Research Article

Determining the Optimal Scalar Intensity Measure of Floor Communication Towers

Bo Li ^{1,2}, Qinghui Lai,³ Endong Guo,¹ Chenxi Mao,¹ and Xiaofei Li²

¹Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

²School of Architecture Engineering, Binzhou University, Binzhou 256600, China

³State Key Laboratory of Precision Blasting, Jiangnan University, Wuhan 430056, China

Correspondence should be addressed to Bo Li; libo20070025@126.com

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Various structural types and ground motion characteristics lead to distinct intensity measures of structural seismic performance. For the lattice high-rise steel structure of communication towers, determining the intensity measures to adjust ground motion is critical. Additionally, a crucial problem is whether the ground motion intensity parameters of pulse-like ground motion and ordinary ground motion are consistent. In this study, a standard floor four-leg angle steeled communication tower was considered the study object, and 50 pulse-like ground motions and 50 ordinary ground motions were identified to form a pulse-like ground motion set and ordinary ground motion set, respectively. For comparative analyses, 15 ground motion parameters, including amplitude, spectrum, duration, and energy parameters, were selected. The results revealed that for the lattice towers, such as communication tower, under the action of pulse-like ground motion or ordinary ground motion, efficiency, practicability, and sufficiency should be considered. Furthermore, the most suitable intensity measure was the spectral acceleration corresponding to the natural period of the tower. This study provides a basis for selecting the ground motion for dynamic time history analysis of the lattice steel tower.

1. Introduction

With the continuous development of 5G communication technology and Internet, portable communication network services and applications, such as smartphone payment, online office and teaching, and webcast, have become an indispensable part of people's daily lives. As the main carrier of the communication antenna, the operation of communication towers is primarily associated with the smoothness of the communication system. Conventionally, the design of communication towers is considered for the perspective of its wind resistance performance [1–3]. However, China's Wenchuan earthquake, Yushu earthquake, and Japan's '311' earthquake and other earthquake damage investigations have revealed that in the event of an earthquake, damage to communication towers results in the suspension of communication with the outside world in some areas [4, 5]. In

such scenarios, rescue operations cannot be performed effectively, causing considerable casualties and loss of property.

Typically, dynamic time history analysis is used to analyse the seismic performance of structures. The results revealed that the ground motion parameters (intensity measures, IM_i) suitable for the study of structural seismic performance differed with the type of structures and ground motion characteristics. For lattice towers, including transmission towers and communication towers, currently, the seismic intensity measures identified by dynamic time history analysis or amplitude modulated ground motion predominantly involve peak acceleration (PGA) [6, 7], peak velocity (PGV) [8], spectral acceleration $S_a(T_1)$ corresponding to the natural period of the structure [9, 10] and the ratio of peak velocity to peak acceleration (V/A) [11]. In theoretical research and

engineering practice, ground motion intensity is typically quantitatively characterised by ground motion parameters, in which scalar parameters predominantly include amplitude parameters, spectrum parameters, duration parameters, and energy parameters [12–14]. The use of appropriate intensity measures to select and adjust natural ground motion and the selection of appropriate engineering demand parameters (EDP) to evaluate structural damage are conducive to reducing the discrete type of structural dynamic time history analysis results and improving calculation efficiency. Therefore, the selection of reliable intensity measures is critical for structural dynamic response analysis. Compared with ordinary ground motion, pulse-like earthquakes typically exhibit a wide response spectrum sensitive area. Because earthquakes produce high-energy input to the structure in a short time, this ground motion typically causes considerable damage to the engineering structure. However, for the lattice high-rise steel structure of the communication tower, determining the type of intensity measure that is the most effective to specify and adjust ground motion is critical. Currently, limited studies have been conducted to determine if the most effective parameters of pulse-like ground motion and ordinary ground motion are consistent.

In this study, a standard floor four-leg angle steered communication tower was considered the research object, 50 pulse-like ground motions and 50 ordinary ground motions were gathered from PEER ground motion data centre to form the pulse and ordinary ground motion sets, respectively. A total of 15 ground motion parameters, including amplitude parameters, spectrum parameters, duration parameters, and energy parameters, were selected for comparative analysis. Considering the uncertainty of the input ground motion, the optimal intensity measures under pulse-like ground motion and ordinary earthquake action were selected from the perspectives of efficiency, practicability, and sufficiency. This study provides a basis of selecting ground motion for dynamic time history analysis of lattice steel tower.

2. Ground Motion Records

In the process of dynamic time history analysis of earthquakes, accurate evaluation of ground motion is critical for determining whether the analysis results are effective. Pulse-like ground motion closely related to the relative position between site and seismic fault has attracted considerable attention in structural engineering. Because its main energy occurs in a concentrated time or frequency domain, pulse-like ground motion is generally recognised as the key factor causing severe damage to all engineering structures.

