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Optimization of the Ground Motion Intensity Measure for Long-Span Suspension Bridges Considering the Impulse Effect

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Abstract

To study the intrinsic relationship between the structural response of long-span suspension bridges and the intensity measures (IMs) and to select the optimal IM to reduce the discreteness in the prediction of structural responses, this paper uses the Incremental Dynamic Analysis (IDA) method to amplitude adjust near-fault pulse-like ground motions and analyzes the response using the curvature at the base of the tower as the structural response index. Then uses the four evaluation indices: efficiency, sufficiency, practicality, and proficiency to evaluate the intrinsic relationship between the structural response and the IMs. The study results indicate that, according to the four evaluation indices, the velocity-related IMs all performed well, while those displacement-related IMs performed the worst. Among them, the effective peak velocity (EPV) performed the best, being optimal in all evaluation indices except for the sufficiency relative to magnitude, which was lower than the maximum incremental velocity (MIV). Therefore, the EPV can be considered the best ground motion IM for predicting the dynamic response of long-span suspension bridges under the action of near-fault pulse-like ground motion. This result can provide a basis for the selection of IMs and structural response prediction for near-fault long-span suspension bridges, considering the impulse effect.

Keywords: Intensity Measure; Suspension Bridge Response; Pulse-Like Ground Motion; Evaluation Index.

1. Introduction

Long-span suspension bridges, as flexible structures, have a long natural vibration period and significant influence from higher modes, making their structural response to ground motions very complex. Predicting the response of bridges and conducting seismic fragility analysis have always been important research topics in the field of bridge seismic resistance. When conducting dynamic elastoplastic time history analysis of bridges with input ground motion, there is a significant discreteness in the predicted response of the bridge [1, 2]. In the performance-based earthquake engineering framework, the ground motion intensity measures (IMs) serve dual roles: linking the characteristics of the ground motion to the structural response and calculating seismic hazard curves. Reasonably selecting the IMs of

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ground motion can reduce the discreteness in predicting the structural response and improve the accuracy of seismic fragility analysis [3-5].

In the field of bridge engineering, the peak ground acceleration (PGA) and spectral acceleration (Sa) are the most commonly used IMs [6, 7]. However, various recent studies have indicated that under different types of ground motion, the PGA and Sa are not sufficiently effective to predict bridge responses, especially for different bridge and ground motion types. As a result, many researchers have investigated the selection of appropriate IMs for predicting bridge responses. Some scholars have focused on the selection of IMs for different bridge types. Padgett et al. [8] used multi-span simply supported steel box girder bridges as an example and analyzed ten commonly used IMs of ground motion based on five evaluation indices; the research results indicated that the PGA was the preferred IM for these bridge structure combinations. Zhong et al. [9] examined common cable-stayed bridges in China and used Padgett's evaluation index to analyze four typical IMs of ground motion; the evaluation results showed that the peak ground velocity (PGV) was the most suitable IM.

Mackie et al. [10] used typical California bridges as models to analyze the advantages and disadvantages of 24 IMs for probabilistic seismic demand analysis and concluded that when the fundamental periods of the bridges corresponded to the $S_a(T_1)$ and $S_v(T_1)$ as IMs, the uncertainty in the demand models was reduced. Wei et al. [11] studied beam bridges with ultra-high piers, analyzed ten common IMs of ground motion, and determined that the PGV could effectively predict the response and damage state of displacement components such as bearings, making it the optimal IM for ultra-high pier bridges. Wen et al. [12] proposed an improved method for selecting IMs and conducted research on the fragility and selection of IMs for high-speed railway bridges through Incremental Dynamic Analysis. The results indicated that AvgSa with a period range of $[0.9T_1, 1.1T_1]$ is the most efficient IM for the fragility analysis of high-speed railway bridges. Other scholars have focused on the selection of IMs for different ground motion types. Zhang et al. [13] used the cloud method to analyze the structural response of long-span suspension bridges under the influence of far-field ground motions, examining 26 IMs of ground motion. They found that the PGA did not yield satisfactory results and determined that the velocity spectrum intensity measure (VSI) was most appropriate.

Avsar et al. [14] considered the efficiency of using multiple IMs of ground motion to predict the response of seismic isolation and reduction bridges under pulse-like and ordinary ground motions and proposed a modified velocity spectrum intensity measure (MVSI) derived by adjusting the VSI with the natural vibration period. The study demonstrated that the MVSI was the most reliable measure under both pulse-like and ordinary ground motion. Liao et al. [15] investigated the relationship between IMs of ground motion and the dynamic response characteristics of isolated bridges subjected to near-fault and far-field ground motions. The study concluded that the responses were most significant under near-fault ground motions, with the pier displacement and the base shearing force of the piers showing a strong correlation with the PGV/PGA. Consequently, the PGV/PGA should be adopted as the IMs of ground motion. Dai et al. [16] analyzed the evaluation results of IMs for seismic isolation bridges under near-fault and far-fault earthquakes using the cloud method. They concluded that Sagm based on the geometric mean of the response spectrum is an optimal IM for seismic isolation bridges compared to traditional IMs, and the optimal period range is $[0.2T_1, 2.5T_1]$.

With the development of machine learning technology, many scholars have introduced machine learning into fragility analysis and the selection of strength indicators. Ding et al. [17] proposed using the elastic net algorithm to select the optimal IMs through the determination coefficient R^2 and regression coefficients, while also discussing the impact of different machine learning methods on the selection results. Wei et al. [18], through the analysis of two types of models that include six popular machine learning methods, proposed that the XGBoost model should be used for seismic fragility assessment and the selection of intensity indices. At the same time, they pointed out that $Sa_{1.0}$ is the optimal seismic intensity index.

