Journal of Engineering Mechanics and Machinery (2025)
Clausius Scientific Press, Canada
DOI: 10.23977/jemm.2025.100113
ISSN 2371-9133 Vol. 10 Num. 1

Potential Damage Grading of Pulse-Like Ground Motion

Zhigang Qiu[1,*], Liwei Yang[2], Lei Xia[1], Hongyu Chen[1], Weiwei Zhu[1]

[1]*School of Architecture and Civil Engineering, Kunming University, Kunming, 650214, China*
[2]*Yunnan Earthquake Agency, Kunming, 650224, China*
**Corresponding author*

Keywords: Pulse-Like Ground Motion; Potential Damage Energy; Grading; V^2 Time-Frequency Spectrum; Vibrational Quality Participation Coefficient

Abstract: Pulse-like ground motions often cause severe structural damage or even collapse. Although there has been extensive research on the causes and parameters of their destructive nature, the parameters previously provided often contain subjective factors and can only qualitatively determine the potential damage-causing seismic motions from the motion itself (or from a simple combination with the basic period of the structure). Moreover, they have not quantitatively distinguished between pulse-like and non-Pulse-like ground motions based on specific structural characteristics, nor provided parameters to assess the potential damaging effects of different pulsating seismic motions on various structures. About 90 pulse-like seismic records were filtered from the PEER (Pacific Earthquake Engineering Research Center) seismic motion database, and based on the V^2 time-frequency response spectrum of the selected seismic records combined with the structural modal mass participation factor, the concept of Potential Damage Energy (PDE) was proposed. The pulsating seismic records were classified by intensity based on the PDE values of the selected records, thus providing a reasonable basis for selecting pulsating seismic records under different design intensity conditions for rare earthquakes.

1. Introduction

The pulse effect of near-fault earthquakes was discovered by Housner and Hudson after studying the 1957 Port Hueneme earthquake in Los Angeles, USA. They found that although the magnitude of this earthquake was only M4.7, it caused significant ground damage, with its peak ground acceleration and response spectrum values being much larger than those recorded for earthquakes of similar magnitude along the Pacific Rim [1].Historically, several famous earthquakes that caused heavy disasters to humanity (San Fernando 1971, Imperial Valley 1979, Landers 1992, Northridge 1994, Kobe 1995, Chi-Chi 1999, Wenchuan 2008) have been found to exhibit this pulse-type seismic motion. Due to the significant velocity and displacement pulses of pulse-type seismic motion, buildings can experience a high energy input that exceeds the expected design in a short period, which can easily lead to severe structural damage, hence attracting the attention of the civil engineering and seismology communities.

Iwan[2] believes that significant low-frequency pulses in the acceleration time history can lead to corresponding pulses in the velocity and displacement time histories. When structures are subjected to such seismic motions, these pulses propagate through the structure in wave form, and response spectrum analysis may not capture this pulse effect. Malhotra[3] studied the characteristics of near-fault pulse-type seismic motions and found that earthquakes with high values have a wide acceleration-sensitive zone in their response spectra, thereby increasing the demands for base shear, inter-story displacement, and ductility in tall structures. Mavroeidis[4] and others conducted a parametric analysis of the dynamic response of a single-degree-of-freedom system under near-fault seismic motions based on their proposed mathematical model and found that using the pulse period can standardize the elastic and inelastic response spectra of actual near-fault seismic motions, which helps in constructing design response spectra for near-fault seismic motions. Baker[5] proposed a method for extracting velocity pulses from earthquakes using wavelet analysis and provided three criteria for determining pulse-type seismic motions. Due to the intense pulses, large amplitudes, and rapid energy release of pulse-type seismic motions, there is a significant threat to the structural integrity of the built environment. The lack of pulse-type seismic motion data in India poses a major challenge for accurate seismic risk assessment of the built environment. An improved random finite fault method based on dynamic angular frequency was used to generate synthetic seismic motions for the 2001 Gujarat earthquake. The expected acceleration time history for specific sites, the spatial distribution of seismic motion characteristics, and the effects of site nonlinearity were studied to assess the reliability and effectiveness of simulated ground motions[6].