By using the simplified and efficient method proposed by Zhai [15] for quantitatively identifying pulse-like ground motions, 50 pulse-like and 50 ordinary ground motions were obtained from the PEER ground motion database to form pulse-like and ordinary ground motion sets, and the cloud analysis method was employed to analyse the structure [16, 17]. The established ground motions are listed in Table 1.

3. Intensity Measures

A reasonable intensity measure is a critical basis for evaluating the structural response and recoverable ability of the structural seismic function. This measure should reflect the structural seismic response index or damage indexes. The selection of intensity measures should be comprehensive and cover three elements of ground motion, namely amplitude parameters, spectrum parameters, and duration parameters, as well as energy parameters [12–14, 18]. The selection of intensity measures should specify representative ground motion parameters with clear physical meaning, wide application range, and high frequency in seismic engineering. The representative intensity measures discussed in this study are presented in Table 2. The intensity measures considered in this study did not include vector parameters.

4. Description of the Model

4.1. Overview of the Selected Tower and Finite Element Model. To analyse object representative, a 50 m high falling four-legged steel tower was selected as the structural prototype of the standard Atlas of communication tower formulated by China Tower Co. Ltd. General finite element software ABAQUS was used to construct the finite element model. Q345 and Q235 section steel was used for main material and inclined material, respectively, which were simulated by the beam element. The damping ratio is 2%. As a high-rise structure, the communication tower is highly influenced by the p-delta effect. Therefore, initial defects were introduced in the analysis process. Considering the influence of bending and shear deformation of members, the contribution to structural stiffness to natural vibration period and frequency was consistent with those in practice, and the geometric nonlinearity of the structure was considered. Because of the material nonlinearity of structural steel, pursuant to the ideal elastic-plastic assumption, von Mises criterion was implemented as the material yield criterion, and the double broken line constitutive model was adopted as the material constitutive model. The mechanical parameters are presented in Table 3. The antenna platform at the top of the tower, lightning rod, bolts, and ladders at each section were applied as additional loads at the horizontal nodes of each section. The sketch of the prototype structure is displayed in Figure 1, and the components size and the additional mass of the tower are displayed in Table 4. The bottom of the tower was absolutely consolidated. According to the modal analysis, the mass participation ratios of the first three modes are 37.2%, 34.4%, and 20.5%, totally 92.1%. The first three mode shapes are shown in Figure 2.

4.2. Model Verification. The rationality of the finite element model is directly relevant to the reliability of the analysis results. To verify the rationality of the aforementioned model, a 50-m four-legged steel tower was designed conforming to the standard Atlas of communication tower in Harbin, Heilongjiang Province, for the frequency test. A three-way acceleration sensor was placed on the top

TABLE 1: Selected ground motions.

