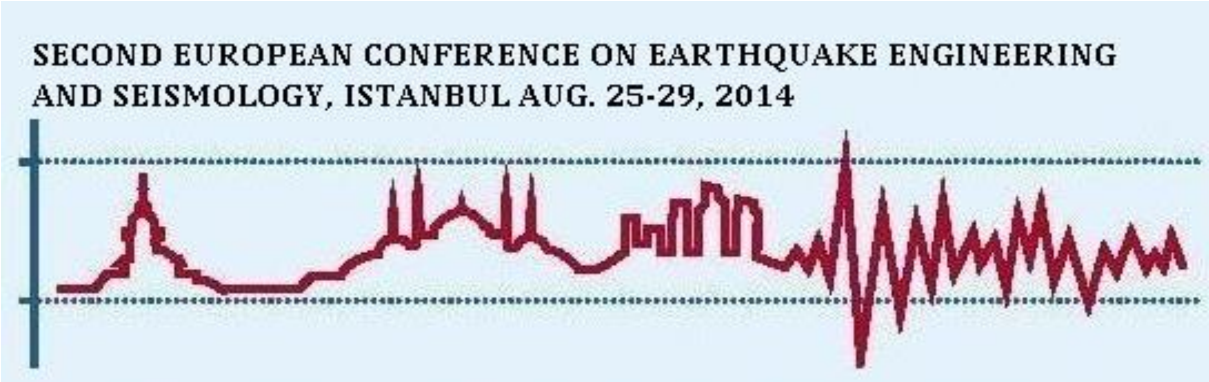

A NEW METHOD FOR THE CLASSIFICATION OF GROUND MOTIONS AS PULSE-LIKE OR NON PULSE-LIKE

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ABSTRACT

Pulse-like seismic records constitute a special category of ground motions of particular interest, since they are capable of causing significant damage to several structures. The pulses inherent in these motions are usually produced by near-field directivity effects and, more rarely, by other reasons. Up to now, the classification of a record as pulse-like has been based on the assumption that the pulse portion of the ground motion contains a significant amount of the total energy. A different approach is presented in this paper based on the value of the recently introduced parameter *CAD* (Cumulative Absolute Displacement), defined as the integral of the absolute ground velocity, compared with the spectral displacement for zero damping $S_{d,0}$ (T_p), associated with the characteristic period T_p of the inherent pulse. It is proven that, for pulse-like ground motions, the ratio $S_{d,0}(T_p)/CAD$ is around π/4, where for non pulse-like ground motions the value of the ratio is much lower. The method is applied to a total of 229 records from the NGA databasewith peak ground velocity larger than 30 cm/sec.

INTRODUCTION

The increased density of recording stations in the near fault areas has permitted the collection of near-field ground motions which present characteristics quite different from those of typical far-field ones. The main difference concerns the presence of large pulses in the ground velocity time histories, especially at sites located in the forward direction of the fault rupture, produced by the so-called 'directivity effects'. Records containing such pulses are characterized as 'pulse-like' and are of special interest in the field of engineering seismology and earthquake engineering, especially for Performance Based Design, due to their effects on the elastic and the inelastic response spectra (Bertero *et al*. 1978, Somerville 1997, 1998 & 2003, Alavi and Krawinkler 2000 & 2004, Luco and Cornell 2007, Zhai *et al*. 2007, Sehhati *et al*. 2011, Champion and Liel 2012). In what regards the elastic response spectra, directivity pulses produce a bell shaped amplification of the displacement spectra around the pulse period T_p (Shahi & Baker 2011), a feature of special interest for performance based design. As far as the inelastic spectra are concerned, the ductility is quite larger than the reduction factor for periods smaller than the pulse period (Iervolino and Cornell, 2008). As the period gets smaller, the ductility-reduction factor ratio gets larger. For periods equal or larger than the pulse period, this ratio is close to unity and the 'equal displacement' assumption holds.

It should be pointed out that, although the majority of pulse-like records containing pulses are attributed to near-fault effects (directivity pulses), significant pulses may be produced by other reasons as well, such as basin effects, soil conditions, deep rupture etc. (Rodriguez-Marek 2000, Baker 2007). In this paper, all types of pulse-like records are considered, independently of the cause of the pulse.

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Velocity pulses inherent in ground motion records are usually visible in the velocity time history. In order to identify their properties, many researchers have presented various methods to simulate or extract the significant pulse, mainly using wavelet analysis. Mavroeides and Papageorgiou (2003) proposed a very efficient model for the mathematical representation of the pulse based on the amplitude, the period, the duration and the phase shift.

Furthermore, Baker (2007) developed a new method for detecting pulses in ground motions. The procedure used wavelet-based signal processing to identify and extract the largest velocity pulse from a ground motion applying two main criteria: the pulse arrives early in the ground motion and the absolute amplitude of the velocity pulse is large. Despite the fact that the aforementioned method is simple and leads to the introduction of a pulse indicator for a quantitative classification of near-fault ground motions, some evidently pulse-like records cannot be identified. A different method for the identification of pulse-like ground motions, based on energy considerations, was introduced by Zhai *et al.* (2013). Specifically, ground motions whose dominant velocity pulses hold energy values greater than a specific amount of the total energy are classified as pulse-like. However, there are many differences between the results of the the aforementioned methods.

In the present paper, a new method for the quantitative characterization of ground motions as pulse-like or non pulse-like is presented. The method is based on the relation between the spectral response that corresponds to the period of the pulse and the recently introduced index *CAD*, which measures the characteristics of the ground motion.

