows a power function of intensity as follows:

$$\boldsymbol{S_D = aIM^b} \tag{2}$$

In which, a and b are constant parameters of linear regression. This equation can be translated in the form of lognormal space as shown in Eq. (3).

$$\boldsymbol{\ln(S_D) = \ln(a) + b \times \ln(IM)} \tag{3}$$

In which, $\ln(a)$ and b are vertical intercepts and the slope parameter and can be computed using a nonlinear dynamic analysis under N number of ground motions, plotting the demand against IM and fitting a linear regression to the data. Figure 1 represents a typical PSDM in log space. The dispersion of the data around the fitted regression line is computed using the equation proposed by Padgett et al. [3] (Eq. (4)).

$$\boldsymbol{\beta_{D|IM} = \sqrt{\frac{\sum_{i=1}^{N}[\ln(d_i) - \ln(S_D)]^2}{N-2}}} \tag{4}$$

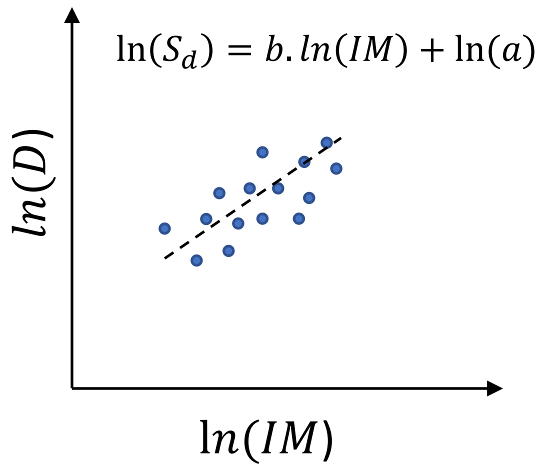


Figure 1. The definition of PSDMs in log space.

OPTIMAL IM SELECTION FRAMEWORK

In this study, three different criteria are considered to assess the optimality of IMs. These metrics are efficiency, practicality, and proficiency. The brief descriptions of metrics are as follows:

Efficiency

The efficiency of an IM is characterized as the degree of variation in the required seismic demand for a particular IM. This metrics is calculated by β, which is presented in Eq. (4). The lower value of β shows less dispersion around the estimated demand, indicating the efficient IMs.

Practicality

Practicality is the second criterion, which indicates how dependent the demand is on IM. This metric is evaluated by the slope (b) of the PSDM in Eq. (3). IMs with a value of *b* close to zero will have no significant effect on demand estimation, indicating that they are impractical, while IMs with higher values of *b* show strong dependency with the demand of the structure.

Proficiency

Proficiency (ζ) was proposed by Padgett et al. [3] to combine two measures of efficiency and practicality. It is defined as the ratio of β and b as shown in Eq. (5). The IMs with the lower value of ζ have stronger correlation with the demands.

$$\zeta = \frac{\beta}{b} \tag{5}$$

SELECTION OF GROUND MOTION RECORDS

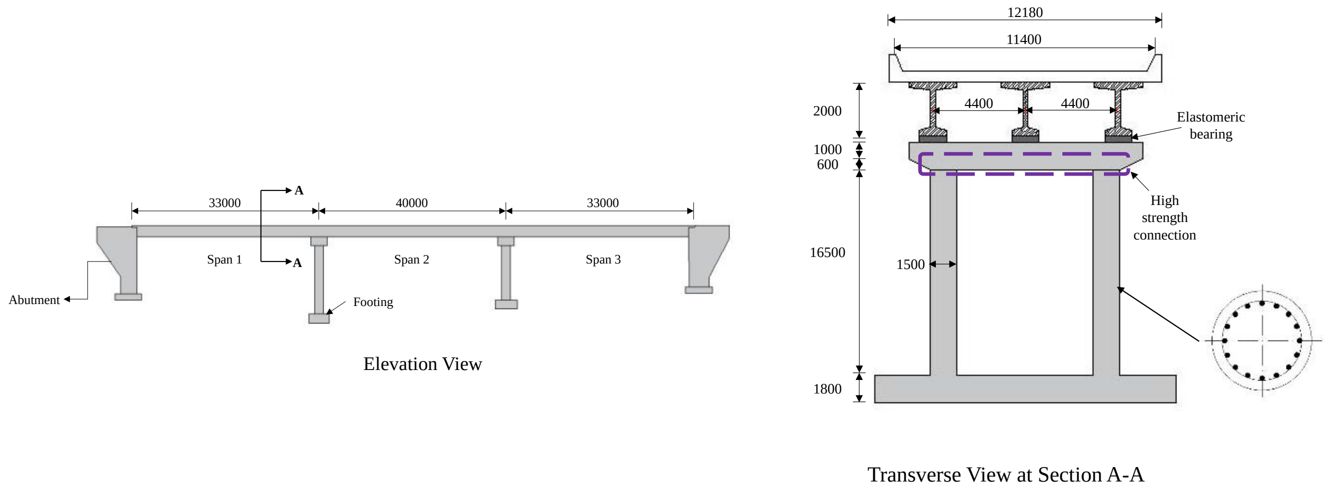
In this study, 40 LD ground motions from two seismic events: Valparaiso, Chile 1985 and Christchurch, New Zealand 2011 have been selected. Two separate earthquake events are selected to see if the earthquake source and location of recorded motions have any impact on the optimality of IMs. These ground motion records are obtained from the PEER ground motion database [11], and Center for Engineering Strong Motion Data [12] . The selected ground motions have the significant duration ($D_s5-95\%$) higher than 25 seconds. Table 1 presents the ground motions selected in this study.