(a) Pulse-like ground motions						
Seq.	RSN	Event	Year	Station	M	EpiD (km)
1	77	San fernando	1971	Pacoima dam	6.61	11.87
2	184	Imperial Valley-06	1979	El centro	6.53	27.23
3	250	Mammoth Lakes-06	1980	Long valley dam	5.94	14.04
4	296	Irpinia, Italy-02	1980	Bagnoli irpinio	6.2	22.29
5	503	Taiwan SMART1(40)	1986	SMART1 C00	6.32	68.18
6	506	Taiwan SMART1(40)	1986	SMART1 I07	6.32	67.98
7	540	N. Palm springs	1986	Whitewater	6.06	4.24
8	614	Whittier Narrows-01	1987	Downey—birchdale	5.99	15.29
9	645	Whittier Narrows-01	1987	LB—orange ave	5.99	20.68
10	732	Loma Prieta	1989	APEEL 2	6.93	63.49
11	738	Loma prieta	1989	Alameda naval air	6.93	90.77
12	764	Loma prieta	1989	Gilroy	6.93	28.11
13	779	Loma prieta	1989	LGPC	6.93	18.46
14	784	Loma prieta	1989	Oakland—title	6.93	91.68
15	787	Loma prieta	1989	Palo alto—SLAC lab	6.93	51.2
16	802	Loma prieta	1989	Saratoga—aloha ave	6.93	27.23
17	803	Loma prieta	1989	Saratoga—W valley	6.93	27.05
18	805	Loma prieta	1989	Stanford park. Garage	6.93	18.60
19	808	Loma prieta	1989	Treasure island	6.93	97.43
20	821	Erzican, Turkey	1992	Erzincan	6.69	8.97
21	879	Landers	1992	Lucerne	7.28	44.02
22	900	Landers	1992	Yermo fire station	7.28	85.99
23	953	Northridge-01	1994	Beverly hills	6.69	13.39
24	960	Northridge-01	1994	Canyon country	6.69	26.49
25	963	Northridge-01	1994	Castaic	6.69	40.68
26	1003	Northridge-01	1994	LA—saturn st	6.69	25.52
27	1004	Northridge-01	1994	LA—sepulveda	6.69	8.48
28	1007	Northridge-01	1994	Los angeles	6.69	36.47
29	1013	Northridge-01	1994	LA dam	6.69	11.79
30	1045	Northridge-01	1994	Newhall	6.69	21.55
31	1050	Northridge-01	1994	Pacoima Dam	6.69	20.36
32	1054	Northridge-01	1994	Pardee—SCE	6.69	25.65
33	1081	Northridge-01	1994	Stone canyon	6.69	21.75
34	1084	Northridge-01	1994	Converter sta	6.69	13.11
35	1085	Northridge-01	1994	Converter sta east	6.69	13.60
36	1106	Kobe, Japan	1995	KJMA	6.90	18.27
37	1116	Kobe, Japan	1995	Shin-osaka	6.90	45.97
38	1119	Kobe, Japan	1995	Takarazuka	6.90	38.60
39	1120	Kobe, Japan	1995	Takatori	6.90	13.12
40	1148	Kocaeli, Turkey	1999	Arcelik	7.51	53.68
41	1170	Kocaeli, Turkey	1999	Sakarya	7.51	90.66
42	1176	Kocaeli, Turkey	1999	Yarimca	7.51	19.30
43	1182	Chi-chi, Taiwan	1999	CHY006	7.62	40.47
44	1197	Chi-chi, Taiwan	1999	CHY028	7.62	32.67
45	1198	Chi-chi, Taiwan	1999	CHY029	7.62	39.70
46	1231	Chi-chi, Taiwan	1999	CHY080	7.62	31.65
47	1244	Chi-chi, Taiwan	1999	CHY101	7.62	31.96
48	1504	Chi-chi, Taiwan	1999	TCU067	7.62	28.70
49	1550	Chi-chi, Taiwan	1999	TCU136	7.62	48.75
50	1602	Duzce, Turkey	1999	Bolu	7.14	41.27
(b) Ordinary ground motions						
Seq.	RSN	Event	Year	Station	M	EpiD (km)
1	432	Taiwan SMART1(25)	1983	SMART1 O01	6.50	100.64
2	1036	Northridge-01	1994	Mojave—hwys 14	6.69	102.24
3	1163	Northridge-01	1994	Rinaldi receiving sta	7.51	101.86
4	1217	Chi-chi, Taiwan	1999	CHY060	7.62	91.08
5	1471	Chi-chi, Taiwan	1999	TCU015	7.62	101.62
6	1747	Little skull mtn, NV	1992	Station #8	5.65	99.66
7	1789	Hector mine	1999	Hesperia—4th and palm	7.13	98.53

TABLE 1: Continued.

(a) Pulse-like ground motions						
Seq.	RSN	Event	Year	Station	M	EpiD (km)
8	1929	Anza-02	2001	Corona	4.92	101.56
9	1969	Anza-02	2001	Riverside	4.92	101.05
10	1973	Anza-02	2001	Riverside Airport	4.92	99.31
11	1995	Gulf of California	2001	El Centro Array #11	5.7	102.56
12	2178	Chi-chi, Taiwan-02	1999	CHY054	6.20	100.24
13	2833	Chi-chi, Taiwan-02	1999	KAU078	6.20	100.58
14	2959	Chi-chi, Taiwan-05	1999	CHY055	6.20	102.15
15	2961	Chi-chi, Taiwan-05	1999	CHY057	6.20	100.40
16	2965	Chi-chi, Taiwan-05	1999	CHY061	6.20	100.17
17	2966	Chi-chi, Taiwan-05	1999	CHY062	6.20	100.04
18	2988	Chi-chi, Taiwan-05	1999	CHY100	6.20	99.39
19	2990	Chi-chi, Taiwan-05	1999	CHY107	6.20	98.67
20	3072	Chi-chi, Taiwan-05	1999	ILA062	6.20	102.97
21	3073	Chi-Chi, Taiwan-05	1999	ILA064	6.20	102.68
22	3074	Chi-chi, Taiwan-05	1999	ILA066	6.20	99.75
23	3165	Chi-chi, Taiwan-05	1999	TCU033	6.20	99.89
24	3194	Chi-chi, Taiwan-05	1999	TCU085	6.20	100.36
25	3280	Chi-chi, Taiwan-06	1999	CHY044	6.30	101.89
26	3286	Chi-chi, Taiwan-06	1999	CHY055	6.30	100.75
27	3287	Chi-chi, Taiwan-06	1999	CHY057	6.30	100.89
28	3291	Chi-chi, Taiwan-06	1999	CHY061	6.30	101.92
29	3292	Chi-chi, Taiwan-06	1999	CHY062	6.30	101.03
30	3316	Chi-chi, Taiwan-06	1999	CHY100	6.30	98.81
31	3392	Chi-Chi, Taiwan-06	1999	ILA066	6.30	100.46
32	3484	Chi-chi, Taiwan-06	1999	TCU094	6.30	100.17
33	3531	Chi-chi, Taiwan-06	1999	TTN024	6.30	100.37
34	3584	Taiwan SMART1(25)	1983	SMART1 I10	6.50	99.30
35	3585	Taiwan SMART1(25)	1983	SMART1 I11	6.50	99.33
36	3586	Taiwan SMART1(25)	1983	SMART1 I12	6.50	99.36
37	3587	Taiwan SMART1(25)	1983	SMART1 M02	6.50	99.47
38	3590	Taiwan SMART1(25)	1983	SMART1 M05	6.50	98.24
39	3601	Taiwan SMART1(25)	1983	SMART1 O09	6.50	99.68
40	3783	Hector mine	1999	Beaumont	7.13	98.80
41	3883	Tottori, Japan	2000	HRS017	6.61	100.23
42	3917	Tottori, Japan	2000	OKY014	6.61	100.93
43	3946	Tottori, Japan	2000	SMN018	6.61	102.27
44	3957	Tottori, Japan	2000	SMNH13	6.61	99.33
45	4152	Niigata, Japan	2004	FKS021	6.63	98.33
46	4154	Niigata, Japan	2004	FKS023	6.63	98.25
47	4240	Niigata, Japan	2004	TCG009	6.63	101.23
48	4244	Niigata, Japan	2004	TCGH09	6.63	101.85
49	5001	Chuetsu-oki, Japan	2007	FKSH01	6.80	99.92
50	5060	Chuetsu-oki, Japan	2007	GNM001	6.80	100.83