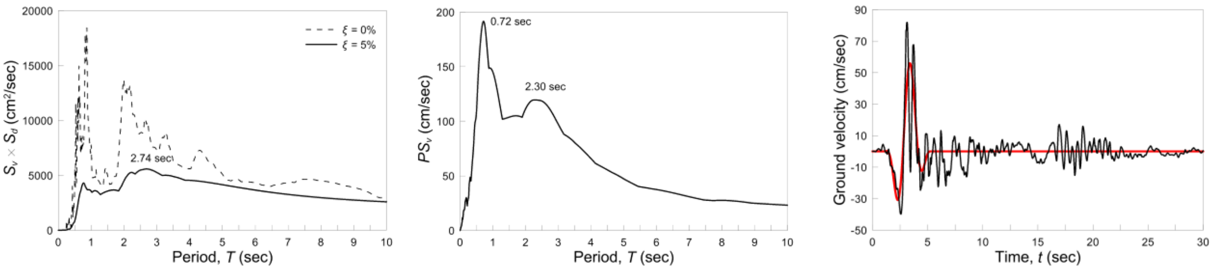
DETERMINATION OF THE PULSE PERIOD

As a common practice, the determination of the period T_p of the pulse inherent in pulse-like ground motions is based on the peak of the pseudo-velocity response spectrum for 5% damping (Alavi and Krawinkler 2000). However, the accuracy of this definition has been questioned by several researchers (Rodriguez-Marek 2000; Baker 2007).

A different method has been proposed by Zhai *et al*. (2013), called 'the peak point method'. In this case, the one cycle time interval, containing the *PGV*, between two consecutive peaks or troughs depending on whether the *PGV* has a negative or a positive sign, is considered as the pulse period.

In the present paper, a recently developed method (Mimoglou 2014) is used for the determination of the pulse period T_p. According to this method, the pulse period is determined from the peak of the product spectrum $S_d \times S_v$, where S_d is the displacement response spectrum and S_v is the velocity response spectrum, both for 5% damping. This definition is based on the observation that, since the pulse inherent in a ground motion affects both the ground acceleration and the ground velocity, to a different degree though, the pulse period T_p should prevail in the convolution integral of these two time-histories and correspond to the peak of the related Fourier spectrum. Taking into account that the undamped velocity and displacement response spectra are adequate envelopes of the Fourier spectra of the ground acceleration and the ground velocity, respectively, and that the Fourier spectrum of the convolution integral is equal to the product of the Fourier spectra of the convolved signals, the Fourier spectrum of the convolution integral can be approximated by the corresponding product of the response spectra for zero damping, $S_{v,0} \times S_{d,0}$. In the proposed method, however, it is suggested to use the response spectra for 5% damping instead of the ones for zero damping.

As an example, let us consider the normal-to-the fault component of the ground motion recorded at Petrolia during the Cape Medocino, 1992 earthquake. Application of the above-mentioned method results to T_p = 2.74 sec (Fig. 1a), a value close to the period of 3.00 sec proposed by Baker (2007). However, as shown in Fig. 1b, this value is close to the second peak of the pseudo-velocity response spectrum for 5% damping (equal to 2.30 sec) and not to the period of the largest peak (equal to 0.72 sec). In Fig. 1c, the pulse determined with the new methodology is compared with the time history of the ground velocity and it is seen that it matches well the predominant pulse inherent in the record.



(a) (b) (c)

Figure 1. Petrolia record (Cape Medocino, 1992 earthquake): (a) $S_d \times S_v$ product spectrum; (b) Pseudo-velocity response spectrum for 5% damping; (c) time history of the ground velocity and the calculated predominant pulse (taken from Mimoglou 2014).

NEW CRITERION FOR THE CLASSIFICATION OF GROUND MOTIONS

Up to now, the classification of ground motions as pulse-like or non pulse-like has been based on the assumption that the energy of a pulse-like ground motion is mostly concentrated at the duration of the pulse. This also implies that the induced structural deformation dissipates energy in a single or few hysteretic cycles.

Various criteria have been proposed by different researchers regarding this classification. Baker (2007) proposed a pulse indicator which takes into account the ratio of the Peak Ground Velocity (*PGV*) of the original record divided by the *PGV* of the residual record (i.e. the time history that is calculated by extracting the velocity pulse from the original ground motion), as well as the ratio of the energies of the original and the residual records. For the latter, the energy index is derived from the squared integral of the ground velocity. The pulse indicator takes values between 0 and 1. If the pulse indicator is larger than 0.85 the record is considered as pulse-like; if the indicator is less than 0.15 the record is classified as non pulse-like; for intermediate values the method is not efficient.

A similar indicator was proposed by Zhai *et al.* (2013), defined by the ratio between the energy contained in the velocity pulse and the total energy of the record. If this ratio is larger than 0.3 the record is classified as pulse-like. A possible handicap of this method is that it takes into account only one cycle of the velocity pulse, while the number of cycles can be larger.

A new method is proposed herein with the use of the recently introduced ground motion parameter *CAD* (Cumulative Absolute Displacement) (Taflampas *et al*. 2009) in analogy with the *CAV* (Cumulative Absolute Velocity) index (EPRI 1991). *CAD* is defined as the time integral of the absolute ground velocity, i.e.

$$CAD = \int_0^{t_{tot}} \left| v_g \right| dt \tag{1}$$

It is noticed that Baker (2007), Zhai *et al*. (2013) and Zamora and Riddell (2011) have also used similar indices, specifically the time integral of the squared acceleration (Arias 1970) and the time integral of the squared velocity (Riddell 2007) as intensity measures of the pulse-like content of the ground motion.