The mentioned research is mainly suitable for medium- and small-span bridges and bridges with seismic isolation and energy dissipation. However, there are significant differences in the applicability and accuracy of IM for different bridge structural types and various types of ground motions. Using the IMs selected from previous studies to predict the response of near-fault long-span suspension bridges under pulse-like ground motion may increase the discreteness of the response predictions. Compared to traditional fragility analysis methods such as IDA and cloud methods, machine learning methods have higher computational efficiency. However, their decision-making process is not transparent and difficult to understand, and the selection of IMs largely depends on the machine learning model used. The specific reasons for choosing IDA analysis include its ability to provide a more transparent and interpretable approach compared to machine learning methods, and it requires fewer ground motion data records compared to methods like the cloud method. Additionally, IDA can effectively capture the nonlinear behavior of structures, which is crucial for fragility analysis. Therefore, this work took long-span suspension bridges as the research object and used the curvature at the bottom section of the tower as the structural response index. 31 records of pulse-like ground motions and 12 IMs of ground motion were selected for dynamic elastoplastic analysis through the IDA method. The best IM was comprehensively evaluated according to four evaluation indices: efficiency, sufficiency, practicality, and proficiency. This study aims to provide a reference for selecting appropriate IMs of ground motion to reduce the discreteness of the structural response predictions for near-fault long-span suspension bridges under pulse-like ground motions. The research framework is organized in Figure 1.

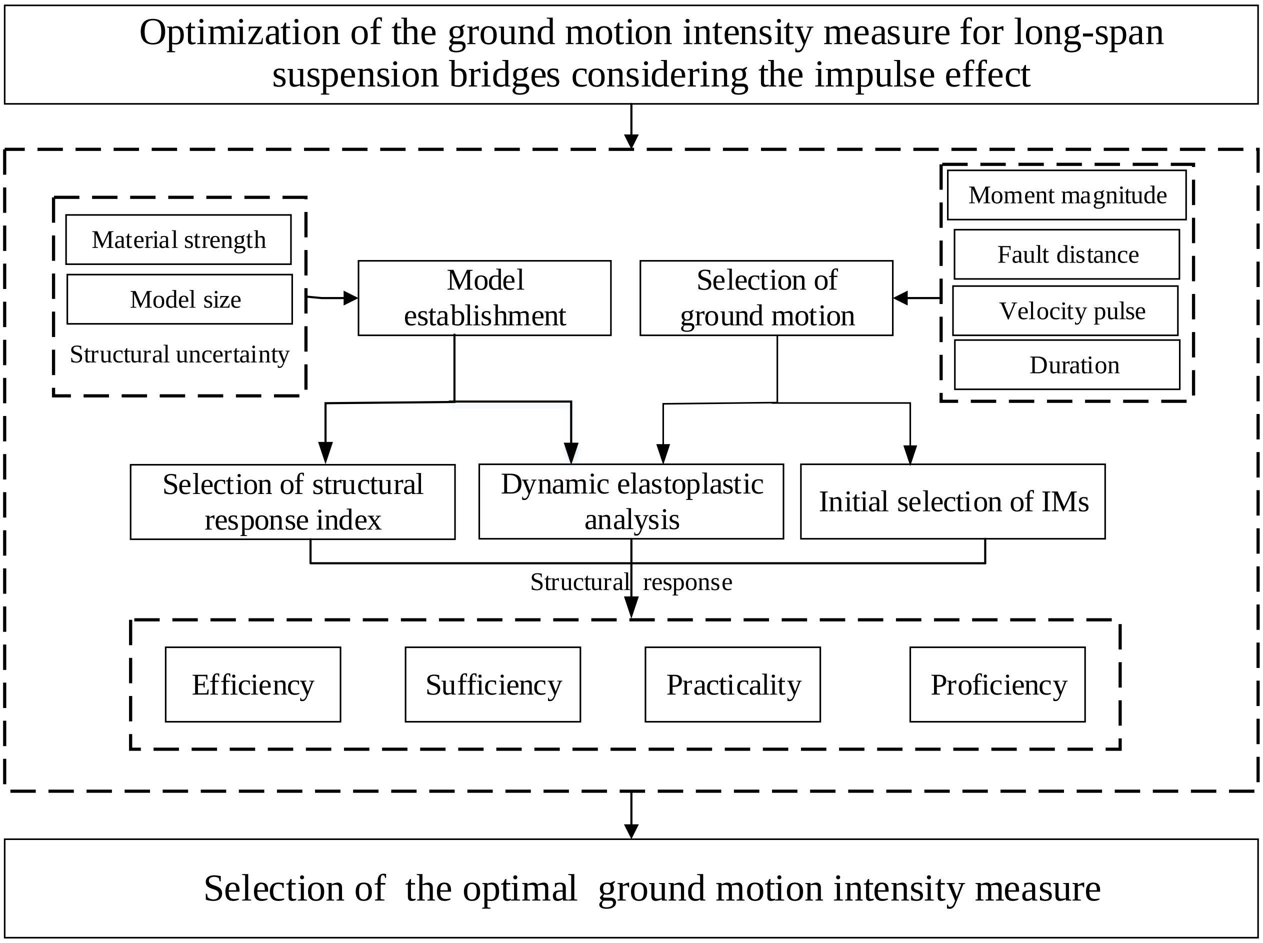


Figure1. Research technology roadmap

2. Selection of Ground Motion Records and Intensity Measure

2.1. Selection of Ground Motion Records

Since the bridge model studied in this work is a long-span suspension bridge, which is a flexible structure with a long vibration natural period, it is more sensitive to near-fault ground motions that consider the impulse effect. This work selected pulse-like ground motion records based on the U.S. PEER database, primarily filtered according to the following criteria:

- Moment magnitude not less than 5.0.
- Fault distance not greater than 30 km.
- Containing a velocity pulse.
- Duration not less than 30 seconds.