CASE STUDY BRIDGE

The continuous three span reinforced concrete bridge is located in Vancouver, British Columbia (BC), Canada. The width and thickness of the deck is 12.18 m and 250 mm. The length of end span and midspan is 33.0 m and 40.0 m. The diameter of the piers is 1.5 m, and the heights are 16.5 and 11.5 m. Figure 2 shows the dimensions of the bridge.

Table 1. Selected long duration ground motions

Events	Magnitude	Station	Significant duration (sec)
Valparaiso, Chile 1985	7.8	Constitucion	37
		Iloca	35
		La Ligua	32
		Santiago	38
		Hualane	34
		Liolleo	41
		Los Vilos	40
		Quintay	40
		San Felipe	36
		San Fernando,	26
		San Isidro	44
		Talca	31
		Valparaiso el Almendral	50
		Ventanas	56
		Vina del Mar	54
		Zapallar	40
		Chillan Institute	36
		Llayllay	40
		Cauqenes	40
		Pichilemu	29
Christchurch New Zealand 2011	6.2	AMBC	45
		CECS	40
		DKHS	38
		DSZ	44
		DUNS	38
		FDCS	44
		GLWS	30
		GORS	34
		HMCS	32
		HSES	30
		IFPS	33
		INGS	26
		KOKS	40
		MACS	62
		QTPS	32
		SKFS	44
		TMBS	26
		TRCS	26
		WIGC	26
		WTMC	32



(a) (b)

Figure 2. Dimensions of the bridge: (a) Elevation view, (b) Transverse view at section A-A.

NUMERICAL MODELING OF BRIDGE

In order to record the response of the bridge, nonlinear time history analyses were performed using OpenSees [13]. It is assumed that the deck and girders are elastic during the analyses. A discretized fiber section with displacement-based nonlinear beam-column elements is used to model the piers. The concrete material and reinforcement steel are model using Concrete07 and Steel02 available in the OpenSees material library. The elastomeric bearings in the transverse direction are modeled with Steel01. The elastomeric bearings are modeled as high stiffness element vertically. No soil structure interaction was considered and the base of the columns are considered to be fixed.

PROBABILISTIC SEISMIC DEMAND MODELS

As previously mentioned, the PSDMs, which is based on the findings of nonlinear time-history analyses, forecasts the demand for the structure given the IM of the ground motion. The demand parameters considered in this study are presented in Table 2. Abutment displacement, bearing displacement, and column rotation are important demand parameters in bridge engineering because they directly affect the structural response of a bridge under earthquakes. Selecting these demand parameters as part of a comprehensive structural analysis can help ensure that the bridge can withstand the expected loads. Therefore, these parameters are considered in this study. For the development of the PSDMs, seven different IMs are taken into consideration in order to examine the optimality of IMs. The selected IMs are PGA, PGV, PGD, $S_a(\text{T1})$, $S_a(0.2s)$, $S_a(1.0s)$, and I_a, which are presented in Table 3.

To develop PSDMs, the demand vs IMs resulted from nonlinear time-history analyses is plotted and then a linear regression is fitted to calculate a and b in Eq. (3). Figure. 3 shows an example of the plotted PSDM and the fitted regression line for the abutment deformation under one of the LD ground motions from Chile earthquake. In the following, the dispersion of the data around the fitted line (β) is calculated using the Eq. (4). Table 4 presents the regression parameters and β for each pair of IM and demand.