The proposed method is based on the observation that, for a harmonic ground motion of several cycles applied as base excitation to an undamped SDOF oscillator, there is a constant relation between the spectral displacement for zero damping at resonance and *CAD*, which can be expressed as (Mimoglou 2014):

$$\frac{S_{d,0}(T_{res})}{CAD} = \frac{\pi}{4} \tag{2}$$

Eq. (2) implies that, for ground motions characterized by velocity pulses, the displacement response spectrum for zero damping, which approximates the Fourier spectrum of the ground velocity as mentioned above, should present a large amplification around the pulse period, T_p, and the ratio of $S_{d,0}(T_p)/CAD$ should be close to $\pi/4$. On the contrary, for non pulse-like ground motions, the Fourier spectrum of the ground velocity is more flat resulting to a value of the ratio $S_{d,0}(T_p)/CAD$ quite smaller than $\pi/4$. In the calculation of this indicator, it is suggested that CAD is not calculated for the whole time duration of the ground motion, but for a smaller time interval, from $t_{\min}$ to $t_{\max}$, where $t_{\min}$ is the time of the first exceedance of the value $0.4PGV$ and $t_{\max}$ is the time of the last exceedance of $0.4PGV$, i.e.

$$CAD = \int_{t_{\min}}^{t_{\max}} \left| v_g \right| dt \tag{3}$$

It is evident from the above discussion that the ratio $S_{d,0}(T_p)/CAD$, in which $S_{d,0}(T_p)$ is the corresponding spectral displacement for zero damping for the pulse period T_p and CAD is defined according to Eq. (3), can be used as an indicator of whether a record is pulse-like or non pulse-like. As suggested by Eq. (2), the threshold for this classification should be set to a value somehow lower than $\pi/4$. Based on the comparison of the results obtained with the proposed method and the above-mentioned methods of Baker (2007) and Zhai *et al.* (2013), which is presented in the ensuing, it is suggested to set the threshold to a value close to $\pi/5$ (= 0.628).

More specifically, the proposed criterion is: if the ratio $S_{d,0}(T_p)/CAD$ is larger than 0.65, the record is characterized as pulse-like; if the ratio $S_{d,0}(T_p)/CAD$ is smaller than 0.55, the record is characterized as non pulse-like. Records in between, with $0.55 < S_{d,0}(T_p)/CAD < 0.65$, are considered ambiguous.

As an example, let us apply the proposed method to the Cape Mendocino (Petrolia), 1992 earthquake, a known pulse-like record. In this case, $t_{\min}$ = 2.4 sec and $t_{\max}$ = 3.9 sec (Fig. 2a) and application of Eq. (3) gives CAD = 75.04 cm. The pulse period, calculated from the peak of the $S_d \times S_v$ product spectrum for 5% damping, is T_p = 2.7 sec (Fig. 2b). The corresponding spectral displacement for zero damping is $S_{d,0}(T_p)$ = 64 cm. Therefore, $S_{d,0}(T_p)/CAD$ = 0.85 significantly larger than 0.65, thus the record is classified as pulse-like.

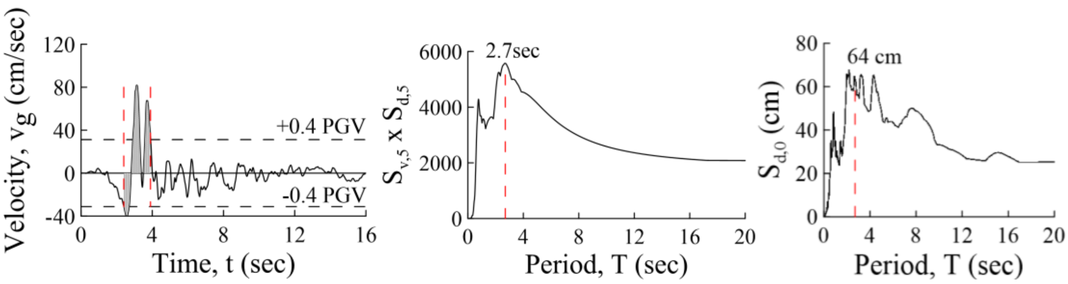


Figure 2. Cape Mendocino, 1992 earthquake: (a) time history of the ground velocity. The shaded area represents the part of the record considered in the calculation of CAD according to Eq. (3); (b) $S_d \times S_v$ product spectrum for 5% damping; (c) displacement response spectrum for zero damping.

As a second example, let us consider a non pulse-like record, specifically the CHY036 record of the Chi-Chi, 1999 earthquake. In this case, $t_{\min}$ = 27sec and $t_{\max}$ = 54sec (Fig. 3a) and application of Eq. (3) gives CAD = 235 cm. The $S_d \times S_v$ product spectrum for 5% damping peaks at T_p = 3.94 sec (Fig. 3b) and from the displacement response spectrum it is found that $S_{d,0}(T_p)$ = 116 cm. Therefore, $S_{d,0}(T_p)/CAD = 0.49 < 0.55$, thus the record is classified as non pulse-like.

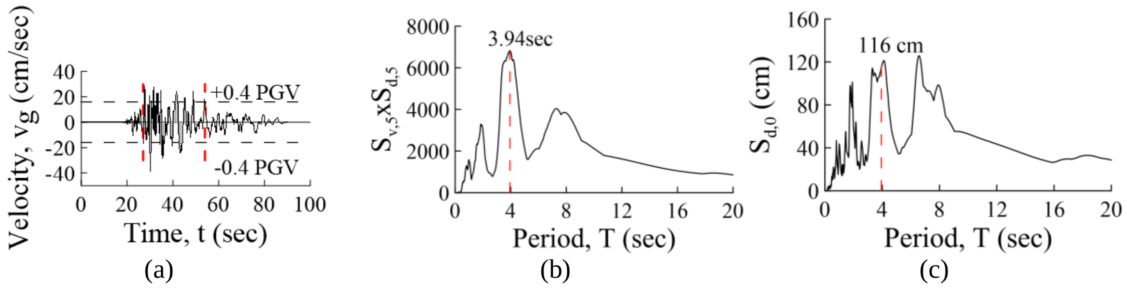


Figure 3. CHY036 record of the Chi-Chi, 1999 earthquake: (a) time history of the ground velocity; (b) $S_d{\times}S_v$ product spectrum for 5% damping; (c) displacement response spectrum for zero damping.