Based on the above screening conditions, we selected 31 near-fault pulse-like ground motion records from the PEER database. The selected earthquake information is shown in Table 1. Figure 2 shows the acceleration response spectrum and the mean spectrum curves for the 31 selected ground motions.

Table 1. Near faults ground motion records

Code	Earthquake name	Ground motion component	Mw	Epicentral distance (km)	Fault distance (km)	PGA (g)	PGV (cm/s)
1	San Fernando, 1971	PUL164	6.61	11.87	1.81	1.22	114.35
2	Imperial Valley-06, 1979	BRA225	6.53	43.15	10.42	0.16	36.57
3	Imperial Valley-06, 1979	ECC002	6.53	29.07	7.31	0.21	38.40
4	Imperial Valley-06, 1979	EMO000	6.53	19.44	0.07	0.32	72.87
5	Imperial Valley-06, 1979	E10050	6.53	28.79	8.6	0.17	50.64
6	Imperial Valley-06, 1979	E11140	6.53	29.53	12.56	0.37	35.98
7	Imperial Valley-06, 1979	E03140	6.53	28.65	12.85	0.27	47.92
8	Imperial Valley-06, 1979	E04140	6.53	27.13	7.05	0.48	39.60
9	Imperial Valley-06, 1979	E05140	6.53	27.8	3.95	0.53	48.86
10	Imperial Valley-06, 1979	E06140	6.53	27.47	1.35	0.45	66.95
11	Imperial Valley-06, 1979	E07140	6.53	27.64	0.56	0.34	51.63
12	Imperial Valley-06, 1979	E08140	6.53	28.09	3.86	0.61	54.44
13	Imperial Valley-06, 1979	EDA270	6.53	27.23	5.09	0.35	75.50
14	Imperial Valley-06, 1979	HVP225	6.53	19.8	7.5	0.26	53.08
15	Morgan Hill, 1984	HVR240	6.19	3.94	3.48	0.31	39.30
16	Chalfant Valley-02, 1986	ZAK360	6.19	14.33	7.58	0.40	44.69
17	Whittier Narrows-01, 1987	OR2010	5.99	20.68	24.54	0.23	31.42
18	Loma Prieta, 1989	GOF250	6.93	28.11	10.97	0.24	23.71
19	Loma Prieta, 1989	G01090	6.93	28.64	9.64	0.48	32.42
20	Loma Prieta, 1989	HSP000	6.93	48.24	27.93	0.37	62.93
21	Loma Prieta, 1989	STG000	6.93	27.23	8.5	0.51	41.54
22	Loma Prieta, 1989	WVC000	6.93	27.05	9.31	0.26	42.02
23	Cape Mendocino, 1992	PET090	7.01	4.51	8.18	0.66	88.42
24	Landers, 1992	LCN260	7.28	44.02	2.19	0.73	133.27
25	Landers, 1992	YER270	7.28	85.99	23.62	0.24	51.07
26	Northridge-01, 1994	ORR090	6.69	40.68	20.72	0.57	51.51
27	Northridge-01, 1994	STN110	6.69	25.52	27.01	0.43	41.54
28	Northridge-01, 1994	SPV270	6.69	8.48	8.44	0.75	77.59
29	Northridge-01, 1994	PUL194	6.69	20.36	7.01	1.29	103.28
30	Northridge-01, 1994	SCS142	6.69	13.11	5.35	0.92	88.44
31	Northridge-01, 1994	SCE011	6.69	13.6	5.19	0.85	120.85

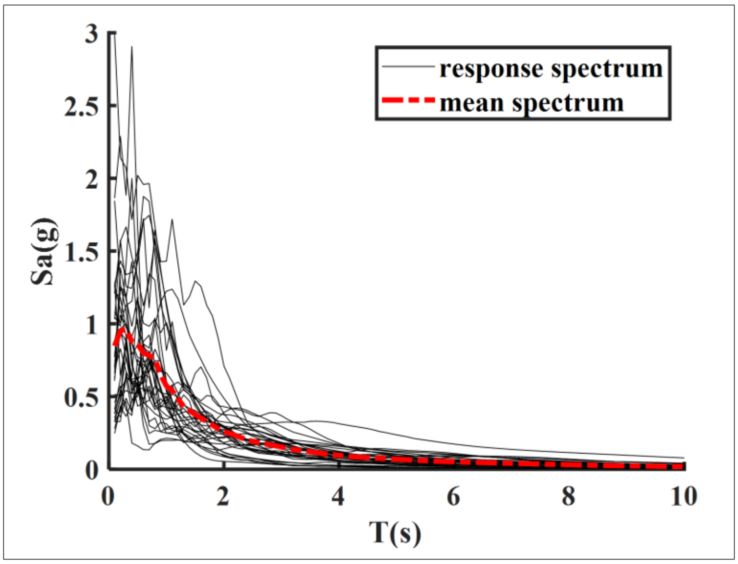


Figure 2. Ground motion acceleration response spectrums curve (ξ=0.05)

2.2. Selection of Ground Motion Intensity Measures

Selecting appropriate and efficient IMs of ground motion can reduce the discreteness when predicting the response of bridge structures [8]. With the continuous advancements in earthquake engineering and structural seismic resistance, researchers have proposed dozens of IMs that reflect different characteristics. Based on the summary of commonly used IMs, we preliminarily selected 12 IMs of ground motion after excluding some parameters with obviously high correlation [19-22]. These IMs were categorized into acceleration-related, velocity-related, and displacement-related types for subsequent evaluation and analysis. Table 2 presents the selected IMs.