platform of the tower with a height of 48.2 m (Figure 3). Pile foundations were used for the tower, and the soil was hard, which can be approximately equivalent to the fixed constraint at the bottom. According to the conversion relationship between the fundamental frequency and the first period, the natural periods in X and Y directions of the actual structure and finite element model were derived, as presented in Table 5. The natural period difference between the finite element model and the prototype structure of both directions was less than 15%, which revealed the finite element model of communication tower based on ABAQUS to be acceptable and reliable.

4.3. Structural Response. The function of the communication tower is to support the transmission antenna to receive and transmit signals in an area. The dynamic response to the tower under an earthquake is principally monitored by using the maximum roof drift (MRD) of the tower top relative to the tower bottom. Furthermore, as a lattice high-rise steel structure, the communication tower exhibits a large acceleration amplification effect at the top of the tower under the action of a horizontal earthquake, whereas the communication antenna and the tower top platform are mainly linked by bolts. The amplified acceleration at the top of the tower exhibits a large dynamic response to the connected bolts.

TABLE 2: IMs considered in this study.

Class	Notation	IMi Definition/references	Expression
Amplitude parameters	PGA	Peak ground acceleration	$PGA = \max a(t) $
	PGV	Peak ground velocity	$PGV = \max v(t) $
	PGD	Peak ground displacement	$PGD = \max d(t) $
	V/A	Ratio of peak velocity to peak acceleration	PGV/PGA
Spectrum parameters	EPA	Effective peak acceleration	$EPA = S_a/2.5$
	EPV	Effective peak velocity	$EPV = S_v/2.5$
	SI	Housner spectral intensity	$S_I(\zeta) = \int_{0.1}^{2.5} S_v(\zeta, T) dt$
	$Sa(T_1)$	Spectral acceleration at the fundamental period	$S_a(T_1, \xi)$
Duration parameters	U_{du}	Consistent duration	$U_{du} = \sum_i t_i$
	S_{du}	Duration of strong ground motion	$S_{90} = t_{95} - t_5$
Energy parameters	CAV	Cumulative absolute velocity	$CAV = \int_{t_1}^{t_{max}} a(t) dt$
	CAV_s	Standard cumulative absolute velocity	$CAV_s = \sum_i \int_{t_i}^{t_{i+1}} W_i a(t) dt$
	MIV	Maximum incremental speed	$MIV = \max(\int_{t_i}^{t_{max}} a(t) dt)$
	MID	Maximum incremental displacement	$MID = \max(\int_{t_i}^{t_{max}} v(t) dt)$
	AI	Arias intensity	$I_A = \pi/2g \int_0^t a^2(t) dt$

TABLE 3: Mechanical properties of Q345 and Q235.