COMPARISON WITH OTHER METHODS

The proposed method was applied to the 91 records that were characterized as pulse-like by Baker (2007) and to a dataset of 160 records used in Zhai *et al.* (2013). The results are shown in Figures 4a and 4b, respectively, on the plane $S_{d,0}(T_p) – CAD$, in which black dots correspond to pulse-like records and grey crosses to non pulse-like ones according to the classification given in the original papers. On the same figures, the lines corresponding to the thresholds of the proposed method, $S_{d,0}(T_p)/CAD$ = 0.55 and $S_{d,0}(T_p)/CAD$ = 0.65, are drawn. The line that corresponds to $S_{d,0}(T_p)/CAD = \pi/4$ is also drawn for comparison.

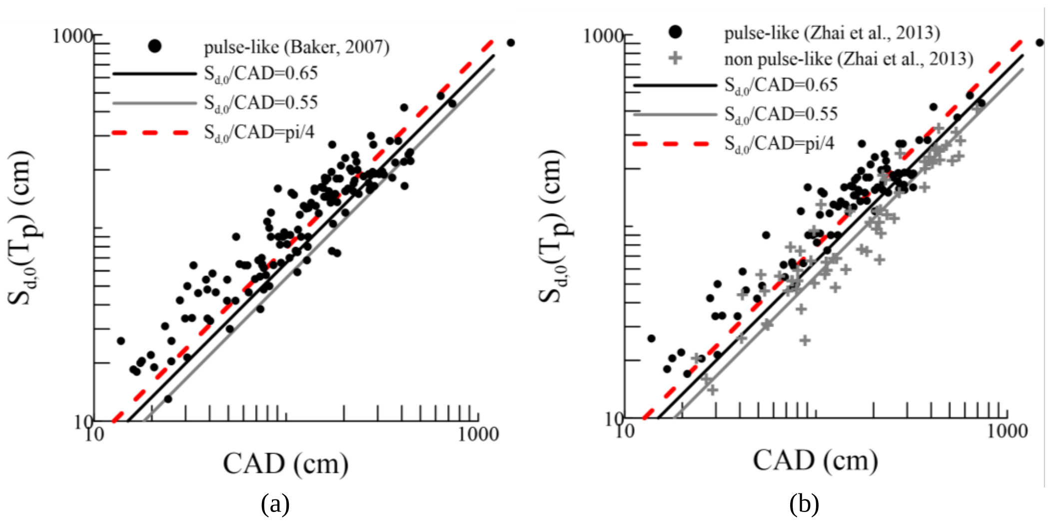


Figure 4. $S_{d,0}(T_p)$ vs *CAD* for the records considered in (a) Baker (2007) and (b) Zhai *et al.* (2013). Black dots correspond to pulse-like records and grey crosses to non pulse-like ones according to the classification given in the original papers.

It is seen that, in most cases, black dots lie on top of the line $S_{d,0}(T_p)/CAD$ = 0.65 and grey crosses lie under the line $S_{d,0}(T_p)/CAD$ = 0.55. There are only few cases in which the proposed classification clearly contradicts the results of Baker and Zhai *et al.*Two examples of such cases are shown in Fig. 5, for the Hollister City Hall (Fig. 5a) and the Sunnyvale – Colton Ave. (Fig. 5b) records of the Loma Prieta, 1989 earthquake, which have been characterized as non pulse-like by Zhai *et al*. and are not mentioned in Baker (2007) as pulse-like. For these records, the ratios $S_{d,0}(T_p)/CAD$ are 1.22 and 0.76 respectively, larger than 0.65 in both cases, therefore the records are classified as pulse-like according to the proposed method. These records, evidently contain significant pulses, as can be seen from the time histories of the ground velocity shown in Fig. 5.

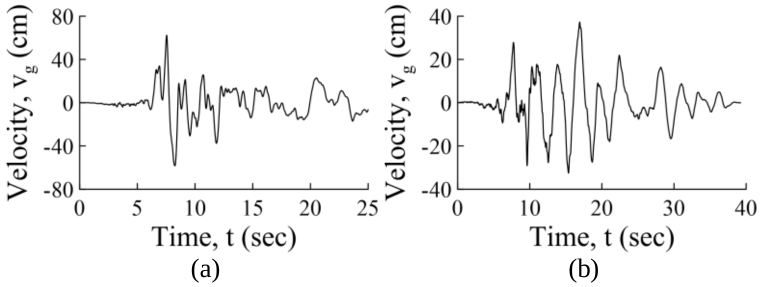


Figure 5. Time histories of the ground velocity of the records: (a) Hollister City Hall and (b) Sunnyvale – Colton Ave. of the Loma Prieta, 1989 earthquake.

APPLICATION TO A WIDE DATASET

The application of the proposed method was extended to a total of 229 records with *PGV* > 30 cm/sec from the PEER-NGA strong motion database. The time histories of the fault-normal components are used. The results are shown in Fig. 6 where two clearly distinguishable regions for pulse-like and non pulse-like ground motions can be observed. Specifically, according to the proposed classification 143 records are classified as pulse-like, 43 as non pulse-like and 43 as ambiguous. The results are tabulated in Tables 1 to 3.