Table 2. Primary selection of IMs of ground motion

Types	IM	Name	Definition
Acceleration-related	PGA	peak ground acceleration	$PGA = max\|a(t)\|$
	$S_a(T_1)$	Spectral acceleration at $T=T_1$	$S_a(T_1, \xi = 0.05)$
	EPA	Effective peak acceleration	$EPA = S_a/2.5$
	AI	Arias intensity	$AI = \frac{\pi}{2g}\int_0^{T_d} a^2(t)dt$
Velocity-related	PGV	Peak ground velocity	$PGV = max\|v(t)\|$
	$S_v(T_1)$	Spectral velocity at $T=T_1$	$S_v(T_1, \xi = 0.05)$
	EPV	Effective peak velocity	$EPV = S_v/2.5$
	MIV	Maximum incremental velocity	$MIV = max\|IV\|$
	CAV	Cumulative absolute velocity	$CAV = \int_0^{t_{max}} \|a(t)\|dt$
Displacement-related	PGD	Peak ground displacement	$PGD = max\|d(t)\|$
	$S_d(T_1)$	Spectral displacement at $T=T_1$	$S_d(T_1, \xi = 0.05)$
	MID	Maximum incremental displacement	$MID = max\|ID\|$

3. Model Establishment and Selection of Structural Response Index

3.1. Model Establishment

Our research subject is an earth-anchored steel truss suspension bridge with unequal heights of the two towers, as depicted in Figure 3. The main span of the suspension bridge consists of a 550 m steel truss girder with a central buckle connecting the main cable and the main beam at the center span. The main cable configuration is 135 m + 550 m + 13 5m, with a rise of arch of 55 m and a rise-span ratio of 1/10. The towers on both sides are reinforced concrete portal frame towers, with the tower legs connected by corrugated steel crossbeams, and dampers are installed at the junctions of the towers and the beams. The heights of the towers on both sides are not the same, with the left tower at 103m and the right tower at 140 m. The towers are founded on a group pile foundation made up of 18 friction piles. The site category of the bridge is Class II, with a seismic fortification intensity of 8 degrees, and the bridge category is Class A.

We established a finite element model of the suspension bridge using Midas Civil and conducted dynamic elastoplastic analysis. The damping ratio was set to 0.02, and modal analysis was performed on the model to obtain the natural vibration period of the structure, which was 6.37 seconds. To consider the elastoplastic deformation of and damage to the structure, the main beam and towers were modeled using nonlinear beam elements, where the main beam was made of Q345 steel, and the towers were made of C50 concrete material with HRB500 main reinforcement bars. The main cables and hangers were modeled using truss elements that only withstand tension. The piers were modeled as rigid elements with the mass concentrated at the centroid. The group pile foundation was simulated using beam elements. And the influence of the surrounding soil pressure was mimicked using soil springs. The spring stiffness was calculated using the traditional "m" method outlined in specification. In accordance with the Specification of Seismic Design for Highway Bridges (JTG/T2231—2020) [23], which states that "the elastoplastic behavior of plastic hinges in beam-column elements can be represented by the yield surface proposed by Bresler." Distributed plastic hinges with a modified Takeda three-line hysteretic model were added to the reinforced concrete towers to analyze their elastoplastic response under the ground motions. At the same time, for the tower cross-section, the Mander constitutive model was used to simulate the cover and core layer of the concrete, and the bilinear constitutive model was used to simulate the longitudinal reinforcement. The hysteretic models of the plastic hinges and the material constitutive relationships are shown in Figure 4.

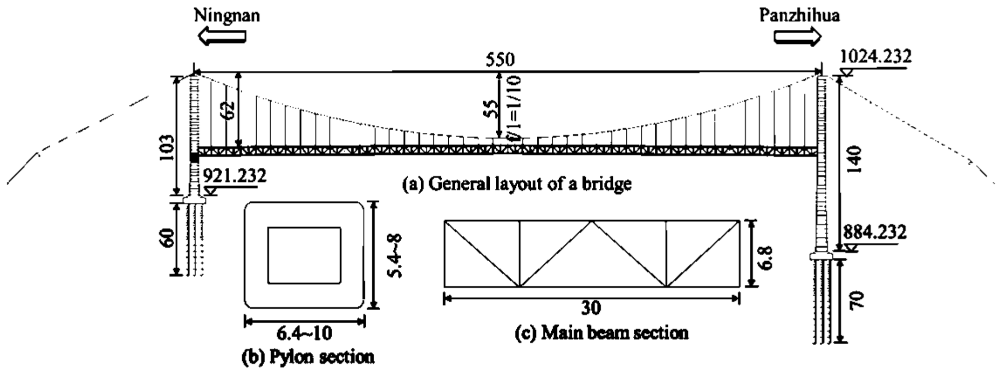
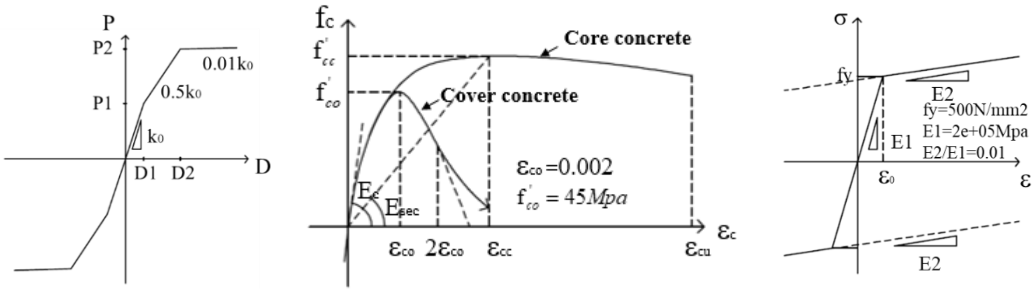