Landslides triggered by earthquakes threaten human life, infrastructure, and the environment. The 7.1 magnitude earthquake in Kumamoto in 2016 caused widespread landslides. At the same time, some pulse-like ground motions were discovered in the area. Research has shown that larger energy velocity pulses have a significant impact on landslides. Additionally, the study confirmed unique directional effects in the Mw 7.1 event, which further increased the likelihood of landslides. The research results will be greatly beneficial for the potential prediction of landslides in areas close to faults [7]. A method was proposed for quantitatively identifying the number of single-cycle pulses in seismic motion. Based on the relative energy of the extracted pulse signals and comprehensive evaluation indicators, the seismic motions were classified into four categories: non-pulse, single-pulse, double-pulse, and ambiguous. The statistical relationship between pulse characteristics and source parameters was discussed, including moment, site conditions, and rupture distance. Furthermore, the relationship between the first arriving pulse signal and the last arriving pulse signal in double-pulse seismic motion was studied. Finally, this method analyzed the distributions of double-pulse and single-pulse seismic motions recorded during the Chi-Chi earthquake in 1999 [8].In order to study the effects of near-field pulse-like ground motion and far-field seismic motion on the seismic performance of base-isolated buildings, a vibration table test was conducted on a half-scale base-isolated reinforced concrete frame structure. Under the maximum considered earthquake, the maximum relative errors between the tested and predicted maximum displacements of the isolation system and inter-story displacements were less than 2.1% and 3.4%, respectively. Subsequently, a numerical analysis was performed on a five-story base-isolated reinforced concrete frame building to quantitatively assess the impact of near-field pulse-like ground motion and far-field seismic motion on its seismic response and elasticity. Under the maximum considered earthquake, the maximum displacement of the isolation system and inter-story displacement ratio, as well as the maximum absolute floor acceleration of the building under pulse-like ground motion, were 1.50 times, 1.36 times, and 1.02 times, respectively, compared to far-field seismic motion [9]. The predicted displacement model based on the Newmark sliding block method has been widely applied in the assessment of landslide susceptibility induced by earthquakes. Four predictive displacement models considering the occurrence probability of pulse-like ground motion were created for sliding and non-sliding events. The results indicate that the models with pulsed ground motion have higher accuracy in non-sliding events compared to those without pulsed ground motion; however, the impact of pulsed ground motion is negligible in sliding events. This result is applicable to the risk assessment of earthquake-induced landslides and can provide a basis for post-earthquake emergency response and disaster reduction[10].

2. The potential destructive energy of pulse-like ground motion

The velocity response spectrum is a series of single degree of freedom systems with unit mass, the same damping, and different frequencies, representing the maximum value of the velocity response when subjected to an input earthquake motion. For a single degree of freedom system with a certain natural period, the kinetic energy $E_i(t)$ at time t can be expressed as:

$$E_i(t) = \frac{1}{2} m_i V_i^2(t) \tag{1}$$

Here, m_i is the mass of the single-degree-of-freedom system with an inherent period T_i, which is numerically equal to 1. $V_i(t)$ is the instantaneous velocity of the single-degree-of-freedom system at that moment t. As we can see, we can ignore the constant term and use only $V_i^2(t)$ to characterize the kinetic energy magnitude of the single degree of freedom system at time t. For a single degree of freedom system with a natural vibration period T_i, we can use formula (2) to calculate the sum of the V^2 time-frequency response spectrum values E_i over the entire duration.

$$E_i = \int_{t_s}^{t_e} V^2(t, T_i) dt \tag{2}$$

Among them, t_s and t_e are the start and end times of the seismic time history, $V^2(t,T)$ is the function of the seismic motion V^2 time-frequency response spectrum, and $V^2(t,T_i)$ is a spectral curve with a period of T_i extracted from the seismic motion V^2 time-frequency response spectrum. In engineering, structures are generally simplified into multi-degree-of-freedom systems for analysis based on the number of considered vibration modes. The cumulative kinetic energy curve defined from a single-degree-of-freedom system can be applied to multi-degree-of-freedom structures using the method of modal superposition.

The modal mass participation factors for each structural mode are different, but the modal mass participation factors considered for each mode correspond to the natural periods of each mode. Assuming a certain structure, let the number of modes considered be n, then the modal mass participation factors corresponding to the 1st to n-th natural periods are $\phi_1 \sim \phi_n$. By utilizing the participation factors $\phi_1 \sim \phi_n$ of these n modes and the cumulative kinetic energy $E_1 \sim E_n$ at the corresponding self-vibration periods from the 1st to the nth point on the cumulative kinetic energy curve, the parameter PDE can be calculated:

$$PDE = \sum_{i=1}^{n} \phi_i \cdot E_i \tag{3}$$

Due to the different numbers of vibration modes n considered by different structures, the corresponding vibrational mass participation factors vary and the periods of each mode are also different. Therefore, it can be said that the parameter PDE varies with the structure and seismic motion, having uniqueness, and can be used to assess the potential damage of seismic motion to structures. Thus, it is referred to as the potential destructive energy of seismic motion [11].