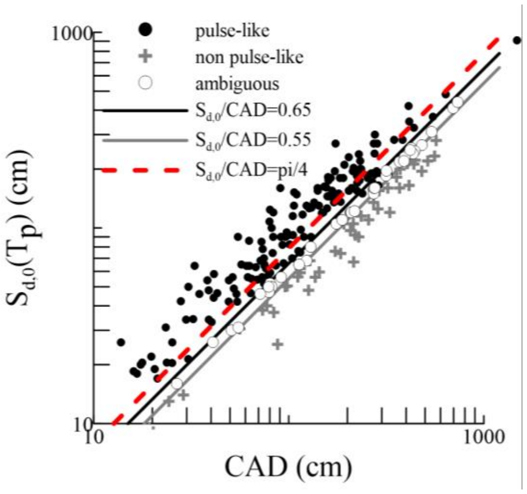


Figure 6. Classification of the 229 records considered according to the proposed method.

Table 1. Pulse-like records

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
1	77	San Fernando	1971	Pacoima Dam (upper left abut)	6.61	1.81
2	126	Gazli, USSR	1976	Karakyr	6.80	5.46
3	143	Tabas, Iran	1978	Tabas	7.35	2.05
4	150	Coyote Lake	1979	Gilroy Array #6	5.74	3.11
5	158	Imperial Valley-06	1979	Aeropuerto Mexicali	6.53	0.34
6	159	Imperial Valley-06	1979	Agrarias	6.53	0.65
7	161	Imperial Valley-06	1979	Brawley Airport	6.53	10.42
8	170	Imperial Valley-06	1979	EC County Center FF	6.53	7.31
9	171	Imperial Valley-06	1979	EC Meloland Overpass FF	6.53	0.07
10	173	Imperial Valley-06	1979	El Centro Array #10	6.53	6.17
11	174	Imperial Valley-06	1979	El Centro Array #11	6.53	12.45
12	178	Imperial Valley-06	1979	El Centro Array #3	6.53	12.85
13	179	Imperial Valley-06	1979	El Centro Array #4	6.53	7.05

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
14	180	Imperial Valley-06	1979	El Centro Array #5	6.53	3.95
15	181	Imperial Valley-06	1979	El Centro Array #6	6.53	1.35
16	182	Imperial Valley-06	1979	El Centro Array #7	6.53	0.56
17	183	Imperial Valley-06	1979	El Centro Array #8	6.53	3.86
18	184	Imperial Valley-06	1979	El Centro Differential Array	6.53	5.09
19	185	Imperial Valley-06	1979	Holtville Post Office	6.53	7.65
20	250	Mammoth Lakes-06	1980	Long Valley Dam (Upr L Abut)	5.94	
21	292	Irpinia, Italy-01	1980	Sturno	6.90	10.84
22	316	Westmorland	1981	Parachute Test Site	5.90	16.66
23	338	Coalinga-01	1983	Parkfield - Fault Zone 14	6.36	29.48
24	407	Coalinga-05	1983	Oil City	5.77	
25	415	Coalinga-05	1983	Transmitter Hill	5.77	
26	418	Coalinga-07	1983	Coalinga-14th & Elm (Old CHP)	5.21	
27	451	Morgan Hill	1984	Coyote Lake Dam (SW Abut)	6.19	0.53
28	459	Morgan Hill	1984	Gilroy Array #6	6.19	9.86
29	495	Nahanni, Canada	1985	Site 1	6.76	9.60
30	496	Nahanni, Canada	1985	Site 2	6.76	4.93
31	503	Taiwan SMART1(40)	1986	SMART1 C00	6.32	
32	508	Taiwan SMART1(40)	1986	SMART1 M07	6.32	
33	527	N. Palm Springs	1986	Morongo Valley	6.06	12.07
34	529	N. Palm Springs	1986	North Palm Springs	6.06	4.04
35	568	San Salvador	1986	Geotech Investig Center	5.80	6.30
36	569	San Salvador	1986	National Geografical Inst	5.80	6.99
37	585	Baja California	1987	Cerro Prieto	5.50	
38	615	Whittier Narrows-01	1987	Downey - Co Maint Bldg	5.99	20.82
39	645	Whittier Narrows-01	1987	LB - Orange Ave	5.99	24.54
40	723	Superstition Hills-02	1987	Parachute Test Site	6.54	0.95
41	723	Superstition Hills-02	1987	Parachute Test Site	6.54	0.95
42	738	Loma Prieta	1989	Alameda Naval Air Stn Hanger	6.93	71.00
43	753	Loma Prieta	1989	Corralitos	6.93	3.85
44	758	Loma Prieta	1989	Emeryville - 6363 Christie	6.93	76.97
45	764	Loma Prieta	1989	Gilroy - Historic Bldg.	6.93	10.97
46	766	Loma Prieta	1989	Gilroy Array #2	6.93	11.07
47	767	Loma Prieta	1989	Gilroy Array #3	6.93	12.82
48	768	Loma Prieta	1989	Gilroy Array #4	6.93	14.34
49	776	Loma Prieta	1989	Hollister - South & Pine	6.93	27.93
50	777	Loma Prieta	1989	Hollister City Hall	6.93	27.60
51	778	Loma Prieta	1989	Hollister Diff. Array	6.93	24.82
52	779	Loma Prieta	1989	LGPC	6.93	3.88
53	783	Loma Prieta	1989	Oakland - Outer Harbor Wharf	6.93	74.26
54	787	Loma Prieta	1989	Palo Alto - SLAC Lab	6.93	30.86
55	802	Loma Prieta	1989	Saratoga - Aloha Ave	6.93	8.50
56	803	Loma Prieta	1989	Saratoga - W Valley Coll.	6.93	9.31
57	806	Loma Prieta	1989	Sunnyvale - Colton Ave.	6.93	24.23
58	821	Erzican, Turkey	1992	Erzincan	6.69	4.38
59	825	Cape Mendocino	1992	Cape Mendocino	7.01	6.96
60	828	Cape Mendocino	1992	Petrolia	7.01	8.18
61	829	Cape Mendocino	1992	Rio Dell Overpass - FF	7.01	14.33
62	838	Landers	1992	Barstow	7.28	34.86
63	848	Landers	1992	Coolwater	7.28	19.74
64	900	Landers	1992	Yermo Fire Station	7.28	23.62
65	952	Northridge-01	1994	Beverly Hills - 12520 Mulhol	6.69	18.36
66	959	Northridge-01	1994	Canoga Park - Topanga Can	6.69	14.70
67	963	Northridge-01	1994	Castaic - Old Ridge Route	6.69	20.72