DISCUSSION OF IM MODELS

In this part, the Cornell et al. [10] framework is used for the case study bridge in order to determine the optimality of the IMs for LD ground motions. These outcomes can be applied in future research to provide more accurate estimates of bridge performance under LD motions.

The efficiency, practicality, and proficiency of the considered IMs for demand parameters of the bridge under Valparaiso, Chile ground motions are presented in Figure 4. As previously mentioned, the lowest value of $\beta_{D|IM}$ indicates the most efficient IM.

According to Figure 4-a, for the demand parameters of Abutment-T, Bearing-L and Col-Rot, PGV is considered as more efficient IM as it has the lowest value of β, while $Sa(T1)$ is considered as more efficient IM for Abutment-L and Bearing-T demand parameters. It is also interesting to note that PGD for all demand parameters are less efficient as the value of β is more than other parameters.

Table 2. Demand parameters used in this study

Demand parameters	Abbreviation	Units
Column rotation	Col-Rot	rad
Bearing: Longitudinal deformation	Bearing-L	mm
Bearing: Transverse deformation	Bearing-T	mm
Abutment: Longitudinal deformation	Abutment-L	mm
Abutment: Transverse deformation	Abutment-T	mm

Table 3. Intensity measures

Intensity Measure	Description	Units
PGA	Peak Ground Acceleration	g
PGV	Peak Ground Velocity	mm/s
PGD	Peak Ground Displacement	mm
$S_a(T_1)$	Peak Spectral Acceleration at natural period	g
$S_a(0.2s)$	Peak Spectral Acceleration at 0.2 s	g
$S_a(1.0s)$	Peak Spectral Acceleration at 1.0 s	g
I_a	Arias Intensity	mm/s

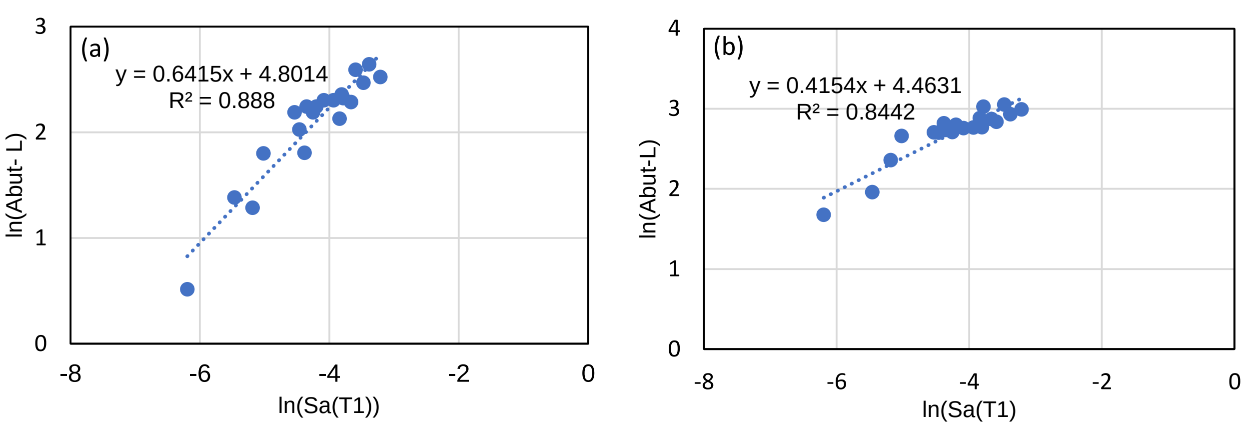


Figure 3. The plotted diagram and the fitted regression line for the abutment deformation and the intensity measure of Sa(T1)

Figure 4-b compares the practicality of IMs for different demand parameters. As it is stated, a higher value of PGV indicates the more practical IM. According to this figure, PGV is considered as the most practical IM for all demand parameters in comparison with other IMs.