3. The potential destructive classification of pulse-like ground motion

The Potential Destructive Energy (PDE) can quantitatively reflect the potential destructiveness of seismic motion on structures. Generally, the PDE values of pulse-type seismic motions are relatively large, but the PDE values can vary significantly among different pulse-type seismic motions, sometimes by several times or even a dozen times. In rare seismic events, the impact of near-fault pulse-type seismic motion should be considered in seismic design. However, when conducting elastic-plastic time history analysis on different structures, if the selected pulse-type seismic motion happens to have a relatively small PDE value, the resulting seismic verification outcomes may not be very reliable. Even if structures are safe under smaller PDE value pulse-type seismic motion, it does not guarantee the same safety under larger PDE value seismic motion, as the failure mechanisms are different. Baker [5] proposed a method to extract velocity pulses from earthquakes using wavelet analysis and provided three criteria for determining pulse-type seismic motions. The American PEER (Pacific Earthquake Engineering Research Center) seismic motion database authenticated and filtered around 90 pulse-like seismic records from the United States and other countries based on these criteria (Tab.1).

We calculate the PDE values of each pulse type seismic motion in the above table (Table 1). Since the peak accelerations of most pulse-type seismic records are relatively close, in order to reflect the potential destructiveness of the original seismic records, the peak acceleration of each pulse-type seismic record has not been adjusted in the calculations.

Table 1 Pulse-like seismic records and their PDE

No.	Earthquake event	Time	Station	T_p	*PGV*	M_w	*PDE*
1	Imperial Valley-06	1979	AEROPUERTO MEXICALI	2.4	44.3	6.5	678.74
2	Imperial Valley-06	1979	AGRARIAS	2.3	54.4	6.5	699.02
3	Loma Prieta	1989	ALAMEDA NAS HANGAR	2.0	32.2	6.9	249.72
4	Kocaeli, Turkey	1986	ARCELIK	6.7	36.1	7.5	68.20
5	Landers	1992	BARSTOW	8.9	30.4	7.3	221.53
6	Imperial Valley-06	1979	BRAWLEY AIRPORT	4.0	36.1	6.5	897.01
7	Coalinga-07	1983	CHP	0.4	36.1	5.2	24.26
8	Chi-Chi,Taiwan,China	1999	CHY006	2.6	64.7	7.6	4629.23
9	Chi-Chi,Taiwan-03	1999	CHY024 (1)	3.2	33.1	6.2	2079.04
10	Chi-Chi,Taiwan,China	1999	CHY024 (2)	9.0	53.7	7.6	3252.02
11	Chi-Chi,Taiwan,China	1999	CHY035	1.4	42.0	7.6	573.71
12	Chi-Chi,Taiwan-03	1999	CHY080	1.4	69.9	6.2	613.79
13	Chi-Chi,Taiwan,China	1999	CHY101	4.8	85.4	7.6	897.51
14	Chi-Chi,Taiwan-06	1999	CHY101CWB	2.8	36.3	6.3	1310.66
15	Morgan Hill	1984	COYOTE LAKE DAM SW ABUT	1.0	62.3	6.2	440.60
16	Whittier Narrows-01	1987	DOWNEY	0.8	30.4	6.0	111.58
17	Imperial Valley-06	1979	EC CO CENTER FF	4.5	54.5	6.5	631.63
18	Imperial Valley-06	1979	EC MELOLAND OVERP FF	3.3	115.0	6.5	2968.00
19	Imperial Valley-06	1979	EL CENTRO ARRAY #10	4.5	46.9	6.5	873.19
20	Imperial Valley-06	1979	EL CENTRO ARRAY #11	7.4	41.1	6.5	910.77
21	Imperial Valley-06	1979	EL CENTRO ARRAY #3	5.2	41.1	6.5	1476.50
22	Imperial Valley-06	1979	EL CENTRO ARRAY #4	4.6	77.9	6.5	788.55
23	Imperial Valley-06	1979	EL CENTRO ARRAY #5	4.0	91.5	6.5	1566.31
24	Imperial Valley-06	1979	EL CENTRO ARRAY #6	3.8	111.9	6.5	2411.73
25	Imperial Valley-06	1979	EL CENTRO ARRAY #7	4.2	108.8	6.5	799.53
26	Imperial Valley-06	1979	EL CENTRO ARRAY #8	5.4	48.6	6.5	1564.81
27	Imperial Valley-06	1979	EL CENTRO DIFF ARRAY	5.9	59.6	6.5	1995.10
28	Erzican,Turkey	1992	ERZIKAN	2.7	95.4	6.7	3827.14
29	San Salvador	1986	GEOTECH INVESTIG CENTER	0.9	62.3	5.8	1253.62
30	Loma Prieta	1989	GILROY ARRAY #2	1.7	45.7	6.9	247.06
31	Coyote Lake	1979	GILROY ARRAY #6(1)	1.2	51.5	5.7	266.58
32	Morgan Hill	1984	GILROY ARRAY #6(2)	1.2	35.4	6.2	38.72