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
68	982	Northridge-01	1994	Jensen Filter Plant	6.69	5.43
69	983	Northridge-01	1994	Jensen Filter Plant Generator	6.69	5.43
70	1003	Northridge-01	1994	LA - Saturn St	6.69	27.01
71	1004	Northridge-01	1994	LA - Sepulveda VA Hospital	6.69	8.44
72	1009	Northridge-01	1994	LA - Wadsworth VA Hospital North	6.69	23.60
73	1012	Northridge-01	1994	LA 00	6.69	19.07
74	1013	Northridge-01	1994	LA Dam	6.69	5.92
75	1044	Northridge-01	1994	Newhall - Fire Sta	6.69	5.92
76	1045	Northridge-01	1994	Newhall - W Pico Canyon Rd.	6.69	5.48
77	1050	Northridge-01	1994	Pacoima Dam (downstr)	6.69	7.01
78	1051	Northridge-01	1994	Pacoima Dam (upper left)	6.69	7.01
79	1052	Northridge-01	1994	Pacoima Kagel Canyon	6.69	7.26
80	1054	Northridge-01	1994	Pardee - SCE	6.69	7.46
81	1063	Northridge-01	1994	Rinaldi Receiving Sta	6.69	6.50
82	1077	Northridge-01	1994	Santa Monica City Hall	6.69	26.45
83	1080	Northridge-01	1994	Simi Valley - Katherine Rd	6.69	13.42
84	1084	Northridge-01	1994	Sylmar - Converter Sta	6.69	5.35
85	1085	Northridge-01	1994	Sylmar - Converter Sta East	6.69	5.19
86	1086	Northridge-01	1994	Sylmar - Olive View Med FF	6.69	5.30
87	1116	Kobe, Japan	1995	Shin-Osaka	6.90	19.15
88	1120	Kobe, Japan	1995	Takatori	6.90	1.47
89	1158	Kocaeli, Turkey	1999	Duzce	7.51	15.37
90	1161	Kocaeli, Turkey	1999	Gebze	7.51	10.92
91	1182	Chi-Chi, Taiwan	1999	CHY006	7.62	9.77
92	1193	Chi-Chi, Taiwan	1999	CHY024	7.62	9.64
93	1194	Chi-Chi, Taiwan	1999	CHY025	7.62	19.09
94	1198	Chi-Chi, Taiwan	1999	CHY029	7.62	10.97
95	1201	Chi-Chi, Taiwan	1999	CHY034	7.62	14.82
96	1202	Chi-Chi, Taiwan	1999	CHY035	7.62	12.65
97	1231	Chi-Chi, Taiwan	1999	CHY080	7.62	2.69
98	1244	Chi-Chi, Taiwan	1999	CHY101	7.62	9.96
99	1403	Chi-Chi, Taiwan	1999	NSY	7.62	13.15
100	1410	Chi-Chi, Taiwan	1999	TAP003	7.62	102.39
101	1471	Chi-Chi, Taiwan	1999	TCU015	7.62	49.81
102	1472	Chi-Chi, Taiwan	1999	TCU017	7.62	54.28
103	1475	Chi-Chi, Taiwan	1999	TCU026	7.62	56.12
104	1476	Chi-Chi, Taiwan	1999	TCU029	7.62	28.05
105	1479	Chi-Chi, Taiwan	1999	TCU034	7.62	35.69
106	1482	Chi-Chi, Taiwan	1999	TCU039	7.62	19.90
107	1483	Chi-Chi, Taiwan	1999	TCU040	7.62	22.08
108	1484	Chi-Chi, Taiwan	1999	TCU042	7.62	26.32
109	1485	Chi-Chi, Taiwan	1999	TCU045	7.62	26.00
110	1486	Chi-Chi, Taiwan	1999	TCU046	7.62	16.74
111	1487	Chi-Chi, Taiwan	1999	TCU047	7.62	35.00
112	1489	Chi-Chi, Taiwan	1999	TCU049	7.62	3.78
113	1491	Chi-Chi, Taiwan	1999	TCU051	7.62	7.66
114	1493	Chi-Chi, Taiwan	1999	TCU053	7.62	5.97
115	1494	Chi-Chi, Taiwan	1999	TCU054	7.62	5.30
116	1496	Chi-Chi, Taiwan	1999	TCU056	7.62	10.50
117	1503	Chi-Chi, Taiwan	1999	TCU065	7.62	0.59
118	1510	Chi-Chi, Taiwan	1999	TCU075	7.62	0.91
119	1511	Chi-Chi, Taiwan	1999	TCU076	7.62	2.76
120	1513	Chi-Chi, Taiwan	1999	TCU079	7.62	10.97
121	1515	Chi-Chi, Taiwan	1999	TCU082	7.62	5.18