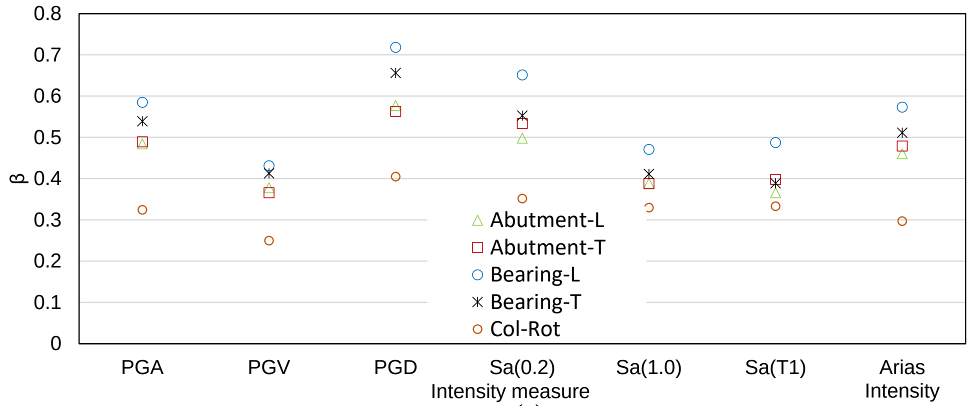
Figure 4-c shows the value of ξ, which is defined as proficiency and combine the metrics of efficiency and practicality. As can be seen, PGV is found as the most proficient IM as the value of ξ is just under 0.5 for all demand parameters, while the PGD is the least proficient IM. It is noteworthy to note that the value of ξ for $Sa(1.0)$ and $Sa(T1)$ is negligibly lower than that of ξ for PGV. Therefore, it can be concluded that PGV, $Sa(1.0)$ and $Sa(T1)$ are three proficient IMs for the development of the PSDMs of bridges under LD ground motions from Chile earthquake.

Figure 5 shows the efficiency, practicality, and proficiency evaluation for the considered IMs and the demand parameters of the bridge components under LD ground motions from New Zealand earthquake. As shown in Figure 5-a, the most efficient IM for all considered demand parameters are $Sa(T1)$ and $Sa(1.0)$ since the value of β is lower than that of β for other IMs. It can also be seen in figure 5-b that the practicality of PGV for all demand parameters is higher than that of other IMs. Figure 5-c compares the proficiency of IMs for different demands and it can be seen that $Sa(T1)$, $Sa(1.0)$, and PGV are the most proficient IMs rather than other IM parameters because they have the lower value of ξ than other IMs.

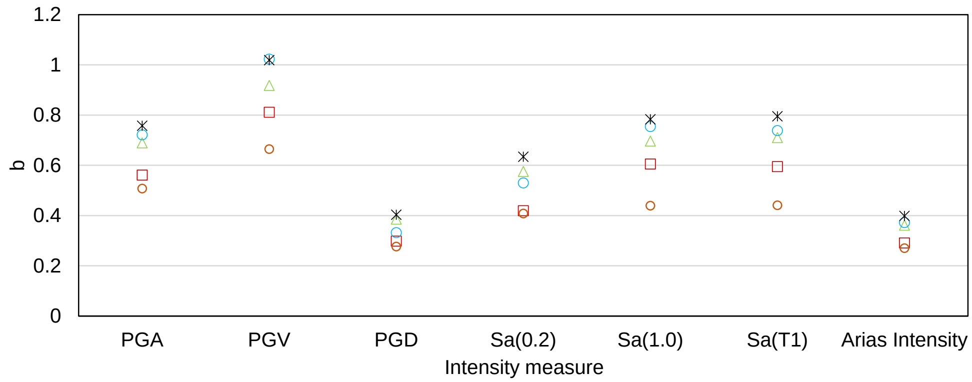
The proficiency of intensity measures was evaluated for the recorded LD earthquakes in Chile and New Zealand. The analysis results show that PGV as the most proficient IM for the Chile earthquake, while Sa(T1) came out as the most proficient IM for the New Zealand earthquake. It is interesting to observed that different earthquake events resulted in different proficient IMs. This indicates that different LD events can result in different types of demands on bridge components and thereby result in different optimal IM for seismic response analysis. To increase the reliability of the seismic hazard analysis, the LD ground motions from both earthquake events were combined, and the optimality of IMs was evaluated. Figure 6 depicts the proficiency of considered IMs under all considered LD ground motions. From Figure 6 it is evident that $Sa(T1)$ and $Sa(1.0)$ are the most proficient IMs. Therefore, it is recommended to use these IMs for the development of probabilistic seismic demand models (PSDMs) for bridges under LD ground motions to ensure a trustworthy result.