33	Imperial Valley-06	1979	HOLTVILLE POST OFFICE	4.8	55.1	6.5	937.64
34	Northridge-01	1994	JENSEN FLT PLT GEN	3.5	67.4	6.7	13449.90
35	Kobe,Japan	1995	KJM	1.0	62.0	6.9	2487.34
36	Superstition Hills	1986	KRN	1.6	31.2	6.3	365.70
37	Northridge-01	1994	LA DAM	1.7	77.1	6.7	3118.55
38	Northridge-01	1994	LA WADSWORTH VA S GND	2.4	32.4	6.7	421.51
39	Whittier Narrows-01	1987	LB-ORANGE AVE	1.0	32.9	6.0	185.69
40	Mammoth Lakes-06	1980	LONG VALLEY DAM UPR L	1.1	33.1	5.9	127.30
41	Landers	1992	LUCERNE	5.1	140.3	7.3	1181.69
42	N.Palm Springs	1986	N PALM SPR P.O.	1.4	73.6	6.1	785.78
43	Yountville	2000	NAPA FIRE STATION #3	0.7	43.0	5.0	176.06
44	Northridge-01	1994	NEWHALL	3.5	67.4	6.7	1901.45
45	Northridge-01	1994	NEWHALL-W PICO CANYON	2.4	87.8	6.7	9162.04
46	Loma Prieta	1989	OAKLAND-OUTER HARBOR WHARF #12	1.8	49.2	6.9	515.33
47	Coalinga-05	1983	OIL CITY	0.7	41.2	5.8	235.54
48	Northridge-01	1994	PACOIMA DAM (1)	0.5	50.4	6.7	328.18
49	San Fernando	1971	PACOIMA DAM (2)	1.6	116.5	6.6	3317.28
50	Northridge-01	1994	PACOIMA DAM UPPER LEFT ABUT	0.9	107.1	6.7	581.16
51	Westmorland	1981	PARACHUTE FACILITY	3.6	35.8	5.9	1602.41
52	Cape Mendocino	1992	PETROLIA	3.0	82.1	7.0	1780.23
53	Superstition Hills-02	1987	PTS	2.3	106.8	6.5	10814.30
54	Northridge-01	1994	RINALDI RECEIVING STA	1.2	167.2	6.7	3879.62
55	Loma Prieta	1989	SARATOGA ALOHA AVE	4.5	55.6	6.9	603.40
56	Irpinia,Italy-01	1980	STURNO	3.1	41.5	6.9	431.92
57	Northridge-01	1994	SYLMAR-CONVERTER STA	3.5	130.3	6.7	21535.35
58	Northridge-01	1994	SYLMAR-CONVERTER STA-EAST	3.5	116.6	6.7	6328.32
59	Northridge-01	1994	SYLMAR-HOSPITAL	3.1	122.7	6.7	6413.12
60	Kobe,Japan	1995	TAKARAZU	1.4	72.6	6.9	2235.55
61	Kobe,Japan	1995	TAKATORI	1.6	169.6	6.9	11316.27
62	Chi-Chi,Taiwan,China	1999	TAP003	3.4	33.0	7.6	4482.27
63	Chi-Chi,Taiwan,China	1999	TAP005	9.2	56.1	7.6	695.31
64	Chi-Chi,Taiwan,China	1999	TCU003	12.9	41.9	7.6	1119.87
65	Chi-Chi,Taiwan,China	1999	TCU006	10.5	60.9	7.6	158.62
66	Chi-Chi,Taiwan,China	1999	TCU010	12.9	43.5	7.6	1261.82
67	Chi-Chi,Taiwan,China	1999	TCU015	12.0	33.7	7.6	235.56
68	Chi-Chi,Taiwan,China	1999	TCU018	5.7	127.7	7.6	201.74
69	Chi-Chi,Taiwan,China	1999	TCU026	12.2	191.1	7.6	295.82
70	Chi-Chi,Taiwan,China	1999	TCU029	6.4	62.3	7.6	638.60
71	Chi-Chi,Taiwan,China	1999	TCU031	6.2	59.9	7.6	742.06
72	Chi-Chi,Taiwan,China	1999	TCU034	8.6	42.8	7.6	656.57
73	Chi-Chi,Taiwan,China	1999	TCU036	5.4	62.4	7.6	767.70
74	Chi-Chi,Taiwan,China	1999	TCU038	7.0	50.9	7.6	1356.97
75	Chi-Chi,Taiwan,China	1999	TCU039	5.1	88.4	7.6	5387.70
76	Chi-Chi,Taiwan,China	1999	TCU040	6.3	53.0	7.6	646.11
77	Chi-Chi,Taiwan,China	1999	TCU042	9.1	47.3	7.6	611.33
78	Chi-Chi,Taiwan,China	1999	TCU046	8.6	44.0	7.6	246.92
79	Chi-Chi,Taiwan,China	1999	TCU049	11.8	44.8	7.6	833.76
80	Chi-Chi,Taiwan,China	1999	TCU052	4.0	63.7	7.6	22888.29
81	Chi-Chi,Taiwan-03,China	1999	TCU076	0.9	59.4	6.2	549.46
82	Chi-Chi,Taiwan,China	1999	TCU098	7.5	32.7	7.6	1154.98
83	Chi-Chi,Taiwan,China	1999	TCU101	10.0	68.4	7.6	1984.58
84	Chi-Chi,Taiwan,China	1999	TCU102	9.7	106.6	7.6	14930.40