Material	Yield stress (Pa)	Strain-hardening ratio	Young' modulus (Pa)	Poisson's ratio	Density (kg/m ³)
Q345	3.45 E + 8	1.37	2.06 E + 11	0.3	7850
Q235	2.35 E + 8		2.06 E + 11	0.3	7850

FIGURE 1: Sketch of the prototype Structure (unit: mm).

TABLE 4: Components size.

Legs (unit: mm)	Braces (unit: mm)	Added mass (kg)
L80 x 6	L50 x 5	1003.3
L100 x 8	L56 x 5	971.6
L125 x 10	L63 x 5	1126.7
L140 x 12	L63 x 5	1247.8
L160 x 14	L63 x 5	273.4
L180 x 16	L70 x 5	290.6
L180 x 16	L80 x 6	270.3
L200 x 16	L90 x 7	280.5
L200 x 18	L100 x 7	295.6

FIGURE 2: Mode shapes of (a) first order, (b) second order, and (c) third order.

FIGURE 3: Measured real (a) angle steel and (b) example of the installed three-directional acceleration transducers used for the measurements.

TABLE 5: Comparison of the natural periods between the model and the prototype structure.

	X		Y	
	F (Hz)	T_1 (s)	f (Hz)	T_1 (s)
Prototype tower	1.51	0.66	1.50	0.67
FE model	1.74	0.57	1.74	0.57
Difference	-	13.6%	-	14.9%

Therefore, the acceleration amplification factor (AAF) at the top of the tower is a critical structural dynamic response demand parameter. Therefore, in this study, MRD and AAF were assigned as EDP. The structural response to the communication tower under the action of pulse-like ground motions and ordinary ground motions along the X direction is listed in Table 6.

5. Evaluation of IM

5.1. Results in Terms of Efficiency. The efficiency of intensity measures reveals that under a certain ground motion intensity condition, the discrete engineering structure requires small parameters. On the premise of not lowering the calculation accuracy, the estimated conditional probability $P(EDP|IM)$ can be reduced, and the number of seismic records and dynamic time history analysis conditions required for analysis can be reduced to a certain extent. Typically, the validity of ground motion parameters is determined by conditional logarithmic standard deviation β to judge, and efficiency is the core index used to measure the superiority over an IM_i [19].

The relationship between the EDP and IM_i approximately satisfies the logarithmic relationship, and its relationship formula is displayed as follows:

$$\ln(EDP) = \ln(a) + b \cdot \ln(IM_i). \quad (1)$$

The aforementioned formula satisfies the univariate linear regression model, and the least square principle can be

used to perform regression analysis on the obtained n scatter points (IM_i, EDP_i) to obtain the empirical regression lines of $\ln(IM_i)$ and $\ln(EDP)$ and obtain the conditional logarithmic standard deviation, as follows.

$$\beta_{\ln(EDP|IM_i)} = \sqrt{\frac{\sum (\ln(EDP) - \ln(a \cdot IM_i^b))^2}{n - 2}}. \quad (2)$$

For any intensity measure IM_i , the smaller the conditional logarithmic standard deviation, $\beta_{\ln(EDP|IM_i)}$, is the smaller the discrete type of seismic response to engineering structure is, indicating that the efficiency of the ground motion parameter IM_i is higher, otherwise, the efficiency is lower.

Under the action of pulse-like ground motions and ordinary ground motions, the conditional logarithmic standard deviation, $\beta_{\ln(EDP|IM_i)}$, corresponding to the intensity measures to be analysed, and the structural dynamic response (MRD and AAF) was calculated by using the cloud analysis method, as displayed in Figure 4.

- (1) For MRD and AAF, the conditional logarithmic standard deviation $\beta_{\ln(EDP|IM_i)}$ of spectrum parameters is the smallest, that is, among the four aforementioned four ground motion intensity parameters, spectrum parameters are the most effective.
- (2) Figure 4(a) reveals for the MRD, under the action of pulse-like ground motions and ordinary ground motions, with the exception that the conditional logarithmic standard deviation $\beta_{\ln(EDP|IM_i)}$ corresponding to $Sa(T_1)$ is basically equal, the values of other intensity measures corresponding to pulse-like ground motions are smaller. The MRD are predicted more efficiently with pulse-like ground motions than with ordinary motions, that is, regression models are better fitted to data from the pulse-like ground motion set than to that from ordinary sets.

TABLE 6: Structural responses to pulse-like GMs and ordinary GMs.