Table 4. Regression parameters and dispersion factor for different IMs and demands

		Abutment-L		Abutment-T		Bearing-L		Bearing-T		Col-Rot	
		b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$
Valparaiso, Chile	**PGA**	0.680	0.485	0.560	0.490	0.721	0.585	0.755	0.539	0.507	0.325
	PGV	0.918	0.378	0.811	0.366	1.023	0.431	1.019	0.413	0.664	0.250
	PGD	0.385	0.577	0.298	0.563	0.331	0.718	0.403	0.656	0.276	0.405
	$\boldsymbol{Sa(0.2)}$	0.576	0.498	0.419	0.534	0.529	0.652	0.634	0.553	0.408	0.352
	$\boldsymbol{Sa(1.0)}$	0.696	0.389	0.605	0.388	0.754	0.471	0.783	0.411	0.439	0.330
	$\boldsymbol{Sa(T1)}$	0.710	0.366	0.594	0.398	0.738	0.488	0.795	0.389	0.441	0.334
	$\boldsymbol{I_a}$	0.361	0.461	0.290	0.479	0.371	0.573	0.398	0.511	0.270	0.297
		b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$	b	$\beta_{D\|IM}$
Christchurch, New Zealand	**PGA**	0.400	0.390	0.543	0.233	0.559	0.509	0.676	0.448	0.384	0.240
	PGV	0.408	0.284	0.636	0.203	0.920	0.419	0.773	0.322	0.390	0.210
	PGD	0.133	0.428	0.229	0.301	0.317	0.639	0.265	0.519	0.141	0.290
	$\boldsymbol{Sa(0.2)}$	0.318	0.463	0.372	0.280	0.695	0.607	0.439	0.555	0.292	0.286
	$\boldsymbol{Sa(1.0)}$	0.380	0.162	0.608	0.156	0.865	0.281	0.732	0.177	0.373	0.220
	$\boldsymbol{Sa(T1)}$	0.415	0.176	0.642	0.138	0.940	0.243	0.778	0.181	0.407	0.147
	$\boldsymbol{I_a}$	0.207	0.381	0.294	0.239	0.470	0.510	0.382	0.414	0.194	0.251



(a)



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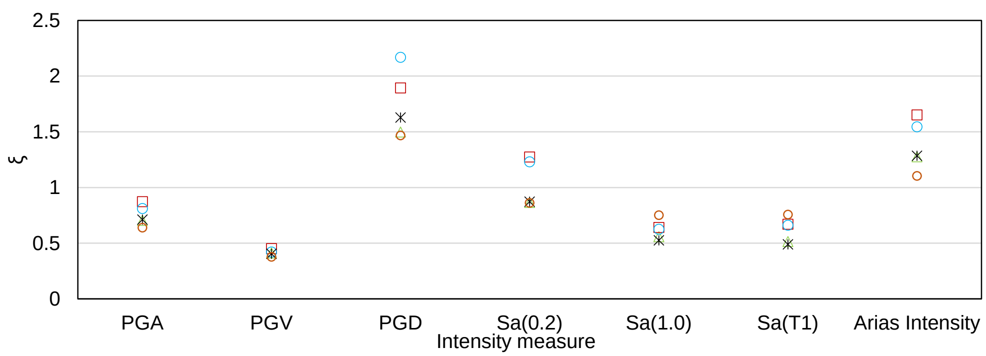

(c)

Figure 4. The efficiency, practicality, and proficiency evaluation for considered IMs and demands under LD Chile earthquake