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
122	1519	Chi-Chi, Taiwan	1999	TCU087	7.62	7.00
123	1523	Chi-Chi, Taiwan	1999	TCU094	7.62	54.53
124	1528	Chi-Chi, Taiwan	1999	TCU101	7.62	2.13
125	1529	Chi-Chi, Taiwan	1999	TCU102	7.62	1.51
126	1530	Chi-Chi, Taiwan	1999	TCU103	7.62	6.10
127	1532	Chi-Chi, Taiwan	1999	TCU105	7.62	17.18
128	1542	Chi-Chi, Taiwan	1999	TCU117	7.62	25.44
129	1545	Chi-Chi, Taiwan	1999	TCU120	7.62	7.41
130	1548	Chi-Chi, Taiwan	1999	TCU128	7.62	13.15
131	1550	Chi-Chi, Taiwan	1999	TCU136	7.62	8.29
132	1595	Chi-Chi, Taiwan	1999	WGK	7.62	9.96
133	1596	Chi-Chi, Taiwan	1999	WNT	7.62	1.84
134	1605	Duzce, Turkey	1999	Duzce	7.14	6.58
135	1629	St Elias, Alaska	1979	Yakutat	7.54	80.00
136	1634	Manjil, Iran	1990	Abhar	7.37	75.58
137	1752	Northwest China-03	1997	Jiashi	6.10	
138	1853	Yountville	2000	Napa Fire Station #3	5.00	
139	2457	Chi-Chi, Taiwan-03	1999	CHY024	6.20	19.65
140	2495	Chi-Chi, Taiwan-03	1999	CHY080	6.20	22.37
141	2627	Chi-Chi, Taiwan-03	1999	TCU076	6.20	14.66
142	3317	Chi-Chi, Taiwan-06	1999	CHY101	6.30	35.97
143	3548	Loma Prieta	1989	Los Gatos - Lexington Dam	6.93	5.02

Table 2. Non pulse-like records

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
1	6	Imperial Valley-02	1940	El Centro Array #9	6.95	6.09
2	160	Imperial Valley-06	1979	Bonds Corner	6.53	2.68
3	368	Coalinga-01	1983	Pleasant Valley P.P. - yard	6.36	8.41
4	558	Chalfant Valley-02	1986	Zack Brothers Ranch	6.19	7.58
5	725	Superstition Hills-02	1987	Poe Road (temp)	6.54	11.16
6	729	Superstition Hills-02	1987	Wildlife Liquef. Array	6.54	23.85
7	765	Loma Prieta	1989	Gilroy Array #1	6.93	9.64
8	864	Landers	1992	Joshua Tree	7.28	11.03
9	901	Big Bear-01	1992	Big Bear Lake - Civic Center	6.46	
10	949	Northridge-01	1994	Arleta - Nordhoff Fire Sta	6.69	8.66
11	1048	Northridge-01	1994	Northridge - 17645 Saticoy St	6.69	12.09
12	1082	Northridge-01	1994	Sun Valley - Roscoe Blvd	6.69	10.05
13	1087	Northridge-01	1994	Tarzana - Cedar Hill A	6.69	15.60
14	1106	Kobe, Japan	1995	KJMA	6.90	0.96
15	1111	Kobe, Japan	1995	Nishi-Akashi	6.90	7.08
16	1141	Dinar, Turkey	1995	Dinar	6.40	3.36
17	1176	Kocaeli, Turkey	1999	Yarimca	7.51	4.83
18	1180	Chi-Chi, Taiwan	1999	CHY002	7.62	24.98
19	1197	Chi-Chi, Taiwan	1999	CHY028	7.62	3.14
20	1203	Chi-Chi, Taiwan	1999	CHY036	7.62	16.06
21	1463	Chi-Chi, Taiwan	1999	TCU003	7.62	86.57
22	1478	Chi-Chi, Taiwan	1999	TCU033	7.62	40.89
23	1488	Chi-Chi, Taiwan	1999	TCU048	7.62	13.55
24	1495	Chi-Chi, Taiwan	1999	TCU055	7.62	6.36
25	1500	Chi-Chi, Taiwan	1999	TCU061	7.62	17.19
26	1501	Chi-Chi, Taiwan	1999	TCU063	7.62	9.80
27	1507	Chi-Chi, Taiwan	1999	TCU071	7.62	5.31
28	1509	Chi-Chi, Taiwan	1999	TCU074	7.62	13.46
29	1517	Chi-Chi, Taiwan	1999	TCU084	7.62	11.24

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
30	1521	Chi-Chi, Taiwan	1999	TCU089	7.62	8.88
31	1527	Chi-Chi, Taiwan	1999	TCU100	7.62	11.39
32	1533	Chi-Chi, Taiwan	1999	TCU106	7.62	14.99
33	1534	Chi-Chi, Taiwan	1999	TCU107	7.62	16.01
34	1535	Chi-Chi, Taiwan	1999	TCU109	7.62	13.08
35	1536	Chi-Chi, Taiwan	1999	TCU110	7.62	11.60
36	1538	Chi-Chi, Taiwan	1999	TCU112	7.62	27.50
37	1543	Chi-Chi, Taiwan	1999	TCU118	7.62	26.84
38	1547	Chi-Chi, Taiwan	1999	TCU123	7.62	14.93
39	1549	Chi-Chi, Taiwan	1999	TCU129	7.62	1.84
40	1551	Chi-Chi, Taiwan	1999	TCU138	7.62	9.79
41	1602	Duzce, Turkey	1999	Bolu	7.14	12.04
42	2734	Chi-Chi, Taiwan-04	1999	CHY074	6.20	6.20
43	3474	Chi-Chi, Taiwan-06	1999	TCU079	6.30	10.05