85	Chi-Chi,Taiwan,China	1999	TCU103	8.3	62.2	7.6	3270.54
86	Chi-Chi,Taiwan,China	1999	TCU104	12.0	31.4	7.6	939.82
87	Chi-Chi,Taiwan,China	1999	TCU128	9.0	78.7	7.6	646.90
88	Chi-Chi,Taiwan,China	1999	TCU136	10.3	51.8	7.6	528.48
89	Coalinga-05	1983	TRANSMITTER HILL	0.9	46.1	5.8	479.22
90	Landers	1992	YERMO FIRE STATION	7.5	53.2	7.3	1280.08

As can be seen from Table 1, the PDE of various pulse-type seismic motions varies significantly, with the maximum reaching 22888.29 (Chi-Chi earthquake recording station TCU052), while the minimum is only 24.26 (Coalinga-07 earthquake recording station CHP). Therefore, it is necessary to classify pulse-type seismic motions according to their PDE. Based on the maximum peak acceleration intervals used for analysing rare earthquake time histories corresponding to the intensity specified in the Chinese seismic design code [12], pulse-type seismic motions are roughly classified according to their PDE (Table 2) to meet the requirements of different seismic fortification intensity analyses for rare earthquakes.

Table 2 Pulse-like seismic records and their PDE

Design intensity	6 degrees (0.05g)	7 degrees (0.10g)	7 degrees (0.15g)	8 degrees (0.20g)	8 degrees (0.30g)	9 degrees (0.40g)
Pulse-like ground motion	$500 \le PDE < 1000$	$2000 \le PDE < 4000$	$4000 \le PDE < 6000$	$6000 \le PDE < 8000$	$8000 \le PDE < 10000$	$10000 \le PDE$

By combining Table 1 and Table 2, a reasonable selection of pulse-type seismic records can be made based on specific engineering conditions. It is not recommended to use pulse-type seismic motions with a PDE value less than 500, as their potential destructive capability is too small and is similar to non-pulse-type seismic motions, which may not fully reflect the engineering characteristics of pulse-type seismic motions under that working condition, and thus cannot provide a relatively reasonable evaluation for seismic design. Additionally, if the original seismic records are not used and instead the peak acceleration is adjusted, the corresponding PDE value will also change. The relationship between the original record PDE value and the new PDE value is:

$$PDE_{new} = \left(\frac{PGA_{new}}{PGA_{orig}} \right)^2 PDE_{orig} \tag{4}$$

In this context, PDE_{orig} and PDE_{new} represent the original earthquake record PDE and the adjusted earthquake record PDE, respectively. PDE_{orig} and PDE_{new} represent the peak ground acceleration of the original record and the peak ground acceleration of the adjusted earthquake record, respectively. The PDE value of the adjusted pulse-type earthquake record can be calculated using formula (4) and table 2, and it can also be selected according to table 2.