Figure 3. General layout of bridge and detailed drawing of components (unit: m)



(a) Plastic hinge hysteretic model: Modified takeda three-line model

(b) Concrete: Mander constitutive model

(c) Reinforcement bars: Bilinear constitutive model

Figure 4. Hysteresis model of plastic hinge and materials constitutive relationship

3.2. Selection of Structural Response Index

In the performance-based seismic design of structures, selecting appropriate structural response indices can help to reflect the damage state of the structure when subjected to ground motion. The primary focus in this work was on the longitudinal response of the bridge. Based on the relevant earthquake disaster investigation data and research findings, the towers are the fragile components of the suspension bridge, with the bottom section of the towers being particularly fragile when subject to ground motions [24, 25]. The elastoplastic time-history analysis results of the suspension bridge model in this work indicated that the shorter tower side reached the yield and collapsed first, as depicted in Figure 5. Studies on bridges with towers and piers of unequal height have yielded similar results, suggesting that plastic hinges in asymmetric structures first emerge on the weaker side of the shorter structure, where the seismic response and fragility of the short piers and tower legs are higher [26, 27]. Concurrently, under the significant influence of higher modes, rotation and displacement are not effective indicators of the damage state of the towers [28]. Therefore, we selected the curvature at the bottom section of the shorter tower for study, and based on the curvature ductility index, we provided the curvature corresponding to different damage state thresholds at the bottom of the tower, as shown in Table 3 [29].

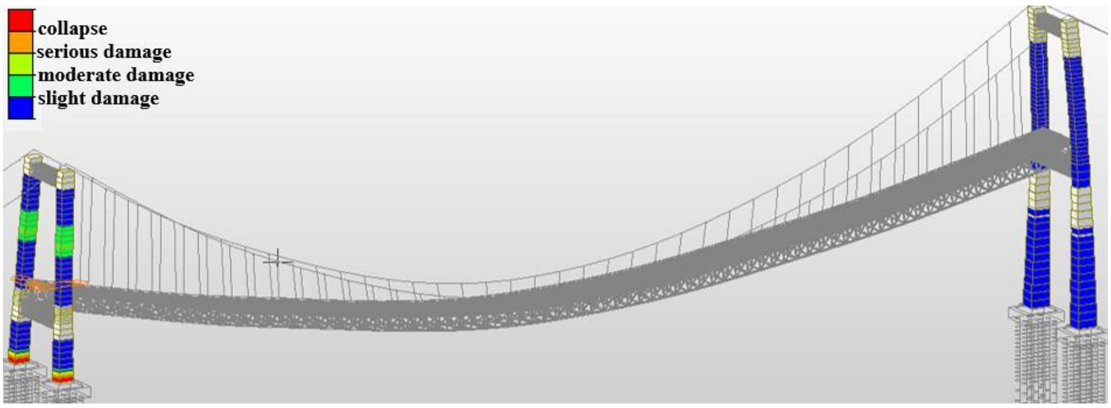


Figure 5. Damage state of bridge tower

Table 3. Section curvature division of tower bottom

Structural response index	Damage state limit value			
	Slight damage	**Moderate damage**	**Serious damage**	**Collapse**
Curvature of tower bottom section (1/m)	0.00047	0.000607	0.001553	0.00461

4. Selection of the Optimal Ground Motion Intensity Measure for Predicting the Bridge Response

When predicting the response of bridge structures under pulse-like ground motions, the reasonable selection of IMs can reduce the discreteness of the predicted responses. Each ground motion record, with the amplitude described by IM, derives a structural response, quantified by the EDP, determining a sample of the EDP-IM pair. This numerical sample is employed to develop a statistical relationship between EDP and IM, through IDA method. The specific process of IDA analysis is as follows:

- According to the conditions of the real bridge, select a number of appropriate ground motion records;
- Initial selection of IMs of ground motion and set a set of amplitude modulation coefficients to adjust the ground motion intensity
- The adjusted seismic waves are used and the nonlinear time history analysis of the established bridge dynamic model is carried out to solve the seismic response of the structure
- The response calculation results are sorted out, evaluates the IMs of ground motion based on four indices: efficiency, sufficiency, practicality, and proficiency.

4.1. Efficiency Evaluation

Efficiency is the evaluation index for the correlation between the IMs of ground motion and the structural response index, commonly assessed using the conditional logarithmic standard deviation β [8]. An efficient IM of ground motion can reduce the discreteness of structural responses. The smaller the value of β, the less the dispersion. Cornell et al. [30] stated that the relationship between the IM of ground motion and the structural response index, along with the corresponding logarithmic standard deviations, can be approximated as follows:

$$ln(EDP) = ln(a) + b \cdot ln(IM) \tag{1}$$

$$\beta = \sqrt{\frac{\sum_{i=1}^{n}[ln(EDP) - (ln\,a) + b\,ln(IM)]^2}{n-2}} \tag{2}$$

To assess the efficiency of the IMs of ground motion a regression analysis was conducted for each IM and the curvature at the bottom section of the tower, based on the relationship formula, to obtain their corresponding logarithmic standard deviations β, as shown in Figure 6. At the same time, to intuitively reflect the ratio of the efficiency between each IM of ground motion and the commonly used IMs of ground motion, PGA, a normalization process was applied to the variances of each IM using the PGA as the benchmark, resulting in the corresponding normalized variances, as shown in Figure 7. The statistical results indicated the following:

- The EPV, MIV, and CAV exhibited lower discreteness with the curvature of the bridge tower, among which, the EPV had the lowest discreteness. Therefore, the velocity-related IMs represented by the EPV are relatively effective for predicting the structural response of suspension bridges under the action of near-fault pulse-like ground motion, the acceleration-related IMs showed higher discreteness when predicting the structural curvature, and the displacement-related IMs such as the PGD and MID exhibited the highest discreteness when predicting the structural curvature.
- The velocity-related IMs represented by the EPV had lower discreteness. Compared to the commonly used PGA and $S_a(T_1)$, the EPV reduced the logarithmic standard deviation β by 16% and 36% and the normalized variance by 30% and 59%, respectively. Therefore, using the EPV enhanced the efficient prediction of the response of large-span suspension bridges under the impulse effect.

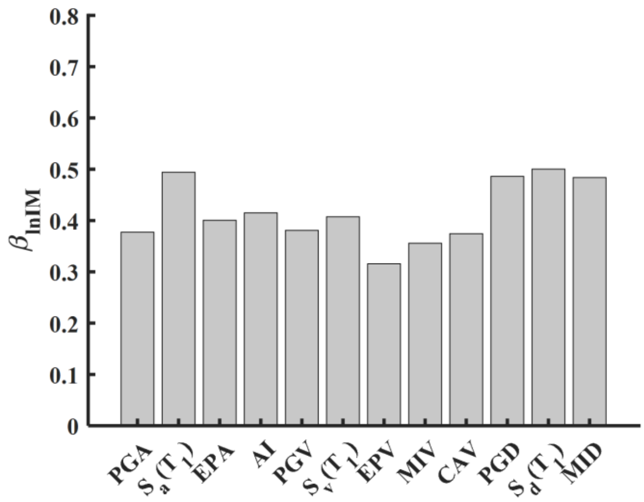


Figure 6. Calculation results of the efficiency of different IMs in predicting structural response

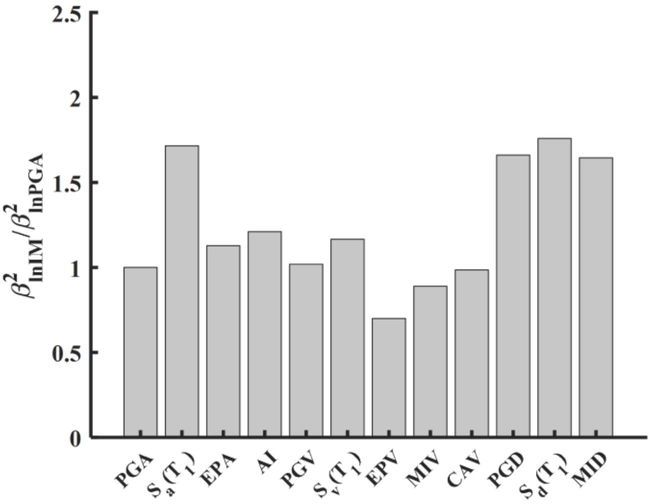
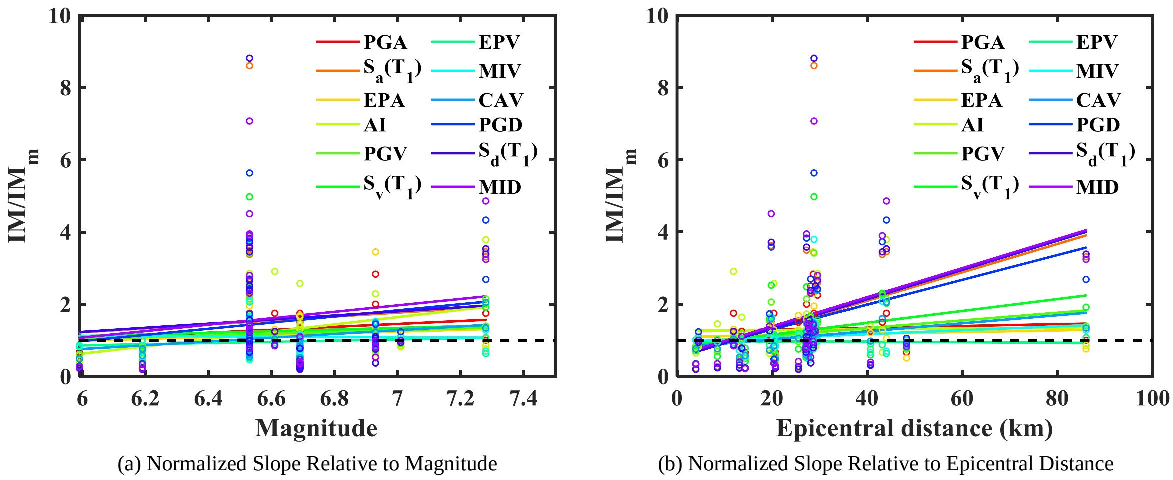


Figure 7. Comparison of normalized variance of IMs based on PGA

4.2. Sufficiency Evaluation

The sufficiency of a IM of ground motion is the conditional independence of the structural response index from factors such as the magnitude and epicentral distance, given the IM [30]. When the sufficiency is poor, the prediction effect is influenced by factors like the magnitude and epicentral distance, which can lead to biases in the predictive outcomes, such as the structural response or collapse strength, and it also cannot verify the rationality of the initially selected ground motions. In this work, the simplified relative sufficiency (SRS) method proposed by Dávalos et al. [31] was used to assess the sufficiency of the IMs of ground motion. The specific procedure of this method involved first normalizing the collapse strength corresponding to each ground motion under various IMs relative to the median value of the collapse strength obtained from the 31 records; second, it involved plotting scatter diagrams of the normalized collapse strength against various ground motion characteristic parameters and performing linear regression; finally, we compared the slope sizes obtained based on each IM. The collapse strength corresponds to the fourth damage state in Table 3 of Section 3.2. The smaller the slope, the closer to 0, the more sufficient the prediction of the structural response using the corresponding IM.