Table 3. Records characterized as ambiguous

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
1	319	Westmorland	1981	Westmorland Fire Sta	5.90	6.50
2	540	N. Palm Springs	1986	Whitewater Trout Farm	6.06	6.04
3	721	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	18.20
4	727	Superstition Hills-02	1987	Superstition Mtn Camera	6.54	5.61
5	741	Loma Prieta	1989	BRAN	6.93	10.72
6	752	Loma Prieta	1989	Capitola	6.93	15.23
7	759	Loma Prieta	1989	Foster City - APEEL 1	6.93	43.94
8	811	Loma Prieta	1989	WAHO	6.93	17.47
9	879	Landers	1992	Lucerne	7.28	2.19
10	953	Northridge-01	1994	Beverly Hills - 14145 Mulhol	6.69	17.15
11	960	Northridge-01	1994	Canyon Country - W Lost Cany	6.69	12.44
12	1080	Northridge-01	1994	Simi Valley - Katherine Rd	6.69	13.42
13	1119	Kobe, Japan	1995	Takarazuka	6.90	0.27
14	1147	Kocaeli, Turkey	1999	Ambarli	7.51	69.62
15	1195	Chi-Chi, Taiwan	1999	CHY026	7.62	29.53
16	1238	Chi-Chi, Taiwan	1999	CHY092	7.62	22.70
17	1246	Chi-Chi, Taiwan	1999	CHY104	7.62	18.04
18	1462	Chi-Chi, Taiwan	1999	TCU	7.62	5.18
19	1477	Chi-Chi, Taiwan	1999	TCU031	7.62	30.18
20	1480	Chi-Chi, Taiwan	1999	TCU036	7.62	19.84
21	1481	Chi-Chi, Taiwan	1999	TCU038	7.62	25.44
22	1490	Chi-Chi, Taiwan	1999	TCU050	7.62	9.51
23	1492	Chi-Chi, Taiwan	1999	TCU052	7.62	0.66
24	1497	Chi-Chi, Taiwan	1999	TCU057	7.62	11.84
25	1498	Chi-Chi, Taiwan	1999	TCU059	7.62	17.13
26	1499	Chi-Chi, Taiwan	1999	TCU060	7.62	8.53
27	1502	Chi-Chi, Taiwan	1999	TCU064	7.62	16.62
28	1504	Chi-Chi, Taiwan	1999	TCU067	7.62	0.64
29	1505	Chi-Chi, Taiwan	1999	TCU068	7.62	0.32
30	1506	Chi-Chi, Taiwan	1999	TCU070	7.62	19.02
31	1508	Chi-Chi, Taiwan	1999	TCU072	7.62	7.03
32	1512	Chi-Chi, Taiwan	1999	TCU078	7.62	8.20
33	1514	Chi-Chi, Taiwan	1999	TCU081	7.62	55.49
34	1526	Chi-Chi, Taiwan	1999	TCU098	7.62	47.67
35	1531	Chi-Chi, Taiwan	1999	TCU104	7.62	12.89
36	1537	Chi-Chi, Taiwan	1999	TCU111	7.62	22.14
37	1540	Chi-Chi, Taiwan	1999	TCU115	7.62	21.78
38	1541	Chi-Chi, Taiwan	1999	TCU116	7.62	12.40

No.	NGA No.	Earthquake Name	Year	Station	M_w	Closest dist. (km)
39	1546	Chi-Chi, Taiwan	1999	TCU122	7.62	9.35
40	1553	Chi-Chi, Taiwan	1999	TCU141	7.62	24.21
41	1633	Manjil, Iran	1990	Abbar	7.37	12.56
42	1787	Hector Mine	1999	Hector	7.13	11.66
43	2114	Denali, Alaska	2002	TAPS Pump Station #10	7.90	2.74

CONCLUSIONS

A new methodology is proposed for the classification of ground motions as pulse-like or non pulse-like. The method is based on the value of the ratio $S_{d,0}(T_p)/CAD$, with $S_{d,0}(T_p)$ being the spectral displacement for zero damping that corresponds to the period of the pulse, T_p, and CAD being the recently introduced Cumulative Absolute Displacement index calculated for the time interval between the first and the last exceedance of the value $0.4PGV$ by the ground velocity. The period of the pulse is determined using a new approach, specifically from the peak of the $S_d \times S_v$ product spectrum for 5% damping.

The upper and lower thresholds for this classification are set to 0.65 and 0.55, respectively. These values are based on the observation that, for a harmonic ground motion applied as base excitation to an undamped SDOF oscillator, the ratio $S_{d,0}(T_{res})/CAD$ at resonance is equal to $\pi/4$. Thus, if the ratio $S_{d,0}(T_p)/CAD$ is larger than 0.65 the record is characterized as pulse-like, while, if it is smaller than 0.55 the record is characterized as non pulse-like. Records in between, with $0.55 < S_{d,0}(T_p)/CAD < 0.65$, are considered ambiguous.

The new approach compares well with previously proposed methods by other researchers and seems to lead to more rational results in case of differences. The new method was applied to 229 records with $PGV > 30$ cm/sec from the PEER-NGA database and 143 records were classified as pulse-like, 43 as non pulse-like and 43 as ambiguous.

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