Pulse-like GMs			Ordinary GMs		
Sequence	MRD (mm)	AAF	No.	MRD (mm)	AAF
PL1	50	4.13	OR1	20	8.63
PL2	30	2.81	OR 2	20	9.47
PL3	78	4.89	OR3	70	13.71
PL4	43	4.65	OR4	40	15.87
PL5	110	7.80	OR5	60	8.71
PL6	72	5.71	OR6	3	8.64
PL7	210	4.79	OR7	14	5.56
PL8	160	6.89	OR8	1	5.88
PL9	380	10.14	OR9	1	7.11
PL10	110	8.10	OR10	1	7.38
PL11	270	4.04	OR11	7	10.36
PL12	160	6.20	OR12	5	8.06
PL13	140	5.77	OR13	25	8.82
PL14	150	6.14	OR14	30	10.91
PL15	70	4.74	OR15	22	12.64
PL16	130	6.24	OR16	11	8.82
PL17	500	14.32	OR17	30	7.68
PL18	160	7.79	OR18	20	9.13
PL19	170	8.19	OR19	10	8.16
PL20	270	10.76	OR20	8	7.30
PL21	80	5.25	OR21	15	13.75
PL22	110	5.77	OR22	20	6.64
PL23	220	6.40	OR23	3	3.87
PL24	150	6.66	OR24	20	10.09
PL25	120	2.91	OR25	43	9.37
PL26	320	5.63	OR26	5	6.00
PL27	210	8.88	OR27	16	9.42
PL28	100	6.26	OR28	20	8.09
PL29	180	5.57	OR29	46	11.51
PL30	390	6.19	OR30	18	13.29
PL31	100	6.54	OR31	10	10.94
PL32	140	7.58	OR32	6	8.93
PL33	80	6.91	OR33	15	10.46
PL34	250	5.88	OR34	16	9.87
PL35	110	5.06	OR35	16	10.46
PL36	80	7.07	OR36	24	13.82
PL37	190	9.15	OR37	120	4.75
PL38	250	7.56	OR38	20	10.41
PL39	200	5.67	OR39	9	4.79
PL40	50	4.93	OR40	16	9.60
PL41	140	12.22	OR41	22	9.02
PL42	70	5.58	OR42	4	5.57
PL43	80	7.45	OR43	16	8.50
PL44	150	7.94	OR44	3	5.21
PL45	130	6.81	OR45	20	6.14
PL46	40	4.13	OR46	23	7.53
PL47	90	5.91	OR47	40	12.10
PL48	150	7.65	OR48	5	6.81
PL49	100	7.05	OR49	2	4.75
PL50	140	8.99	OR50	8	4.30

- (3) Figure 4(b) reveals that for the AAF, $\beta_{\ln(\text{EDP}|IM_i)}$ corresponding to the duration parameters (U_{du} and S_{du}) and CAV in the energy parameters under the action of pulse ground motion is significantly less than that under the action of ordinary ground motion, while the values of $\beta_{\ln(\text{EDP}|IM_i)}$ corresponding to other ground motion parameters are

close under the action of pulse-like ground motions and ordinary ground motions.

- (4) The aforementioned results revealed that for MRD and AAF, the discrete type of ground motion parameters considered in this study were less than that under ordinary ground motion. From the perspective of efficiency, the top-five most effective intensity measures are amplitude parameter PGA, spectrum parameters $S_a(T_1)$ and EPA, and energy parameters CAV and CAVs. The logarithmic standard deviation $\beta_{\ln(\text{EDP}|IM_i)}$ from duration parameter conditions is higher than 0.5, representing large discrete and unreliable intensity measures.

5.2. Results in Terms of Practicality. Practicality refers to whether a direct correlation exists between an IM and the engineering demand placed on the structure. For a specified intensity measure, the practicability is not strong, which indicates that the seismic response to the engineering structure is slightly influenced by the change in this parameter. The quantitative index of practicability can be assessed by using linear regression coefficient b given in (1). The larger the value of b is, the greater the influence of the change of intensity measures on the seismic response to engineering structures is, that is, the stronger the correlation is, the higher the practicability is; if the value of b is close to 0, the change in intensity measures does not affect the seismic response to engineering structures [20]. An example of the relative practicality of intensity measures is displayed in Figure 5.

The regression coefficient b corresponding to various intensity measures can be derived by fitting the straight line of (1), as displayed in Figure 6. For intensity measures, the requirements of efficiency and practicability must be simultaneously met; therefore, only the practicability of the five most effective ground motion parameters evaluated in the previous step can be compared. The practicability of the selected intensity measures under the action of pulse-like ground motions is stronger than that under the action of ordinary ground motions. For the spectrum parameters EPA and $S_a(T_1)$, the regression coefficient b corresponding to $S_a(T_1)$ is larger. Thus, the practicability of $S_a(T_1)$ is stronger than EPA. This result reveals that $S_a(T_1)$ related to the vibration characteristics of the structure is more sensitive to the structural demand parameters than EPA. Furthermore, according to Figure 6(a) and 6(b), the regression coefficient b corresponding to CAVs under ordinary ground motion is close to 0, indicating poor practicability, that is, there is small or no dependence of the level of engineering demand on the CAV level. Typically, the amplitude parameter PGA, spectrum parameter $S_a(T_1)$, and energy parameter CAV are highly practical.