In this work, commonly used ground motion characteristic parameters, such as the magnitude and epicentral distance, were selected to assess the sufficiency of the IMs of ground motion. The calculated slope results are shown in Figure 8 and Table 4, where the horizontal axis represents the ground motion characteristic parameters, and the vertical axis represents the normalized collapse strength. As can be seen in Figure 8(a), the MIV, EPV, and $S_v(T_1)$ were the three IMs with the smallest slope relative to the magnitude, indicating that using these velocity-related IMs to select near-fault pulse-like ground motion records is more sufficient than using other IMs. As shown in Figure 8(b), the IM with the smallest linear regression slope for the normalized collapse strength relative to the epicentral distance was the EPV, whose slope was essentially horizontal. As shown in Table 4, displacement-related IMs represented by PGD have the poorest sufficiency with respect to both magnitude and epicentral distance. Acceleration-related IMs perform better, and velocity-related IMs have the best sufficiency. Among them, the normalized slope of the EPV relative to the magnitude was half that of the PGA and one-third that of the $S_a(T_1)$, and the normalized slope relative to the epicentral distance was reduced by one to two orders of magnitude. A comprehensive evaluation concluded that the EPV was the most sufficient IM to verify the rationality of the ground motion selection and to characterize the structural response, compared to other IMs.



(a) Normalized Slope Relative to Magnitude (b) Normalized Slope Relative to Epicentral Distance

Figure 8. Comparison of the SRS of IMs relative to the ground motion characteristic parameters

Table 4. Normalized slope of IMs of ground motion relative to magnitude and epicenter distance

IMs of ground motion	Magnitude	Epicentral distance
PGA	0.4049	0.0025
$S_a(T_1)$	0.5436	0.0393
EPA	0.2505	0.0022
AI	1.0102	0.0011
PGV	0.2423	0.0106
$S_v(T_1)$	**0.2257**	0.0165
EPV	**0.1645**	**0.0006**
MIV	**0.0416**	0.0054
CAV	0.5202	0.0112
PGD	0.8496	0.0343
$S_d(T_1)$	0.5667	0.0405
MID	0.8901	0.0404

4.3. Practicality Evaluation

The practicality describes the degree of dependence of the structural response index on the IMs of ground motion, that is, the sensitivity of the response index to variations in the IMs. In terms of quantifying the practicality of IMs, Nielson et al. [32] suggested that the regression coefficient b from Cornell's proposed relationship formula could be used. As depicted in Figure 9, with the IMs of ground motion on the horizontal axis and the structural response index on the vertical axis, the slope of the line obtained from a double logarithmic linear regression, tanα, represents the regression coefficient b value. The smaller the b value, the less association there is between the changes in the response index and the IMs, indicating worse practicality.

The results of the coefficient b derived from the regression analysis of each IM of ground motion are illustrated in Figure 10. The statistical results indicated the following:

- $S_d(T_1)$, $S_a(T_1)$, PGD, MID have the least b value, indicating that for long-span suspension bridges and other flexible structures with significant influence from higher modes, IMs that reflect the spectral characteristics at the structure's natural vibration period T_1 and displacement-related IMs are not suitable. EPV, PGA, PGV have the greatest b value, among which the Effective Peak Velocity (EPV) performs the best.
- The commonly utilized $S_a(T_1)$ yielded a comparatively smaller b value, only 55% of that calculated based on the EPV, suggesting its limited applicability for predicting the response of large-span suspension bridges subjected to pulse-like ground motion.

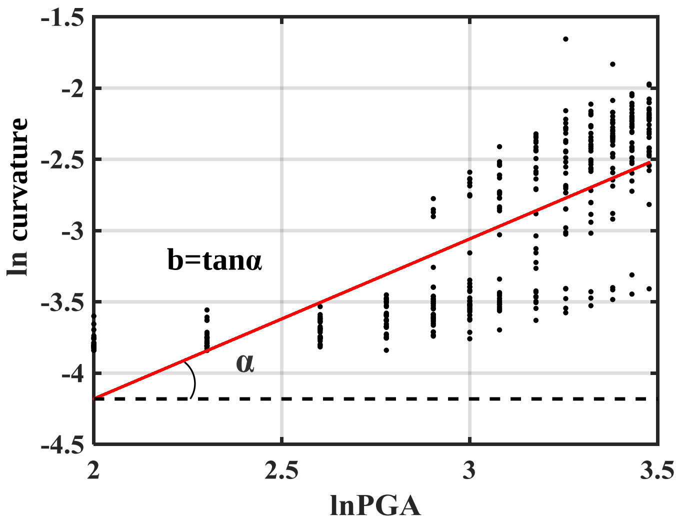


Figure 9. Diagram of regression coefficient b value

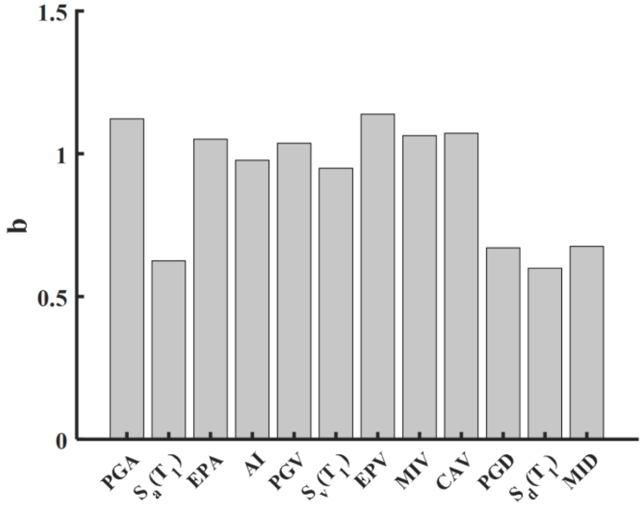


Figure 10. Practicality calculation results of predicting structural response with different IMs