4. Conclusions

Pulse-like ground motions often cause severe damage or even collapse of structures. There has been extensive research on the reasons and parameters for their destructive power. However, the parameters provided in the past often contain a degree of subjectivity and can only qualitatively determine some potentially damaging seismic motions based on the seismic motion itself (or simply in relation to the basic period of the structure), without considering the specific characteristics of the structure. Furthermore, there is no quantitative distinction provided regarding parameters that differentiate between pulse-like and non-pulse-like seismic motions, nor is there information on the potential degree of damage caused by different impulse-type seismic motions to various structures.

Approximately 90 pulse-like earthquake records were selected from the PEER (Pacific

Earthquake Engineering Research Center) seismic motion database. Based on the V^2 time-frequency response spectrum of the selected earthquake records, combined with the structural modal mass participation factors, the concept of "Potential Destructive Energy (PDE)" was proposed. The Potential Destructive Energy (PDE) not only reflects the engineering characteristics of seismic motion, but it can also quantitatively predict the potential destructiveness of seismic motion by integrating the modal information of engineering structures. The PDE values of the selected earthquake records were used to classify the pulse-like earthquake records based on potential destructiveness into intensity categories, thus providing a reasonable basis for selecting pulse-like earthquake records in the event of rare earthquakes under different fortification intensity conditions.

Acknowledgements

The support of Frontier Research Team of Kunming University 2023 is gratefully acknowledged. The authors also acknowledge the financial support from the Yunnan Province Foreign Talent Introduction Special Project-Key Foreign Expert Project (Grant No. 202505AO120030). The authors also acknowledge the support of Kunming University Science and Technology Innovation Team 2020.

References

[1] Housner G W, Hudson D E. The Port Hueneme earthquake of March 18, 1957[J]. Bulletin of the Seismological Society of America, 1958, 48(2)163-168.
[2] Iwan W D. Drift spectrum measure of demand for earthquake ground motions[J]. Journal of structural engineering, 1997, 123(4)397-404.
[3] Malhotra P K. Response of buildings to near-field pulse-like ground motions[J]. Earthquake engineering & structural dynamics, 1999, 28(11)1309-1326.
[4] Mavroeidis G P, Dong G, Papageorgiou A S. Near-fault ground motions, and the response of elastic and inelastic single-degree-of-freedom (SDOF) systems[J]. Earthquake engineering & structural dynamics, 2004, 33(9):1023 - 1049.
[5] Baker J W. Quantitative classification of near-fault ground motions using wavelet analysis[J]. Bulletin of the Seismological Society of America, 2007, 97(5)1486-1501.
[6] Wani F M , Vemuri J .Simulation of pulse-like ground motions with directionality effect for the 2001 Mw 7.6 Bhuj, India earthquake and sensitivity analysis of uncertain model input parameters[J]. Soil Dynamics and Earthquake Engineering. 2024, 183(1)108-120.
[7] Li Z , Chen G , Feng X C .The influence of pulselike ground motion caused by the directivity effect on landslide triggering[J].Bulletin of engineering geology and the environment, 2024, 83(1)48.1-48.18.
[8] Feng J , Zhao B , Wang Z .Single-pulse-like and double-pulse-like characteristics of near-fault ground motions[J]. Soil dynamics and earthquake engineering, 2024, 177(Feb.)108438.1-108438.14.
[9] Wang X , Xie L , Chong X ,et al. Influence of near-field pulse-like ground motions on seismic resilience of isolated reinforced concrete frame building[J].Journal of Building Engineering, 2024, 95(000).
[10] Liu J , Zhang Y , Xu P ,et al. Predictive Displacement Models Considering the Probability of Pulse-Like Ground Motions for Earthquake-Induced Landslides Hazard Assessment[J].Journal of Earthquake Engineering, 2024, 28.
[11] Qiu Zhigang, Luo Qifeng. Potential damage energy analysis for pulse-like ground motions[J].China Civil Engineering Journal, 2014, 47(12)56-63.
[12] National Standard of the People's Republic of China. GB50011-2010 Code for seismic design of buildings[S]. Beijing China Building Industry Press,2010.