5.3. Results in Terms of Sufficiency. Sufficiency is a crucial index to assess the independence of the ground motion parameter and indicates the correlation between the ground motion parameter (IM_i) and ground motion information parameter (magnitude M or source-to-site distance R). A

FIGURE 4: Reveals the following: (a) MRD and (b) AAF, obtained from the cloud analysis subjected to pulse-like and ordinary ground motions.

FIGURE 5: Example of the relative practicality of intensity measures.

FIGURE 6: Regression coefficient, b , corresponding to the engineering demanded parameters (a) MRD and (b) AAF, obtained from the cloud analysis subjected to pulse-like and ordinary ground motions.

sufficient ground motion parameter should be statistically independent of the ground motion information parameter. If the demand residuals and seismic information parameters are not statistically independent of each other, the p value of regression analysis would be less than the given significance level, indicating that the sufficiency of IM_i is poor. The p value of 0.05 was considered the cutoff for an insufficient IM_i . If the p value value is larger, the sufficiency of IM would be stronger [21]. Because of the limitations on the length of the article, only the scatter and fitting line expressions of the required residual of AAF and magnitude M when PGA is a ground motion parameter are presented in Figure 7.

The p values derived from the three highly practical intensity measures PGA, $Sa(T_1)$, and CAV for the seismic

magnitude and source-to-site distance F -text are displayed in Figure 8. The results reveal that under the action of ordinary ground motions, the p value among PGA, CAV, and magnitude M is equal to 0, indicating a complete linear correlation and sufficiency is 0. If PGA or CAV is taken as IM to select the ground motions for the dynamic time history analysis of the floor four-leg angle steeled communication tower, the results are strongly related to the magnitude of the earthquake event. Under the action of pulse-like ground motions, the p value between PGA and source-to-site distance R is equal to 0, demonstrating complete linear correlation. Only the correlation coefficient p value between the spectrum parameter $Sa(T_1)$ and the magnitude M or source-to-site distance R is greater than the

FIGURE 7: Testing the sufficiency of PGA with respect to M for predicting AAF.

FIGURE 8: Median p values obtained from investigating the sufficiency of typical IMi with respect to (a) magnitude and (b) source-to-site distance.

given significance level of 0.05 under the action of pulse-like ground motions or ordinary ground motions, that is, it satisfies the sufficiency requirements.

Briefly, for the lattice tower such as the communication tower, irrespective of whether under the action of pulse-like and ordinary ground motions, the most suitable intensity measure is the spectral acceleration $Sa(T_1)$ corresponding to the natural period of the structure from the three aspects of efficiency, practicability, and sufficiency.

6. Conclusions

In this study, a standard floor four-leg angle steel communication tower was considered. Based on the cloud analysis method, a linear logarithmic regression fitting method of intensity measures, considering the uncertainty of input ground motion, the optimal intensity measures under

pulse-like ground motions, and ordinary ground motions, was determined from the perspectives of efficiency, practicability, and sufficiency.

- (1) For MRD and AAF, the discrete type of ground motion parameters considered in this study is less than that under the action of impulse ground motion. From the perspective of efficiency, the top-five most effective intensity measures are amplitude parameter PGA, spectrum parameter $Sa(T_1)$ and EPA, and energy parameter CAV and CAVs. The duration parameters are discrete and noneffective intensity measures.
- (2) Under the action of pulse ground motion, the practicability of the selected intensity measures is stronger than that of ordinary ground motion. For the spectrum parameters EPA and $Sa(T_1)$, $Sa(T_1)$ is

more practical than EPA. Furthermore, the regression coefficient b corresponding to CAVs under ordinary ground motion is close to 0, indicating that the practicability is considerably poor. Typically, the amplitude parameter PGA, spectrum parameter $Sa(T_1)$, and energy parameter CAV are highly practical.

- (3) For the lattice tower, such as the communication tower, irrespective of whether the measure is under the action of pulse-like ground motion or ordinary ground motion, considering from the three aspects of efficiency, practicability, and sufficiency, the most suitable intensity measure is the spectral acceleration $Sa(T_1)$ corresponding to the natural period of the structure.