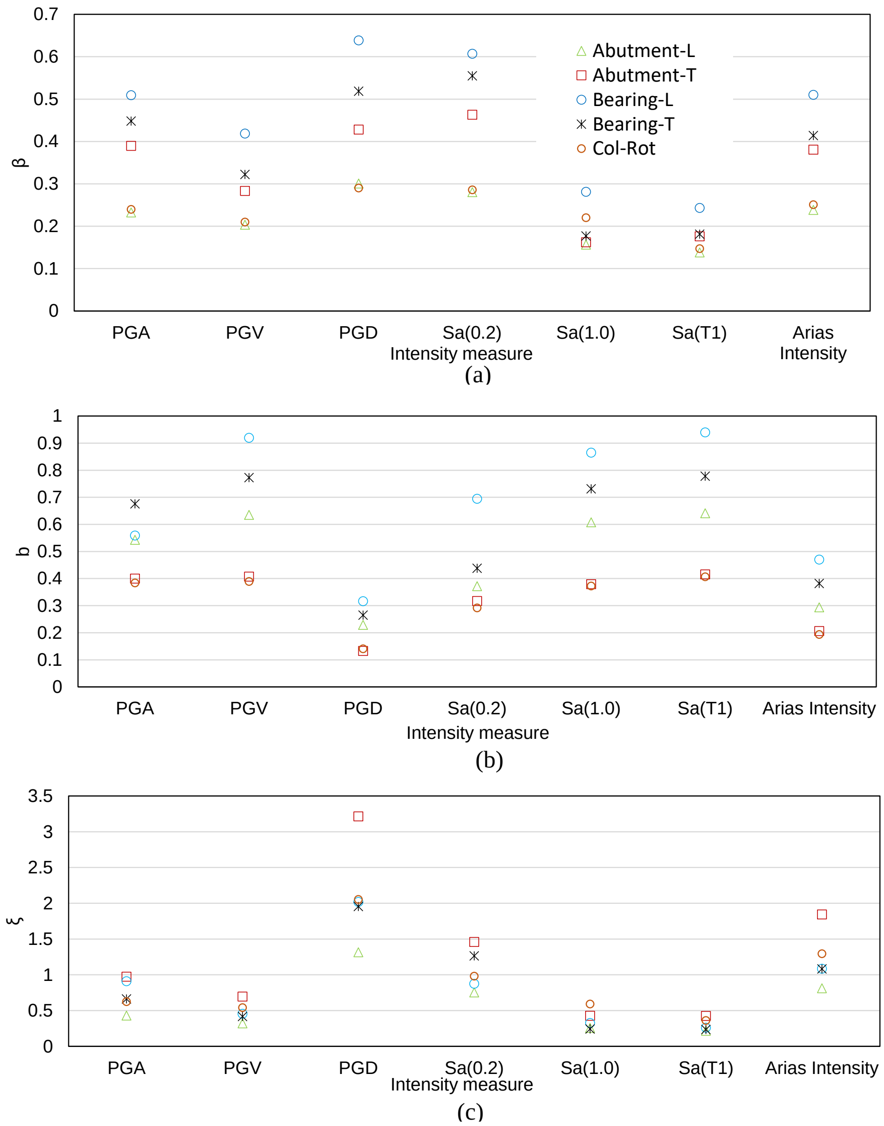

Figure 5. The efficiency, practicality, and proficiency evaluation for considered IMs and demands under LD New Zealand earthquake

Abutment-L	Abutment-T	Bearing-L	Bearing-T	Col-Rot
Sa(T1)	Sa(1.0)	Sa(T1)	Sa(1.0)	Sa(T1)
Sa(1.0)	Sa(T1)	Sa(1.0)	Sa(T1)	Sa(1.0)
PGV	PGV	PGV	PGV	PGV
PGA	PGA	PGA	PGA	PGA
Sa(0.2)	Sa(0.2)	Sa(0.2)	Sa(0.2)	Sa(0.2)
PGD	PGD	Arias Intensity	Arias Intensity	PGD
Arias Intensity	Arias Intensity	PGD	PGD	Arias Intensity

More Proficient

Figure 6. The proficiency of different IMs for the LD earthquake

CONCLUSION

This study evaluated and compared the optimality of different intensity measures (IMs) for a bridge subjected to LD ground motions recorded in Chile and New Zealand using three metrics. Nonlinear time history analyses were conducted to assess the response of the bridge in terms of abutment displacements, bearing displacements, and column rotations. The demands were then correlated to the considered IMs to identify the most optimal intensity measures that would reduce uncertainty in the probabilistic seismic demand models.

The study found that the peak ground velocity (PGV) is the most efficient IM for the considered demand parameters of the bridge under LD ground motions from Chile earthquake. Sa(T1) was the most efficient parameter for the bridge response analysis under LD ground motions from New Zealand earthquake.

To increase the reliability of the seismic hazard analysis, the LD ground motions from both earthquakes were combined, and the optimality of IMs was evaluated. It is found that Sa(T1) and Sa (1.0) are more optimal than other IMs for the development of PSDMs of a bridge under LD ground motions. The use of these intensity measures can significantly enhance the reliability and usability of PSDMs for performance-based seismic analyses.

Overall, this study provides essential insights into the selection of optimal intensity measures for bridges under LD ground motions in Chile and New Zealand. The findings of this study could be instrumental in improving the seismic design and performance evaluation of bridges, thus enhancing public safety and infrastructure resilience under LD ground motions. However, further studies should be conducted using recorded LD ground motions from other events as well as scaling them to site specific response spectrum.

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