4.4. Proficiency Evaluation

Proficiency is a comprehensive evaluation index for efficiency and practicality. Padgett et al. [8] proposed the use of ζ, the ratio of the logarithmic standard deviation β, derived from linear regression, to the regression coefficient b for quantification. That is:

$$\zeta = \frac{\beta_{ln(DI|IM)}}{b} \tag{3}$$

When distinguishing between efficiency and practicality for evaluation, it is difficult to decide how to balance these two evaluation indices for a comprehensive assessment, and using one evaluation index alone makes it challenging to achieve a reasonable evaluation of the IMs of ground motion. Therefore, considering both efficiency and practicality, Padgett proposed the concept of proficiency to enhance the effect of IM selection. The larger the ratio ζ, the worse the proficiency of the corresponding IM is deemed to be. The proficiency evaluation results for each IM are shown in Figure 11. It can be observed from the figure that among the 12 IMs of ground motion, the EPV had the best proficiency, with a 65% reduction in ζ compared to $S_a(T_1)$ and a 18% reduction in ζ compared to PGA; moreover, the velocity-related IMs generally exhibited better proficiency, while the displacement-related IMs performed relatively poorly.

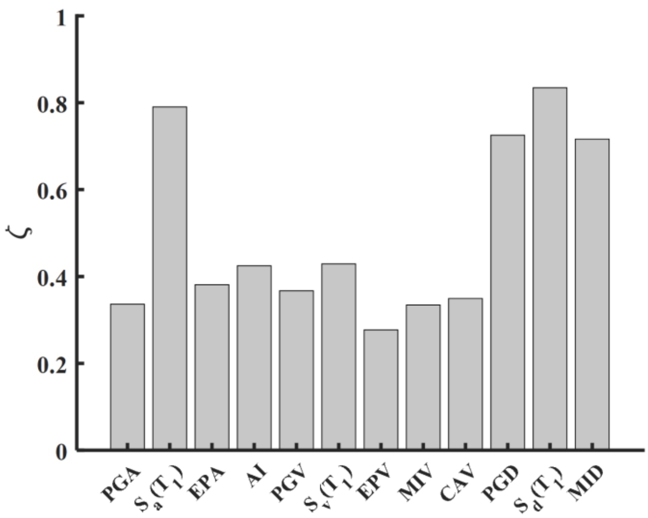


Figure 11. Proficiency calculation results of predicting structural response with different IMs

5. Conclusions

This research focused on the study of long-span suspension bridges under the action of near-fault pulse-like ground motions, investigating the selection of the optimal IM of ground motion for predicting structural responses. By employing the IDA method, the selected ground motion records that considered the impulse effect were input into the bridge model for dynamic elastoplastic analysis. The IMs were comprehensively evaluated for efficiency, sufficiency, practicality, and proficiency. The main conclusions of the study are as follows:

- Through evaluations of the efficiency and sufficiency, compared to the commonly used PGA and $S_a(T_1)$, the logarithmic standard deviation β of the EPV decreased by 16% and 36%, respectively, and the normalized variance decreased by 30% and 59%, respectively, significantly improving the efficiency; the normalized slope of the EPV relative to the magnitude was half that of the PGA and one-third that of the $S_a(T_1)$, and the normalized slope relative to the epicentral distance was reduced by one to two orders of magnitude, indicating that the EPV is more sufficient compared to the commonly used $S_a(T_1)$ and PGA.
- Through evaluations of the practicality and proficiency, compared to the commonly used $S_a(T_1)$, the regression coefficient b value of the EPV nearly doubled, while the ratio ζ was less than half of that of the $S_a(T_1)$, significantly enhancing the practicality and proficiency.
- Under the four evaluation criteria of efficiency, sufficiency, practicality, and proficiency, $S_d(T_1)$, $S_a(T_1)$, PGD, MID performed the worst, indicating that for long-span suspension bridges and other flexible structures significantly affected by higher modes and long-period components, IMs that reflect the spectral characteristics at the structure's natural vibration period T_1 and displacement-related IMs are not suitable.
- Through a comprehensive evaluation of efficiency, sufficiency, practicality, and proficiency, considering the impulse effect of near-fault ground motions and the higher modes of long-span suspension bridges, the commonly used PGA and $S_a(T_1)$ and the displacement-related IMs were determined not to be suitable as IMs. The velocity-related IMs generally predicted the structural response of bridges effectively, with the EPV being the optimal IM for predicting the response of long-span suspension bridges considering the impulse effect.

6. Declarations

6.1. Author Contributions

Conceptualization, J.S. and Q.L.; methodology, Q.L.; software, J.S.; validation, J.H., L.X., and Li.X.; formal analysis, J.S.; investigation, J.S.; resources, Y.Z.; data curation, J.S.; writing—original draft preparation, J.S.; writing—review and editing, Q.L.; visualization, J.S.; supervision, Q.L.; project administration, Q.L.; funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Acknowledgements

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6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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