The scalar intensity measures are considered in this study. In a subsequent study, the vector intensity measures can be elaborated.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] L. Tian, X. Zhang, and X. Fu, "Collapse simulations of communication tower subjected to wind loads using dynamic explicit method," *Journal of Performance of Constructed Facilities*, vol. 34, no. 3, 2020.
- [2] X. Fu, H.-N. Li, L. Tian, J. Wang, and H. Cheng, "Fragility analysis of transmission line subjected to wind loading," *Journal of Performance of Constructed Facilities*, vol. 33, no. 4, 2019.
- [3] Z. Meng, G. F. Zhao, L. L. Wang, and J. Li, "Wind-induced coupling vibration effects of high-voltage transmission tower-line systems," *Shock and Vibration*, vol. 2017, Article ID 1205976, 34 pages, 2017.
- [4] X. Wang, "Thoughts left by the 311 earthquake in Japan," *City and disaster reduction*, vol. 2017, no. 5, pp. 31–35, 2017, (Chinese).
- [5] A. W. Liu, S. Xia, H. S. Lv, K. Chen, and W. J. Xu, "Typical damage analysis for mobile communication base stations in the extremely damage area of Wenchuan earthquake," *Telecom Engineering Technics and Standardization*, vol. 25, no. 12, pp. 82–86, 2012, (Chinese).
- [6] H. Pan, C. Li, and L. Tian, "Seismic fragility analysis of transmission towers considering effects of soil-structure interaction and depth-varying ground motion inputs," *Bulletin of Earthquake Engineering*, vol. 19, no. 11, pp. 4311–4337, 2021.
- [7] M. Sadeghi, F. Mohajeri, and E. Khalaghi, "Seismic performance and communication failure of cell phone towers in Iran's seismic zones, case study: developing structural and communicational fragility curves for 24M monopole tower," in *Proceedings of the 7th International Conference on Urban Earthquake Engineering (7CUEE) & 5th International Conference on Earthquake Engineering (5ICEE)*, Tokyo Institute of Technology, Tokyo, Japan, March 2010.
- [8] L. Tian, X. Gai, and B. Qu, "Shake table tests of steel towers supporting extremely long-span electricity transmission lines under spatially correlated ground motions," *Engineering Structures*, vol. 132, pp. 791–807, 2017.
- [9] L. Tian, R. Ma, and B. Qu, "Influence of different criteria for selecting ground motions compatible with IEEE 693 required response spectrum on seismic performance assessment of electricity transmission towers," *Engineering Structures*, vol. 156, pp. 337–350, 2018.
- [10] G. G. Amiri and S. R. Massah, "Seismic response to 4-legged self-supporting telecommunication tower," *IJE Transactions B: Applications*, vol. 20, no. 2, pp. 107–126, 2007.
- [11] M. A. Khedr and G. McClure, "A simplified method for seismic analysis of lattice telecommunication towers," *Canadian Journal of Civil Engineering*, vol. 27, no. 3, pp. 533–542, 2000.
- [12] N. Luco and C. A. Cornell, "Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions," *Earthquake Spectra*, vol. 23, no. 2, pp. 357–392, 2007.
- [13] J. W. Baker, *Vector-valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis [D]*, Stanford University, California, 2006.
- [14] Q. H. Lai, J. J. Hu, L. L. Xie, J. Y. Tan, and Z. F. Zhao, "Correlation analysis potential damage parameters of pulse-like ground motion," *World Earthquake Engineering*, vol. 36, no. 1, pp. 35–43, 2020, (Chinese).
- [15] C. Zhai, C. Li, S. Kunnath, and W. Wen, "An efficient algorithm for identifying pulse-like ground motions based on significant velocity half-cycles," *Earthquake Engineering & Structural Dynamics*, vol. 47, no. 3, pp. 757–771, 2018.
- [16] F. Jalayer and C. A. Cornell, *A Technical Framework for Probability-Based Demand and Capacity Factor Design (DCFD) Seismic Formats*, Pacific Earthquake Engineering Center (PEER), California, USA, 2003.
- [17] F. Jalayer, R. De Risi, and G. Manfredi, "Bayesian cloud analysis: efficient structural fragility assessment using linear regression," *Bulletin of Earthquake Engineering*, vol. 13, no. 4, pp. 1183–1203, 2015.
- [18] A. K. Kazantzi and D. Vamvatsikos, "Intensity measure selection for vulnerability studies of building classes," *Earthquake Engineering & Structural Dynamics*, vol. 44, no. 15, pp. 2677–2694, 2015.
- [19] E. Hossein, J. Fatemeh, L. Andrea, M. Fabrizio, and M. Gaetano, "Preliminary ranking of alternative scalar and vector intensity measures of ground shaking," *Bulletin of Earthquake Engineering*, vol. 13, pp. 2805–2840, 2015.
- [20] J. E. Padgett, B. G. Nielson, and R. DesRoches, "Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios," *Earthquake Engineering & Structural Dynamics*, vol. 37, no. 5, pp. 711–725, 2008.
- [21] M. Yakhchalian and G. Ghodrati Amiri, "A vector intensity measure to reliably predict maximum drift in low- to mid-rise buildings," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 172, no. 1, pp. 42–54, 2019.